GAME RANCHING IN MACHAKOS DISTRICT, KENYA: AN APPLICATION OF MATHEMATICAL PROGRAMMING TO THE STUDY OF WILDLIFE POLICY

by

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Abstract

This study employed a bioeconomic, mathematical programming model to analyse ranch resources allocation among cattle and game animals, and Kenya's wildlife conservation and game harvesting policies. The objective function was comprised of discounted net income flows over 30 periods of 6–months each (15 years) and was optimised subject to the population dynamics (modeled as logistic growth functions), initial animal populations and institutional constraints (Kenya Wildlife Service policies). Game animal harvests were modelled as decay functions, while carrying capacity in the logistic growth models is a function of rainfall. Cattle population is modelled as a linear difference equation.

Simulation results show that abandoning the earlier preservation policy that placed the burden of wildlife conservation on private landowners was a good decision. If continued, the pre–1989 game animal preservation policy would likely not only dissipate available rent, but also extinguish non–competitive animal species, thus making this policy economically unfavorable and biologically unsustainable. After 1989, ranchers were granted (limited) user rights to wildlife, but wildlife ownership continued to reside with the Kenya Wildlife Service (KWS). In this study various ways in which KWS could exercise ownership are examined. The objectives of KWS are to conserve wildlife ungulates while providing appropriate economic incentives to ranchers. The current policy of attaining this objective is by allowing ranchers to harvest a given proportion of the game populations. Simulation results indicate that this policy is non–optimal and only marginally sustainable. When a Shannon biodiversity index is used as a constraint, game conservation was also found to be unsuitable. The biodiversity index can be attained at very low population levels, making its sustainability questionable. A better alternative is constraining the end–period populations to be equal to or greater than initial populations. This policy yields a reasonable net return and is unambiguously sustainable. The best policy, however, combines the

end–period constraint with a policy that gives landowners full property rights. Ranchers can use animals in any way they wish. This approach yields a much higher net return than any other policy and is also unambiguously sustainable. A summary of simulation results is provided in the following table.

Policy simulation	Net discounted return (mil. KS)	Mean Numbers (AUs)	Carrying capacity (ha AU^{-1})	Effect on wildlife herbivore populations
Unconstrained	136.1	1959	4.13	Game populations driven to extinction or near extinction in the final two periods
Preservation	100.15	2334	3.47	Some wildlife herbivore populations driven to extinction due to competition from other animals, including cattle.
End–period population constraint	131.04	1935	4.19	Sustainable
Maintain biodiversity measure, *S*=0.615	134.31	1925	4.21	Sustainable; numbers similar to the end–period population constraint policy, except rapid harvest in final year
KWS harvest rate	111.54	2201	3.68	Sustainability threatened
Full property rights	133.24	1934	4.19	Sustainable; differs from end–period population constraint policy by net return
Drought	124.18	1672	4.84	Sustainable, but only due to end–period constraint that final populations are at least 0.5 of initial population

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Daniel G. Irungu and Raphael M. Irungu and my daughters,

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CHAPTER 1

INTRODUCTION

1.1 Background

The Republic of Kenya is located on the eastern seaboard of Africa, straddling the equator, and has a total land area of 569,260 km^2. The agricultural productivity of this land is, to a large extent, determined by availability of moisture, although soils and topography are important. Based on moisture availability, the land is categorised into six eco-climatic zones (Table 1.1).

The eco–climatic zones vary in climate, agricultural potential and land–use. Eco–climatic zone 1 has an afro-alpine climate with scattered moorland and grassland vegetation.[1] Due to harsh environmental conditions, it has no potential for agriculture but is used as a water catchment area and, due to its scenic beauty, for tourism. Eco–climatic zone 2 has a humid to dry sub-humid climate with a forest (and its derivatives) vegetation. It has high agricultural potential and is used mainly for intensive agriculture, including cash crop farming. Eco–climatic zone 3 has a dry sub-humid to semi-arid climate with a moist woodland, bushland or savanna vegetation. It has medium agricultural potential and is used for mixed crop and livestock production. Eco–climatic zone 4 has a semi-arid climate with a dry form of woodland and savanna vegetation. It has marginal agricultural potential but high rangeland potential and is used for livestock operations and wildlife conservation. Eco–climatic zone 5 has an arid climate with a dry thorn-bushland vegetation. It has low agricultural potential but medium rangeland potential and is used for extensive livestock operations and wildlife conservation. Eco–climatic zone 6 has a very arid climate with a dwarf shrub annual grassland or shrub annual grassland vegetation. It has very

[1]This eco–climatic zone is found at elevations above 3200 metres where climate is governed by temperature rather than moisture.

low agricultural potential and low rangeland potential and is used for extensive livestock operations and wildlife conservation.

From the above eco–climatic zonation, the largest portion of Kenya's land resource is classified as rangelands—a term that, in an East African context, refers to land with natural or semi-natural vegetation that provides habitat suitable for herds of wild or domestic ungulates (Pratt and Gwynne 1977). These lands constitute 87% of the total land area and are comprised of eco–climate zones 4, 5 and 6, and a portion of eco–climatic zone 3 that has a mean annual rainfall of less than 900 mm; this is the limit of sustainable arable cropping (Brown 1963). On account of their large area, these lands have an important role to play in Kenya's economy. Their main uses are livestock production and wildlife conservation as demonstrated by livestock and wildlife numbers, and species richness in 15 rangeland districts (Table 1.2).[2]

Table 1.1: Eco-climatic Zones of Kenya: Moisture and Livestock Carrying Capacity

Eco-climatic zone	Area (km^2)	Mean annual Precipitation (mm)	Moisture index[a]	Livestock carrying capacity (ha/animal unit)
Ecozone 1	800	n/a[b]	n/a[b]	-
Ecozone 2	53,000	1250 to 2500	> -10	0.8
Ecozone 3	53,000	750 to 1250	-10 to -30	1.6
Ecozone 4	53,000	450 to 750	-30 to -42	4.0
Ecozone 5	300,000	225 to 450	-42 to -51	12.0
Ecozone 6	112,000	<225	-52 to -57	42.0

Source: Maitha and Senga (1976); Pratt and Gwynne (1977); Jahnke (1982)
[a] Moisture index of zero is equated to 1500 mm of rainfall while moisture index of –60 is equated to 0 mm of rainfall.
[b] This eco–climatic zone is found at elevations above 3200 metres where climate is governed by temperature rather than moisture.

[2]Populations were recorded from a range area of 427,224km^2 comprised of fifteen districts, namely, Baringo, Garissa, Isiolo, Kilifi, Laikipia, Lamu, Marsabit, Narok, Samburu, Tana River, Turkana, Wajir, West Pokot, Kajiado and Mandera.

Table 1.2: Major Domestic and Wild Herbivorous Species in Kenya's Rangelands: Estimated Numbers and Density for 1989

Animal species	Number	Density (Animals/km^2)	Animal species	Number	Density (Animals/km^2)
Cattle	2,902,093	6.7929	Oryx	24,152	0.0565
Sheep and goat	6,547,441	15.3256	Ostrich	23,962	0.0561
Camel	586,454	1.3727	Gerenuk	23,464	0.0549
Donkey	110,876	0.2595	Eland	12,897	0.0302
Burchella zebra	127,879	0.2993	Warthog	10,624	0.0249
Grant's gazelle	121,216	0.2837	Kongoni	9,544	0.0223
Thomson's gazelle	106,572	0.2495	Waterbuck	7,492	0.0175
Impala	103,832	0.2430	Elephant	7,464	0.0175
Topi	102,503	0.2399	Lesser kudu	5,488	0.0128
Wildebeest	67,619	0.1583	Grevy zebra	4,276	0.0100
Giraffe	40,291	0.0943	Hunter's hartbeest	1,911	0.0045
Buffalo	31,363	0.0734	Greater kudu	160	0.0004

Source: Government of Kenya (1989)

The livestock production in Kenya's rangelands operates under various extensive forms referred to as range livestock production systems. These incorporate different livestock species, different livestock products, different livestock functions and different management principles. Depending on their production characteristics, the range–livestock production systems are broadly grouped into pastoral range–livestock production systems and ranching systems (Jahnke 1982).

The pastoral range–livestock production systems are geared towards satisfaction of pastoral subsistence needs that are met, to a large extent, through milk production, satisfaction of social cultural objectives, such as prestige associated with ownership of livestock, and provision of "capital equity" by virtue of the role of livestock as assets (Jahnke 1982). Their management is characterized by migratory movements in pursuit of forage and water, communal ownership of grazing lands, and minimal sale of livestock and their products.

Based on land productivity, the pastoral range–livestock production systems are categorized into three subsystems, namely, nomadic pastoralism, semi-sedentary pastoralism ("transhumance") and agro-pastoralism (sedentary pastoralism) (Harrington 1981). The nomadic pastoralism occurs in high aridity areas (0-200 mm annual rainfall) and its key livestock species are camels and goats. Management is characterized by erratic and long-range migration of livestock and humans as practised by Gabbra tribe. The semi–sedentary pastoralism occurs in medium aridity areas (200-400 mm annual rainfall) and its key animal species are a combination of camels, sheep, goats and cattle. Management is characterized by medium to long-range migration of livestock and humans as practised by Masai. The agro-pastoralism occurs in low aridity areas (400 mm annual rainfall) and its key livestock species are cattle and sheep; however, in contrast to nomadic and semi-sedentary pastoralisms, it combines both crop and livestock operations, with livestock providing the major subsistence base. Management is characterized by short–range migration of livestock as practised by Kamba tribe.

In 1974, the pastoral range–livestock production systems underwent innovative changes including institutional developments and tenure reforms that were administered through the Kenya Livestock Development Project Two (International Bank for Reconstruction and Development 1997). In the case of nomadic pastoralism, these innovations gave rise to grazing blocks where pastoralists formed kinship or clan-based groups to which grazing land was allocated; no title deed was provided. In the case of semi–sedentary pastoralism and agro-pastoralism, the innovations gave rise to group ranches where land was allocated and registered under kinship groups through the Group Representatives Act of 1968 (Sadera 1986); a group title deed was provided. In both the grazing blocks and the group ranches, however, resource use and management remained communal. Further to these innovations, areas under pastoral range–livestock production systems have recently been the target for creation of nature reserves, particularly, in eco–climatic zone 6 resulting in conflict between nature reserve creation and migration livestock herding.

In contrast to the pastoral range–livestock production systems, the ranching systems are geared towards production of a marketable livestock product, mainly live animals for slaughter, wool and milk; their main objective is provision of cash income and generation of profit to the resource owners. Individual ownership of land characterizes management.

Based on their ownership arrangements and organizational structures, ranching systems are categorized into four types, namely, individual, cooperative, company and group ranches. Individual ranches are owned and operated by individuals who are registered as the proprietors of the land. Cooperative ranches are owned by societies that are registered under the Cooperative Act of 1966, with membership through share contributions (Langat 1986). Company ranches are limited–liability companies governed by the Companies Act (Cap 486) (Langat 1986). Group ranches (as discussed under pastoral range–livestock production systems) are also classified under ranching systems. Apart from the group ranches, which have both a subsistence and market orientation, all the other types of ranches are broadly referred to as "commercial ranches" because they are primarily market oriented (see below).

As mentioned earlier, wildlife conservation is the other major use of Kenya's rangelands, in addition to livestock production. These lands have diverse vegetation types, namely, semi-desert vegetation, bushland thicket and scrub, permanent swamp vegetation, grassland, wooded grassland, woodland, and forest that provides habitat for a great diversity of wildlife (Government of Kenya 1979; Leaky and Lewin 1996). For example, semi-desert vegetation harbours gerenuk (*Litocranius walleri*); bushland thicket and scrub harbours lesser kudu (*Tragelaphus imberbis*), black rhinoceros (*Diceros bicornis*) and dik-dik (*Rhynchotragus kirkii*); grassland harbours wildebeest (*Connochaetes taurinus*), Thomson's gazelle (*Gazella thomsoni*), Grant's gazelle (*Gazella granti*), oryx (*Oryx beisa*) and zebra (*Equus burchelli*); wooded grassland harbours impala (*Aepyceros melampus*) and eland (*Taurotragus oryx*); woodland harbours buffalo

(*Syncerus caffer*), topi (*Damaliscus korrigum*), giraffe (*Girrafe camelopardalis*) and kongoni (*Alcelaphus buselaphus*); forest harbours elephants (*Loxodonta africana*); and permanent swamp vegetation harbours hippopotamus (*Hippopotamus amphibius*) and waterbuck (*Kobus spp.*). Besides being rich in wildlife diversity, they also accommodate large numbers of wild animals (Table 1.2).

Based on their land ownership and wildlife protection status, these wildlife–rich rangelands are categorized into three classes, namely, (1) national parks and national reserves, (2) "dispersal areas and corridors", and (3) "non-adjacent areas" (Kenya Wildlife Service 1990); these categories are the focus of wildlife policy in Kenya.

The national parks and national reserves, constituting approximately 8 per cent of Kenya's total land area (Kenya Wildlife Service 1990), are protected lands for the sole use by wildlife. They are owned by the government and county councils, respectively, but management and conservation of wildlife is the responsibility of the Kenya Wildlife Service (KWS). They include major parks and reserves such as Amboseli National Park, Tsavo National Park, Lake Nakuru National Park, Nairobi National Park, Masai Mara National Reserve and Buffalo Springs National Reserve.

The dispersal areas and corridors are "unprotected" lands that are adjacent to national parks and reserves where wild animals from parks and reserves seasonally migrate onto. In this respect, they act as wild animals "spill-over" areas and hence play a vital role as wildlife habitats complementing the ecosystems of the associated national parks and reserves. However, in contrast to the national parks and reserves, they are privately owned.

The non-adjacent areas are, also, "unprotected" lands that are rich in wildlife, harbouring more than half of Kenya's game animals (KWS 1990) but, in contrast to the dispersal areas and corridors, are not directly connected to the national parks and reserves. On account of being rich in wildlife, they are an important component in wildlife conservation but, as in the case of the dispersal areas and corridors, are privately owned.

Commercial ranches are a key form of land use in "adjacent areas and corridors" and "non-adjacent areas" hence are an integral part of wildlife protection/preservation (KWS 1990). Accordingly, management of these ranches must be tailored to meet the objectives of the private land owners and the KWS; these are to secure the greatest continuous profit (Jahnke 1982 ; Kearl 1984; Bransby 1989) and to preserve/conserve wildlife, respectively. The conservation objective of KWS serves as a constraint to allocation of resources by private landowners. Rather than allocate their resources in a "laissez-faire" situation where they pursue profit maximization unhampered, they must also take into account institutional requirements related to wildlife, as laid down by Kenya's wildlife policy. Essentially, they have an additional "imposed" wildlife conservation or preservation objective as spelt out by the Kenya wildlife policy.

The Kenya wildlife policy and wildlife conservation/preservation has evolved through history (KWS 1990; Murray 1993). Before the 1890s, there was no formal wildlife policy, but wild animals in Kenya and East Africa, in general, were plentiful in numbers and diverse in species because the pastoral tribes, notably Masai, lived in harmony with nature. They were very accommodating towards wildlife, grazing their herds and flocks of domestic herbivores side by side with wild animals.

Due to lack of a wildlife preservation/conservation policy, the period 1890 to 1898 witnessed heavy rifle–hunting of game animals, and this brought to the limelight the need for a wildlife conservation policy. The earliest form of wildlife conservation policy began in 1898 when legislation established game reserves and introduced controls on game hunting. Notwithstanding, the spirit of wildlife preservation was still lacking and the period 1899 to the early 1930s was, also, marked by heavy rifle hunting of wild animals (Murray 1993). In 1907, the Department of Game was established and empowered to manage wildlife and game hunting. In 1909, U.S. President Theodore Roosevelt, in a hunting "safari" in East Africa, brought with him the spirit of wildlife conservation. By 1938, the result of this initiative was evident as game photography had started to replace rifle–shooting. In 1945, through an ordinance, a Board of Trustees was established and mandated to administer National Parks. Through it, Nairobi and Tsavo East National Parks were established in 1946 and 1948, respectively.

In 1977, a presidential decree banned all hunting of wild animals in a bid to control poaching. This was followed by the revoking of all trophy and curio dealer licences through an Act of Parliament. In 1989, the Wildlife Conservation and Management Act was legislated, through which the KWS was created, as a government corporation attached to the Ministry of Tourism and Wildlife and mandated with responsibility for conserving wildlife in Kenya. Richard Leaky was appointed director of the corporation. The goals of the Act are to conserve the natural environments of Kenya, and its fauna and flora, for the nation's economic development and for the people living in wildlife areas and to protect people and property from injury or damage by wildlife. Also, in 1989, wildlife conservation was given a boost by the international community through the trade ban on African elephant ivory. By 1990, game photo–viewing had completely replaced the rifle–hunting safaris.

With respect to commercial ranches, the evolution of the wildlife policy was marked by two distict policies—preservation and conservation.

1.1.1 Wildlife Preservation Policy

The preservation policy was in force until 1989 and, with respect to commercial ranches, it required the protection of wildlife for its own sake, as a national heritage. Implicitly, wildlife was viewed as state (public) property with no benefits accruing to the private ranch manager. To the commercial ranch manager, this required preservation of any and all wildlife found on ranches. However, the private rancher bore all costs arising from wildlife externalities, which included use of ranch forage and water by wildlife, predation of domestic livestock, spread of diseases and destruction of private property by wildlife. As a result, the private landowners regarded wildlife as a liability. In the manager's resource allocation problem, wildlife was taken as given; the ranch resources were allocated to various livestock enterprises subject to a certain allowance for use by wildlife, depending on the biomass of wildlife resident on the ranch (see Chapter 2).

This wildlife policy provided no economic incentives for ranchers to protect wildlife and encouraged them to reduce wildlife on their property. In the past, private land owners exhibited a high degree of tolerance to conservation efforts, despite their having to bear all the costs. However, 1981 marked a change in thought in Kenya's wildlife management philosophy regarding wildlife on private commercial ranches when the Department of Wildlife Conservation and Management commissioned pilot projects on sustainable commercial game cropping. This marked a policy change from preservation to conservation. This policy change was re–enforced by KWS when it replaced the Department of Wildlife Conservation and Management in 1989 as it was found to be in line with the Wildlife Conservation and Management Act (1989). In other words, KWS is committed to changing the unsustainable preservation policy—private land owners cannot continue to subsidize national and international wildlife preservation efforts. The new policy provides adequate financial incentives to the private land owners, either by directly compensating them for the resources used by game animals or indirectly by allowing them to utilize, economically and sustainably, the game animals found on their land (KWS 1990). This gives rise to a conservation policy.

1.1.2 Wildlife Conservation Policy

The conservation policy was ushered in after 1989, and, with respect to commercial ranches, it involved the utilization of wildlife on a sustainable basis. Under this policy, wildlife is still owned by the state, but unlike the preservation policy, conditional user rights to wildlife found on a ranch are extended to the private landowner. Embedded in the policy, therefore, are clear definitions of benefits from wildlife to the private landowners, thus providing economic incentives that induce them to conserve wildlife on their land. However, the policy does not allow for automatic sale of trophy; such sales are limited to ad hoc licences (Sommerlatte and Hopcraft 1994). Currently, wildlife is cropped, with game meat and its by-products sold locally. Game cropping occurs to make money or to reduce wildlife populations and their demand for ranch resources. Management of game animal populations is part of the manager's operations, while attainment of a certain level and mix of wildlife species is an imposed objective of management. The resource allocation problem, particularly with respect to forage resources, treats game animal species as natural and renewable economic resources in their own right, able to compete with other range users (livestock enterprises) for the limited ranch resources, subject to institutional constraints on cropping quotas.

The current method of determining cropping quotas is based on population percentages (Table 1.3). This method is inherently static and does not consider interactive relationships among animal species. It has the following shortcomings.

1) It ignores the dynamics of game populations and interspecies interactions, which are inherent in game and livestock populations, making system stability elusive. In particular, it treats wildlife decisions as separate from livestock decisions.

2) It does not consider economic efficiency, resulting in lost rents from game animal cropping.

3) It lacks explicit decisions on the optimal wildlife population levels, a decision that pertains to total ranch forage resource allocation among the potential users (i.e., livestock and game animal species).

These shortcomings are addressed in this study.

Table 1.3: Allowable Wildlife Cropping Quotas for Machakos District, 1996

Animal Species	Allowable Quota (% of population harvested in 6 months)	Animal Species	Allowable Quota (% of population harvested in 6 months)
Thomson's gazelle	5	Impala	7.5
Grants gazelle	7.5	Zebra	7.5
Kongoni	10	Oryx	6
Wildebeest	10	Giraffe	7.2[a]

Source: Machakos Wildlife Management Unit (1996)
[a]Realized quota for the David Hopcraft Ranch. Quotas for other ranches are apportioned by KWS based on the need to crop giraffe.

1.2 Economics of Range Improvements: Literature Review

Range economics has changed dramatically over the past 15 years as a result of two factors. First, new techniques of analysis, based on optimal control theory, have been introduced into natural resource economics and management. Second, accompanying the mathematical advances have been increases in computing power and application programs in operations research that have taken advantage of these developments. In this subsection, I review some of the recent literature in range economics.

1.2.1 Definition of an Animal Unit

An animal unit month (AUM) is defined as the amount of forage required to support a steer with a live weight of some 454 kg (1000 lbs), or a cow and accompanying calf, for one month (Workman 1986). An animal unit (AU) refers to a steer or cow/calf without reference to the period over which forage is required. An animal unit coefficient is defined as:

$$\text{Animal Unit Coefficient} = \frac{W^{0.75}}{(BeefAU)^{0.75}},$$

where a *BeefAU* refers to the standard AU and W is the live weight of another herbivore species. The term $W^{0.75}$ represents ungulate metabolic body weight. In this study, Animal Unit Coefficients serve to standardise numbers of different herbivore species to a continuous standard AU scale.

Stocking rate refers to the number of AUs that are grazed on a given area for a given period of time, and measured in hectares per AUM (ha per AU). Stocking rate directly influences grazing pressure and, consequently, the range's standing vegetation forage biomass, plant species composition and diversity (Williamson *et al.* 1989). It also affects herbivore-plant interaction and economic returns (Westoby, Walker and Noy–Meir 1989). In essence, a stocking decision allocates vegetation forage and/or land among potential users (Loomis, Donnelly and Sorg–Swanson 1989).

Cattle operators can be divided into four categories: cow–calf, cow–yearling, background and finishing. Cow–calf and cow–yearling operators have a substantial investment in a cowherd that generally includes one bull for every 20 cows. Bulls are replaced every three years, although some ranchers lease bulls to avoid the costs of winter feed and to provide greater flexibility in breeding. Approximately 80% of the cows give birth to calves that are born in the early spring. In the fall, 15% of the herd is generally culled and calves are sold, except for those to be used as replacement heifers. (For genetic reasons, replacement bulls are always purchased.) A cow–yearling operator will keep the calves somewhat longer, selling them the following year as short or long yearlings depending upon whether they are sold the following spring or fall, respectively. Background operators have no investment in a cowherd but purchase calves in the fall for sale the following year. Finishing occurs in beef lots. Here, I focus on cow–calf and cow–yearling operations because these rely most upon range resources. Since much of the literature is based on conditions in North America, I assume for the purposes of this review that there is a summer range and a wintering area (pasture or sheltered area where animals can be fed).

1.2.2 Partial Equilibrium (Budget) Analysis

The main factor determining stocking rates is the source and availability of feed during each of the 12 months of the year (Workman 1986, p.152). An analysis of the economic feasibility of potential investments in range improvements must first determine whether there are constraints to increasing stocking rates at other times of the year that would prevent the manager from taking advantage of the range's increased productivity. One should only invest in those activities that lead to an increase in cattle throughput.

In addition, the rancher has to make decisions concerning the allocation of privately–owned improved and unimproved lands subject to the availability of public range or community pastures, if any. If access to public or summer range is limited, investments in improvements on private range may not be economically feasible; if the availability of forage from private range is the limiting factor, investments in improvements on public range may not be economically feasible. If forage availability from one source is a limiting factor, investments that yield more forage elsewhere may not be feasible.

Once it has been determined that the range improvement will not be redundant, but will increase forage available to domestic livestock, it is necessary to answer two questions. First, how many additional brood cows, along with the complement of bulls, heifers and calves, can be supported over the year as a result of the range improvement? Second, what is the economic feasibility of the range improvement? An answer to the former question requires knowledge of the biology of the range (specifically as it relates to the increases in range productivity and additional forage), as well as about the ranch operation. To answer the latter question requires both an answer to the first question and information on costs, prices and a host of other economic variables, including the risk attitude of the manager. The economic question can be addressed in a variety of ways, depending on the particular issue to be investigated. Workman (1986, pp.141–82) provides an excellent overview of net present worth (PNW), or net present value (NPV), as the criterion for judging the economic feasibility of a proposed range improvement. This is the standard and well–known budget analysis that, for the most part, gives the "correct" answer.

Workman (1986, p.155) also points out that, for the most part, budgeting has given way to linear programming (LP). This is because (partial) budgeting considers only the feasibility of particular management practices or proposed investments, ignoring the optimum combination of proposed range management (and range improvement) practices. Budgeting is unable to handle the complexity of multiple decisions. For example, as noted above, before one should consider the feasibility of a particular range improvement, it is first necessary to identify whether forage constraints at other times of the year might make the range improvement redundant. With LP, forage constraints in other periods, or any other constraints, will be taken into account within the model itself. The analyst may be able to identify investments or changes in forage availability outside the period covered by the range improvement, which might make the range investment even more profitable than that identified in the budget analysis. Workman (1986–pp.155–56) provides a number of references to the use of LP in range management .

1.2.3 A Review of Recent Dynamic Approaches to Range Economics

Beginning with a seminal article by Oscar Burt (1971), the economics of range improvements has employed techniques of dynamic optimisation as developed in the natural resource economics, agricultural economics and forest economics literature.[3] The advantage of dynamic optimisation methods is that they take into account the impacts of today's decisions on the future state of the system (e.g., range condition). Theoretical economic range models integrate biological dynamics and the resulting economic behavioural response, but empirical applications remain few.

Burt (1971) used deterministic dynamic programming (DP) to say something about the feasibility of range improvements. Although he employed some rather contrived data, the analysis was primarily meant to be methodological. Nonetheless, it sparked considerable debate about the appropriateness of dynamic programming models in empirical range economics research (Martin 1972; Burt 1972). Subsequent developments in range economics have proved Burt correct, although lack of data continues to be cited by researchers as an obstacle to the application of dynamic models in range economics (e.g., Bernardo 1989; Lambert and Harris 1990; van Kooten, Bulte and Kinyua 1997).

Although Burt used a deterministic model, he suggested that it might be appropriate to employ stochastic dynamic optimisation approaches. In particular, climate is a random variable in forage production and, hence, returns from range improvements are also a random variable. Karp and Pope (1984) used stochastic DP to investigate uncertainty in range improvements and risk averseness on the part of the decision–maker. They transformed the stochastic problem into an LP to determine optimal range treatment frequencies and stocking rates. Rather than using net present value as the objective of the range manager, they maximised the discounted value of (risk–adjusted) expected utility.[4] Like Burt, Karp and Pope (1984) made a number of simplifying assumptions because they too lacked the required data. Both assumed only one range treatment, that vegetation

[3]Overviews of applicable techniques in forestry, agriculture and other natural resource areas can be found in, for example, Kennedy (1986), Conrad and Clark (1987), Clark (1990), and van Kooten and Bulte (1998).

response to be independent of range condition, and that the response to treatment was immediate and known with certainty.

Bernardo (1989) addressed these shortcomings using a form of stochastic DP known as markov programming. In this case, probability transition matrices are needed to transform the system from one state to another—these serve as the equations of motion in markov programming. These matrices give the probabilities $p^k(i,j)$, of the system moving to state j at time t+1 if it is in state i at time t and control k is applied at t (see Kennedy 1986).[5] In Bernardo's model, the state variables are range condition (forage production measured in lbs. of DM per acre) and time since last treatment. There are four control or decision variables: choice of livestock enterprise (season–long or intensive–early stocking), stocking rates, application of the chemical tebuthiuron to control unwanted invaders, and prescribed burning, with the latter two being range improvements. Model results suggest that prescribed burning for the study site in central Oklahoma is viable only if range productivity exceeds 1,250 lbs. DM per acre. However, chemical treatments are profitable, although sensitive to chemical prices. To overcome data limitations, Bernardo used a biophysical simulator to obtain the information needed to construct the probability transition matrices.[6]

Lambert and Harris (1990) also used stochastic optimisation to investigate the profitability of investments in seeding of crested wheatgrass in Nevada to stabilise spring forage supplies. The increase in spring forage brought about by this range improvement is a random variable in their model. Rather than use markov chain programming, these authors used chance–constrained programming, which was a technique pioneered by Charnes and Cooper (1950). They found crested wheatgrass seeding to yield positive net returns. Cattle prices are also subject to

[4]Utility is assumed to be a concave function of income, which implies that losses in income are valued more highly than gains of an equal amount.
[5]Van Kooten, Young and Krautkraemer (1997) demonstrate how markov programming is applied. Their application considers how to include risk averseness on the part of decision makers in a dynamic framework, thereby providing insights to Karp and Pope's (1984) problem.
[6]Passmore and Brown (1991) used stochastic DP to analyze range degradation in Australia.

uncertainty, with decisions being made one or more years before actual prices are known. Tronstad and Gum (1993) investigated optimal culling and replacement decisions under price uncertainty. They also converted the stochastic DP specification into a linear program, and found that, by taking into account uncertainty, flexible culling and replacement decisions enhanced profits.

Many investigations in range economics focus on stocking rates, because they are "... considered one of the most important grazing management decisions from the standpoint of vegetation, livestock, wildlife, and economic returns" (Torell, Lyon and Godfrey 1991, p.795). Torell, Lyon and Godfrey (1991) maximised the net present value of annual profits subject to dynamic linear constraints (i.e., a form of LP) to examine optimal stocking rates. The problem with static models is that they are driven by falling animal performance (reduced weight gain, smaller calf crop and lower conception rates) as stocking rates increase, but ignore the impact of grazing on future range condition and production. The model employed by these researchers corrects for the latter problem via the equations of motion (dynamic constraints) for range quality and herbage production. None of the range investments they considered yielded a positive net present value; rather, range condition in their study area (Colorado) was of sufficient quality that it could be maintained by appropriate stocking of the range. Upon comparing the static and dynamic approaches, they concluded that the benefits of the multiple–period, dynamic model are small relative to the standard model. That is, their dynamic approach led to the same conclusion (and almost the same net present value) as the standard budgeting approach of Workman (1986) discussed above.

Using a similar model, however, Pope and McBryde (1984) came to an opposite conclusion. They found that profit was higher if the range was systematically overstocked, with appropriate range treatments applied periodically to improve the range quality. Pope and McBryde studied range in southern Texas.

For a serious evaluation of range improvements (ones that go beyond "back–of–the–envelope calculations"), it is imperative that dynamic optimisation methods are employed. At the very least, an LP approach is preferred over simple budget analysis, because a budget analysis might lead to decisions that are not optimal from the point of view of the total enterprise. Dynamic optimisation is preferred over the static (one–period) LP approach, because effects on future range condition and ranch returns are taken into account. As indicated, dynamic optimisation models take a number of different forms, from multiple–period LPs to more complicated stochastic models such as stochastic dynamic programming and chance–constrained programming. These types of models are generally adequate in situations where range condition (productivity) and the cattle enterprise are the only components of the ranch decision that need to be taken into account. Techniques for analysing investments in range improvements, and range decisions more generally, have become increasingly sophisticated in the past several years as both computing power has increased (and more powerful software is available) and as more is understood about bioeconomic modeling. I now review these advances.

1.2.4 Mathematical Bioeconomics and Range Improvements: A Review

The most exciting advances in the literature on range improvements stem out of the natural resource economics literature more generally. Theoretical models employ particular functional forms to model the range dynamics, often relying on Noy–Meir's (1976, 1978) models for vegetation growth on the range.[7] The theoretical models have been used to provide important insights into range improvements and other components of range management. In Boyd's (1991) model

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[7]The equation most often employed is: $\frac{dy}{dt} = \dot{y} = gy - syS$, where y is perennial grass stock, g is a vegetation growth parameter, s is the livestock grazing parameter, and S is stocking rate. As they are interested in the effect of soil erosion on soil condition, Hu, Ready and Pagoulatus (1997), for example, modify this equation by multiplying the first term on the right–hand–side by soil depth.

(discussed briefly in the previous section), the response of range condition depends on the interactions among weeds, grasses and grazing by herbivores. Competition between weeds and grass is modeled using differential equations of time; the effects of grazing on plant vigour (ability to respond to invaders) and other relationships are modeled in a similar fashion. What is important is the equilibrium that the system is capable of achieving (and its stability) and the approach dynamics to the equilibrium. The conclusion (noted above) depends on the parameters used in the mathematical equations.

Boyd (1991) was not interested in economic aspects. Nonetheless, his dynamic equations could form the constraints for a bioeconomic model of range. Such an approach was used by Hu, Ready and Pagoulatus (1997), who examined the role of soil erosion in a model of range improvements, arguing that this is an often neglected aspect of range improvements in very arid regions. They applied their model to a region in Mongolia, concluding that economically optimal grazing may not lead to sustainable grazing. This conclusion was based on assumptions based on limited data, a recurring theme in the analysis of the economics of range improvements.

Hufaker and Wilen (1989) employed a predator–prey model to investigate optimal stocking decisions for range. In this case, the predator was cattle while forage is the prey. The researchers derived a phase–plane diagram (see Conrad and Clark 1987; Clark 1990) and analyse the approach dynamics. They show that economic profitability depends on the initial forage conditions and the interplay between a physical conversion parameter and an economic conversion parameter, both of which appear in the mathematical equations that act as constraints on the system. In effect, these authors demonstrate the importance of the interplay between biological and economic factors in dynamic analyses. They reiterate the need for bioeconomic modeling.

Standiford and Howitt (1992) use a bioeconomic model to study empirically multiple use values in range economics (see also Bowes and Krutilla 1989). They point out that empirical applications of bioeconomic models of range improvements have been limited by several factors. (1) The number of state and control variables precludes easy solution of range problems by dynamic programming—the so–called curse of dimensionality. (2) Because multiple–use range investments involve variables with different time steps (e.g., trees take longer to reach maturity, while vegetation is available within one year), there has been difficulty nesting such variables in a single model. (3) Some variables have inequality constraints, and this is difficult to handle using dynamic programming or optimal control theory (see below). (4) Finally, available data cover different periods and need to be integrated.

For the most part, Standiford and Howitt ignore the crucial role of forage, assuming that grazing does not affect forage availability, and vice versa. However, their model does make a contribution to range economics, and indirectly to the evaluation of range improvements. They examine investments where three products are available—cattle, fuel wood (oak trees) and wildlife that are hunted (with all hunting benefits accruing to the landowner). The model has four control variables—forage allocated to hunting, supplemental feed purchases, number of cattle to hold as replacement heifers and quantity of firewood harvested and sold—and two state variables—number of cow–calf pairs and standing volume of oak timber for firewood. The effect of stochastic variables on management was reflected using chance constraints, price expectations and variability in precipitation (p.431). The model used was a non–linear program (NLP). Only recently has it been possible to solve large–scale NLP problems, although even then there are limits to the size of the model. Size is limited by both computing power and the problems inherent in finding an optimal (e.g., local versus global optimum, degeneracy of solutions, *etc.*). Standiford and Howitt used GAMS (Brooke, Kendrick and Meeraus 1988) to solve their NLP. GAMS is more commonly used in agricultural and forestry applications.

This study employs bioeconomics to study range allocation in Kenya. The problem is to allocate the range among domestic livestock and wildlife, with the objective of policy to conserve wildlife ungulates. What policies are best at accomplishing this task? The answer to this question is provided with the aid of a deterministic, nonlinear bioeconomic model that is solved using GAMS.

1.3 Research Objectives and Methodology

The study focuses on private commercial ranches in Machakos district, Kenya, that are involved in game cropping. The objective is to examine economic incentives for accomplishing the task of allocating range resources, particularly the forage resource, in a way that achieves the conservation goals of the Wildlife Conservation and Management Act (1989) and leads to the greatest economic benefits to the ranchers (and society). A further objective is to develop a conceptual framework for guiding the formulation of game cropping policy. To examine this issue, a dynamic economic model of multiple-use resource allocation amongst livestock and wildlife populations is employed. Sensitivity analysis is used to examine economic incentives that cause private landowners to conserve wildlife on their land. Shadow prices of game animals are determined so that they can be a guide to alternative policies, involving compensation of ranchers for resources used by game animals.

The general method adopted for this investigation is multidimensional dynamic programming, which captures not only the livestock and game population dynamics but also the interactions among the various animal species (Conrad and Clark 1987). At any given time, the private commercial ranch system is comprised of a state variable vector of livestock and game populations. This vector of state variables traces a trajectory through time, guided by the population dynamics or the species equations of motion. The equations of motion capture the livestock and game dynamics and their interactions. They also incorporate game harvests and livestock sale levels, which are the control variables in the model. The objective function consists of the discounted net returns from harvesting game animal species and sale of livestock over the planning horizon. The optimization of the objective function, constrained by the equations of motion and the initial state vector values, yields optimal state vector, control vector and shadow prices vector values. These optimal vectors constitute the solution to the economic problem facing the private commercial ranch operator. Finally, different scenarios of the harvesting policy are analysed.

Further to the above, a background review of the commercial ranch management and bio–economic models are provided in Chapter 2. A static economic analysis of game/domestic livestock ranching is given in Chapter 3. An estimation of population growth and production relations is addressed in Chapter 4. Chapter 5 focuses on the bioeconomic model solution and harvesting policy analyses, while recommendations and conclusions are found in Chapter 6.

CHAPTER 2

A BIOECONOMIC MODEL FOR RANGE ALLOCATION IN KENYA

Ranch managers make and implement management decisions within the context of the ranch ecosystems. To guide these decisions, managers employ economic tools. The ranch ecosystem constitutes the biological and business environment of that ranch business and an appropriate economic tool for guiding ranch management decisions is the bio–economic model.

2.1 Commercial Ranch Ecosystem Model

A "ranch management plan" is a 'blueprint' of ranch business (Stoddart, *et al* 1975) representing a ranch business organization. It is a complicated entity (Evans and Workman 1994) that views the ranch as a system: on the one hand, it views the ranch as a package of resources (current ranch resources) and, on the other, as a package of various enterprises and management operations (current ranch operations). The management objectives form a link between these two components. To attain these objectives, the manager makes complex resource allocation decisions where complexity emanates from the dynamic nature of livestock, wildlife and vegetation forage resources by virtue of being biological. These resource allocation decisions result in adjustments to the current resources yielding a new package of "proposed resources" and to the current operations and enterprises yielding a new package of "proposed operations and enterprises".

2.1.1 Ranch Resources

Owned Land

With regards to commercial ranching in Kenya, owned land resources determine the economic viability of commercial ranching. Tenure, size, soils and rainfall characterize these resources. Land tenure of commercial game ranches varies from freehold to leasehold while the unit size varies with ecological zone. In ecozones 3 and 4, the average ranch size is 7,000–12,000 ha and in zone 5, the ranch size varies from 10,000–20,000 ha. The main soil types, characterizing owned land resources, are sands, sandy loams or black clay soils (Pratt and Gwynne 1977).

Forage

The prevailing vegetation types produce the forage resources. In eco–climatic zone 5 dry thorn-bushland, woodland, shrubland, bush grassland, shrub grassland, wooded grassland, grasslands and permanent swamps prevail. They vegetation types are dominated by *Commiphora* and *Acacia* tree and shrub species, and *Cenchrus ciliaris* and *Chloris roxburghiana* grass species. In ecozones 3 and 4, woodland, bushland, shrubland, wooded grassland, bush grassland, shrub grassland, grassland and permanent swamps vegetation types prevail. They are dominated by *Acacia, Terminalia, Albizia, Lantana, Combretum, Euclea* and *Tarchonanthus* tree and shrub species, and *Themeda, Hyperthelia, Loudentia, Hyparrhenia, Panicum, Cynodon, Setaria, Sporobolus, Chloris* and *Cymbopogon* grass genera.

The vegetation forage resource comprises of browse and herbage which are sources of food for browsing and grazing herbivores, respectively. Browse refers to the portions of woody plant species, such as twigs, leaves, flowers and fruits (Cook and Stubbendieck 1986), that are consumed by animals, while herbage is the aerial parts of non-woody plant species. Under conditions of treeless grasslands, herbage constitutes the entire forage resource. Under conditions of wooded and bushed grasslands, the total forage biomass is the sum of herbage and browse production. In the latter situation, herbage and browse plant species grow in interspersion with each other and, although they use different ecological niches, they compete for sunlight; but, compared to treeless grasslands, the increased browse production compensates for the reduced herbage production (Blair and Kassam 1980; Deshmukh 1994). In Kenya's arid and semi-arid rangelands, seasonal vegetation forage biomass is a function of rainfall (Boutton, Tieszan and Imbamba 1988), which is the most limiting factor (Table 1.1) and hence rainfall based models have practical application in predicting vegetation forage biomass (Phillipson 1975; Jahnke 1982; Wylie, Pieper and Southward 1992; Jurgen 1994) and carrying capacity (Phillipson 1975). For example, annual rainfall regimes of less than 700 mm yield 2.5 kg of dry matter herbage per hectare per milimetre (Jahnke 1982).

Domestic Livestock

Livestock resources are a key ranch capital investment and comprise of three main species, namely, cattle (*Bos indicus*), sheep (*Ovis aries*) and goat (*Capra hirtus*). The commonly found cattle breeds are Improved Boran, Sahiwal and Sahiwal crosses, crosses of Zebu and exotic breeds, and exotic breeds. The commonly found sheep breed is Dorper, which is a cross breed of Dorset Horn and Blackheaded Persian. And the commonly found goat breed is Galla. Individual ranches hold cattle singly or in combination with sheep and/or goats.

Water

Ranch water resources include ground water and surface water. The ground water resources comprise of springs, shallow wells and bore-holes. The surface water resources include permanent streams and rivers, earth dams, weirs and rock catchments. Boreholes and earth dams are the most common sources of water.

Other Capital Resources

In addition to livestock and water, other ranch capital resources include dips, buildings, livestock handling facilities, tools and machinery, and fencing. The ranch also holds operating capital investments (inputs) such as mineral supplements, drugs, fuel and oil, and stationery. These capital investments serve to increase the ranch's profitability, after livestock and water investments are in place.

Human Resources

Human resources include all personnel employed by the ranch, ranging from labour specifically employed to look after cattle to general labourers. A completely developed commercial ranch needs an equivalent of 12 to 15 persons per 1000 head of cattle (Pratt and Gwynne 1977). Capital investments help to substitute for human labour or improve its efficiency. In addition, the ranch employs at least a manager and an assistant manager.

Wildlife Herbivores

Wildlife resources are a natural and renewable resource that comprises of various game animal species. The commonly found animal species are Thomson's gazelle, kongoni, zebra and wildebeest as principal grazers; giraffe and eland as principal browsers; impala, Grant's gazelle and oryx as mixed feeders; and ostrich (*Struthio camelus*) as a mixed feeder game bird. There are also resident or occasional predators that include cheetah (*Acinonyx jubatus*), hyena (*Crocuta*

crocuta), jackal (*Canis sp*), lion (*Panthera leo*) and wild dog (*Lycaon pictus*) (Sommerlatte and Hopcraft 1992).

Wildlife and livestock resources are biological, so their stocks change through time or are temporally interrelated. Given a fixed land area (ranch), the rate of change of their population biomass equals birth rate net of mortality rate plus immigration net of emmigration. This change is a function of standing population biomass, harvest/sale levels and rainfall. Rainfall impacts biomass change indirectly through vegetation forage.[1] A general model depicting this dynamic behaviour is comprised of difference equations of the general form:

(2.1) $$H_{it+1} - H_{it} = f_i(H_{1t}, H_{2t}, \ldots, H_{nt}; R_t; Y_{it}) for i = 1,2,\ldots,n \, .$$

H_{it} is a state variable representing herbivore standing biomass of species i during period t; Y_{it} is a harvest/sale control variable of herbivore species i during peiod t; and R_t is total seasonal rainfall in period t.

2.1.2 Ranch Enterprises and Operations

Ranch managers allocate their ranch resources amongst the ranch "enterprises"; that is, ranch "enterprises" are the "objects" against which ranch resources are allocated. There are two categories of ranch enterprises, namely, livestock enterprises and wildlife "enterprises". These two enterprises operate side-by-side. This coexistence of wildlife and livestock on commercial ranches inevitably results in resource conflicts. Such conflicts take the form of competition for forage and water between livestock and wildlife, predation of livestock by wild carnivores,

[1]Serial data on seasonal vegetation forage biomass were not available. This makes it impossible to model rainfall-forage-herbivore biomass directly.

transmission of disease to livestock by wildlife, and destruction of property by wildlife. Although there exists a potential displacement of wildlife by livestock, these conflicts are not so serious as to rule out the dual use of a given rangeland by livestock and wildlife (International Livestock Center for Africa 1978). In other words, a combined livestock and wildlife range use (or multiple-use of the range) is a technical feasibility and, ecologically, it may even represent a more efficient way of tapping the range resources (Kreuter and Workman 1994).

Livestock enterprises comprise of cattle, sheep and goats. Ranchers operate sheep and/or goats together with cattle, although some ranches operate cattle as a single enterprise. All the livestock operations rely on natural grassland.

Cattle are primarily grazers and their main ranch product is beef complemented by milk. The latter is a product of dairy ranching and its occurrence depends on the availability of a milk market, for example, in proximity to urban centres, and it is always operated in combination with beef production. Beef production incorporates a breeding herd (cow-calf) and fattening. It may also incorporate finishing of immature stocks bought from off the ranch. The average daily weight gain is 0.36 kg and age at first calving is two to three years, depending on management standards. Well managed ranches have attained an average calving rate of 80% (Skovlin 1971). The breeding herd comprises of the ratio of three bulls to one hundred cows. Culling is done at the age of twelve years.

Sheep are primarily grazers, preferring low grasses, and are normally kept in combination with cattle. The main product is mutton. Ranches attain an average daily gain of 255 g, live weight of 34 kg in five months and lambing percentage of close to 100%; despite twinning ability, the latter is low due to poor sheep management standards (Pratt and Gwynne 1977). A breeding flock generally comprises of one ram to sixty ewes. Average culling age is six years with a replacement rate of 17% per year.

Goats are primarily browsers and ranchers normally keep them in combination with cattle. Meat is their main product. Well managed ranches attain an average daily gain of 150 g, live weight of 22 kg in four months and an average kidding rate of over 100% due to multiple kidding ability. Average breeding age is eighteen months and a typical breeding flock comprises of one buck to twenty-five females. Average culling age is at ten years, so the replacement is 10% per year.

Wildlife "enterprises" involve operations such as game habitat and population management. Habitat management involves maintaining and/or setting aside preferred game habitats or food sources. Ranchers manage game population through cropping. By this means, ranchers realise output from wildlife "enterprises;" however, it requires hunting "effort"(E) —the time, in hours, spent to search and shoot an animal. This is in contrast to livestock that are simply walked to market. The major wildlife "enterprises" include various grazers, mixed feeders and browsers.

Grazers include Thomson's gazelle, kongoni, wildebeest, and zebra (Government of Kenya 1979). Thomson's gazelle prefer habitat in open plains or light Acacia woodlands, including tall grasslands that have been grazed low by other animal species. Their social organisation comprises of herds of 5 to 60 animals or more (Government of Kenya 1979). Their gestation period is five months. And they attain a mature weight of 18.2 to 27.2 kg (Sachs 1967; Government of Kenya 1979). Kongoni prefer habitat in open country (plains) and tall savanna woodlands. Their social organisation commonly comprises of herds of 4 to 5 animals, although larger herds are also found (Government of Kenya). They belong to the *Alcelaphines* "tribe" (Huxley 1961; Moss 1975) and grow to a mature weight of 127-205 kg (Sachs 1967; Government of Kenya 1979). Wildebeest y prefer habitats in open and wooded grasslands. Their social organisation comprises of large herds that can be migratory but, with a permanent source of water, are resident as is in the case of commercial ranch populations. They belong to the *Alcelaphines* "tribe" and grow to a mature weight of 100 to 270 kg. Their gestation period is eight months (Government of Kenya 1979). Zebra prefer habitats in open grassland plains, wooded grasslands, and sub-desert and arid bushlands. Their social organization comprises of the family unit of up to 15 animals, comprised of one stallion, mares and their young. They attain a mature weight of 227 to 320 kg and have a gestation period of one year.

Mixed feeders include Grant's gazelle, oryx and impala (Hillman and Hillman 1977; Government of Kenya 1979). Grant's gazelle prefer habitat in open grassland plains, ranging from short grass bush to thick bush. Their social organisation comprises of small herds. Together with Thomson's gazelle and impala, they belong to the medium-sized antelope "tribe" called the *Antilopinestrue* (Huxley 1961; Moss 1975). They attain a mature weight of 45 to 78 kg (Sachs 1967; Government of Kenya 1979). Oryx prefer habitat in open bushlands and short grasslands. Their social organisation comprises of herd sizes ranging from 6 to 40 animals and they tend to be associated with Grant's gazelle and zebra. They grow to a mature weight of 132 to 205 kg (Government of Kenya 1979). Impala prefer habitats in wooded grasslands (Talbot and Talbot 1961). They are resident and socially gregarious, forming breeding herds composed of females, dependent young animals and one dominant male. Bachelor herds consist of males of all ages. They attain a mature weight of 40 to 65 kg and have a gestation period of 196 days.

Browsers include giraffe and eland (Government of Kenya 1979). Giraffe prefer habitats in wooded or bushed grassland and riparian woodlands and feed on a wide range of tall trees and bushes with a special liking for Acacia and Balanites tree species They are not highly territorial but individual populations move within a large identifiable area. They live in unstable groups comprised of several families (Government of Kenya 1979). A male giraffe attains a mature weight of 1,100 kg (Sachs 1967). Eland prefer habitat in wooded grassland, light forest and bushland, although they also occur on open grasslands. Their social organisation comprises of large herds of up to 200 animals, but more commonly 20-50 animals, composed of one mature male, females, yearlings and animals less than one year old. They belong to the large antelope "tribe" called *Alcelaphines* with an average mature weight of 590 to 680 kg. Their gestation period is 262 days (Government of Kenya 1979).

Concomitant with these "enterprises". are the various ranch operations, namely, grazing (animal) distribution, range improvements, and livestock and wildlife management.

Grazing (and animal) distribution is a grazing strategy for equitable and efficient use of ranch forage (Heady 1981) and is much more easily achieved with livestock than with wildlife since the latter are not amenable to direct human control. Techniques for controlling livestock distribution are salt lick placement, distribution of watering points, herding, fencing and deployment of grazing systems. The latter includes continuous grazing and rotational grazing systems (Holechek, Pieper and Herbel 1989). Ranchers attain distribution and control of wildlife through habitat manipulating, in terms of food, cover and water availability, and through game–proof fencing.

Range improvement refers to "structures and practices employed in management of a range for the purpose of maximizing productivity of the range system" (Booysen 1978) including manipulation of vegetation. Vegetation range improvement practices are a means of increasing its productivity (Booysen 1978) and influencing wildlife habitat; the latter results in greater control of wildlife (Holechek, Pieper and Herbel 1989). These practices include bush control and range seeding (Heady 1981). Bush control is necessary in Kenya's arid and semi-arid rangelands because the successional force of vegetation is towards woody type or bushland thicket (Harrington 1981), leading to exclusion of herbaceous plant species; notable tree and shrub plant species that constitute a bush problem in commercial ranches are *Acacia drepanolobium, Tarchonanthus camphoratus, Acacia brevispica, Euclea divinorum* and *Combretum* spp. Grasslands occur as a result of arresting these successional trends by manipulating the vegetation. This also leads to higher grass production due to reduction of competition from the woody species; grass productivity increases from bush control of 50% are feasible (Pratt and Gwynne 1977). It also leads to reduction of tsetse-fly infestation and attains greater control of animals. Methods of bush control include hand removal, use of fire or controlled burning, chemical control, mechanical control and biological control involving browsers such as goat, giraffe and eland. Choice of control method is governed by financial feasibility. The most commonly employed methods are hand control, use of fire and biological control. Range seeding restores grass cover of the desired plant species on run–down ranges. It serves as a land reclamation measure for these badly denuded areas. As a range improvement practice, it not only increases grass production but also arrests soil erosion.

Another form of range improvement is manipulation of the ranch physical environment and comprises of water development and distribution, and construction of ranch structures. Water serves as a tool for distributing animals and, hence, is an integral component of grazing improvement and planning. Its development is, therefore, crucial to the success of ranching. On average, livestock need a minimum daily water intake equivalent to 25 litres per animal unit. Additional water is needed for the attendant human–labour–force; this is estimated at 10% of the total livestock water requirements (Pratt and Gwynne 1977)—the more livestock there are in a ranch, the higher the human attendant labour force and the higher the total human water requirements. Game animals water need must also be taken into account. That is, the long term water developments should aim at satisfying the total ranch (potential) livestock carrying capacity including allowances for the attendant human labour force and game animals. Its even distribution is equally important. A single watering point should serve an area of approximately 50 km^2. This is equivalent to a distance of 4 km from a watering point to the farthest grazing area. Physical ranch structures include fencing/paddocking, and construction of yards and crushes, dips and spray races, fire-breaks and roads. Fencing-paddocking improves the efficiency of herding labour and facilitates grazing control. Yards and crushes facilitate handling animal. Dips/spray races facilitate tick control. Firebreaks and roads facilitate fire control and communication on the ranch.

As mentioned earlier, the other two ranch operations concomitant with "enterprises" chosen are wildlife and livestock management. Wildlife management involves cropping and habitat control through vegetation manipulation and water development to attain appropriate animal distribution and equitable range use. Livestock management is much more elaborate. It aims at attaining high livestock performance standards. As a first step, it is necessary to structure the herd/flock based on similarities of management requirements. For example, a basic cattle herd structure comprises of (1) breeding heifers and cows with calves (with or without bulls as appropriate), (2) weaned calves and stock under breeding age, and (3) steers and bulls not in service. Herd/flock structure facilitates implementation of breeding control, disease control and routine operations. Breeding control involves culling and selecting replacement stock, and synchronising calving/lambing/kidding with forage availability and sales strategy. Maintenance of animal health involves dipping or spray racing animals to control ticks, de-worming, prophylactic veterinary caring and animal vaccinating. The presence of wildlife has an epidemiological effect on herbivores that may increase expenditures on livestock disease control; however, it is possible to attain a stable equilibrium between herbivores and grazing–acquired diseases as an environmental adaptation (Morley 1981). Routine practices include branding, castration, animal counting, supervision to guard against predators, supplemental feeding, keeping records and marketing; branding serves as an identification tag for tracing stolen and stray animals. These operations aim at attaining high standards of animal performance.

The ranch operations involve labour, capital and managerial skills and account for ranch production expenses per period. The ranch operating capital (expenses) is comprised of labour and management expenses, purchased inputs expenses, and maintenance expenses. Depreciation is the cost associated with intermediate–term capital investments (working capital) such as vehicles and machinery, fences, and livestock. Interest on working capital, which for a debt-free ranch is an imputed cost, represents an additional cost item. Returns to capital tied-up on land and investments fixed on it, such as boreholes, are the residual from gross ranch income after deducting operating capital, depreciation on working capital and interest on working capital and is primarily a return to land (Kearl 1984).

For purposes of static economic analysis, fixed costs are sunk costs, so the relevant net income is net cash cost (or rent)—gross return less variable cost. This is primarily return to management, capital and land. Gross return per period comprises of off-take from livestock and game animals. Cattle off-take per period comprises of monthly sales net of purchases, while game animal off-take per period comprises of total harvest over the period.

Off-take represents output from each ranch enterprise, so each ranch "enterprise" has an embedded "production function". For a fixed area of rangeland, sales/harvest levels (Y_{it}) is a function of stocking level or standing herbivore population biomass (H_{it}) and harvesting effort (E_{it}). The following are suitable representations of this "production function" (Conrad and Clark 1987):

(2.2) $$Y_{it} = H_{it}(1 - e^{-\alpha_i E_{it}}) \text{ and}$$

(2.3) $$Y_{it} = \alpha_i H_{it} \text{ for i =1,2,...,n.}$$

Model (2.2) applies to wildlife, while (2.3) applies to livestock, provided herd-flock growth is generated from a breeding herd-flock. Under circumstances where herd/flock growth is generated from purchased livestock that are finished at ranches to a sale weight, the output function is:

$$Y_{it} = S_{it} \quad (2.4)$$

where S_{it} is livestock sales of species i in period t—a control variable.

2.1.3 Commercial Ranch Management Objectives

Ranch management objectives are to secure the greatest continuous profit (Jahnke 1982; Kearl 1984; Bransby 1989) and to achieve certain wildlife-related objectives (Kenya Wildlife Service 1990). The ranch manager allocates the resources at his disposal amongst various ranch enterprises (livestock and wildlife) in such a way that the management objectives are realized. However, the manager has limited resources and several competing uses (livestock enterprises and wildlife "enterprises"). Therefore, he faces an economic problem of allocation. He endeavors to maximize the sum of discounted net returns per period over his planning horizon.

In addition to the profit maximization objective, the ranch manger has an "imposed" wildlife conservation objective. Rather than allocating ranch resource in a "laissez-faire" situation, where he pursues profit maximization unhampered, he must do so in such a manner that satisfies restrictions imposed by institutional requirements related to wildlife, as laid down by Kenya's wildlife policy.

Allocation of ranch resources may or may not lead to adjustments in resources and operations. The former applies if the existing "management plan" is optimal. If, on the other hand, the optimal solution results in a different "management plan", there is concomitant need for adjustments in current resources and operations. For example, a wildlife policy change from game preservation to conservation led to adjustments in prevailing capital stock to include investments in game cropping (slaughter house, cropping vehicles, cropping labour, etc) and adjustments in prevailing operations to include population management through game cropping. This resulted in a "new" ranch management plan—a package of new resources and new operations.

2.2 Commercial Ranch Bioeconomic Model

The dynamics of domestic and wild herbivores, within the broader context of the dynamics of commercial ranch grazing systems, are an integral consideration in determining proper stocking rates and the herbivore species mix. Wildlife and livestock resources are dynamic by virtue of being biological. In the absence of harvesting/sale, their stocks change through time at a rate equal to the birth rate less mortality rate and net migration. This rate of change is a function of standing population biomass and seasonal rainfall; the latter influences the system through carrying capacity (Phillipson 1975). Change in population biomass of individual herbivore species is further influenced by its interactive relationships to other herbivore species as a result of a common resource base. Interactive relationships are negative, positive or zero depending on whether the interacting species are competitive, complementary or supplementary (van Kooten, Bulte and Kinyua 1997).

Carrying capacity serves as an upper bound on the stocking rate. It is the maximum stocking without causing permanent damage to vegetation or soil, although some have questioned the validity of carrying capacity as a notion (see Budiansky 1995). It is used in this study to suggest a limit to the capacity of range to "hold" more herbivores in competition with each other given limited forage availability. In Kenya's arid and semi-arid rangelands, carrying capacity fluctuates due to erratic rainfall (Pratt and Gwynne 1977); in order to capture this aspect, carrying capacity is explicitly modeled as a function of total seasonal rainfall. This makes it possible to analyze the effect of drought on optimal solution values. It also has the added advantage that, by treating carrying capacity as a variable, it is endogenous to the model.

The change in standing population biomass is modeled as a discrete–time logistic equation (Starfield and Bleloch 1986; Anderson 1991; Caughley and Sinclair 1994):

$$(2.5) \quad H_{it+1} - H_{it} = \beta_i H_{it}\left(1 - \frac{H_{it} + \sum_{j=1}^{n-1} \lambda_{ij} H_{jt}}{\delta_i R_t}\right), \text{ for } i, j = 1, \ldots, n, \text{ and } i \neq j.$$

Here H_{it} represents the biomass of herbivore i in period t; R_t is total rainfall in period t; β_i represents the rate of population biomass change for herbivore species i. Due to the parameter δ_i, each animal species has a unique carrying capacity, which was also documented by Bothma (1996). The term λ_i represents the interaction effect of herbivore species j on species i—the interaction parameter is negative, zero or positive depending on whether the interactive relationship is complementary, supplementary or competitive, respectively. It gives an estimate of exchange ratio or grazing pressure equivalence among species. Heady and Child (1994) have proposed approximate exchange ratios based on metabolic weights (Table 2.1) that could be applied to herbivores with similar diets as a guide; for species with different habitat requirements, these exchange ratios should be modified accordingly. In 2.7, exchange ratios are endogenously determined, thereby taking into account differences in habitat requirements among species. The term $\delta_i R_t$ is the "horizontal intercept", or carrying capacity that depends on rainfall. It is the realised or endogenously determined carrying capacity. In turn, δ_i represents the effect of rainfall on the carrying capacity of herbivore species i. The time step is six months, consistent with the bimodal distribution of rainfall distribution that in turn gives rise to two growing seasons and two grazing seasons.

Table 2.1: Approximate Exchange Ratios for Mature Animals Based on Metabolic Body Weight

Species	Approximate weight (kg)	Exchange ratios (No. per Au)
Cow	455	1.0
Eland	455	1.0
Zebra	272	1.5
Wildebeest	182	2.0
Hartebeest (kongoni)	136	2.5
Sheep	55	5.0
Impala	55	5.0
Goat	45	6.0
Thomson's gazelle	23	10.0

Source: Heady and Child (1994)

A model that incorporates sales and cropping is obtained by modifying (2.5) as:

$$(2.7) \qquad H_{it+1} - H_{it} = \beta_i H_{it}\left(1 - \frac{H_{it} + \sum_{j=1}^{n-1} \lambda_{ij} H_{jt}}{\delta_i R_t}\right) - Y_{it}, \text{ for } i, j = 1, \ldots, n, \text{ and } i \neq j.$$

where Y_{it} represents the harvest and sale of herbivore *i* during period t

Treating carrying capacity as an upper bound on stocking rate has a rational meaning in the context of the animal forage demand rate vis-à-vis animal forage allowance (Caughley and Sinclair 1994). Conceptually, δ_i R_t represents maximum animal units of herbivore species *i* that can be supported through period t (6 months). Accordingly, the maximum available forage biomass in period t is (6 δ_i R_t) AUMs, on the one hand. On the other hand, the total forage demand rate in period t by herbivore species *i* is $\{6(H_{it} + \sum_{j}^{n-1} \lambda_{ij} H_{jt})\}$AUMs, where λ_{ij} plays the role of the species exchange ratio that converts H_{jt} animal units into i-equivalents, and 6 refers to the number of months in each season. Three cases can then be identified.

(2.7) Case 1: $\delta_i R_t > (H_{it} + \sum_{j}^{n-1} \lambda_{ij} H_{jt})$

This implies that available forage exceeds the dry–matter satiation requirements of the standing population of herbivore species i. Under such circumstances, animals select high quality forage with the result that they derive enough nutrients to meet their maintenance requirements and leave a balance for growth and reproduction. The standing herbivore population increases.

(2.8) Case 2: $\delta_i R_t = (H_{it} + \sum_{j}^{n-1} \lambda_{ij} H_{jt})$

This implies that the available forage exactly matches the voluntary intake dry–matter requirements of the existing population of herbivore species i, and, under poor quality forage, this amount is just enough to meet the animals' maintenance requirement (Kearl 1984). In other words, animals are not able to select a high-quality diet; what is on offer is just enough to satisfy the animals' voluntary intake. Although the animal is able to meet its voluntary intake dry–matter requirements, quality rather than quantity is the most limiting factor. Without an opportunity to select, animals barely meet their maintenance nutrient requirements, leaving no surplus nutrients for growth and reproduction. As a result, standing population change is zero, implying that H_{it} is at maximum sustainable level.

(2.9) Case 3: $\delta_i R_t < (H_{it} + \sum_{j}^{n-1} \lambda_{ij} H_{jt})$.

In this case forage demand by herbivore species *i* is greater than the carrying capacity. The result is a decrease in standing population of herbivore species *i*.

Stocking level is contingent upon management goals (Evans and Workman 1994) and, from a biological point of view, the range management goal is broadly stipulated in the objective of achieving the highest level of animal production commensurate with maintaining or improving range condition which coincides with maximum sustainable yield. The stocking rate implied by this goal is:

(2.10) $$H_{it} = \frac{\delta_i R_t}{2}(1 + \sum_{j=1}^{n} \lambda_{ij} H_{jt}),$$ for $i, j = 1, \ldots, n$, and $i \neq j$.

That is, the stocking level that is commensurate with maximum sustained herbivore off-take and the herbivore grazing optimisation hypothesis (Williamson *et al* 1989). This management approach was used by van Rooyen (1994) in a computer simulation study on maximum sustainable harvesting strategies for impala. Contrary to theoretical expectations, the maximum sustainable yield was attained at population levels greater than 50% of the carrying capacity, an artefact of model assumptions on the relationship between fecundity and density (van Rooyen 1994).

The goal of ranch management, however, is assumed to be profit maximisation—the major function of commercial ranching systems is generation of income, in contrast to satisfying subsistence needs (relevant to pastoral systems), and the more net income they generate the better, hence the assumption of profit maximisation objective. The stocking level implied by this objective is based on economic efficiency. That is, the basis of determining the appropriate stocking rate is net return to the land, which is the most limiting production factor under rangeland conditions (Workman 1986). This approach of determining herbivore stocking rates and, more generally, allocating land resources amongst domestic and wild herbivores in Kenya's rangelands (and African semi-arid savannas in general) has been lacking (Kreuter and Workman 1994). As noted in Chapter 1, economic analysis of commercial ranching systems has been mainly partial, focusing on livestock, *and static*, with the main economic tools having included linear programming, partial budgeting and simulation studies (see also Scarnecchia 1994). In contrast, commercial ranching systems are complex dynamic processes, and multiple-use considerations are important. A dynamic approach to economic analysis is therefore appropriate.

In this study, I use an optimal control model to analyse the economics of commercial game ranching systems. In the model, ranchers are assumed to maximise discounted net returns from sale of domestic livestock and from cropping (hunting and sale of) wildlife ungulates subject to herbivore population dynamics, initial standing populations and game animal policy restrictions. Although wildlife are a public good, the perspective taken in this study is that of private optimisation. Ranchers are provided user rights to wildlife but such rights might be constrained. One purpose of this study is to investigate these constraints. The objective function can be specified as:

$$(2.11) \quad Max\sum_{t=1}^{T}\rho^{t}(\sum_{i=1}^{n}P_{i}Y_{it}-\sum_{i=1}^{n}WE_{it}+P_{Ca}Y_{Cat}-W_{Ca}Purc_{t}),$$

where $\rho = (\frac{1}{1+r})$ and r is the real private rancher(s) time discount rate; P_i is real gross price per animal unit adjusted for all variable costs except effort in the case of game and livestock purchases in the case of cattle; W is the real cost of effort per hour; E_{it} is in hours; (Y_{it}) is off–take in animal units; and $Purc_t$ is purchases of long yearlings in period t.

The constraints on ranchers are at least three and possibly more when government restrictions are taken into account. First is the wildlife population dynamics, given by:

(2.12) $$H_{it+1} - H_{it} = \beta_i H_{it}(1 - \frac{H_{it} + \sum_{j=1}^{n-1} \lambda_{ij} H_{jt}}{\delta_i R_t}) - Y_{it}, \text{ for } i, j = 1, \ldots, n, \text{ and } i \neq j,$$

where there are n (=8) game herbivore species. A second constraint constitutes the population dynamics for cattle, namely,

(2.13) $$Ca_{t+1} - Ca_t = \beta_{Ca} Ca_t + Purc_t - Y_{Cat}.$$

Then there is a constraint determined by the starting population levels:

(2.14) $$[H_{10}, H_{20}, \ldots, H_{n0}] = [a_1, a_2, \ldots, a_n].$$

Other relevant constraints reflect the wildlife objectives of government (policy constraints), and these are considered in more detail in Chapter 5.

2.2.1 Herbivore Species Mix

The multiple-use of range resources involves combined use of ranch forage by different domestic and wildlife species. Co-existence is made possible due to ecological separation (niche separation) derived from differences in forage and habitat preferences (Dunbar 1978). For example, grazers derive their food requirements mostly from herbage plants, particularly grass plants, while browsers feed mainly on trees and shrubs; mixed feeders, with a preference for a wide range of plant species are intermediate between the two groups. Within each category of animals, dietary requirements are further separated based on preferences for different plant species or different plant parts; for example, giraffe feeds at a higher browse line compared to impala on the same browse plant species (Leuthold and Leuthold 1972). Preference for different plant parts by different animal species may result in grazing succession. Ecological separation shows up in the occupation of different habitats by different species or temporal variation in occupation of the same habitat by different species (Dunbar 1978). Also a given habitat may provide feeding for some species, while for others it provides cover. This is yet another example of niche separation.

The basis for differences in dietary selectivity is anatomical. Grazers have their lower incisors oblique to the lower jaw almost parallel to its anterior floor, and the more selective grazers have narrower faces and mouths. Browsers, on the other hand, have their lower incisors upright to the jaw making it easy to strip off leaves from branches. Mixed feeders anatomically occupy an intermediate position between grazers and browsers. Under conditions of low forage availability, however, animals are less selective, being mainly driven by hunger.

Differences in dietary preferences underlie differences in optimal vegetation structure for individual herbivore species or groups of species, from which they derive maximum nutrient intake at lowest energy expenditure. Individual species have affinity to areas which meet their optimal vegetation structure requirements and this results in a grazing mosaic. Sometimes, mutually facilitative foraging relationships develop when the optimum vegetation structure of one species depends on the foraging effect of another (or more) species. For example, smaller animal species tend to graze areas over-utilized by larger species. This follows because, on account of their size, smaller animals have lower absolute forage requirement per day and as such tend to be more selective, compared to larger animals that are rough feeders with a quest to satisfy higher absolute forage requirement per day. Thus, smaller animals are able to select high nutrient plant parts from grazing aftermath resulting from grazing by ranch animals and in this way satisfying their nutrient requirements. Sometimes the smaller animals are more successful in obtaining enough forage when supply is sparse. As the larger animals move to other foraging areas to meet maintenance needs when their intake per unit time becomes critically low, the residual forage left behind, though sparse, may still be adequate to satisfy the requirements of smaller animals, which lag behind, on account of their selectivity.

Notwithstanding ecological separation, however, competition for forage eventually sets in at high population levels of species with similar diets and feeding habits (Dunbar 1978). Competition may also take place between grazers and browsers due to the impact of their feeding on vegetation. Within certain limits, grazing provides a positive feedback on grass growth by maintaining high plant vigor and more competitiveness against woody plant species; but low intensity or lack of grazing results in negative feedback by encouraging moribund grass that is less vigorous and less competitive against invasion by woody plant species. Although browsing can initiate more sprouts, in contrast to grazing, its dominant effect is a negative feedback on woody plant species as it controls their height and spread.

The optimal species mix is generated as the solution to the optimal control model described above. The population growth equations for the optimal control model are derived based on prevailing vegetation structures, or vegetation structure *status quo,* that has realistically catered to all relevant species diets and provided for other habitat requirements, namely, water, cover and space. Consequently, the optimal species mix implicitly assumes existence of the *status quo*, and management efforts would have to be directed towards maintaining the *status quo* through use of burning or another method to control bush encroachment and expansion of underutilized areas arising from the grazing mosaic. These management techniques are implicit in the model.

In this study, it is assumed that the vegetation communities that have been existing over the period covered by the data that are used to estimate species population growth equations (see Chapter 4) represent a desirable stable non-equilibrium seral state under multiple use involving domestic and wildlife herbivores. A further assumption is that management efforts are geared towards maintaining these vegetation communities by use of fire and/or other bush control methods. In essence, these vegetation communities represent the most "ideal" range condition class for the purpose at hand. Furthermore, population growth equations incorporate variable "carrying capacity," which is a function of rainfall as noted above. Hence, the model has in place an inherent mechanism for absorbing exogenous shocks to the grazing system due to rainfall variation. Moreover, the variable carrying capacity is endogenously determined from the model making it consistent with the vegetation communities that have prevailed over the data period.

Model Solution

The current–value Hamiltonian ($H_{ham.}$) for the bio–economic model represented by (2.12), (2.13) and (2.14) (see Conrad and Clark 1987; Clark 1990) is:

$$(2.15)\quad H_{ham.} = \sum_{i=1}^{8} P_i \, H_{it}(1 - e^{-\alpha_i E_{i1}}) - \sum_{i=1}^{8} WE_{it} + P_{Ca} Y_{Cat} - W_{Ca} Purc_t$$

$$+\rho\sum_{i=1}^{8}\mu_{i\,t+1}[\beta_i H_{it}(1-\frac{H_{it}+\sum_{j=1}^{8}\lambda_{ij}H_{jt}}{\delta_i\ R_t})-H_{it}(1-e^{-\alpha_i E_{it}})$$

$$+\rho\mu_{Ca1}[\beta_{Ca}Ca_t + Purc_t - Y_{Cat}]\text{, and } \ i\neq j,$$

The first Order Conditions are as follow:

(2.16) $$\frac{\partial H_{ham.}}{\partial E_{itt}}=0\Rightarrow(\alpha_i P_i-\rho\mu_{i,t+1})H_{i\,t}e^{-\alpha_i E_{it}}-W=0,\ \forall\, i;$$

(2.17) $$\frac{dH_{ham.}}{dY_{Ca\,t}}=0\Rightarrow P_{Ca}-W_{Ca}\frac{dPurc_t}{dY_{Cat}}+\rho\mu_{Ca}(\frac{dPurc_t}{dY_{Ca}}-1)=0$$

$$\Rightarrow P_{Ca}dY_{Cat}-W_{Ca}dPurc_t+\rho\mu_{Ca}(dPurc_t-dY_{Ca})=0;$$

and (2.18) $$\frac{dH_{ham.}}{dPurc_t}=0\Rightarrow P_{Ca}\frac{dY_{Cat}}{dPurc_t}-W_{Ca}+\rho\mu_{Ca}(1-\frac{dY_{Cat}}{dPurc_t})=0$$

$$\Rightarrow P_{Ca}dY_{Cat}-W_{Ca}dPurc_t+\rho\mu_{Ca}(dPurc_t-dY_{Ca})=0$$

(2.19) $$\rho\mu_{i,t+1}-\mu_t=-\frac{\partial H_{ham.}}{\partial H_{i\,t}}\Rightarrow$$

$$\rho\mu_{i,t+1}-\mu_t=$$

$$(P_i-\rho\mu_{i,t+1})(1-e^{-\alpha_i E_{it}})+\rho\mu_{i,t+1}\beta_i(1-\frac{2H_{it}}{\delta_i\ R_t})-\rho\mu_{i\,t}\beta_i\frac{\sum_{j=1}^{n-1}\lambda_{ij}H_{jt}}{\delta_i\ R_t}$$

$$-\rho\sum_{j\neq i}^{n}\mu_{j,t+1}\beta_j\lambda_{i\,j}\frac{H_{jt}}{\delta_j\ R_t},\ \forall\, i.$$

(2.20) $$\rho\mu_{Ca,,t+1} - \mu_{Cat} = -\frac{\partial H_{ham.}}{\partial Ca_t}$$

$$\Rightarrow \quad \rho\mu_{Ca,t+1} - \mu_{Cat} = \rho\mu_{Ca,t+1}\beta_{Ca} - \rho\mu_{itt}\beta_i \frac{\sum_{i\neq Ca}^{n}\lambda_{ij}H_{jt}}{\delta_{Ca}\ R_t} \forall\ i.$$

(2.21) $$\beta_i H_{it}(1-\frac{H_{it}+\sum_{j=1}^{8}\lambda_{ij}H_{jt}}{\delta_i\ R_t}) - H_{it}(1-e^{-\alpha_i E_{it}}) + H_{it} - H_{i,t+1} = 0\ \ \forall\, i \text{ and } \ i \neq j.$$

(2.22) $$\beta_{Ca}Ca_t + Purc_t - Y_{Cat} + Ca_t - Ca_{t,+1} = 0,$$

(2.23) $H_{it} \geq 0$ and $E_{it} \geq 0$, $\forall$ i,

(2.24) $$\mu_{iT} = \beta_i(1-\frac{2H_{Ti}}{\delta_i\ R_T}) - \beta_i \frac{\sum_{j=1}^{n-1}\lambda_{ij}H_{jT}}{\delta_i\ R_T} - (1-e^{-\alpha_i E_{iT}}) - \sum_{j\neq Ca}^{n} B_j\lambda_{ij}\frac{H_{jT}}{\delta_j\ R_T}\ \ \forall\ i \neq j \text{ in the}$$

case of game animals, and

(2.25) $$\mu_{Ca,T} = \beta_{Ca} - \sum_{j\neq Ca}^{n} B_j\lambda_{ij}\frac{H_{jT}}{\delta_j\ R_T}$$

in the case of cattle, where T is the last period of the planning horizon.

(2.26) $$\frac{\partial V}{\partial E_{it}} = \alpha_i P_i H_{it} e^{-\alpha_i E_{it}} - W, \forall\ i \text{ for game animals,}$$

(2.27) $$\frac{\partial V}{\partial Y_{Ca\,t}} = P_{Ca} \text{ for cattle sales, and}$$

(2.28) $$\frac{\partial V}{\partial Purc_t} = -W_{Ca}. \text{ for long yearling purchases,}$$

where:

(2.29) $V(.) = \sum_{t=1}^{n} P_i H(1 - e^{-\alpha_i E_{it}}) - \sum_{i=1}^{n} WE_{it} + P_{Ca} Y_{Ca,t} - W_{Ca} Purc_t$ is net return per period;

and

(2.30) $\mu_{it+1} \dfrac{\partial(H_{it+1} - H_t)}{\partial E_{it}} = \rho\mu_{it+1}\, \alpha_i\, H_i e^{-\alpha_i E_{it}}$ for game animals,

(2.31) $\mu_{Y_{Ca,t+1}} \dfrac{\partial(H_{it+1} - H_t)}{\partial Y_{Ca,t}} = \rho\mu_{Y_{Ca,t+1}}$ for cattle sales, and

(2.32) $\mu_{Purc_{t+1}} \dfrac{\partial(H_{it+1} - H_t)}{\partial Purc_t} = \rho\mu_{Purc_{t+1}}$ for long yearling purchases.

Condition (2.21) and (2.22) are the original dynamic equations or dynamic constraints; conditions (2.24) and (2.25) are boundary conditions; and condition (2.23) constitutes the Khun–Tucker conditions. Condition (2.16)–(2.18) combine two components, namely, partial derivatives of net return per period with respect to control variables (2.26)–(2.28) and multiples of lagrangians with partial derivatives of dynamic constraints with respect to their control variables (2.30) and (2.32). Equations (2.26). (2.27) and (2.28) represent marginal return per unit effort, cattle sale and cattle purchase, respectively, while equations (2.30), (2.31) and (2.32) show the how the control variables affect the state variables—a user cost. At optimal solution μ^*_{it+1} is shadow price of one animal unit increase at the margin.

The model is solved as a non-linear program using GAMS/MINOS (Brooke, Kendrick and Meeraus 1988). This is done is Chapter 5. In the next chapter, I provide the background data that are used to estimate the relationships in the above model. Also included in Chapter 3 is a farm budget analysis for the ranch. This is needed to determine the economic variables—prices and costs—that are needed to achieve an optimal solution. The actual regression results are provided in Chapter 4.

CHAPTER 3

ECONOMIC ANALYSIS OF THE GAME CROPPING RANCH

3.1 Study Area

The study area is located south-east of Nairobi on the Athi–Kapiti Plains along the Nairobi–Mombasa road in Machakos District, Eastern Province of the Republic of Kenya. It comprises nine ranches covering a total of 65,870 hectares (ha): Athi Kapiti Plains ranch (13,000 ha), Machakos Ranching company (6,000 ha), East African Portland ranch (6,629ha), Konza ranch (10,100 ha), Mwaazoni (Manzoni) ranch (3,265ha), Malili ranch (8,980 ha), Aimi-ma-Kilungu ranch (7,347ha), New Astra ranch (2,449ha) and David Hopcraft ranch (8,100 ha).

The area falls in eco-climatic zone 4 (Table 1.1). Based on rainfall data from the David Hopcraft ranch, the area has a mean annual rainfall of 510 mm with a bi–modal distribution, giving rise to two growing seasons and consequently two grazing seasons per year. In contrast to areas with mono–modal rainfall distribution, bi–modal rainfall distribution results in higher rangeland carrying capacity for equal annual rainfall. The "long" rains growing season starts in March/April, while the "short" rains growing season starts in September/October. Over a period of fifteen years (1981–1995) recorded seasonal mean rainfall is 260 mm with a coefficient of variation (CV) of 46% (Figure 3.1). For the same period, the mean precipitation of the "long" rains is 310 mm with a CV of 42% (Figure 3.2), while that for the "short" rains is 200 mm with a CV of 35% (Figure 3.3). From Table 1, the minimum annual rainfall for eco–clomatic zone 4 is 450 mm; thus, out of 15 years, five (1981, 1983, 1984, 1987 and 1992) are "drought" years.

The typical vegetation of the area is wooded or tree grassland 'savanna' dominated by *Themeda–Acacia* or *Themeda–Blanites* wooded grassland, but, under conditions of grumosolic soils that impede drainage, *Acacia drepanolobium* wooded grassland vegetation replaces

Themeda–Acacia or *Themeda–Balanites* wooded grassland. *Themeda triadra*, a tufted perennial with a height range of 50-150 cm and valuable for grazers, is the dominant grass species, while the genera *Acacia* and *Balanites* is the dominant woody plant species. Controlled burning is an integral management practice of this vegetation type to prevent encroachment of woody plant species and to enable some of the smaller and more palatable grasses to persist in competition with the taller species, which tend to become rank and unpalatable as they mature. Potentially, this vegetation type has a carrying capacity of less than 4 ha to sustain one animal unit for one year. Both grass and browse are important forage resources.

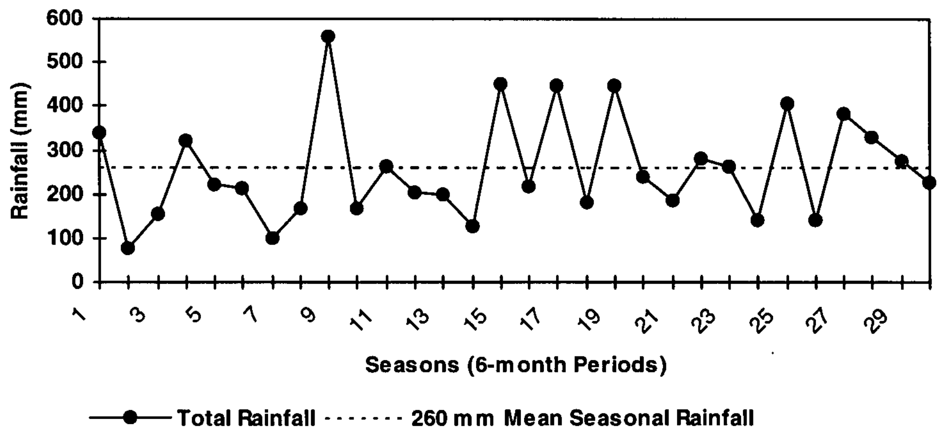

Figure 3.1. Total rainfall distribution (mm) over 6–month periods (each year has two periods: January–June and July–December) at the David Hopcraft Ranch, 1981–1995. CV of the mean seasonal rainfall is 46% and, out of the 30 recorded seasons, 17 received less than the mean rainfall.

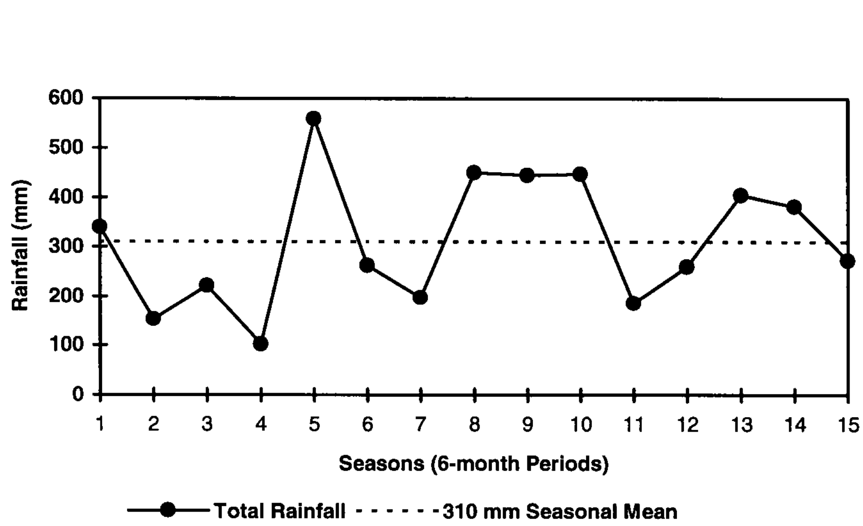

Figure 3.2. "Long" rains season (January–June) rainfall distribution at the David Hopcraft Ranch, 1981–1995. CV of mean of the "long"rains season is 42% and, out of the 15 recorded seasons, 8 received less than the mean rainfall.

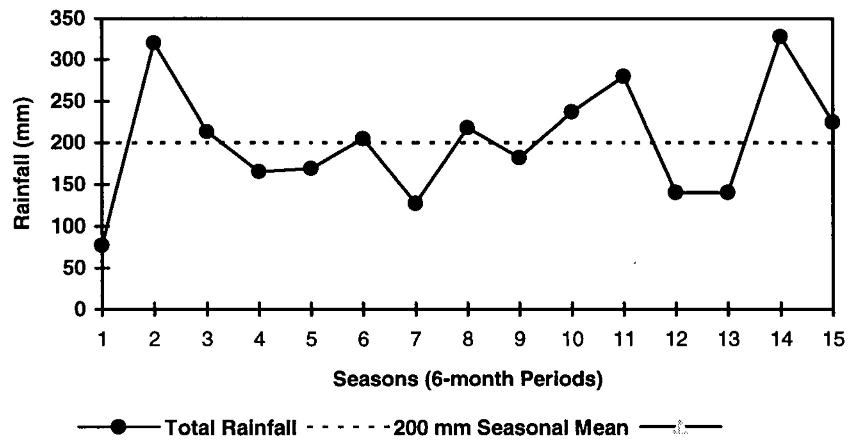

Figure 3.3. "Short" rains season (July–December) rainfall distribution at the David Hopcraft Ranch, 1981–1995. CV of mean of the "short" rains is 35% and, out of the 15 recorded seasons, 7 received less than the mean rainfall.

Extensive commercial ranching and wildlife conservation are the major forms of land use. Commercial ranching based on beef production, solely or in combination with milk production, is the major livestock enterprise. In addition, ranches keep mutton sheep and/or meat goats as complementary enterprises. Wildlife conservation, coupled with game harvesting, is comprised of various game animal species such as Grant's gazelle, Thomson's gazelle, giraffe, eland, oryx, ostrich, zebra, wildebeest, kongoni and impala (Chapter 2). These species have varying local importance for different ranches.

The David Hopcraft ranch, located 40 km south east of Nairobi along the Nairobi–Mombasa road, is the key ranch in the study because of data availability. As noted above, it has a land area of 8100 ha and is 1600m to 1700m above sea level. Its vegetation is typical of eco-climatic zone 4 — about 4% of the ranch is covered by *Themeda triandra* grassland, 46% is covered by a mixture of *Balanites glabra–Themeda triandra* tree grassland, 44% by *Acacia drepanolobium* and *Balanites glabra* bush grassland, and 6% by *Acacia seyal* and *Acacia xanthoploea* riverine woodland. Livestock production is based on beef cattle mainly purchased for finishing to a market weight of 350 kg (Sommeratte and Hopcraft 1994). From 1989-90, the ranch also started leasing grazing services as a complement to the beef enterprise. Wildlife conservation and game cropping have been carried out at the ranch since 1981 and, to facilitate it, the ranch has made specialized investments. These include a 2.40 m high game–proof perimeter fence and a central slaughterhouse, duly licensed by the Veterinary Department (Kenya Government), where cropped animals are bled, eviscerated, skinned and inspected by a government meat inspector.

I conducted on–site visits to the ranches in the region during 1995 and 1996. Data on commercial livestock enterprises, wildlife and economics were collected from ranch records and ranch correspondence, complemented by personal interviews with ranch employees. The data cover livestock and game animals on all ranches, except in the case of the East African Portland ranch where only wild animal data are included. Based on personal interviews with the ranch manager, Mr. Mwangoma, the beef cattle population stood at 1400 animals as of June 1995. At the David Hopcraft ranch, sheep are not a commercial enterprise; they are intended for ranch consumption with occasional sale. As a result, sales records were not kept and data gathered through personal interviews with the livestock manager, Mr. Osman Egge Egal, are incomplete. Thus, only population data on sheep are included.

3.2 Animal Numbers and Biomass

Average live weight estimates of game populations and livestock at David Hopcraft ranch are adopted from those traditionally used (Table 3.1). For the other ranches, average live weights for cattle, sheep and goats (Table 3.1) were estimated from Manzoni ranch inventories. These live weight estimates are used to transform physical animal numbers into biomass and animal unit estimates.

The total number of livestock in the region, comprised of cattle, sheep and goats, is 22,526, equivalent to a density of 34 per km^2 or a biomass of 5,930kg/km^2 .[9] In addition to livestock, the region is rich in wildlife. Average total number of game animals, comprised of Grant's gazelle, Thomson's gazelle, giraffe, eland, oryx, ostrich, zebra, wildebeest, kongoni and impala, is 14,454 equivalent to a density of 22/km^2 or a biomass of 1,873kg/km^2. Wildlife constitute 24% of the total herbivore biomass. Of the total wildlife biomass, grazers (T. gazelle, zebra, wildebeest and kongoni) constitute 1208kg/km^2 or 65%; mixed feeders (G. gazelle, oryx, ostrich and impala) constitute 225kg/km^2 or 12%; and browsers (Eland and giraffe) constitute 439kg/km^2 or 23%. This composition reflects vegetation distribution (Sommerlatte and Hopcraft

[9] This is the six-month average of monthly counts of domestic animals in the region over the period 1981–1996 for the David Hopcraft ranch; over 1988–1996 for Machakos Ranching Company; over 1991–1996 for East African Portland, Konza, Kapiti, Malili and Aimi–Ma–Kilungu ranches; over 1992–1996 for Manzoni ranch; and over 1994–1996 for the New Astra ranch. The same time periods apply in the case of wildlife species.

1994). Abundance and biomass vary with individual game species (Figures 3.4 and 3.5, respectively).

Table 3.1: Average Game Animal and Livestock Live Weights and Animal Unit Coefficients, Study Region

Species/Cattle	Weight (kg)	AUC[a]	Species	Weight (kg)	AUC[a]
G. gazelle	35	0.1463	Oryx	85	0.2846
T. gazelle	16	0.0813	Zebra	125	0.3800
Impala	35	0.1463	Giraffe	550	1.1547
Kongoni	85	0.2846	Eland	315	0.7602
Wildebeest	125	0.3800	Ostrich	85	0.2846
Cattle (David Hopcraft ranch)	283[b]	0.7015	Goat	27	0.1204
Cattle (other ranches)	207	0.5549			
Sheep	40	0.1617			

[a] Animal unit coefficients are derived from Equation (2.1)

[b] Average cattle live weight for David Hopcraft ranch is 283kg due to purchasing well-formed animals from outside the ranch. Breeding herds on other ranches produce lower average herd weight.

Source: Ranch records

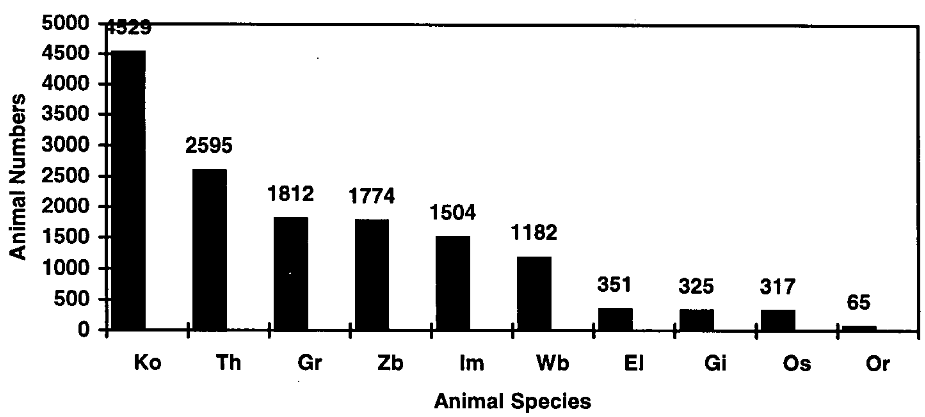

Figure 3.4: Average Number of Game Species, Machakos District, 1981-1996

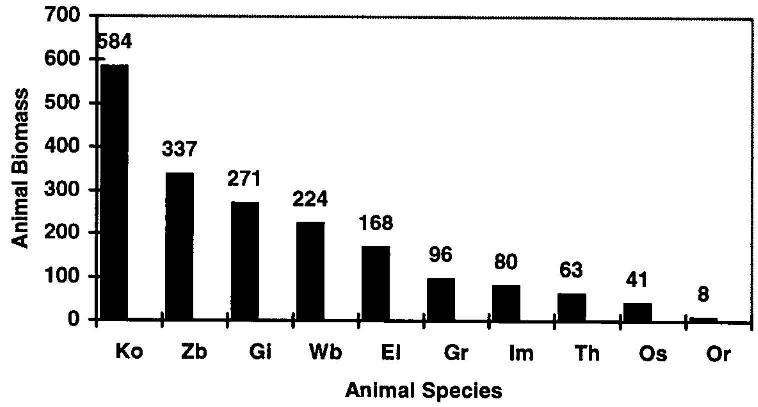

Figure 3.5: Average Biomass (kg/km^2) of Game Species, Machakos District, 1981-1996

Distribution of domestic and wild herbivores across individual ranches presents a unique species mix (see Tables 3.2a and 3.2b). Thomson's gazelle, kongoni and impala are the most ubiquitous and oryx the least, being found at the David Hopcraft ranch only. The average distributions of livestock numbers and biomass vis–a–vis wild animal numbers and biomass is also unique for each ranch (Figures 3.6 and 3.7). For all the ranches, livestock biomass per km^2 is greater than wildlife biomass.

Table 3.2a: Average Distribution of Livestock and Game Species Numbers by Ranch[a]

Species	DHR	KAP	MAL	NAR	MAZ	AMK	MRC	EAP	KOZ
Gr	296	315	237	282	31	–	300	136	215
Th	430	277	580	258	258	52	355	75	310
Gi	56	61	36	27	11	31	47	45	11
El	7	88	55	42	–	80	70	8	1
Or	65	–	–	–	–	–	–	–	–
Os	106	61	12	36	–	–	63	19	20
Zb	87	277	8	446	–	–	553	403	–
Wb	521	87	–	324	–	–	207	43	–
Ko	439	1296	1430	237	30	26	385	119	567
Im	66	98	182	67	88	421	252	237	93
Ca	1572	2548	2839	973	906	2828	1473	1400	2888
Sh	336[b]	–	533	–	826	–	1349	–	160
Go	–	–	522	–	522	553	298	–	–

[a] DHR stands for the David Hopcraft ranch, KAP for Kapiti plains ranch, MAL for Malili ranch, NAR for New Astra Ranch, MAZ for Manzoni ranch, AMK for Aimi–Ma–Kilungu ranch, MRC for Machakos Ranching Company, EAP for East African Portland and KOZ for Konza ranch. Average is based on monthly counts averaged over six-month intervals. Monthly counts over 1981–1996 DHR; 1988–1996 for MRC; 1991–1996 for EAP, KOZ, KAP, MAL and AMK; 1992–1996 for MAZ; and 1994–1996 for NAR.
[b] Although sheep are included here, they are not a commercial enterprise but kept for ranch consumption.

Table 3.2b: Average Distribution of Livestock and Game Species Biomass (kg/km^2) by Ranch[a]

Species	DHR	KAP	MAL	NAR	MAZ	AMK	MRC	EAP	KOZ
Gr	128	85	92	404	33	–	175	72	74
Th	85	34	103	169	126	11	95	18	49
Gi	380	258	223	599	190	231	429	373	59
El	26	213	192	540	–	344	366	37	2
Or	68	–	–	–	–	–	–	–	–
Os	111	40	12	125	–	–	89	24	17
Zb	134	267	11	2278	–	–	1153	760	–
Wb	804	84	–	1653	–	–	431	80	–
Ko	461	847	1353	822	79	30	546	152	477
Im	29	26	71	96	94	201	147	125	32
Ca	5492	4057	6544	8224	5746	7969	5082	4372	5919
Sh	166[b]	–	237	–	1012	–	899	–	63
Go	–	–	157	–	431	203	134	–	–

[a] DHR stands for the David Hopcraft ranch, KAP for Kapiti plains ranch, MAL for Malili ranch, NAR for New Astra Ranch, MAZ for Manzoni ranch, AMK for Aimi–Ma–Kilungu ranch, MRC for Machakos Ranching Company, EAP for East African Portland and KOZ for Konza ranch. Average is based on monthly counts averaged over six-month intervals. Monthly counts over 1981–1996 DHR; 1988–1996 for MRC; 1991–1996 for EAP, KOZ, KAP, MAL and AMK; 1992–1996 for MAZ; and 1994–1996 for NAR.
[b] Although sheep are included here, they are not a commercial enterprise but kept for ranch consumption.

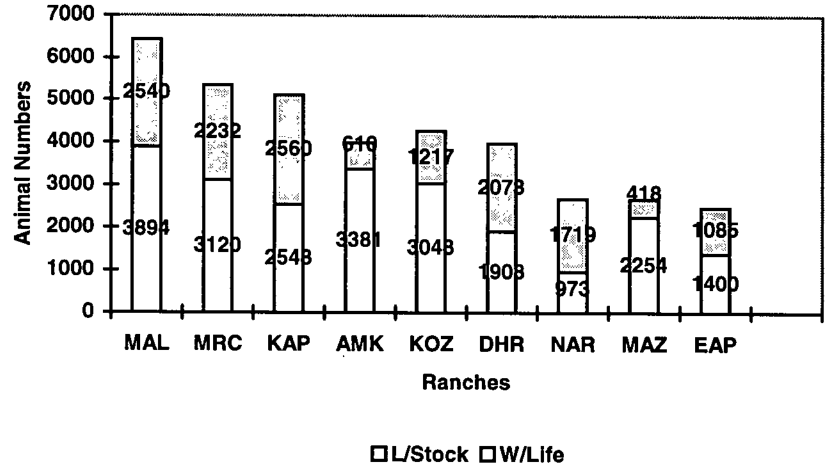

Figure 3.6: Distribution of Livestock and Game Species Numbers by Ranch, Machakos District, 1981–1996

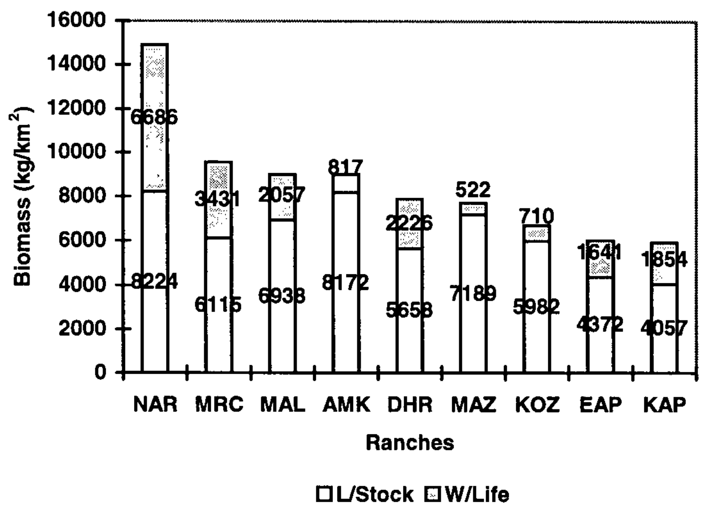

Figure 3.7: Distribution of Livestock and Game Species' Biomass (kg/km^2) by Ranch, Machakos District, 1981–1996

Based on forage preferences, the proportionate distribution of wildlife grazers, browsers and mixed feeders across ranches reflects vegetation type for individual ranches (Table 3.3). Grazers comprise 61–74% of the total wildlife biomass at the David Hopcraft, Athi Kapiti plains, Malili, New Astra, Machakos Ranching Company, East African Portland and Konza ranches (Table 3.3). This is consistent with the high proportion of grassland that characterizes these ranches. Aimi–Ma–Kilungu ranch, which is characterized by a high proportion of woody vegetation, has a higher proportion of browsers (70%). Manzoni ranch, which has approximately 50% grassland and 50% woody vegetation, has a proportionate distribution of grazers and browsers of 39% and 37%, respectively.

Table 3.3: Distribution of Game Species' Biomass (kg/km²) across Ranches by Forage Preferences[a]

Ranch	Grazers	Mixed feeders	Browsers	Year cropping began
David Hopcraft (DHR)	1484(67)	336(15)	406(18)	1981
Kapiti Plains (KAP)	1232(67)	151(8)	471(25)	1991
Malili (MAL)	1467(71)	175(9)	415(20)	1991
New Astra (NAR)	4922(74)	624(9)	1139(17)	1994
Manzoni (MAZ)	205(39)	127(24)	190(37)	1992
Aimi–Ma–Kilungu (AMK)	41(5)	201(25)	575(70)	1991
Machakos Ranching Company (MRC)	2225(65)	411(12)	795(23)	1988
East African Portland (EAP)	1010(61)	241(14)	410(25)	1991
Konza (KOZ)	526(74)	123(17)	61(9)	1991

[a] Proportion (%) of feed preference class biomass to total ranch wildlife biomass is shown in parentheses

The extent to which populations migrate/disperse across ranches and the degree to which populations are resident within individual ranches is captured by the "coefficient of variation" (CV) around population means. This varies with animal species and by ranches (Table 3.4). Populations of Grant's gazelle are the least variable or the most strongly resident in all the ranches with an average "coefficient of variation" of 37%. Populations of eland, on the other hand, are the most highly variable with an average CV across ranches of 102% indicating that the species has very strong dispersal tendencies. Variation of the populations of other species falls in between these two. A low coefficient of variation implies high residency status of game animals, and can be explained, for some ranches, by electrical fences installed in areas of the ranch that have high game animal concentrations (e.g., Athi Kapiti Plains ranch). The David Hopcraft ranch has a chain–link game–proof perimeter fence but, in 1986, there was a break in the fence and this appears to have resulted in high emigration of animals from the ranch, particularly with respect to eland, as portrayed by the relatively high average CVs across species. Machakos Ranching Company and Aimi–Ma–Kilungu ranches that have the highest CVs do not have any game–proof perimeter fencing.

Table 3.4: Coefficient of Variation (%) for Wildlife Populations by Ranch and Species

Species	DHR	KAP	MAL	NAR	MAZ	AMK	MRC	EAP	KOZ	Mean
Gr	32	31	40	28	37	–	56	25	50	37
Th	48	39	28	17	25	82	46	54	23	40
Gi	21	23	48	77	73	61	64	35	126	59
El[a]	202	49	98	74	–	62	53	145	136	102
Or	86	–	–	–	–	–	–	–	–	86
Os	20	34	28	53	–	–	56	54	38	40
Zb	49	28	40	31	–	–	31	55	–	39
Wb	44	48	–	47	–	–	92	52	–	57
Ko	35	20	12	37	57	104	118	42	13	73
Im	55	34	26	6	30	20	42	35	29	46
Mean	59[a]	34	40	41	44	66	62	55	59	

[a] Excluding Eland, the mean CV for the David Hopcraft ranch is 43% . Eland is highly migratory compared to the other species as evidenced by high CVs across ranches, including on the David Hopcraft Ranch where a fence does not appear to contain the species. The lowest CV is for the Kapiti Plains Ranch that uses electrical fencing so that species are more highly resident.

Variation of livestock and wildlife numbers and biomass over time is illustrated for the David Hopcraft ranch in Tables 3.5a and 3.5b. Livestock density at the end of January, 1981, was 35 per km^2 or a biomass of 8,478 kg per km^2; Sommerlatte and Hopcraft (1994) report an equivalent biomass of 8,620 kg per km^2, which was based on cattle live weight of 288 kg. From 1982 to 1986, there was a decline in livestock numbers, reaching a density of 13 per km^2 or a biomass of 3,391 kg per km^2 at the end of January 1986. From 1987 onwards, livestock numbers increased, reaching a density of 27 per km^2 or biomass of 6,809kg per km^2 in January 1989. By January, 1990 total livestock numbers stood at a density of 46 per km^2 equivalent to a biomass of 11,928kg per km^2, which included ranch owned livestock biomass of 6600kg per km^2 (Sommerlatte and Hopcraft 1994). Outsiders, notably Mr. Penta, grazed cattle on the ranch, and later on Masai used grazing lease arrangements; the lease payment was in-kind at 50 kg per animal sold. In contrast, the wildlife population in January, 1981 stood at 24 per km^2, or a biomass of 1,624 kg per km^2. This increased to 28 per km^2 or a biomass of 2,379 kg per km^2 in January of 1983, but was followed by a dramatic decline in 1985-86, reaching a recorded low density of 14 per km^2 and biomass of 1,130 kg per km^2 in January 1986. This decline was associated with heavy cropping, drought and a break in the fence (Sommerlatte and Hopcraft 1994). Heavy cropping at the time was not related to drought, however. From 1987 onwards, there was a general increase in animal numbers and biomass (Tables 3.5a and 3.5b), which was associated with a reduction in harvesting intensity. At the highest count, the population was 2,209 with a density of 27.3 per km^2 and biomass of 2,257 kg per km^2. In July 1996, density was 34 animals per km^2 and biomass 3,368 kg per km^2, representing 34% of total herbivore biomass at the David Hopcraft ranch. The average wildlife biomass composition at the David Hopcraft ranch is 67% grazers (T. gazelle, zebra, wildebeest and kongoni), 15% mixed feeders (G. gazelle, oryx, ostrich and impala) and 18% browsers (giraffe and eland).

3.3 Wildlife Harvests and Livestock Production

Dates at which game cropping began at each of the ranches are provided in Table 3.3. Until October 1996, cumulative game harvested was 14,269 animals (Table 3.6). In terms of numbers, the four most important commercial species are kongoni, T. gazelle, Wildebeest and G. gazelle, while the four most important ranches involved in game cropping are the David Hopcraft, Athi Kapiti Plains, Machakos Ranching Company and Malili ranches. Six-month average game harvest for the period is provided in Table 3.7. Although not shown in the tables, game harvesting is gaining in prominence as a commercial activity, especially at the ranches indicated. However, it is clear that domestic livestock production remains the dominant activity (Table 3.7).

As in the case of standing populations, variation of game harvests and livestock sales over time can be illustrated using data for the David Hopcraft ranch. Based on total harvests per six–month period, harvest in 1981 was 237 animals, and since then, cropping intensity increased, reaching a recorded high of 488 animals in 1985 (Table 3.8). In 1986, only 168 animals were harvested. Thereafter, cropping intensity remained relatively low. In contrast, cattle sales were fairly irregular ranging from a six–month low of 3 animals in 1987 to a high of 2,241 animals in 1993. Similar trends for both wildlife and cattle are portrayed by the off-take rate (%) over six-month periods (Table 3.9). During the period 1981–1989 game harvests were equal to and even exceeded cattle sales, but from 1990 onwards cattle sales were much higher than game harvests as a result of increased off-take of non–ranch owned cattle.

Table 3.5a: Livestock and Wildlife Numbers per km^2 at David Hopcraft Ranch by Species, 1981–1996

Period[a]	Gr	Th	Gi	El	Or	Os	Zb	Wb	Ko	Im	Ca	Sh
81-1	552	765	55	–	–	–	25	249	465	35	2285	527
81-2	397	687	60	–	–	–	28	243	557	34	2237	559
82-1	386	660	54	56	0	–	26	340	612	40	1786	509
82-2	301	580	45	22	0	–	28	444	546	16	1629	347
83-1	278	716	40	39	0	–	22	387	530	13	1616	92
83-2	298	650	47	5	0	–	34	378	511	34	1378	102
84-1	357	971	49	8	8	–	43	413	557	22	1237	95
84-2	274	798	56	5	17	–	52	394	458	3	967	94
85-1	205	408	44	5	18	–	66	336	327	20	963	106
85-2	177	477	34	7	18	–	64	316	312	40	894	121
86-1	138	422	43	2	22	–	55	249	224	36	903	140
86-2	140	329	50	0	23	–	76	223	225	59	1510	162
87-1	141	329	45	1	30	99	72	285	206	57	1041	195
87-2	164	330	45	0	14	124	97	319	251	71	1172	206
88-1	233	442	49	0	20	127	103	391	240	97	1370	307
88-2	156	268	59	0	46	115	81	331	144	56	1062	378
89-1	271	288	61	1	44	95	105	483	298	71	1778	389
89-2	308	449	82	0	63	115	125	600	351	105	3212	419
90-1	292	503	41	1	59	131	91	420	328	131	2914	430
90-2	344	466	62	0	80	99	114	506	337	114	2986	513
91-1	368	562	66	0	72	137	152	732	470	108	3041	460
91-2	289	230	58	0	105	109	57	539	497	103	2337	410
92-1	285	285	73	0	101	106	117	645	432	125	1090	358
92-2	339	305	74	0	102	96	123	797	508	111	1709	376
93-1	339	305	74	0	102	96	123	797	508	111	682	403
93-2	392	324	75	0	109	85	128	949	583	96	1444	381
94-1	225	155	51	0	130	71	64	645	404	93	435	472
94-2	365	214	53	0	138	89	113	748	504	85	1001	624
95-1	348	230	59	0	139	87	134	839	604	66	671	620
95-2	330	245	65	3	142	84	154	930	703	46	1105	505
96-1	366	206	62	17	164	117	152	894	691	58	1971	221
96-2	401	166	58	31	185	150	149	858	679	69	1874	224

[a] 1 refers to January through June, 2 refers to July through December.

Table 3.5b: Livestock and Wildlife Biomass (kg/km^2) at David Hopcraft Ranch by Species, 1981–1996

Period[a]	Gr	Th	Gi	El	Or	Os	Zb	Wb	Ko	Im	Ca	Sh
81-1	239	151	373	–	–	–	39	384	488	15	7983	260
81-2	172	136	407	–	–	–	43	375	585	15	7816	276
82-1	167	130	367	218	0	–	40	525	642	17	6240	251
82-2	130	115	306	86	0	–	43	685	573	7	5691	171
83-1	120	141	272	152	0	–	34	597	556	6	5646	45
83-2	129	128	319	19	0	–	52	583	536	15	4814	50
84-1	154	191	333	31	8	–	66	637	585	10	4322	47
84-2	118	158	380	19	18	–	80	608	481	1	3379	46
85-1	89	81	299	19	19	–	102	519	343	9	3365	52
85-2	76	94	231	27	19	–	99	488	327	17	3123	60
86-1	60	83	292	8	23	–	85	384	235	16	3155	69
86-2	60	65	340	0	24	–	117	344	236	25	5276	80
87-1	61	65	306	4	31	104	111	440	216	25	3637	96
87-2	71	65	306	0	15	130	150	492	263	31	4095	102
88-1	101	87	333	0	21	133	159	603	252	42	4787	152
88-2	67	53	401	0	48	121	125	511	151	24	3710	187
89-1	117	57	414	4	46	100	162	745	313	31	6212	192
89-2	133	89	557	0	66	121	193	926	368	45	11222	207
90-1	126	99	278	0	62	137	140	648	344	57	10181	212
90-2	149	92	421	4	84	104	176	781	354	49	10433	253
91-1	159	111	448	0	76	144	235	1130	493	47	10625	227
91-2	125	45	394	0	110	114	88	832	522	45	8165	202
92-1	123	56	496	0	106	111	181	995	453	54	3808	177
92-2	146	60	502	0	107	101	190	1230	533	48	5971	186
93-1	146	60	502	0	107	101	190	1230	533	48	2383	199
93-2	169	64	509	0	114	89	198	1465	612	41	5045	188
94-1	97	31	346	0	136	75	99	995	424	40	1520	233
94-2	158	42	360	0	145	93	174	1154	529	37	3497	308
95-1	150	45	401	0	146	91	207	1295	634	29	2344	306
95-2	143	48	441	12	149	88	238	1435	738	20	3861	249
96-1	158	41	421	66	172	123	235	1380	725	25	6886	109
96-2	173	33	394	121	194	157	230	1324	713	30	6547	111

[a] 1 refers to January through June, 2 refers to July through December.

Table 3.6: Cumulative Numbers of Game Harvested over the Period 1981–1996, Machakos District, by Ranch and Species[a]

Species	DHR	KAP	MAL	NAR	MAZ	AMK	MRC	EAP	KOZ	TOTAL
Gr	898	204	113	11	9	–	282	40	131	1688
Th	1810	188	268	10	64	50	752	33	214	3389
Gi	100	–	5	3	1	–	2	–	1	112
El	27	54	8	3	–	37	29	–	–	155
Or	98	–	–	–	–	–	–	–	–	98
Os	46	–	–	–	–	–	16	–	–	62
Zb	131	292	–	8	–	–	177	194	–	802
Wb	1957	80	–	9	–	–	337	8	–	2391
Ko	1775	1396	808	9	7	15	270	54	324	4658
Im	194	77	120	7	22	168	140	136	50	914
Total	7036	2291	1322	60	103	270	2005	465	720	14269

[a] See Table 3.3 for a description of ranch acronyms.

Table 3.7: Six-month Average Game Harvested and Livestock Sold in Machakos District, by Species and Ranch, 1981–1996[a]

Species	DHR	KAP	MAL	NAR	MAZ	AMK	MRC	EAP	KOZ	Total
Gr	28	20	14	6	5	–	28	10	16	127
Th	57	24	30	5	16	10	75	11	24	252
Gi	4	–	1	2	1	–	2	–	1	11
El	3	7	8	3	–	5	5	–	–	31
Or	9	–	–	–	–	–	–	–	–	9
Os	8	–	–	–	–	–	8	–	–	16
Zb	8	24	–	4	–	–	18	28	–	82
Wb	61	8	–	5	–	–	34	4	–	112
Ko	55	107	90	5	4	8	27	11	36	343
Im	7	10	20	4	7	24	14	19	8	113
Total[b]	240	200	163	34	33	47	211	83	85	1096
Ca	607	443	273	106	143	301	230	–[c]	346	2449
Sh	–[d]	–	64	–	192	–	208	–	25	489
Go	–	–	74	–	80	75	112	–	–	341

[a] Periods without harvests were not considered (see Table 3.3 for ranch acronyms).
[b] This row is total game harvested by ranch
[c] East African Portland ranch livestock sales data were not covered
[d] David Hopcraft ranch sheep are not a commercial enterprise

Table 3.8: Summary of Livestock Sales and Game Animal Harvests, David Hopcraft Ranch, 1981–1996

Period[a]	Gr	Th	Gi	El	Or	Os	Zb	Wb	Ko	Im	Total W/Life	Cattle
81-1	86	110	–	–	–	–	–	13	28	–	237	153
81-2	66	135	–	–	–	–	–	22	69	–	292	593
82-1	42	64	–	1	–	–	–	32	85	7	231	194
82-2	45	83	–	–	–	–	–	76	105	6	315	324
83-1	49	140	–	–	–	–	–	42	68	9	308	285
83-2	5	51	–	9	–	–	–	81	114	3	263	173
84-1	17	56	2	8	–	–	–	104	122	5	314	319
84-2	38	96	–	2	–	–	–	132	165	4	437	96
85-1	32	123	–	3	–	–	1	150	101	2	412	116
85-2	47	173	1	1	–	–	–	167	95	4	488	50
86-1	8	39	5	–	–	–	–	66	47	3	168	258
86-2	9	58	2	–	–	–	–	22	45	2	138	763
87-1	2	39	1	1	–	–	1	6	23	–	73	3
87-2	4	45	–	–	–	–	–	27	28	1	105	359
88-1	1	32	1	–	–	–	4	8	18	1	65	396
88-2	25	73	2	–	–	–	6	60	45	19	230	419
89-1	13	21	2	1	–	–	2	42	9	2	92	204
89-2	25	44	4	–	–	–	3	20	27	10	133	348
90-1	38	51	3	1	–	1	–	17	17	7	135	941
90-2	43	57	7	–	–	–	13	38	51	26	235	1471
91-1	29	62	10	–	5	10	9	23	7	3	158	499
91-2	32	98	6	–	4	13	26	9	6	7	201	1766
92-1	22	33	2	–	3	3	16	36	12	11	138	995
92-2	17	39	4	–	1	11	6	50	65	16	209	2130
93-1	22	–	6	–	16	–	8	75	10	6	143	513
93-2	64	39	12	–	7	8	15	118	34	10	307	2241
94-1	1	–	6	–	3	–	–	101	57	1	169	162
94-2	45	18	3	–	13	–	11	35	65	7	197	404
95-1	7	3	5	–	–	–	–	110	49	5	179	478
95-2	33	21	7	–	21	–	5	52	65	5	209	217
96-1	13	5	7	–	9	–	2	87	32	5	160	1940
96-2	18	2	2	–	16	–	3	136	111	7	295	92
Total	898	1810	100	27	98	46	131	1957	1775	194	7036	18902

[a] 1 refers to January through June, 2 refers to July through December.

Table 3.9: Livestock and Game Animal Off-take Rates as a Percent of Standing Population, David Hopcraft Ranch, 1981–1996

Period[a]	Gr	Th	Gi	El	Or	Os	Zb	Wb	Ko	Im	Cattle
81-1	15.6	14.4	–	–	–	–	–	5.2	6.0	–	6.7
81-2	16.6	19.7	–	–	–	–	–	9.1	12.4	–	26.5
82-1	10.9	9.7	–	1.8	–	–	–	9.4	13.9	17.5	10.9
82-2	15.0	14.3	–	–	–	–	–	17.1	19.2	37.5	19.9
83-1	17.6	19.6	–	–	–	–	–	10.9	12.8	69.2	17.6
83-2	1.7	7.8	–	180[b]	–	–	–	21.4	22.3	8.8	12.6
84-1	4.8	5.8	4.1	100[b]	–	–	–	25.2	21.9	22.7	25.8
84-2	13.9	12.0	–	40.0	–	–	–	33.5	36.0	133.0[b]	9.9
85-1	15.6	30.1	–	60.0	–	–	1.5	44.6	30.9	10.0	12.0
85-2	26.6	36.3	2.9	14.3	–	–	–	52.8	30.4	10.0	5.6
86-1	5.8	9.2	11.6	–	–	–	–	26.5	21.0	8.3	28.6
86-2	6.4	17.6	4.0	–	–	–	–	9.9	20.0	3.4	50.5
87-1	1.4	11.9	2.0	100[b]	–	–	1.4	2.1	11.2	–	0.3
87-2	2.4	13.6	–	–	–	–	–	8.5	11.2	1.4	30.6
88-1	0.4	7.2	2.0	–	–	–	3.9	2.0	7.5	1.0	28.9
88-2	16.0	27.2	3.4	–	–	–	7.4	18.1	31.3	33.9	39.5
89-1	4.8	7.3	3.3	100[b]	–	–	1.9	8.7	3.0	2.8	11.5
89-2	8.1	9.8	4.9	–	–	–	2.4	3.3	7.7	9.5	10.8
90-1	13.0	10.1	7.3	100[b]	–	0.8	–	4.0	5.2	5.3	32.3
90-2	12.5	12.2	11.3	–	–	–	11.4	7.5	15.1	22.8	49.3
91-1	7.9	11.0	15.2	–	6.9	7.3	5.9	3.14	1.5	2.8	16.4
91-2	11.1	42.6	10.3	–	3.8	11.9	45.6	1.7	1.2	6.8	75.6
92-1	7.7	11.6	2.7	–	3.0	2.8	13.7	5.6	2.8	8.8	91.3
92-2	5.0	12.8	5.4	–	1.0	11.5	4.9	6.3	12.8	14.4	124.6[b]
93-1	6.5	–	8.1	–	15.7	–	6.5	9.4	2.0	5.4	75.2
93-2	16.3	12.0	16.0	–	6.4	9.4	11.7	12.4	5.8	10.4	155.2[b]
94-1	0.4	–	11.8	–	2.3	–	–	15.7	14.1	1.1	37.2
94-2	12.3	8.4	5.7	–	9.4	–	9.7	4.7	12.9	8.2	40.4
95-1	2.0	1.3	8.5	–	–	–	–	13.1	8.1	7.6	71.2
95-2	10.0	8.6	10.8	–	14.8	–	3.2	5.6	9.2	10.9	19.6
96-1	3.6	2.4	11.3	–	5.5	–	1.3	9.7	4.6	8.6	98.4
96-2	4.5	1.2	3.4	–	8.6	–	2.0	15.9	16.3	10.1	4.9
Mean	9.3	13.6	7.2	77.0	7.0	7.3	7.9	13.2	13.4	17.0	38.7

[a] 1 refers to January through June, 2 refers to July through December.

[b] Standing population was highly variable and when averaged over six months was lower than harvest, resulting in greater than 100% off take rate.

3.4 Economic Analysis for David Hopcraft Ranch

The output from the David Hopcraft ranch is game meat and fattened beef cattle. These two outputs are the focus of economic analysis. I begin by considering game meat production and its value.

3.4.1 Game Meat Production at David Hopcraft Ranch

Average cold dressed weight of game animals was calculated from a sample of game harvests and corresponding cold dressed weight after slaughter (Table 3.10). This information and data in Table 3.8 are used to derive total annual cold dressed weight from the David Hopcraft ranch for the years 1981–1986, while cold dressed meat production from 1987–1995 is based on actual meat production data (Table 3.11). The most important species in game meat production are wildebeest and kongoni, while the least important is ostrich (Table 3.11).

Table 3.10: Average Species Cold Dressed Weight[a]

Species	Animal Numbers	Total cold–dressed weight (kg)	Average cold–dressed weight (kg)
G. gazelle	412	11975.4	29.07
T. gazelle	644	6678.55	10.37
Giraffe	81	27253.0	336.46
Eland	3	655.0	218.33
Oryx	68	5705.0	83.90
Ostrich	46	2772.0	60.26
Zebra	118	16792.5	142.31
Wildebeest	803	71902.2	89.54
Kongoni	562	32475.80	57.79
Impala	131	3455.2	26.38

[a] Based on actual data from David Hopcraft Ranch's slaughterhouse.

Table 3.11: Annual Meat Production ('000s kg cold–dressed weight), 1981–1995[a]

Year	Gr	Th	Gi	El	Or	Os	Zb	Wb	Ko	Im
1981	4.42	2.54	–	–	–	–	–	3.13	5.61	0.026
1982	2.53	1.52	–	0.22	–	–	–	9.67	10.8	0.343
1983	1.57	1.98	–	2.40	–	–	–	11.0	10.5	0.317
1984	1.60	1.56	0.67	2.62	–	–	–	21.1	16.6	0.237
1985	2.30	3.07	0.34	0.87	–	–	–	28.4	11.3	0.158
1986	0.44	0.90	2.36	–	–	–	–	7.16	5.03	0.132
1987	0.18	0.88	0.34	0.19	–	–	0.16	2.74	1.66	0.022
1988	0.88	1.10	1.16	–	–	–	1.54	6.24	3.76	0.590
1989	1.16	0.62	3.13	0.08	–	–	0.67	6.00	2.63	0.296
1990	2.14	1.03	3.44	0.39	–	0.08	1.84	5.14	4.30	0.734
1991	2.01	1.59	4.98	–	0.54	1.46	5.17	3.04	0.78	0.261
1992	1.17	0.68	2.19	–	0.34	0.79	2.90	8.70	4.51	0.690
1993	1.97	0.36	5.53	–	1.96	0.45	2.26	16.0	2.37	0.368
1994	1.26	0.16	2.79	–	1.22	–	1.60	10.8	6.23	0.261
1995	1.25	0.25	3.40	–	0.60	–	0.69	13.2	6.24	0.234
Total	24.9	18.2	30.3	6.77	4.66	2.78	16.83	152.32	92.32	4.669

[a] From 1981 to 1986, total cold–dressed weight is derived from average cold–dressed weights and number of carcasses in meat records. Total cold–dressed weight data were available for 1987-1995.

The major market outlets for game meat are Nairobi and Mombasa, with meat prices in Nairobi differing from those in Mombasa by transportation cost only. Real prices of game meat in Nairobi for 1990–1995 are provided in Table 3.12. The prices in Table 3.12 are nominal prices adjusted for the rate of inflation, which averaged 21.4% over 1990-1996 (IMF 1997). The most highly valued game species are ostrich, Thomson's gazelle, Grant's gazelle and impala, while the lowest valued species are wildebeest, kongoni and zebra. From data in Tables 3.11 and 3.12, it is possible to calculate real gross income by species for the period 1990 through 1995 (Table 3.13). Total gross income from game cropping averaged 877,700 Ksh per year with the highest income realized in 1993; wildebeest contributed the most to income over the period with an annual average of 294,200 Ksh.

Table 3.12: Real Average Gross Price (1990 KSh) per kg of Game meat in Nairobi, by Species, 1990–1996

Year	Gr	Th	Gi	El	Or	Os	Zb	Wb	Ko	Im
1990	80	80	46	46	–	46	46	46	46	80
1991	66.8	66.8	38.4	38.4	38.4	38.4	38.4	38.4	38.4	66.8
1992	51.5	51.5	38.7	38.7	38.7	61.2	32.2	32.2	32.2	51.5
1993	46.4	46.4	35.4	35.4	35.4	66.3	28.7	28.7	28.7	46.4
1994	47.9	47.9	41.1	41.1	41.1	78.8	30.8	30.8	30.8	47.9
1995	54.4	68	47.6	47.6	47.6	84.9	30.6	30.6	30.6	54.4
1996	69	78.1	43.7	43.7	43.7	93.7	31.2	31.2	31.2	68.7
Mean	59.4	62.7	41.6	41.6	40.8	67	34	34	34	59.4

Table 3.13: Real Gross Returns from Game Cropping ('000s 1990 KSh), David Hopcraft Ranch, 1990–1995

Year	Gr	Th	Gi	El	Or	Os	Zb	Wb	Ko	Im	Total
1990	171.4	82.8	158.3	17.9	–	3.5	84.6	170.6	71.4	58.7	819.2
1991	134.4	106.0	191.2	–	20.5	56.0	198.6	116.6	29.8	17.4	870.5
1992	60.3	35.1	84.5	–	13.0	48.4	92.9	280.4	145.2	30.4	790.2
1993	91.4	16.8	195.4	–	69.4	29.8	65.0	460.1	68.0	17.1	1013.0
1994	60.5	7.7	114.5	–	50.3	–	49.2	333.3	191.9	12.5	819.9
1995	68.0	16.9	161.6	–	78.4	–	21.2	404.1	190.7	12.7	953.6
Total	586.0	265.3	905.5	17.9	231.6	138	511.5	1765	697.0	148.8	5266.4
Mean[a]	97.7	44.2	150.9	3.0	38.6	23.0	85.3	294.2	116.2	24.8	877.7
AUs[b]	51.64	34.23	81.98	0.76	20.78	13.1.	41.42	252.3	124.7	15.22	636.11
GP[c]	11.35	7.75	11.05	23.6	11.15	10.5	12.35	7.0	5.59	9.78	8.28

[a] Average gross return per year
[b] Total harvest in animal units
[c] Gross return per animal unit

Variable costs of game cropping are effort, transport, ammunition, meat inspection, meat marketing, carcass and skin processing, power for cooling and storage, and water. Effort pertains to the labour input of a cropping unit for one hour. A Cropping unit is comprised of a marksman, driver/assistant and Muslim meat blesser (halal–man) who is also the spotlight man. The unit uses a four wheel drive vehicle with a capacity for five carcasses. Cropping operations start at 7 pm and end at midnight for all game species except giraffe and ostrich, which are cropped during the day. Thus, on a five-day working week, the cropping unit effort input is 120 hours per month. The average shooting distance is 70 to 100 m and small animals have smaller flight distances compared to large animals; as a result it takes less cropping time (effort) to harvest the former than the latter (Table 3.14).

In addition, game cropping requires investments that include slaughterhouse and associated utilities, cropping and meat marketing vehicles, guns and game–proof fencing, although the latter is an optional requirement. The gun is a 0.22 calibre Hornet for small animals, and of 0.243 or 0.308 calibre for large animals. There are two slaughterhouses in the study area that are licensed by the Veterinary Department of the Government of Kenya—one at Machakos Ranching Company and the other at the David Hopcraft ranch. Cropped animals are bled, eviscerated, skinned and inspected by a Government meat inspector at the slaughterhouse, after which carcasses are stored at a temperature of two degrees centigrade until time of sale.

The cost of effort is derived from the real monthly wage rate paid to the cropping crew in 1994 as provided in Table 3.15. The total monthly payment was 21,268 Ksh. At the total cropping time of 120 hours of effort per month, the equivalent cost of effort per hour is 177 Ksh. As indicated in Table 3.15, the 1994 labour and other costs have been converted into 1990 values using the inflation rate for the period. A cost breakdown analysis has been carried out by the Wildlife Manager, Mr. Sinnary, involving 14 kongonis, 2 oryxes, 20 wildebeests, 2 zebras, 2 giraffes, 5 G. gazelles, 2 T. gazelles and 7 impalas cropped during August–October, 1996 is found in Table 3.16. Net return over these "other variable costs" is also provided. The corresponding proportionate breakdown is provided in Table 3.17. From data in Tables 3.13 and 3.17, it is possible to calculate the real cost of cropping (Table 3.18). The corresponding real net cash income (rent) by species for the David Hopcraft ranch for the period 1990 to 1995 is provided in Table 3.19; average net cash income per animal and per animal unit cropped is also provided.

Table 3.14: Average Effort (hours) per Animal Cropped, by Species, David Hopcraft ranch,

Species	Numbers cropped	Total effort (hours)	Average effort (hours)
G. gazelle	423	129.62	0.31
T. gazelle	626	186.23	0.30
Giraffe	60	56.37	0.94
Oryx	70	37.77	0.54
Zebra	101	69.05	0.68
Wildebeest	1211	432.40	0.36
Kongoni	741	320.05	0.43
Impala	130	53.23	0.41

Table 3.15: Monthly Nominal and Real Wage Rates of Cropping Crew at David Hopcraft Ranch, 1994

Crew category	Nominal wage rate (1994)	Real wage rate (1990)
Driver/assistant	18,600	6,370
Halal–man/spotter	20,776	7,115
Marksman/hunter	22,725	7,783
Total	62,101	21,268
Average monthly cropping effort (hours)	120	120
Cost of effort per hour	518	177

Table 3.16: Real Cost Breakdown of Non-labour Variable Costs, by Species, August–September 1996, David Hopcraft Ranch ('000s 1990 KSh)

Item	Gr[a]	Th[b]	Gi[b]	Or[c]	Zb[c]	Wb[c]	Ko[c]	Im[b]
Gross income	10.255	1.206	25.384	4.011	6.099	33.221	14.960	7.798
Cropping transportation	0.263	0.105	0.105	0.105	0.105	1.051	0.736	0.368
Ammunition	0.213	0.085	0.085	0.085	0.085	0.853	0.597	0.299
Meat inspection	0.156	0.062	0.062	0.062	0.062	0.625	0.437	0.219
Marketing	0.473	0.04	7.989	0.258	0.571	3.343	1.631	0.360
Other costs	0.308	0.026	1.131	0.167	0.370	2.168	1.058	0.234
Net income[d]	8.842	0.888	16.012	3.334	4.906	25.181	10.501	6.318

Source: A.S.M. Sinnary (pers. comm.) and Ranch Records

[a] September 1996 harvest data and August 1996 prices used

[b] October 1996 harvest data and August 1996 prices used

[c] August 1996 harvest data and prices were used

[d] Net Income over variable costs excluding cost of effort.

Table 3.17: Allocation of Gross Income to Species, David Hopcraft Ranch (% of gross income)

Item	Gr	Th	Gi	Or	Zb	Wb	Ko	Im
Gross income	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Cropping transportation	2.56	8.72	0.41	2.62	1.73	3.16	4.92	4.72
Ammunition	2.08	7.07	0.34	2.13	1.40	2.57	3.99	3.83
Meat inspection	1.52	5.17	0.25	1.56	1.02	1.88	2.92	2.80
Marketing	4.62	3.29	31.47	6.43	9.35	10.06	10.91	4.62
Other costs	3.0	2.12	4.45	4.17	6.07	6.53	7.07	3.0
Net income	86.22	73.63	63.08	83.12	80.04	75.80	70.02	81.02

Table 3.18: Total real Cost of Game Cropping by Species, David Hopcraft ranch, 1990–1995 ('000s 1990 Ksh)

Year	Gr	Th	Gi	Or	Zb	Wb	Ko	Im	Total
1990	23.62	21.83	58.44	–	16.89	41.28	21.41	11.14	194.61
1991	18.52	27.95	70.59	3.46	39.64	28.22	8.93	3.30	200.61
1992	8.31	9.26	31.20	2.19	18.54	67.86	43.53	5.77	186.66
1993	12.59	4.43	72.14	11.71	12.97	111.34	20.39	3.25	248.82
1994	8.34	2.03	42.27	8.49	9.82	80.66	57.53	2.37	211.51
1995	9.37	4.46	59.66	13.23	4.23	97.79	57.17	2.40	248.31
Subtotal	80.75	69.96	334.3	39.08	102.09	427.15	208.96	28.23	1290.52
Number[a]	353	421	71	73	109	664	438	104	2233
Effort[b]	109.43	126.30	66.74	39.42	74.12	239.04	188.34	42.64	886.03
Ef cost[c]	19.369	22.355	11.813	6.977	13.119	42.310	33.336	7.547	156.827
Total[d]	100.12	92.315	346.11	46.057	115.21	469.46	242.30	35.777	1447.35

[a] Aanimals harvested from 1990 through 1995
[b] Total effort used
[c] Total cost of effort @ 177 Ksh per hour
[d] Total cost of harvesting

Realised net cash income (Table 3.19) accrues to David Hopcraft ranch. However, the ranch also buys game animals from other ranches. The average real price that David Hopcraft pays to other ranchers for game taken on their ranch is given in Table 3.20. The David Hopcraft ranch incurs all costs associated with game cropping on other ranches, compensating the ranchers only for the animals (and thus for the forage foregone).

Table 3.19: Net Cash Income (Rent) by Game Species, David Hopcraft Ranch, 1990–1995 ('000s Ksh)

Year	Gr	Th	Gi	Or	Zb	Wb	Ko	Im	Total
1990	147.78	60.97	99.86	–	67.71	129.32	49.99	47.56	603.19
1991	115.88	78.05	120.61	17.04	158.96	88.38	20.87	14.1	613.89
1992	51.99	25.84	53.30	10.81	74.36	212.54	101.67	24.63	555.14
1993	78.81	12.37	123.26	57.69	52.03	348.76	47.61	13.85	734.38
1994	52.16	5.67	72.23	41.81	39.38	252.64	134.37	10.13	608.39
1995	58.63	12.44	101.94	65.17	16.97	306.31	133.53	10.3	705.29
Net Return[a]	505.25	195.34	571.20	192.52	409.41	1338	488.04	120.57	3820.33
Number[b]	353	421	71	73	109	664	438	104	2233
Mean[c]	1.431	0.464	8.045	2.637	3.756	2.015	1.111	1.159	1.711
AUs[d]	51.644	34.227	81.984	20.776	41.42	252.32	124.65	15.215	622.246
Mean[e]	9.783	5.707	6.967	9.266	9.884	5.303	3.915	7.924	6.140
Net[f]	485.88	172.99	559.39	185.54	396.29	1295.7	454.70	113.0	3663.49
Mean[g]	9.408	5.054	6.823	8.93	9.568	5.135	3.648	7.427	5.888

[a] Total net return excluding effort cost
[b] Total animals harvested from 1990 through 1995
[c] Average net return per animal, excluding effort cost
[d] Total animal units harvested from 1990 through 1995
[e] Average net return per animal unit excluding effort cost. This is the net price per animal unit before effort cost deductions.
[f] Net return after accounting for effort cost
[g] Average net return per animal unit after accounting for effort cost.

Table 3.20: Real Prices Paid to Ranchers Per Animal Cropped from their Ranches (1990 KSh), 1990–1996

Period[a]	Gr	Th	Gi	El	Or	Os	Zb	Wb	Ko	Im
90-1	200	100	4500	900	340	160	800	600	400	200
90-2	200	100	4500	900	340	160	800	600	400	200
91-1	166.9	83.5	3756.3	751.3	283.8	133.6	667.8	500.8	333.9	166.9
91-2	166.9	83.5	3756.3	751.3	283.8	133.6	667.8	500.8	333.9	166.9
92-1	128.9	64.4	2899.5	579.9	289.9	103.1	515.5	386.6	257.7	128.9
92-2	148.2	70.9	2899.5	773.2	289.9	103.1	579.9	386.6	257.7	148.2
93-1	101.6	48.6	1988.5	530.3	402.1	70.7	397.7	265.1	176.8	101.6
93-2	132.6	88.4	1988.5	1060.5	402.1	70.7	596.6	353.5	220.9	101.6
94-1	119.9	68.5	1541.1	821.9	311.6	54.8	684.9	274.0	205.5	119.9
94-2	119.9	68.5	1541.1	821.9	311.6	54.8	684.9	274.0	205.5	119.9
95-1	118.9	68.0	1529.1	815.5	309.2	54.4	679.6	271.8	203.9	118.9
95-2	118.9	68.0	1529.1	815.5	309.2	54.4	679.6	271.8	203.9	118.9
96-1	109.3	62.5	1561.5	1093.1	412.2	50.0	749.5	312.3	234.2	218.6
96-2	218.6	156	1561.5	1093.1	412.2	50.0	749.5	312.3	234.2	218.6
Mean[b]	146.5	80.8	2539.4	836.3	335.5	89.5	661.0	379.3	262.0	152.1

[a] 1 stands for January to June; 2 for July to December
[b] Average price per game animal bought from other ranchers

3.4.2 Cattle Production

Cattle grazed at David Hopcraft Ranch (DHR) are owned by the ranch itself, or by outsiders who graze cattle on lease arrangements, paying (in-kind) 50 kg weight at the time the cattle are withdrawn from the ranch. This payment in–kind is referred to as a maintenance or grazing fee. Long yearling cattle are brought on the ranch for fattening at an average weight of 250kg and sold at 350kg. Real gross sale and purchase cattle prices are presented in Table 3.21.

Table 3.21: Average Cattle Sales and Purchase Prices per Head and per AU, David Hopcraft Ranch, 1993 to June 1996 ('000s 1990 Ksh)

Item	1993	1994	1995	1996	Average
Sale price per head	6.960	5.753	6.184	6.012	6.227
Sale price per au	9.922	8.201	8.815	8.570	8.877
Purchase price per head	3.038	2.568	2.973	3.123	2.926
Purchase price per AU	4.331	3.661	4.238	4.452	4.171

Both the ranch–owned and renter–owned cattle are managed as a single unit. Operation expenses are dipping, herding labour, salt and veterinary medicine. These expenses are incurred by DHR, but dipping expenses for cattle not owned by DHR are re–imbursed at the real rates provided in Table 3.22. From information in Table 3.21, summary ranch accounts data, other ranch data and net cash income, excluding immature purchase expenses, are calculated for 1994 and 1995 (Table 3.23). With respect to the David Hopcraft ranch–owned cattle, net cash income compensates for capital and land resources. For lease cattle, part of the net cash income constitutes a grazing fee (at the rate of 50 kg per animal sold) plus dipping cost (refund).

3.4.3 Game and Cattle Summary

Gross price, net price excluding effort cost in the case of game and immature purchase cost in the case of cattle, and immature purchase cost per animal unit are summarised in Table 3.24. Cost of effort per hour is also included. Gross price per unit varies from one animal to another, which reflects consumer tastes for various meats. The economic values in Table 3.24 constitute base–line values for the bio–economic model. In addition, I consider an alternative to the base–line values, which I refer to as (game) trophy adjusted economic values; trophy values are 6.9% higher. This is derived from an estimated income of 56,374 Ksh realized from sale of game hides and horns in 1990 (Sommerlatte and Hopcraft 1994). During the same period, gross income from game was Ksh 819,190. Hide and horns would add some 6.9% to gross income. Game animal prices after making this "trophy adjustment" are shown in Table is 3.24.

Table 3.22: Real Dipping Costs per Head of Cattle charged Outside–owned Cattle per Month (Ksh), David Hopcraft Ranch, 1993–1996

Item	1993	1994	1995	1996	Average
Dipping Charges per month	8.84	7.53	8.15	8.12	8.16
Dipping Charges per 6–month	53.04	45.18	48.90	48.72	48.96

Table 3.23: Cattle Net Cash Income Excluding Long Yearling Purchase Expenses, David Hopcraft Ranch, 1994–1995 ('000s 1990 Ksh)

Item	Jan94-Jun94	Jul94-Dec94	Jan95-Jun95	Jul95-Dec95	Total
Gross income	932.192	2,324.315	2,956.167	1,341.828	1,888.63
Herding labour	9.932	22.945	17.329	28.882	19.772
Dipping cost	19.521	45.205	32.960	54.027	37.928
Salt & vet. cost	53.767	123.288	82.229	135.236	98.63
Net cash income (NCI)[a]	848.972	2,132.877	2,823.649	1,123.683	1,732.30
NCI per animal sold	5.241	5.279	5.907	5.178	5.401
NCI per animal unit sold	7.471	7.525	8.421	7.381	7.700

[a] Net cash income excluding long yearling purchase cost

Table 3.24: Real Average Gross Price, Net Return and Cost of Immature Purchase per Animal Unit, and Cost of Effort per Hour for Game and Cattle ('000s 1990 Ksh), David Hopcraft Ranch

Item	Gr	Th	Gi	Or	Zb	Wb	Ko	Im	Ca
Gross Price[a]	11.35	7.75	11.05	11.15	12.35	7.0	5.59	9.78	8.88
Net Return[b]	9.78	5.71	6.97	9.27	9.88	5.30	3.92	7.92	7.70
Adjusted NR[c]	10.453	6.103	7.45	9.908	10.56	5.665	4.19	8.465	7.70
Effort cost[d]	0.177	0.177	0.177	0.177	0.177	0.177	0.177	0.177	–
Purchase cost[e]	–	–	–	–	–	–	–	–	4.17

[a] per animal unit
[b] per animal unit excluding effort and immature purchase cost, excluding trophy earning
[c] Net return per animal unit excluding effort and immature purchase cost after adjusting for trophy earning
[d] per hour
[e] Immature purchase cost per animal unit

CHAPTER 4

STATISTICAL ESTIMATION OF BIOECONOMIC RELATIONS

In this chapter, I estimate the logistic population growth functions and the cropping off-take, or production, functions for commercially important herbivore species, namely, Grant's gazelle, Thomson's gazelle, giraffe, oryx, zebra, wildebeest, kongoni, impala and cattle.

4.1 Population Growth Models

The general form of the population growth function for game animals is given by equation (2.7). The relevant econometric model is:

(4.1) $$H_{it+1} - H_{it} + Y_{it} = \beta_i H_{it}\left(1 - \frac{H_{it} + \sum_{j=1}^{n-1} \lambda_{ij} H_{jt}}{\delta_i R_t}\right)$$, for $i = 1, 2, ..., 9$ and $i \neq j$,

where Y_{it} represents the off-take of species i at time t. Cattle are included on the right-hand-side (RHS) of equation (4.1), but cattle population is itself a function of management and stocking rates. Cattle are bought and sold, and calving is highly controlled. Thus, the decision to increase or decrease the cattle herd rests with management, and interactions with wild herbivores are considered only via the wildlife population equations. The cattle equation of motion is:

(4.2) $$Ca_{it+1} - Ca_{it} = \beta_i Ca_{it} + Purc_t - Y_{Ca,t},$$

where β is the parameter generated from births and deaths, $Purc_t$ is the number of purchased cattle in period t, and $Y_{Ca,t}$ is number of cattle sold in period t. The relevant econometric model is:

$$(4.3) \qquad Births_t - Deaths_t = \beta Ca_t .$$

All variables in equations (4.1) through (4.3) are measured in animal units.

I proceed first by estimating (4.1) for each game species separately and (4.3) for cattle using the David Hopcraft ranch data, for the period mid–1982 through 1995. A nonlinear maximum likelihood procedure, coupled with correction for autocorrelation, was used for game animals, while ordinary least squares estimation was used for cattle (White 1978). In each case, Δt is 6 months, which constitutes the growing and grazing cycle. This follows from the bimodal distribution of rainfall.

The hypotheses for a zero coefficient on individual variables and on all coefficients simultaneously in (4.1) were tested using asymptotic t-ratios for the former, and the Wald chi-square asymptotic statistic for the latter; for cattle, the relevant statistic is the t-ratio (White 1986). The joint and simultaneous tests for non–zero slope were statistically significant for all models at the 0.1 level of significance, except impala (see below). However, for game species, not all individual slope parameters were significantly different from zero at the 0.1 significance level, so selection of the most appropriate set of regressors was carried out. This step was necessary in order to screen out regressors that were so highly correlated with others as to duplicate them and were not fundamental to the model based on significance tests (Neter, Wasserman and Kutner 1983).

Procedures used for selecting regressors were governed by subjective judgement about species interactions and pragmatism (Neter, Wasserman and Kutner 1983). Using stepwise regression and taking into account required and potential biological interactions, the final regressors were selected and results presented in Table 4.1. These portray the direction of interactive relationships between and among species. A negative parameter implies complementarity, while a positive parameter implies competition. Parameter values imply strength of the interactive relationships.

The parameter β in the cattle equation (4.3) is estimated to be 0.0222 with t–statistic of 4.11. Sample size was 16 and $R^2 = 0.529$.

Table 4.1: Final Parameter Estimates for Logistic Population Functions (n = 28)[a]

Species	Gr	Th	Gi	Or	Zb	Wb	Ko	Im
Gr	0.2855 (4.4686)**		-0.6773 (-3.8276)**	0.1978 (1.1200)		-3.5884 (-8.6689)**	-2.0223 (-2.1938)**	
Th		0.3488 (3.6342)**						
Gi	-0.1684 (-0.6932)		0.2935 (4.4534)**	0.2973 (3.9265)**				
Or				0.4302 (3.4536)**	-0.6505 (-3.7518)**	-2.1417 (-2.5300)**		
Zb		3.2089 (2.6677)**			0.4771 (5.0687)**			
Wb				-0.1370 (-5.0849)**		0.3229 (6.0879)**		
Ko				-0.0943 (1.8072)*			0.3318 (4.6791)**	
Im			-1.6412 (-3.4369)**	-0.1744 (-0.5469)		-4.6289 (-2.6405)**	4.0185 (1.7595)*	0.074104 (1.8432)*
Cattle		-0.0452 (-1.5276)				0.0723 (3.6014)**		
Rain- Fall	0.2309 (2.2650)**	0.5801 (2.8065)**	0.1335 (3.6800)**	0.0593 (6.1442)**	0.1529 (7.0616)**	0.4783 (2.8713)**	0.6848 (1.6451)*	71578 (0.0029)
R^2	0.4424	0.4042	0.5246	0.7447	0.5639	0.7117	0.2436	0.0342
Rho (ρ)	-0.4019 (-2.2801)**	-0.3917 (-2.3320)**	-0.2144 (-0.9532)	-0.5158 (-2.1193)**	0.4555 (2.6611)**	-0.4054 (-2.2417)**	-0.2154 (-1.1552)	-0.1822 (-0.9804)
WCS[b]	274.2224**	67.4579**	1203.3905**	5273.0391**	558.9745**	4000.6198**	363.6849**	3.4025

[a] Results are for equations identified in top row of table, with explanatory variables in left–hand column. Asymptotic t–statistics are in parenthesis: ** indicates significant at the 0.05 level, * at the 0.1 level.
[b] WCS is the Wald chi statistic, an asymptotic counterpart of F–test.

Empirical results show that seasonal rainfall is an important determinant of carrying capacity for all game species except impala; a fact also portrayed by the general trend of wildlife biomass with seasonal rainfall (Figure 4.1).[10] The salient features of the population equations and the interactive relationships among species is discussed below, including graphical representation of logistic models for Grant's gazelle, Thomson's gazelle and kongoni at 150 mm, 180 mm, 210 mm, 230 mm and 260 mm rainfall regimes.

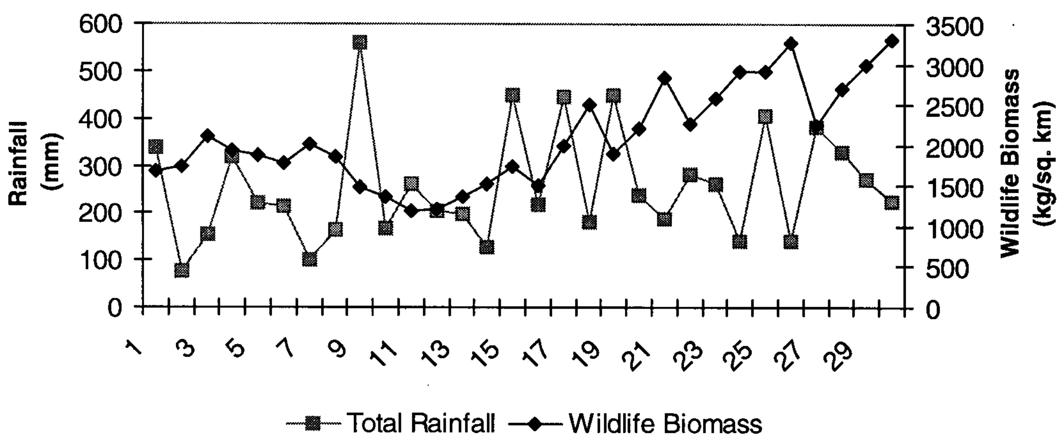

Figure 4.1. Seasonal total rainfall and wildlife biomass at the David Hopcraft ranch, 1981–1995.

[10]A logistic model for combined game animals was estimated as:

$$\sum_{I=1}^{8} \Delta H_{it} = 0.343 \sum_{i=1}^{8} H_{it} \left(1 - \frac{\sum_{i=1}^{8} H_{it} + 0.25 Ca_t}{6.187 R_t}\right) \text{ for } i \neq \text{Ca.}$$

Estimated parameters were significant at the 0.01 level, except cattle was significant at 0.14, R^2 between observed and predicted was 0.494 and the Wald Chi–square statistic was 278.44.

4.1.1 Grant's gazelle

The model shows that giraffes have a complementary influence on G. gazelle. The latter is a mixed feeder while the former is a highly adapted browser and both species share diet plant species to an extent (Leuthold and Leuthold 1972). Giraffes influence its habitat by restricting canopy cover and the height of tree and shrub species (Pratt and Gwynne 1977). It would then appear that, by so doing, giraffes create habitat suitable for G. gazelle, because they restrict browse species to heights within the reach of gazelle and opens up the herb layer to the advantage of G. gazelle. At the recorded average giraffe population of 65 animal units from 1981–1996 and average seasonal rainfall of 260 mm, Figure 4.2 portrays the logistic model for Grant's gazelle.

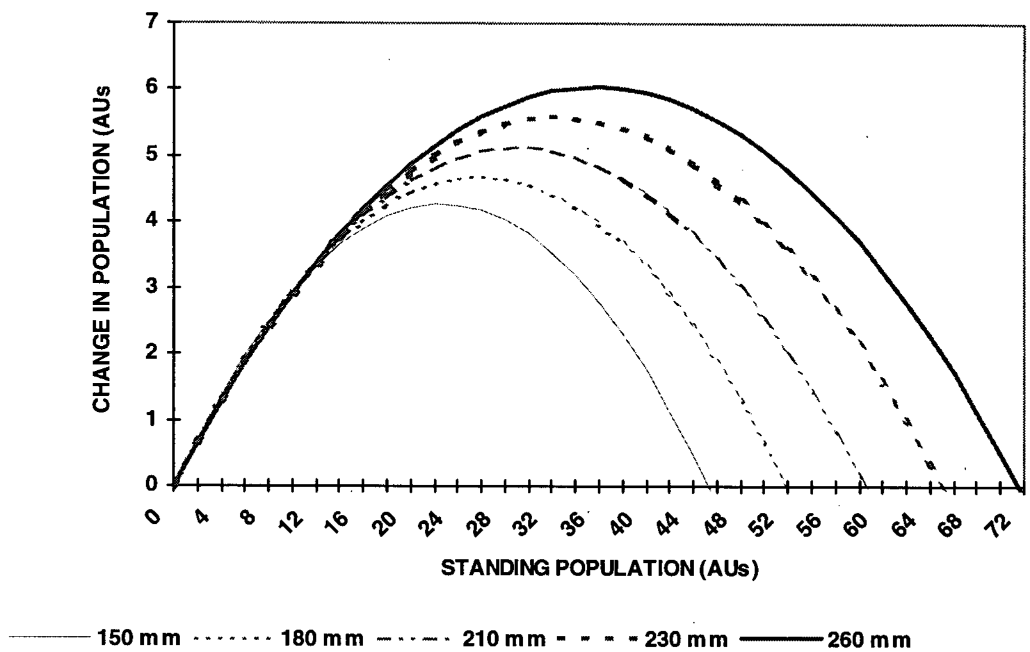

Figure 4.2. Logistic model of Grant's gazelle at mean population of giraffe (65 AUs) and rainfall regimes of 150 mm, 180 mm, 210 mm, 230 mm and 260 mm. For given a giraffe population, G. gazelle carrying capacity increases with rainfall. (1 G. gazelle = 0.1463 AUs)

4.1.2 Cattle

Cattle growth is largely impacted by decisions to purchase or sell rather than seasonal rainfall; unlike wildlife biomass, the seasonal biomass of cattle is not related to seasonal rainfall (Figure 4.3). These management decisions result in either decreases or increases in the standing population, rather than interactive relationships with other herbivores. Cattle interactions do show up in the herbivore functions (Table 4.1), which means that cattle are given preeminent status with respect to forage.

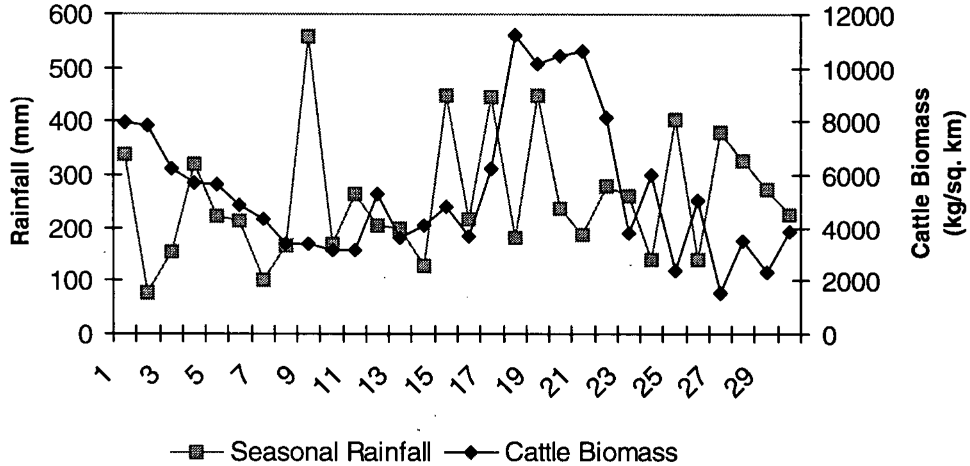

Figure 4.3. Cattle biomass and total seasonal rainfall at the David Hopcraft Ranch, 1981–1995.

4.1.3 Thomson's gazelle

Cattle are complementary to Thompson's gazelle but not significantly so (p>0.10), while zebra are competitive. Zebra would be expected to compete with T. gazelle due to diet overlap and both species are grazers and tend to share similar habitats (Schenkel 1966). Thompson's gazelle prefers short grass and takes advantage of tall grasses that have been grazed down by bigger animals (zebra and cattle). Due to its preference for short grass, T. gazelle grazes unevenly, while grazing cattle spread the short grass areas over the mosaic created by gazelle. This way, cattle increase the area of optimal vegetation available to and preferred by T. gazelle. Figure 4.4 depicts the T. gazelle logistic model for varying rainfall levels, for 1981–1996 cattle and zebra populations.

4.1.4 Giraffe

Grant's gazelle and impala are complementary with giraffe and both consume the same plant species (Leuthold and Leuthold 1972). Giraffe is a browser that feeds on a large variety of tall trees and bushes, while G. gazelle and impala are mixed–feeders that are similar in size. The latter tend to share habitat close to that of giraffes—wooded grasslands and open wooded areas in the case of impala and short to thick bush grassland in the case of G. gazelle. As they are smaller than a giraffe, their browse–line would be lower, thus posing no competition. Their dual role as grazers would, conceivably, encourage woody plant species due to the reduction in competitive vigor of herbaceous plants, which favours giraffe.

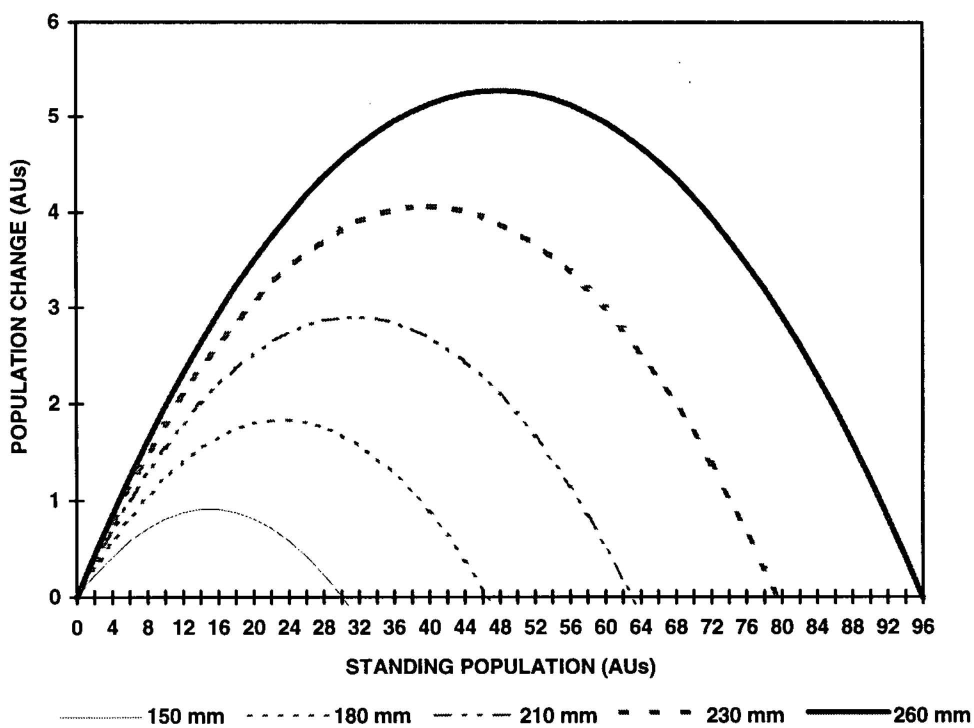

Figure 4.4. Logistic model of Thomson's gazelle at mean populations of cattle (1103 AUs) and zebra (33 AUs), and rainfall regimes of 150 mm, 180 mm, 210 mm, 230 mm and 260 mm. (1 T. gazelle = 0.0813 AUs).

4.1.5 Zebra

Oryx is complementary to zebra, with oryx often found in association with zebra. Zebra is a grazer while oryx is a mixed feeder. Oryx browsing on woody plant species opens up more area for herbs preferred by zebra. Also oryx has affinity for coarse grasses, which rejuvnates the herb layer by reducing rank growth to the advantage of zebra. The complementarity of oryx to zebra is consistent with its feeding behaviour.

4.1.6 Oryx

Grant's gazelle and giraffe are competitive with oryx, while kongoni and wildebeest are complementary. This result is consistent with the feeding behaviour of these species. Oryx and G. gazelle are mixed feeders, so they compete due to dietary overlap. Further, the two tend to be found in the same habitat. Giraffe is a browser so its diet overlaps with that of oryx from the point of view of browsing. Both kongoni and wildebeest, on the other hand, are grazers with an affinity for short grass. By selecting short grass, they inadvertently encourage rank coarse grass favoured by oryx. Impala is a mixed feeder, but there appears to be some complementarity with oryx, probably because they prefer different browse species and different parts of plants/shrubs.

4.1.7 Kongoni

The logistic model for kongoni indicates complementarity with G. gazelle and competitiveness with impala. Kongoni is a grazer that prefers short grasses, while both G. gazelle and impala are mixed feeders, and the three species share the same habitat (Schenkel 1966). Complementarity of G. gazelle emanates from its attributes as a browser, so it helps keep woody plants in check, thereby encouraging the herb layer. Competition of impala with kongoni, on the other hand, is based on its grazing activities and a diet that overlaps with that of kongoni, resulting in competition. Figure 4.5 depicts the kongoni logistic model for varying rainfall amounts and average 1981–96 G. gazelle and impala populations.

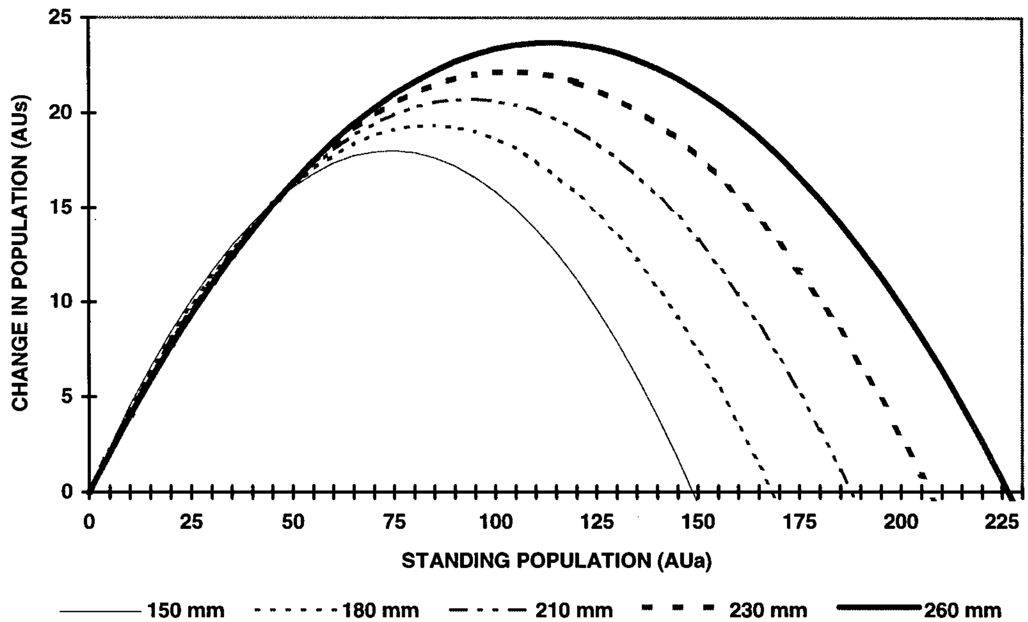

Figure 4.5. Logistic model of kongoni at mean population of G. gazelle (43 AUs) and impala (10 AUs) and rainfall regimes of 150 mm, 180 mm, 210 mm, 230 mm and 260 mm. (1 kongoni = 0.2846 AUs).

4.1.8 Wildebeest

Grant's gazelle, impala and oryx are complementary to wildebeest and the four species overlap in terms of habitat. Cattle are competitive. Wildebeest is a grazer with an affinity for short grass, as is the case for cattle. As a result, the diets of these two species overlap, leading to competition. G. gazelle, oryx and impala, on the other hand, are mixed feeders. On the basis of their browsing activities, they are able to suppress woody plants resulting in an environment that favours establishment of the herb layer, which is favorable for wildebeest.

4.1.9 Impala

Impala is a mixed feeder that relies on a wide range of forage plant species making it able to switch diet depending on plant availability. Further, it does not need free surface water to survive (Lamprey 1963). Adaptability to a general diet and water economy makes it drought–tolerant, thus explaining the lack of statistical significance on the rainfall term. Impala have been observed to maintain relatively stable numbers under extreme climatic conditions (Hillman and Hillman 1977). Changes in the population and iteractive impacts by other herbivore species are low as indicated in Table 4.1.

4.2 Harvest or Off-take Production Functions

The general form of the production function is given by equation (2.2). The log–linear form of (2.2) is:

$$(4.4) \qquad \ln \frac{(H_{it} - Y_{it})}{H_{it}} = -\alpha_i E_{it}, \text{ for i = 1, 2, ...,8.}$$

Production functions (4.4) are estimated using the OLS procedure in Shazam (White 1986). The results are provided in Table 4.2. These show that, other things being equal, the relative cropping efficiency per animal unit decreases in the following order: impala, zebra, giraffe, oryx, T. gazelle, G. gazelle, kongoni and wildebeest. However, when harvest is in terms of actual numbers of animals, the order favours small animals, decreasing as follows: impala, T. gazelle, g. gazelle, oryx, zebra, kongoni, giraffe and wildebeest.

Table 4.2: Regression Results for Harvest Production Functions

Equation	Coefficient	T–ratio	Raw moment R^2	No. of observations
G. gazelle	0.01029	12.170*	0.9025	17
T. gazelle	0.01099	10.030*	0.8483	19
Giraffe	0.01482	5.650*	0.7801	10
Oryx	0.01476	7.208*	0.8666	9
Zebra	0.01583	4.446*	0.6640	11
Wildebeest	0.00398	6.594*	0.7072	19
Kongoni	0.00526	5.993*	0.6540	20
Impala	0.02703	10.550*	0.8883	15

*Significant at the 0.05 significance level

CHAPTER 5

ANALYSIS OF GAME CROPPING POLICY IN KENYA: BIOECONOMIC MODEL RESULTS

The bioeconomic model consists of the biological relationships developed in Chapter 4 (and particularly estimated values in Tables 4.1 and 4.2), the economic data of Chapter 3 (particularly Table 3.24), and initial population values for the second six–month period of 1996 (Table 3.5a). The average discount rate in Kenya over the period 1990–1996 was 26.5%, while the average inflation rate was 21.4% (IMF 1997). Subtracting yields a real discount rate equal to 5.1%. In the bioeconomic analysis, I use a real discount rate of 4% to err on the side of conservation. The bioeconomic problem represented by relations (2.11) through (2.14), plus non–negative constraints and institutional (policy) constraints discussed below, is solved for thirty periods (fifteen years) using GAMS/MINOS (Anthony, Kendrick and Meeraus 1988). The GAMS file is provided in the Appendix.

I begin by examining the validity of the model. This is followed by a number of policy simulations that start with the "pre–1989 wildlife preservation" policy and the "post–1989 wildlife conservation" policy. Other policy options are considered in order to investigate whether they might lead to improved private net returns and, at the same time, greater numbers of wildlife ungulates.

5.1 Model Validation

Two approaches are used to validate the model. First, actual populations, harvests, cattle sales and purchases are compared with the simulated data. That is, I simulate populations using equations (2.12) and (2.13), with estimated parameters for (2.12) given in Tables 4.1 and β_{Ca}=0.0222 in (2.13), and the first–period starting values (Table 3.5a). The population simulation is for the period 1982 through 1995 (28 periods), with simulated data compared to actual data for the period. The predicted mean of total herbivore population (averaged over six–month periods) is 3,449 head, which is equivalent to 1,596 AUs. Projected mean carrying capacity is 5.1 ha per AU. The observed mean of total herbivore populations is 3,425 head (equivalent to 1,579 AUs) per period, and carrying capacity of 5.1 ha per AU. The predicted and observed herbivore populations are not statistically different from one another (Table 5.1); coefficients of variation between the two are also similar (Table 5.2). . Also, the trend of predicted game populations is similar to the observed trend (Figures 5.1 and 5.2).[11] Similarly, the trend of observed cattle population is very close to predicted (but not shown in the figures).

This validation employed only the dynamic equations of motion, which were derived from the actual data and thus implicitly incorporated David Hopcraft Ranch game cropping decisions for some portion of the time period. Hence, it is not surprising that there is no statistically significant difference between the populations. This is not to suggest, however, that the game cropping and cattle stocking decisions by David Hopcraft Ranch were somehow optimal. The Ranch was permitted to game crop as an experiment, and a certain degree of learning was associated with those decisions. Further, decisions were less than optimal, as we demonstrate below, due to continual "bargaining" with KWS.

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[11] For both model validation and simulation results, graphical presentations of herbivore populations and harvests are handled separately for grazers, and mixed feeders and browsers in order to improve clarity.

Table 5.1: Model Validation. Tests for Differences in Means between Simulated and Observed Populations

	Validation I (28 observations)			Validation II (24 observations)		
Species	Observed mean	Predicted mean	F–ratio[a]	Observed mean	Simulated mean	F–ratio[a]
Gr	276	276	0.00	270	361	22.04*
Th	410	408	0.00	389	776	56.34*
Gi	56	56	0.01	57	34	51.57*
Or	63	63	0.00	67	102	7.20*
Zb	91	91	0.00	96	54	21.83*
Wb	535	532	0.00	537	562	0.21
Ko	420	421	0.00	395	605	37.79*
Im	70	74	0.18	76	55	6.37*
Ca	1,504	1,529	0.01	1,480	1,589	0.37
Total	3,425	3,449	0.01	3,367	4,137	11.63*

[a] 0.00 indicates a very small number; * implies significance at the 5% level or better

Table 5.2: Model Validation. Coefficient of Variation (%) of Simulated and Observed Wildlife Populations

	Validation I (28 observations)		Validation II (24 observations)	
Species	Observed population CVs (%)	Predicted population CVs (%)	Observed population CVs (%)	Simulated population CVs (%)
Gr	29	25	31	13
Th	47	48	48	22
Gi	22	19	22	27
Or	82	80	69	44
Zb	43	41	34	57
Wb	42	42	42	27
Ko	36	34	37	13
Im	54	55	47	47
Total	31	24	27	12

As a second validation exercise, the optimal mathematical programming results were obtained using actual rainfall over the period 1984 to 1995 coupled with the starting values for the first half of 1984, but constraining ending populations and effort to be equal to observed values for the last period of 1995. This simulates the actual situation during these 24 periods (as opposed to 28 periods in the first validation). A comparison of the simulated and observed values is provided in Figures 5.3 (for grazers) and 5.4 (for browsers and mixed feeders). With the exception of wildebeest and cattle, simulated populations are statistically different from observed populations (Table 5.1). The optimised mean of total herbivore populations is 4,137 head, equivalent to 1713 AUs and a carrying capacity of 4.7 ha per AU, while the observed mean of total herbivore population is 3,367 head, equivalent to 1,558 AUs and a carrying capacity of 5.2 ha per AU. It also turns out that the simulated game *populations* are less irregular than the observed values, which suggests that the effect of optimisation is to reallocate range resources among species and make populations less variable over time. Neither the optimised nor observed total ranch carrying capacities exceed that proposed for livestock in eco–climatic zone 4 (Table 1.1), where the ranch is located.

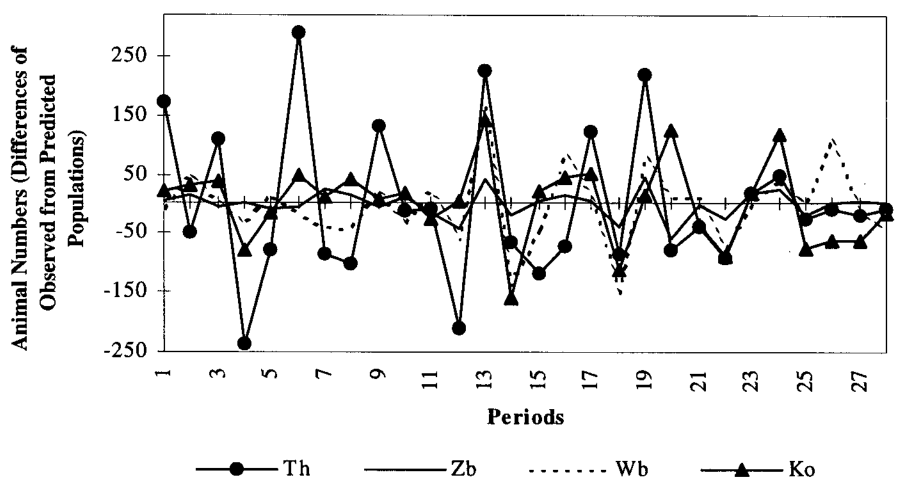

Figure 5.1: Model Validation I: Predicted minus Observed Populations, 1982–1995, Grazers

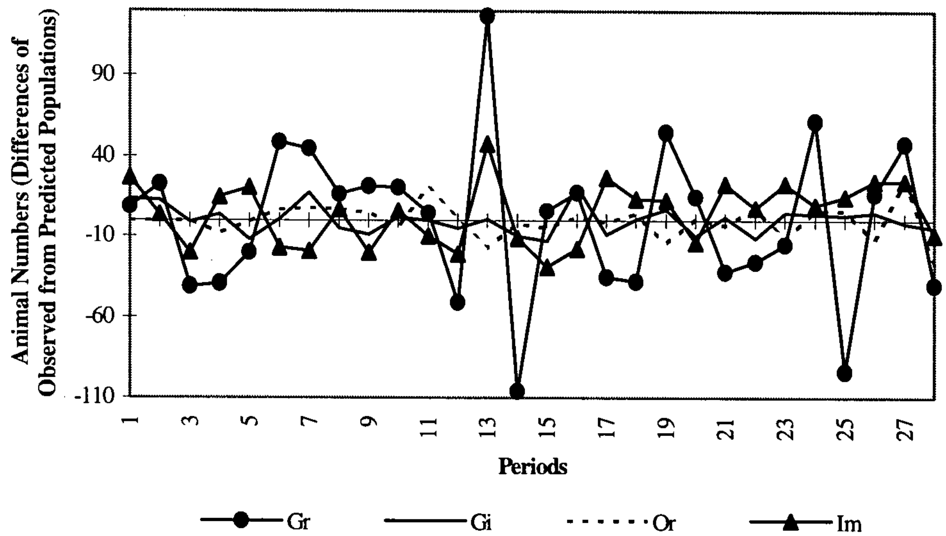

Figure 5.2: Model Validation I: Predicted minus Observed Populations, 1982–1995, Browsers and Mixed Feeders

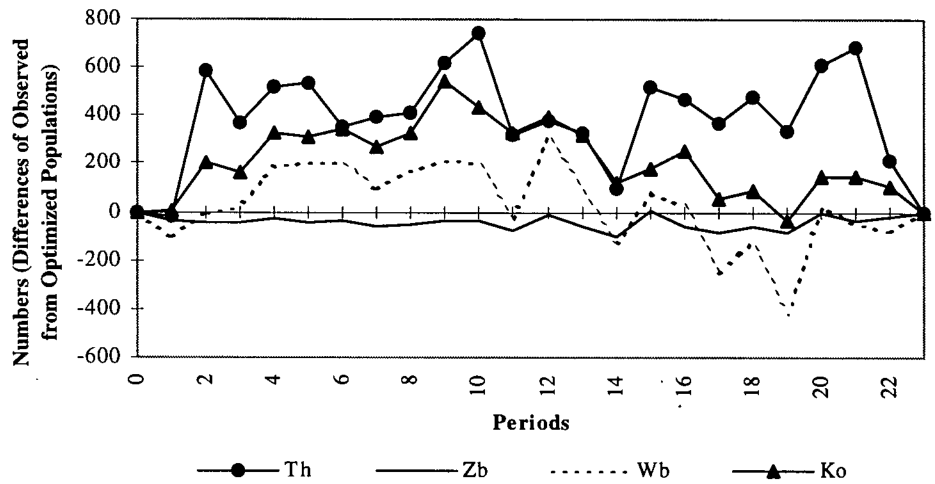

Figure 5.3: Model Validation II: Optimised minus Observed Populations, 1984–1995, Grazers

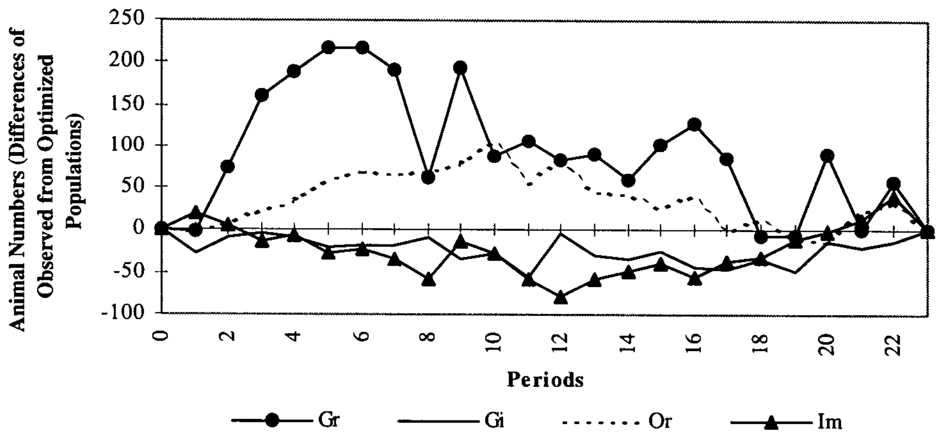

Figure 5.4: Model Validation II: Simulated (Optimised) minus Observed Populations, 1984 to 1995, Browsers and Mixed Feeders

The difference between simulated (optimised) and observed populations is not unexpected, but there are several possible explanations not captured in the model. First, the ranch manager may not be optimising net discounted revenues from game cropping, perhaps because of uncertainty related to public policy (e.g., there is no guarantee that wild meat can be sold in Nairobi restaurants in the future). This was already noted above. Second, the relationships in the model may not be entirely satisfactory. Perhaps the price and cost data are not truly reflective of the real prices and costs encountered by game ranchers. Third, the optimisation model fails to capture certain political and institutional constraints. One of these is investigated in a later section (5.4), namely, that KWS only permits ranchers to harvest a fixed proportion of each species. This was also hinted at above. Finally, other factors (political and cultural) play an unknown role (e.g., KWS limits on what can be done with products from harvested animals). In any event, these illustrate the difficulty of modeling individual behaviour and the role of institutions within a bioeconomic model.

For the second validation, simulated game *harvests* can be compared with actual harvests. Compared to observed harvests, simulated harvests exhibit much greater variation from one period to the next (see Figures 5.5 and 5.6). Except for impala and giraffe, simulated harvests tend to be greater than actual harvests, perhaps because the KWS restricted harvests for each species over the period to a proportion of the species' total population. Also notice that, for some wildlife ungulates, ranchers crop heavily in the final period to meet the model's end point constraints.

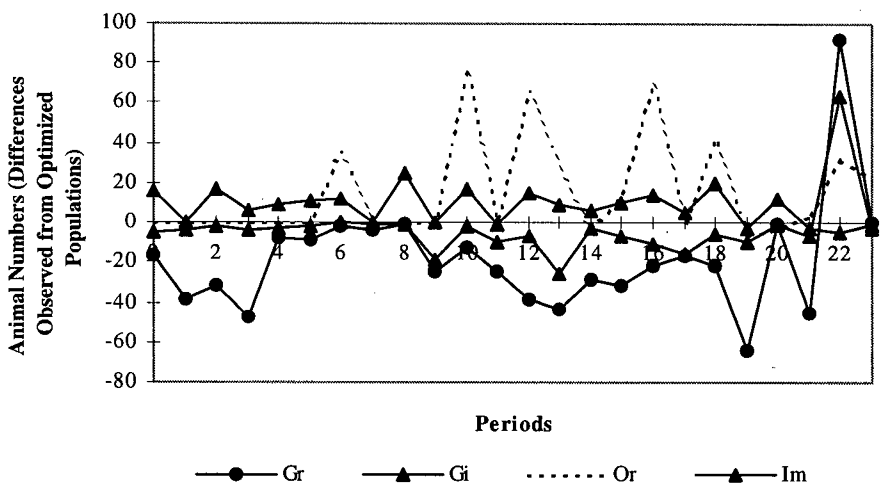

Figure 5.5: Model Validation II: Simulated minus Observed Harvests, 1984 to 1995, Grazers

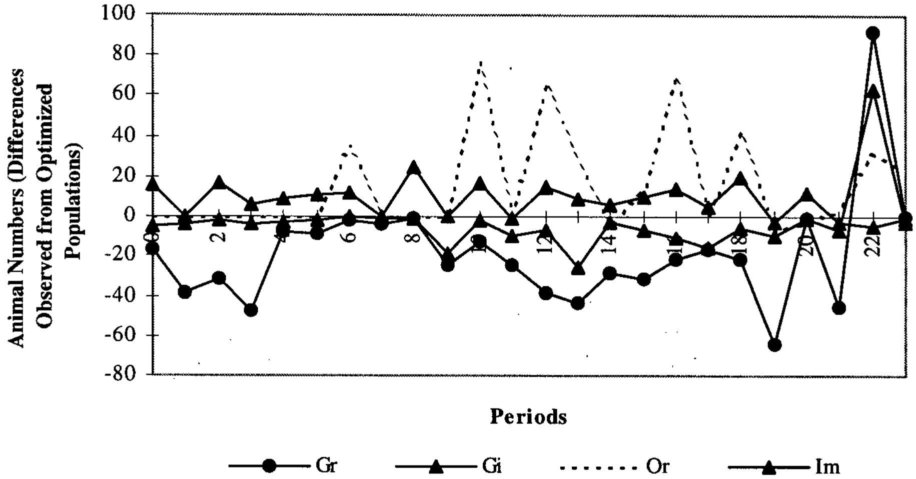

Figure 5.6: Model Validation II: Simulated minus Observed Harvests, 1984 to 1995, Browsers and Mixed Feeders

In the next sections, I investigate a number of different policies using the bioeconomic model. I begin by considering the approach that characterised Kenya's wildlife policy prior to 1989—I refer to this as the preservation policy as no game harvests are permitted. This captures the period when owners had no user rights to wildlife on their land. I then consider what I refer to as the conservation policy; this represents the era where landowners have been given (variable) rights to wildlife on their ranch. I begin by considering an unconstrained profit maximisation scenario. In the unconstrained scenario, there are no institutional constraints on wildlife take and, thus, no end–point constraints. This scenario has the least number of constraints; it consists of a nonlinear objective function and 270 nonlinear constraints. Due to difficulties in solving highly nonlinear constrained optimisation problems, it was not possible in GAMS to obtain solutions for more than 30 periods (15 years).

In the case where benefits accrue and costs are incurred for a period of 15 years only, any remaining wildlife at the end of the time horizon still has value to the rancher and/or society.

The end-period wildlife can be valued using shadow values for the end period, but, in this model, shadow values are highly interdependent. In any period, a species' shadow value depends on the price meat fetches in Nairobi and on the population of that species, which determines harvest as a function of effort (and thus cost of harvesting animals). In addition, a species' value depends on the numbers of other species, because other species impinge on the one under consideration via forage availability. Attempts to determine consistent end-point shadow values failed. As a result, no attempt is made to value animals available in the final period. I only model rancher behaviour over the 30 periods (15 years), with ranchers assumed to have no interest in animals beyond this time horizon. In other words, it is assumed that ranchers maximise their profits from game ranching and stocking of cattle over 15 years, with the wildlife that remain at the end of the time horizon simply reverting back to KWS ownership. Given the vagaries of Kenyan wildlife policies, this is not an unrealistic assumption. The KWS is then assumed to rely on regulations to ensure that sufficient wildlife remain in the future to satisfy societal concerns. Different forms of these regulations are investigated in the bioeconomic model to determine which one(s) might be most successful in maximising rancher well being while attaining conservation goals.

5.2 Preservation Policy Simulation

For the preservation policy, the bioeconomic model employs the mean seasonal rainfall of 260 mm and, due to lack of user rights, treats game animals, from the ranchers' point of view, as non–economic "enterprises," that is, no harvest of wildlife occurs with cattle ranching being the only economic activity. Nonetheless, the presence of game constrains the system because both wildlife ungulates and cattle affect the range resources. This policy results in a total mean herbivore population of 5,274 equivalent to 2,334 AUs. The associated carrying capacity is 3.5

ha per AU, which is significantly (in the statistical sense) above that proposed for livestock in zone 4 (Table 5.3).

Table 5.3: Statistical Tests for Simulated Mean Carrying Capacities Against Expected Livestock Carrying Capacity in Eco-climatic Zone 4 (Ho: Carrying Capacity = 4 Ha/AU)

Scenario	Carrying capacity (ha per AU)	t-ratio[a]
Preservation[b]	3.49	-9.860**
Unconstrained	4.25	1.755**
End–period population constraint	4.36	1.637**
KWS harvesting rates constraint[b]	3.71	-5.101**
Shannon's index constrained	4.25	2.872**
Full property rights	4.36	1.647*
Drought	5.27	2.623**

[a] *Significant at 10% level, **Significant at 5% level

[b] These scenarios significantly exceed the expected carrying capacity in eco-climatic zone 4, based on livestock carrying capacity. This explains why populations under these two scenarios crash. For all other scenarios, carrying capacity is significantly below the expected carrying capacity (i.e., >4 ha per AU).

In the absence of game cropping, wildebeest numbers trend upwards (with some downturns) to an initial peak in period 15, which is followed by a population crash (Figure 5.7). The upward trend then continues reaching a peak in period 27 before crashing again. Kongoni initially increase and thereafter exhibit gradual decline. Grant's gazelle, impala and giraffe gradually increase throughout (Figure 5.8). Oryx show a gradual increase coupled with population crashes and eventual extinction in the twenty–seventh period. Zebra exhibit a gradually increasing trend coupled with mild population declines (Figure 5.7). Thomson's gazelle gradually decline to a very low level (almost near extinction) by the end of the planning horizon. The reason for the population crashes is that the stocking rate for cattle is above that recommended for zone 4, which occurs because ranchers do not take into account the forage requirements of wildlife herbivores in their livestock stocking decisions.

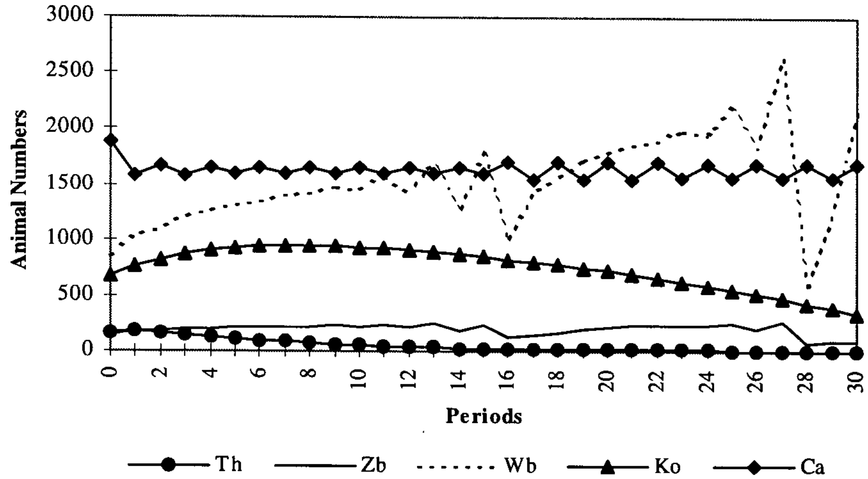

Figure 5.7: Preservation Policy: Grazer Populations

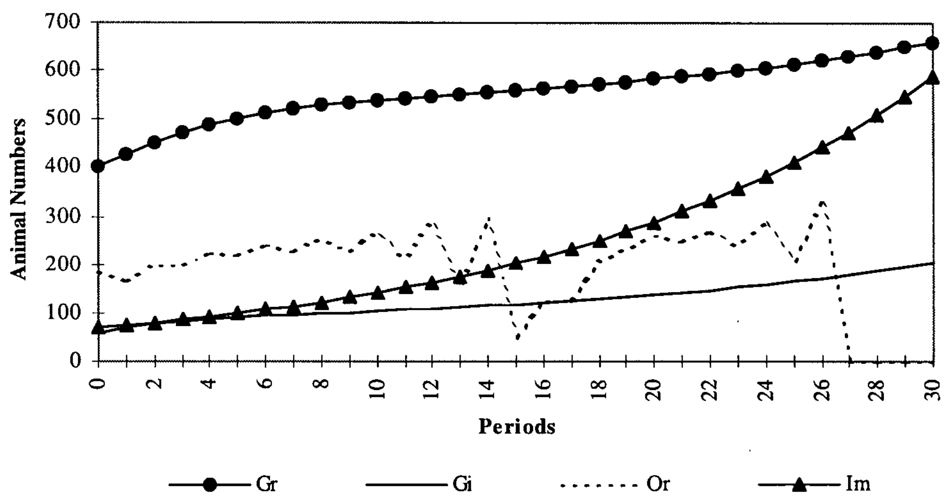

Figure 5.8: Preservation Policy: Browsers and Mixed Feeder Populations

Simulated (optimal) cattle populations are also provided in Figure 5.7. The cattle population in the initial period is 1,874, while sales are 1,667. For the most part, cattle populations and sales track each other quite closely, as expected. However, as kongoni numbers decline, and whenever wildebeest populations crash, ranchers respond by grazing more cattle. Hence, while optimal cattle numbers oscillate throughout the period (Figure 5.7), these oscillations grow in size as a response to changes in the numbers of large wildlife ungulates.

In the remaining policy scenarios, the rancher is able to harvest wildlife ungulates in addition to the cattle activity. Thus, the rancher needs to take into account how range resources are allocated so that he or she earns the greatest net discounted returns. What distinguishes various policies is the constraints that are imposed on wildlife activities.

5.3 Unconstrained Profit–maximizing

Consider first the case where there is a limited time horizon with no constraints. Mean seasonal rainfall is assumed to be 260 mm and game harvesting is not constrained, and ranchers desire only to maximise discounted net returns over the 30–period (15–year) time horizon. This scenario results in a mean total herbivore population of 4,699 animals equivalent to 1,959 AUs and a carrying capacity of 4.1 ha per animal unit (see Table 1.1). Obviously, since there is no benefit to retaining species beyond the final period, an attempt is made to extinguish all game in the final two periods. Game animals are not all driven to extinction because the costs of doing so are simply too high (harvesting costs increase as population falls). While large expenditure of effort on harvests is likely unrealistic (and is an artefact of the model as discussed above), this would be the outcome if remaining game have no value beyond the end period, and assuming there are no other constraints that prevent ranchers from exerting maximum harvest effort.

In order to take into account decisions beyond the 15–year limit in the model, simulations were made employing shadow values for wildlife remaining in the final period. However, when a variety of shadow prices generated via the model were employed, wildebeest and oryx were still driven to extinction. Because these species reproduce slowly, but consume substantial forage in competition with and to the detriment of other species, ranchers have every incentive to rid their ranches of these species (an exception is discussed below). This is likely a reason why KWS implements constraints on harvests of various species. I consider these constraints in the context of sustainable game cropping.

5.4 Sustainable Game Cropping

Three scenarios are considered for representing sustainability: (1) a constraint on species' populations at the end of the time horizon, (2) KWS harvesting rate constraints and (3) a Shannon bio–diversity index constraint. One further scenario is investigated that potentially leads to sustainability. This scenario permits ranchers to sell hunting and other wildlife access services (e.g., tourism) and permits them to sell all animal products at the highest price available in the market. That is, ranchers have exclusive rights over the game on their ranch without any restrictions.

5.4.1 End-Period Population Constraint

Perhaps the simplest constraint for the KWS to employ is that of constraining final period populations to be the same as initial period populations. This guarantees one form of sustainability, but it does little to provide incentives to ranchers to increase populations of wildlife. I refer to this scenario simply as the end–period population constrained scenario as game populations in the final period are constrained to be equal to or greater than those at time zero. The end–period population constrained scenario results in a mean of total herbivore population of 4,643, which is equivalent to 1,935 AUs and a carrying capacity of 4.2 ha per AU. The carrying capacity is lower than the stocking rate recommended for zone 4 (Table 5.2). The optimal paths of the various species are provided in Figures 5.9 and 5.10. Only cattle populations behave erratically near the end of the time horizon in response to changes in the populations of the wildlife ungulates—cattle use of the range needs to be modified in order to provide adequate forage for game, thereby enabling them to achieve required levels.

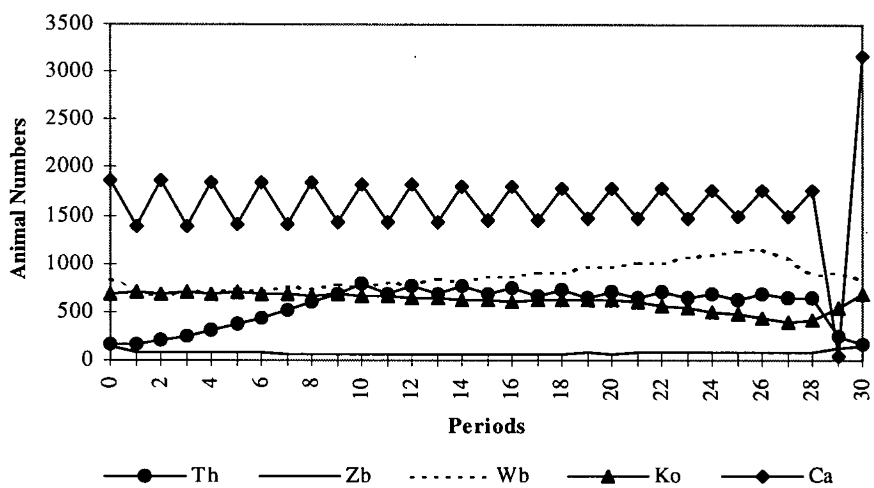

Figure 5.9: End–period Population Constrained Scenario: Grazers

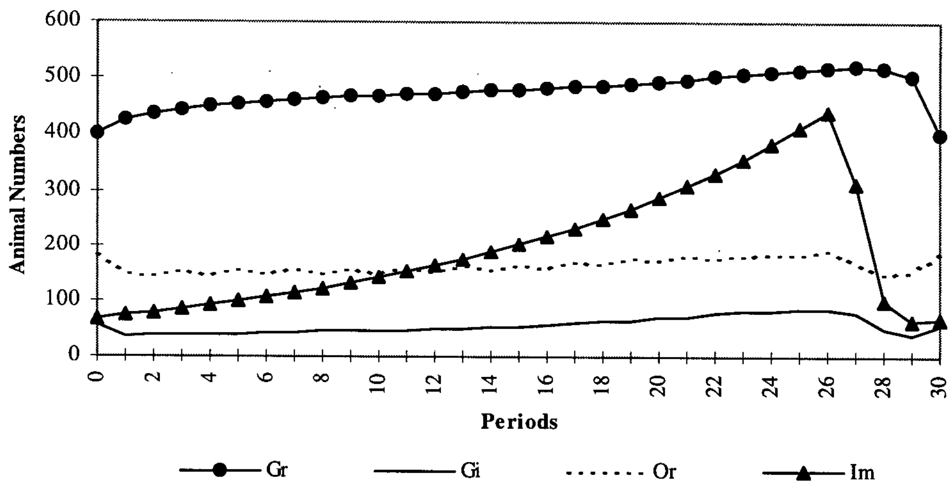

Figure 5.10: End–period Population Constrained Scenario: Browsers and Mixed Feeders

5.4.2 KWS Harvesting Rates Strategy

The KWS restricts game ranchers to uniform harvest rates (Table 1.3). That is, in any given period, ranchers can only harvest a fixed proportion of the available population of each species of wildlife ungulates on the ranch. Again a seasonal rainfall of 260 mm is assumed, and harvest is constrained to be equal or less than KWS rates in every period. The policy results in a mean total herbivore population of 4,871, equivalent to 2,201 AUs and a carrying capacity of 3.7 ha per animal unit, which is the second highest carrying capacity after that under the preservation policy scenario. As with the preservation policy, carrying capacity exceeds recommended stocking rate for livestock in zone 4 (Table 5.2). Since harvests are restricted to fixed rates, some game species exhibit an upward trend before reaching a peak followed by a population crash (e.g., wildebeest and oryx), while Thomson's gazelle shows a steady, continuous decline reaching very low level by the end of the time horizon (Figures 5.11 and 5.12). Interestingly, this policy may not be sustainable because it does not prevent a precipitous decline in some wildlife populations. This result demonstrates the importance of accounting for the population dynamics and interactions among species. Corresponding harvest levels are shown in Figures 5.13 and 5.14.[12] Harvests fall to zero in the last period because they were restricted to zero in the simulation.

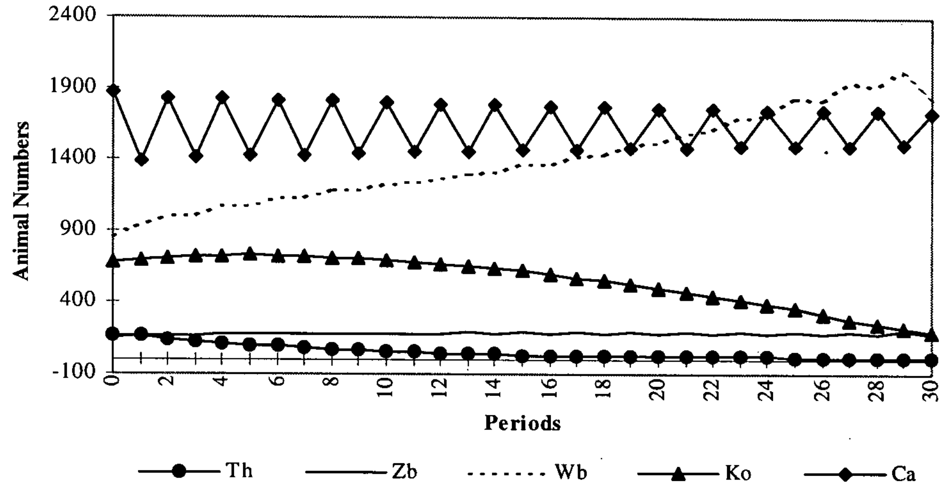

Figure 5.11: KWS Harvest Rate Strategy: Grazer Populations

[12] Due to the number of species involved, graphical presentations of populations and harvests are handled separately in order to avoid obscuring trend details.

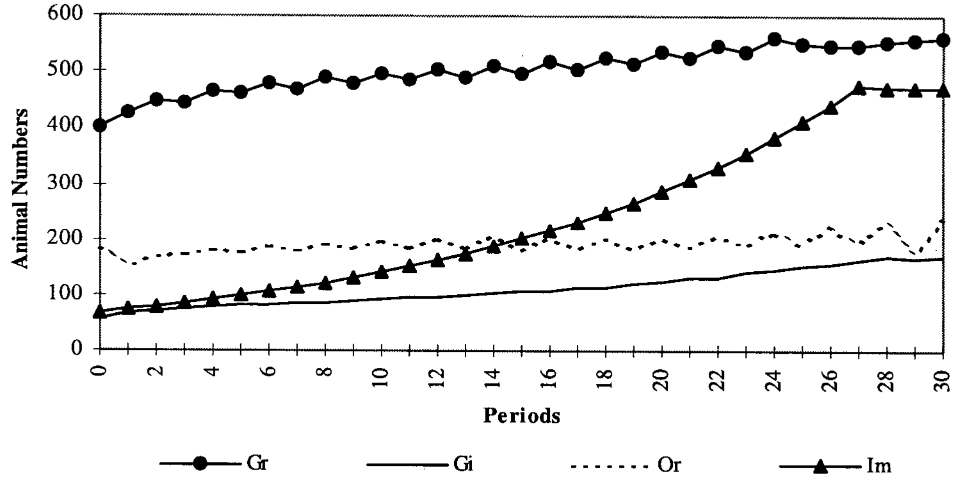

Figure 5.12: KWS Harvest Rate Strategy: Browser and Mixed Feeder Populations

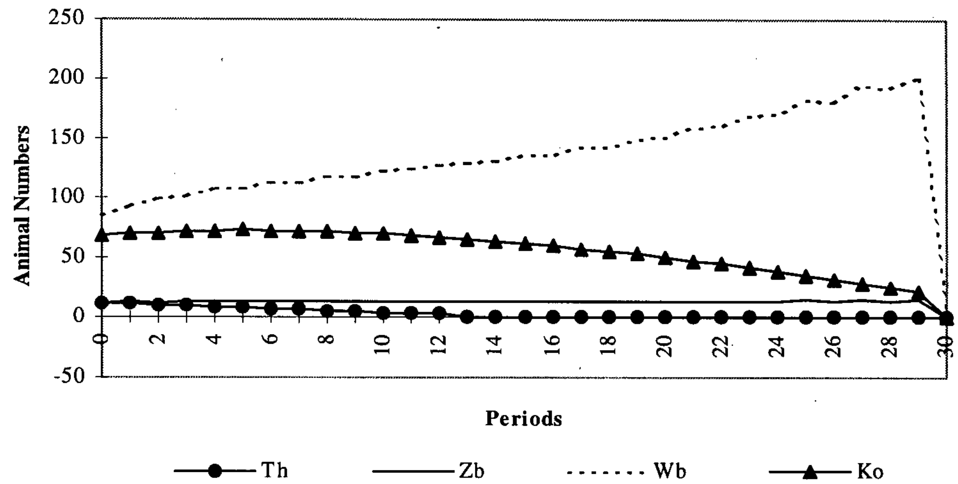

Figure 5.13: KWS Harvest Rate Strategy: Grazer Harvests

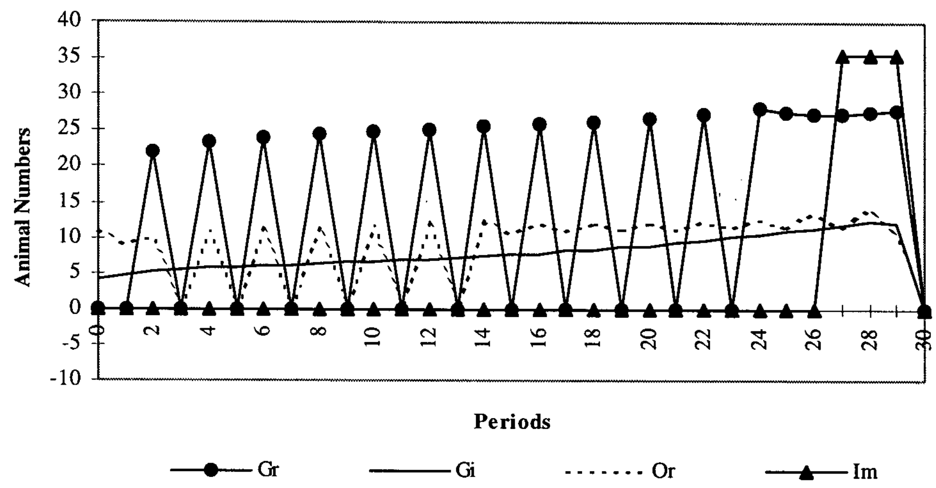

Figure 5.14: KWS Harvest Rate Strategy: Browser and Mixed Feeder Harvests

5.4.3 Shannon Biodiversity Index as a Constraint

Rather than rely on an arbitrary harvest rate for conserving wildlife populations, perhaps it is possible to implement an explicit biodiversity constraint (see van Kooten and Bulte 1998). In this regard, Shannon's index of biodiversity offers a reasonable mechanism for implementing a biodiversity constraint. Shannon's biodiversity index (S) is defined as follows (Pielou 1977):

$$(5.3) \qquad S = -\sum_{i=1}^{n}\left(\frac{H_i}{\sum_{j=1}^{n} H_j}\right)\log_{10}\left(\frac{H_i}{\sum_{j=1}^{n} H_j}\right) = -\sum_{i=1}^{n} k_i \log_{10} k_i \, ,$$

where k_i is the proportion of the total population of wildlife ungulates accounted for by species *I* and *log_{10}* refers to the logarithm of a number to the base 10. In this case, $0 \leq S \leq 1$; higher values of *S* indicate a greater degree of diversity of the wildlife ungulate species on the ranch.

In this simulation, seasonal rainfall is set at 260 mm, and populations are constrained to maintain the Shannon biodiversity index at 0.615, which is the highest observed value of the Shannon index. Total mean herbivore population is 4,602, which is equivalent to 1,925 AUs and a carrying capacity of 4.2 ha per animal unit. The general distribution of species is quite even up to the 29th period, but, without an end–period population constraint, populations are driven to very low levels in the last period. In other words, the Shannon biodiversity index constraint creates a bumper harvest in the 29th period, but populations are minimised in the last period in response to economic forces (Figures 5.15 and 5.16).

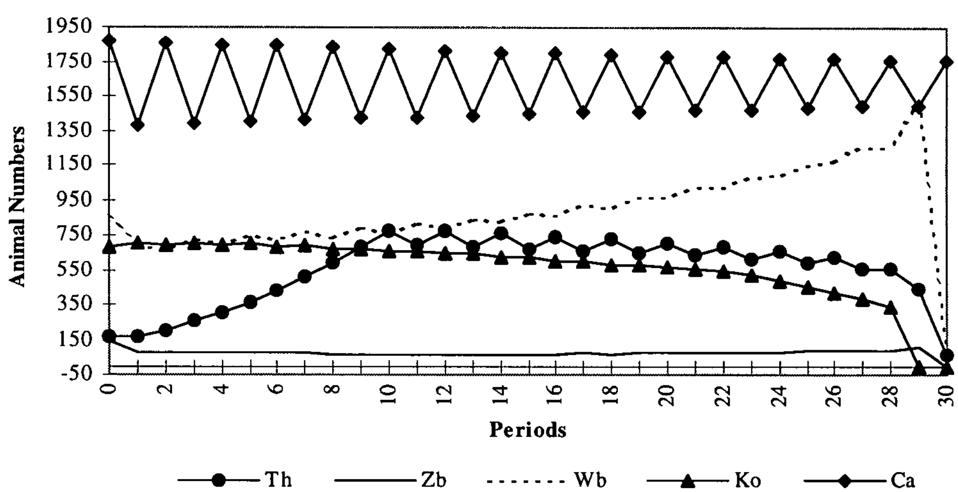

Figure 5.15: Shannon Biodiversity Index Constraint: Grazer Populations

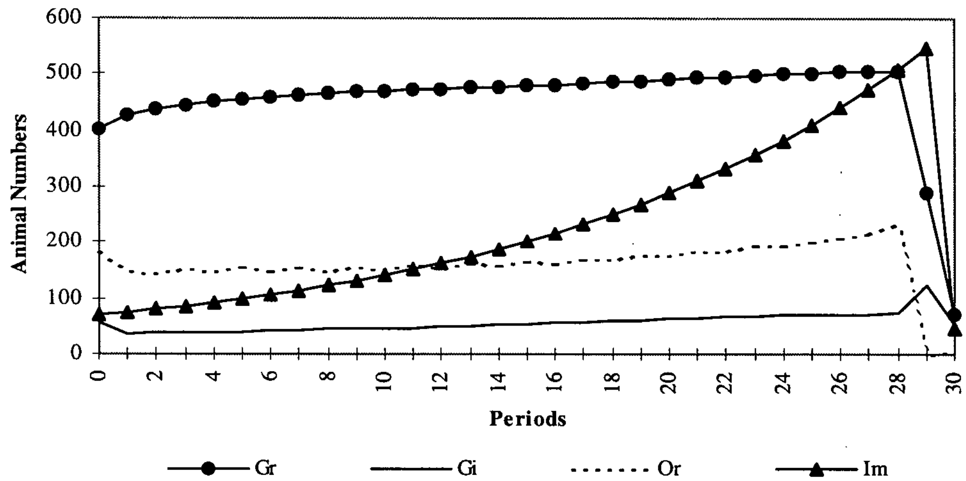

Figure 5.16: Shannon Biodiversity Index Constraint: Browser and Mixed Feeder Populations

The Shannon biodiversity index says nothing about total populations, only relative populations, so it is possible for all populations to decline while leaving relative populations the same. By itself, therefore, this policy could be unsustainable or marginally sustainable. What is needed is information on minimum viable populations, say. Corresponding harvest levels are shown in Figures 5.17 and 5.18.

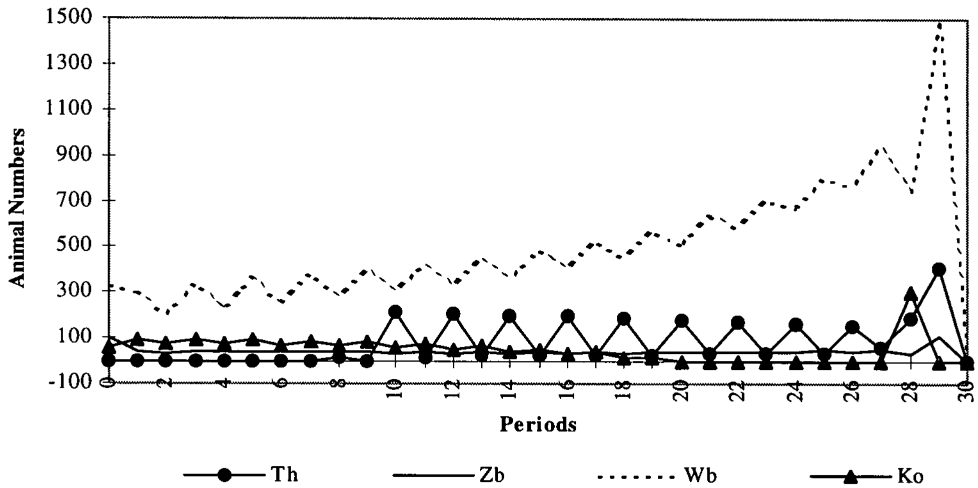

Figure 5.17: Shannon Biodiversity Index Constraint: Grazer Harvests

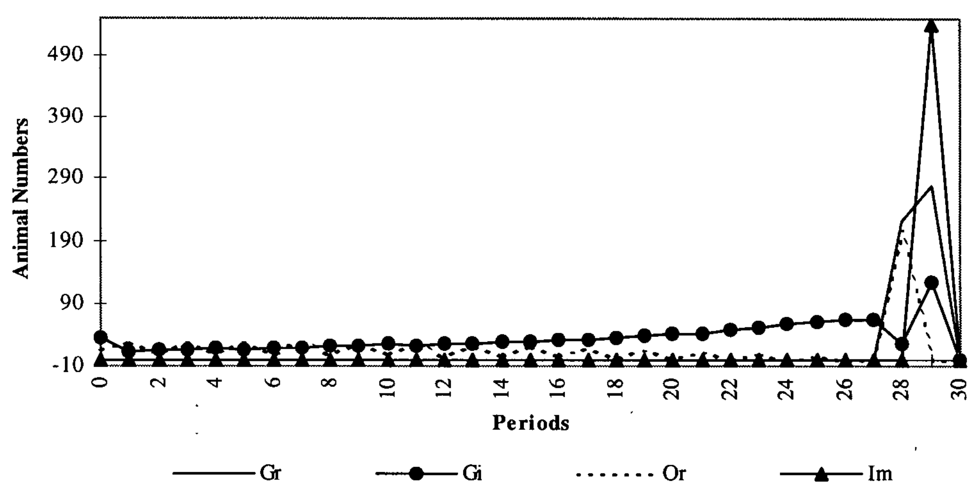

Figure 5.18: Shannon Biodiversity Index Constraint: Browser and Mixed Feeder Harvests

5.4.4 Full Property Rights Scenario

If ranchers were able to capture all of the possible user benefits associated with wildlife on their ranch, wildlife would be a more valuable resource. To mimic the higher returns that a rancher could expect in this case, game prices are simply adjusted upwards to reflect the higher value, especially for larger game animals that are valuable in trophy hunting and likely have higher product value than that associated simply with game meat. Again, mean seasonal rainfall is 260 mm and end–period game populations are constrained to be equal or greater than starting populations. Unlike the end–period population constraint, game prices have been adjusted to reflect the value of wildlife in trophy hunting or game viewing.

A full property rights policy results in a total mean herbivore population of 4,642, which is equivalent to 1,934 AUs and a carrying capacity of 4.2 ha per AU (see Table 5.2). Optimal game populations (Figures 5.19 and 5.20) and harvests (Figures 5.21 and 5.22) portray similar trends as in the end–period population constrained scenario, as do optimal cattle populations, purchases and sales.

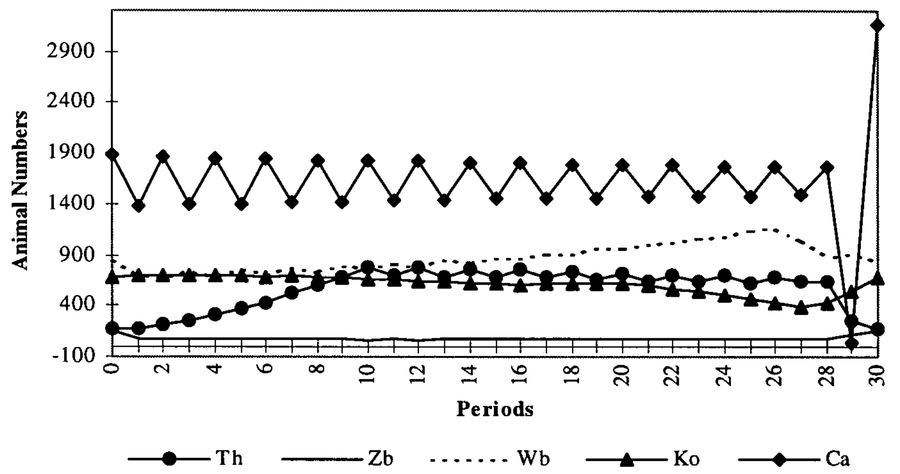

Figure 5.19: Full Property Rights Scenario: Grazer Populations

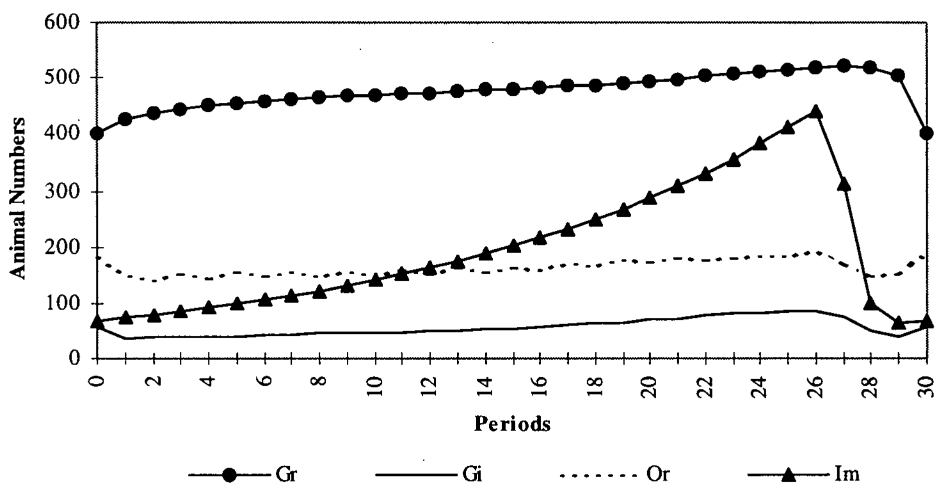

Figure 5.20: Full Property Rights Scenario: Browser and Mixed Feeder Populations

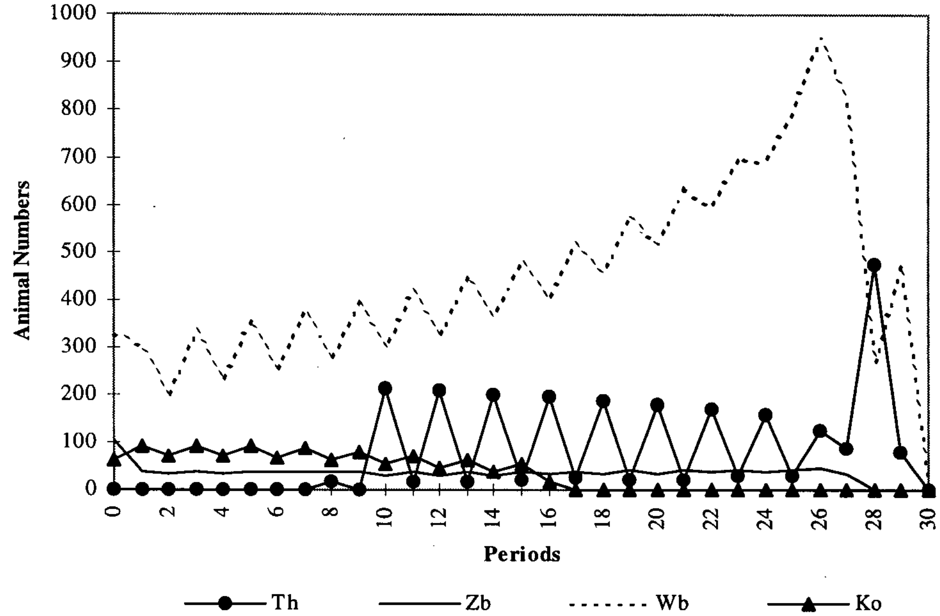

Figure 5.21: Full Property Rights Scenario: Grazer Harvests

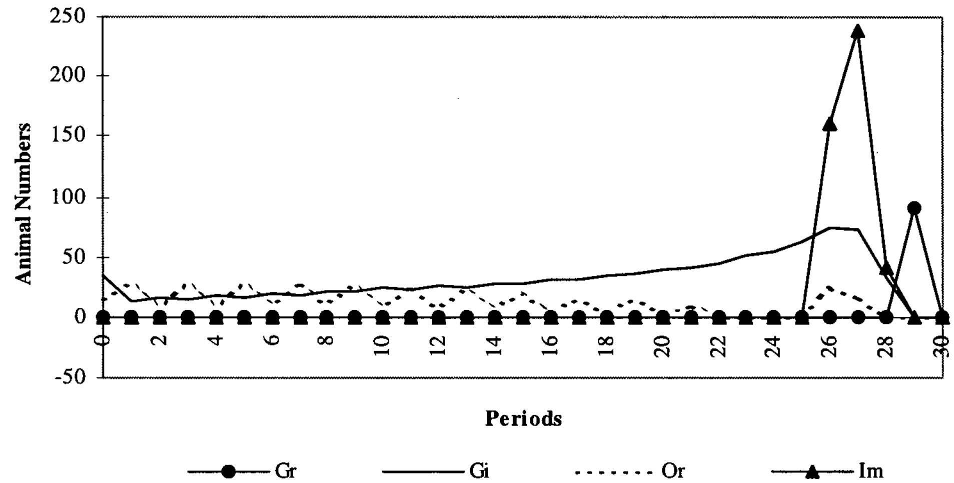

Figure 5.22: Full Property Rights Scenario: Browser and Mixed Feeder Harvests

5.5 The Effect of Drought

Drought is an ever–present reality in Eastern Africa. In this section, I examine the impact of drought on wildlife populations and harvests (and economic returns) using the bioeconomic model. To simulate drought conditions, a mean seasonal rainfall of 260 mm is assumed for the first period. Precipitation is then reduced over a period of five years to 150 mm, remaining at this level for the remainder of the planning horizon; the rainfall level of 150 mm is the mean rainfall for 9 seasons of lowest observed rainfall, excluding an outlier seasonal rainfall of 77 mm in 1981 "short" rains season. End game populations are constrained to be equal or greater than one–half of what they were in the first period, since the initial populations are not consistent with drought conditions.

The simulation results in a total mean herbivore population of 3,735, which is equivalent to 1,672 AUs and a carrying capacity of 4.8 ha per AU. Optimal game populations and harvest levels are shown in Figures 5.23 to 5.26. Again, the trends are similar to the end–period population constraint and trophy–adjusted scenarios. Although cattle populations and sales are not affected by the low rainfall level assumed for the drought scenario (an artefact of the model– see 4.2), the combined game and cattle carrying capacity is at the lowest under this.

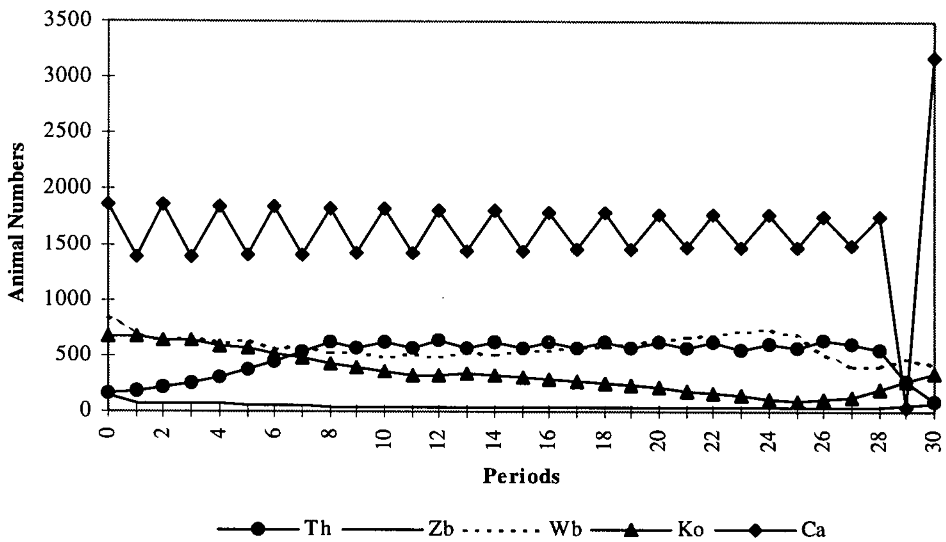

Figure 5.23: Drought: Grazer Populations

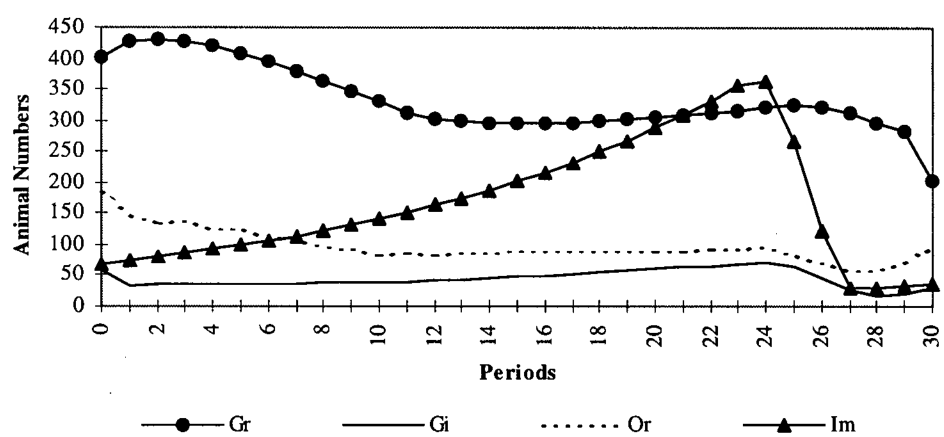

Figure 5.24: Drought: Browser and Mixed Feeder Populations

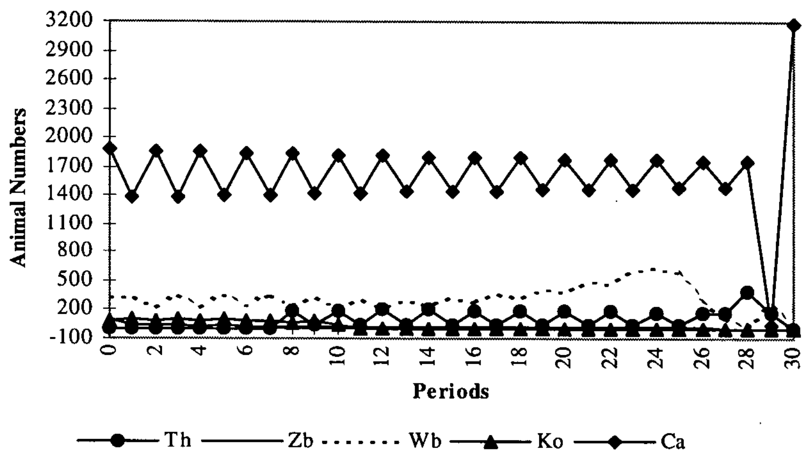

Figure 5.25: Drought: Grazer Harvests

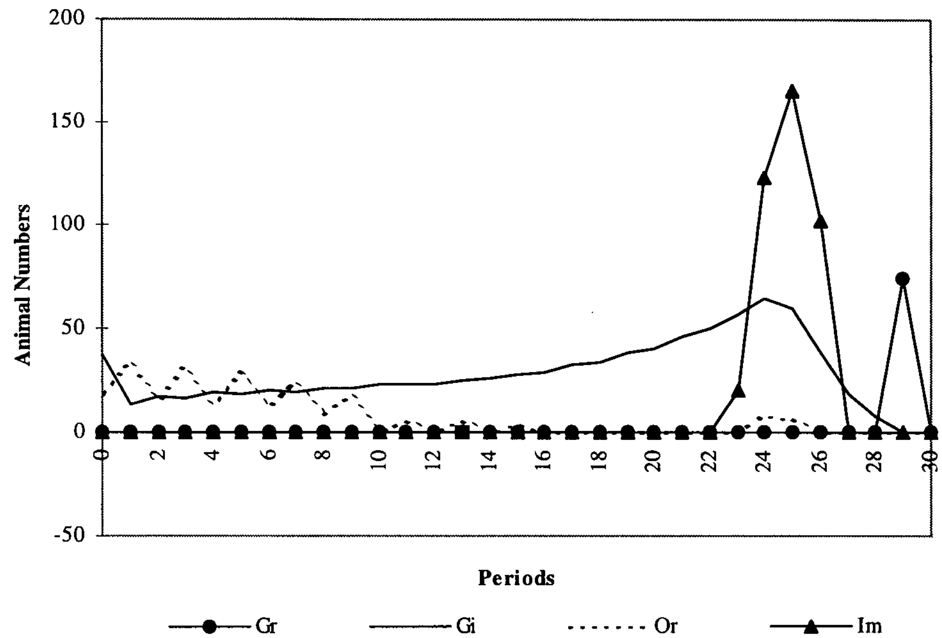

Figure 5.26: Drought: Browser and Mixed Feeder Harvests

5.6 Comparing Key Game Species across Scenarios

In this section, I briefly review the main results for the optimal populations and harvests of some key game species—giraffe, zebra, oryx, wildebeest and kongoni.

Giraffe populations under the preservation and KWS harvest rate scenarios are distinctly higher than in the other scenarios. In these two scenarios, they increase gradually throughout, ending in the range 150 to 200, while numbers are generally well below 100 in the other scenarios. It is not surprising, therefore, that harvests of giraffe are lowest under the KWS' fixed rate harvest scenario and non–existent in the preservation scenario. Under the other scenarios, harvests initially decline to below 20, but then rise gradually to exceed 50, dropping again in the final periods to ensure end–point conditions are met (except in the unconstrained case and that of the Shannon biodiversity index constraint). Surprisingly, harvests of giraffe increase until year 12 under the drought scenario, then declining towards zero.

Optimal populations of zebra under preservation and KWS harvesting rate scenarios are also significantly higher than is the case under the other scenarios. However, zebra numbers fluctuate erratically under the preservation scenario, falling dramatically in period 16 (year 8) before rising to pre–crash levels by period 24 (year 12). However, the zebra population crashes to near extinction (on the ranch) in the final 2 ½ years of the preservation simulation. This is quite unexpected. Zebra populations are more stable in all other scenarios, although they exhibit a dramatic decline in the last year under the Shannon biodiversity constraint scenario. Harvests of zebra are highest under the unconstrained and full property rights scenarios, and are most stable under the KWS' fixed rate of harvest scenario. Under the drought scenario, harvests are high initially (to cull animals that are affected by drought), but then fall to a more stable level from year 5 to year 13, and then fall to zero.

As was the case for zebra, oryx populations behave erratically in the preservation simulation—they peak at about 300 animals in year 7, crash to nearly 50 animals in year 8, rise to a yet–higher peak of about 340 animals in year 13 and then go extinct. Again this is surprising because one expects a policy that does not permit the harvest of wildlife (denoted preservation in this study) to lead to stable wildlife populations. However, such a policy ignores the impact of other herbivores, and particularly cattle, on wildlife ungulates. That is, the dynamics of the herbivory make it impossible to protect all game species by focusing economic value on only one of the species in the herbivory, namely cattle. However, cattle affect oryx (or any other species for that matter) not only directly, but indirectly through the other species in the herbivory.

Optimal populations of oryx are rather stable in the other scenarios. In all scenarios, except the preservation and drought scenarios, population remains steady at about 150 or slightly higher. This is surprising given that harvests across all scenarios are highly irregular, generally exhibiting a two–period cycle—high in one period and near zero in the next. This is true even for the KWS harvest rate scenario, although harvests are relatively stable after year 7.

Wildebeest populations under the preservation scenario are similar to what they are in the case of zebra and oryx, displaying instability in the mid–range of the time period (years 7 and 8) and the end period (years 13–15). However, wildebeest do not go extinct. Ignoring the case of preservation, populations over the time horizon are highest for the KWS' fixed harvest rate scenario and lowest in the case of drought. Obviously, then, harvests of wildebeest are lowest for the fixed harvest rate scenario, but are highest for the full property rights case.

Beginning with some 700 animals, kongoni populations decline almost consistently across all scenarios. Kongoni numbers are highest for the preservation scenario; they increase to over 900 animals in the first four years and then decline steadily to some 400 animals at the end of the time period. For the Shannon biodiversity constraint simulation and the unconstrained scenario, numbers decline to near zero by year 15. With three exceptions, kongoni harvests all take place in the early part of the time horizon, ceasing after the 10th year. For the fixed harvest rate simulation, harvests decline slowly from the first period to zero in the final period. For the unconstrained and Shannon biodiversity constraint scenarios, harvests are non–existent after year 10 (or earlier) but they exhibit a single large spike in the 15th and 14th years, respectively.

While it is difficult to tease out a consistent theme with respect to populations and harvests of large herbivores, the one thing that needs to be emphasised is the fact that the herbivory is a dynamic, inter–active system. As a result, policy cannot be focused on one or two species, but must take into account all of the interactions between and among species, as well as the behaviour of humans who affect the system through their cattle stocking decisions and the efforts they devote to harvest of wildlife. It is the human activities that are affected by economic incentives, and policy constraints and institutions. We now consider the economic benefits to ranchers under each of the scenarios.

5.7 Summary

A summary of the policy insights of the bioeconomic simulation model is provided in Table 5.4. Under the unconstrained policy, all of the wildlife populations on the ranch are driven to extinction or very low levels in the final two periods. Interestingly, the preservation policy does not result in the preservation of all populations of wildlife herbivores on the ranch; it leads to the extinction of non–competitive species (oryx) and the near extinction of others (Thomson's gazelle, zebra). The reason is that the other animals, and particularly cattle, drive out those populations that are least able to compete for forage. Hence the conservation policy that was implemented in 1989 (but previously experimented with on one ranch near Nairobi) appears to have been a positive step.

Under conservation, a number of sustainable policies are examined, including the current KWS policy that controls the rates at which ranchers cull wildlife populations. Surprisingly, sustainability is threatened as this situation is similar to the preservation result where some animals are better able to compete than others for forage. Despite its low rate of harvest relative to population, Thompson's gazelle, in particular, are projected to be driven to extinction, at least on the ranch. This is clearly an unintended consequence of what might otherwise be considered a policy to guarantee sustainability. The end–period population constraint, where final populations are constrained to be at least as great as starting period populations, shows that game ranching is clearly a socially sustainable enterprise. Under the Shannon biodiversity index constrained policy, animal populations are adjusted in the last two periods of the model in a fashion similar to the unconstrained case—all excess animals (i.e., those not needed to satisfy the biodiversity constraint) are harvested in the last period. This implies that the use of Shannon's biodiversity index as a judge for sustainability leads to an erroneous conclusion about the sustainability of the system. The full property rights policy, where prices are adjusted upwards to reflect potential income from game hunting or viewing by foreign tourists, is similar in sustainability to the case of the end–point constraint and, of all sustainable policies, results in the highest net return. The drought situation results in some animals falling to a precipitously low level (particularly oryx) and it has a greater degree of population fluctuation. Otherwise, the system remains relatively sustainable under drought. This offers further evidence that end point constraints on population are the best means for ensuring that populations of wildlife herbivores on a game ranch are maintained.

Table 5.4: Effects of Various Kenyan Government Game Ranching Policies on Ranch Returns, Population of Wildlife Herbivores and Carrying Capacity, Model Simulation Results, 15 years

Policy simulation	Net discounted return (mil. KS)	Mean Numbers (AUs)	Carrying capacity (ha AU^{-1})	Effect on wildlife herbivore populations
Unconstrained	136.1	1959	4.13	Game populations driven to extinction or near extinction in the final two periods
Preservation	100.15	2334	3.47	Some wildlife herbivore populations driven to extinction due to competition from other animals, including cattle.
End–period population constraint	131.04	1935	4.19	Sustainable
Maintain biodiversity measure, S=0.615	134.31	1925	4.21	Sustainable; numbers similar to the end–period population constraint policy, except rapid harvest in final year
KWS harvest rate	111.54	2201	3.68	Sustainability threatened
Full property rights	133.24	1934	4.19	Sustainable; differs from end–period population constraint policy by net return
Drought	124.18	1672	4.84	Sustainable, but only due to end–period constraint that final populations are at least 0.5 of initial population

Also provided in Table 5.3 are the net discounted present values of the policies. By comparing these across policies, it is possible to say something about the costs of various policies. As expected, the unconstrained case yields the highest returns to the ranchers. The biodiversity constraint results in the next highest returns, followed by the policy that constrains final period populations to be no less than initial period populations; this policy is judged to be the most sustainable and the remaining policies are compared relative to it. In this regard, the Kenya Wildlife Service's policy reduces discounted net income over the 15 years by some 19.5 million Kenyan shillings, but does nothing to enhance sustainability. A policy that permits ranchers to bring foreign tourists onto their lands for viewing and hunting (or enables ranchers to sell more of the product, such as hides) is also sustainable, and actually increases net income by 2.2 million KS. This is therefore the preferred policy option.

Finally, it is notable that, according to the model presented here, abandoning the previous preservation policy was a good decision. Not only was it not sustainable, it also lowered a rancher's income by some 30.9 million KS over the 15–year time horizon.

CHAPTER 6

DISCUSSION, POLICY IMPLICATIONS AND CONCLUSION

This research has contributed to knowledge in three ways. First, it documents wildlife ungulate populations on commercial ranches in Kenya over a period of some 15 years, and shows that such wildlife resources have tremendous potential for sustainable commercial game meat production, given appropriate wildlife policies. Second, one possible way to encourage private conservation of wildlife on private ranches is to increase their value to the rancher so that wildlife are economically competitive with livestock. In this research, I demonstrate that dynamic optimisation is a powerful tool for examining the multiple–use resource allocation problem on privately–owned commercial ranches and for analysing Kenyan wildlife policies. The commercial ranch is modeled as a system with logistic population growth models that capture system biological behaviour, including species interactions. In contrast to static economic procedures, dynamic optimisation captures system dynamic behaviour inherent in biological systems. The bioeconomic model indicates that game ranching can be competitive with domestic wildlife under certain conditions, and that it is sustainable.

Third, seasonal rainfall is relevant for modeling carrying capacity in logistic population growth functions. By explicitly including precipitation, one provides a biological interpretation for the endogenously determined (estimated) carrying capacity of the ranch system. In this respect, carrying capacity is variable rather than constant, making it possible to analyse the system bioeconomics under different rainfall regimes, including drought. Thus, complex ecological behaviour of wild herbivore populations in arid and semi–arid rangelands of Kenya is empirically captured using "rainfall–based," logistic population growth models.

With respect to private commercial ranches, KWS needs to adopt a wildlife policy that has the dual objective of conserving wildlife and yielding maximum economic benefits to ranch owners. Since ranch resources upon which wildlife depend are also utilised by livestock, the ranch manager's task is to allocate limited resources among wildlife and livestock. It requires that KWS provide economic incentives to private land owners that causes them to allocate their resources to wildlife at terms competitive with livestock. Without such incentives (the pre–1989 preservation policy), allocation of ranch resources to wildlife would depend on the goodwill of private land owners. In this case, the rancher's main focus is livestock. They maintain a fairly constant cattle population over time, ranging from 1,500 to 1,700 head (Figure 5.7). Game animals are allocated residual range resources after cattle requirements are met, with ranchers ignoring interactive effects of cattle on wildlife since wildlife do not directly contribute to the objective function. As a result, less competitive game species are driven to extinction (oryx) or near extinction (Thomson's gazelle), as shown in Figures 5.7 and 5.8. The pre–1989 preservation policy may not be effective in preserving species.

There are two ways KWS can provide economic incentives to private land owners: (1) allowing land owners to commercially harvest game animals, and (2) compensating land owners for ranch resources utilised by game. The latter is simply too expensive. A policy allowing landowners to commercially harvest game animals may be necessary, but it may also not be sufficient to cause them to conserve game animals. If implemented unrestrained, it yields the highest net present income but could lead to extinction of all game. For it to be sustainable, a commercial game harvesting policy would require checks and balances in order to ensure conservation of game animals.

Three policies for sustainability were investigated within the commercial game harvesting policy framework: (1) the Shannon biodiversity index constraint, (2) a proportion of population constraint on game harvests, and (3) a constraint on end–period populations so that these are at least as great as the populations at time zero.

The Shannon biodiversity index constraint on game harvests yields the second highest net income (Table 5.2), but it also minimises ending populations to lowest possible levels compatible with the biodiversity index constraint (Figures 5.17 and 5.18). This makes the Shannon biodiversity index a poor basis for commercial game harvesting policy, because it leads to a result that is closer to the unconstrained case. It may not be sustainable.

Constraining game harvesting to fixed off–take proportions (a fixed proportion of population) results in near extinction of some game species (e.g., Thomson's gazelle). For other species, population builds up, but is inevitably followed by a crash in population, as is the case for oryx. While generally conserving game, the fixed off–take policy yields the second lowest net present income and runs the risk that it is not sustainable as it fails to take into account interspecies interactive effects and population dynamics. This makes it a poor basis for commercial game cropping.

Constraining end–period populations to be equal to or greater than starting populations appears to be the ideal sustainable game harvesting policy. It ensures an excellent distribution of game populations over time and unambiguously ensures sustainability and conservation of game (Figures 5.9 and 5.10). Moreover, it yields substantial net present income that is close to the Shannon index constrained and unconstrained harvesting policies. This policy is ideal; it provides necessary economic incentives to the private landowners for accomplishing the task of allocating ranch resources to game and cattle in such a way that conservation goals of KWS are attained and greatest economic benefit accrues to ranchers.

Within the context of the end–period population constrained policy framework, the study provides insights into additional economic incentives to landowners through sale of other products besides meat and hunting and game viewing expeditions; it also provides cautionary insight into game cropping policy under a drought situation. The study shows that allowing landowners full property rights to wildlife (over and above game meat) might not compromise game conservation standards (Figures 5.19 and 5.20) and at the same time it presents ranchers with an opportunity to earn higher net present income (Table 5.2). It should be encouraged, therefore, as benefits are positive from the standpoint of KWS. It also has the added feature that less monitoring is required by KWS.

Under conditions of drought, the study shows a general decline of game populations (Figures 5.23 and 5.24) and ranchers have to make do with lower harvest levels (Figures 5.25 and 5.26) and lower net present income (Table 5.2). Drought represents a critical time for commercial game cropping, requiring restraint on the part of ranchers and close monitoring by KWS to avoid potentially irreversible damage to wildlife numbers.

Instead of providing economic incentives to landowners by allowing them to commercially harvest game animals, the alternative is to compensate them for ranch resources utilised by game. This study provides a basis for determining compensation rates, using the shadow prices (user costs) per animal obtained under the best game–cropping framework. Ranchers strive to get the highest economic benefit possible from game, so the best cropping framework, from their standpoint, is to permit fuller use of wildlife ungulates, including trophy hunting and sale of tourist expeditions, because it yields the highest net present income and, at the same time, attains KWS conservation objectives.

These results have been arrived at within the context of a deterministic model that is considered adequate for the purpose of wildlife policy analysis. For management purposes, however, a stochastic model is considered to be more appropriate. This is the suggested direction for future research.

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Appendix

GAMS Prototype Program (End–Period Population Constrained Scenario)

```
Sets
   i animals  /Gr, Th, Gi, Or, Zb, Wb, Ko, Im, Ca/
   t time    /0*30/;
Set tfinal(t) final time period
   cat(i)     cattle stopper /Ca/;
tfinal(t) = yes$(ord(t) eq card(t));
parameters
   g(i) logistics intrinsic growth
      / Gr 0.286
        Th 0.349
        Gi 0.294
        Or 0.430
        Zb 0.477
        Wb 0.323
        Ko 0.332
        Im 0.074
        Ca 0.0  /
   au(i) Animal unit coefficients
      / Gr 0.1463
        Th 0.0813
        Gi 1.1547
        Or 0.2846
        Zb 0.3800
        Wb 0.3800
        Ko 0.2846
        Im 0.1463
        Ca 0.7015 /
   d(i) rainfall adjuster for carrying capacity
      / Gr 0.231
        Th 0.580
        Gi 0.134
        Or 0.059
        Zb 0.153
        Wb 0.478
        Ko 0.685
        Im 71578.0
        Ca 1.0  /
   e(i) effort coefficients
      / Gr 0.0103
```

```
      Th  0.0110
      Gi  0.0148
      Or  0.0148
      Zb  0.0158
      Wb  0.0040
      Ko  0.0053
      Im  0.0270
      Ca  0.0  /
  p(i)  net rent or price per animal unit (thous. shillings)
    / Gr  9.780
      Th  5.710
      Gi  6.970
      Or  9.270
      Zb  9.880
      Wb  5.300
      Ko  3.920
      Im  7.920
      Ca  0.0 /
  rho(t)  discount factor;
scalar r discount rate /1.04/;
rho('0')=1/(r**0);
rho('1')=1/(r**0.5);
rho('2')=1/(r**1);
rho('3')=1/(r**1.5);
rho('4')=1/(r**2);
rho('5')=1/(r**2.5);
rho('6')=1/(r**3);
rho('7')=1/(r**3.5);
rho('8')=1/(r**4);
rho('9')=1/(r**4.5);
rho('10')=1/(r**5);
rho('11')=1/(r**5.5);
rho('12')=1/(r**6);
rho('13')=1/(r**6.5);
rho('14')=1/(r**7);
rho('15')=1/(r**7.5);
rho('16')=1/(r**8);
rho('17')=1/(r**8.5);
rho('18')=1/(r**9);
rho('19')=1/(r**9.5);
rho('20')=1/(r**10);
rho('21')=1/(r**10.5);
rho('22')=1/(r**11);
rho('23')=1/(r**11.5);
rho('24')=1/(r**12);
rho('25')=1/(r**12.5);
rho('26')=1/(r**13);
rho('27')=1/(r**13.5);
```

```
rho('28')=1/(r**14);
rho('29')=1/(r**14.5);
rho('30')=1/(r**15);
alias(i,j);
table a(i,j)   Table of logistic interaction coefficients
        Gr       Th      Gi       Or       Zb       Wb       Ko       Im       Ca
Gr      1.0              -0.168
Th               1.0                       3.209                                -0.045
Gi      -0.677           1.0                                          -1.641
Or      0.198            0.297    1.0               -0.137   -0.094   -0.174
Zb                                -0.651   1.0
Wb      -3.588                    -2.142            1.0               -4.629   0.072
Ko      -2.022                                               1.0      4.019
Im                                                                    1.0
Ca                                                                                 ;
scalar rain average seasonal rainfall in mm  /262.4/;
scalar cc cost of effort /0.177/;
scalar pur  purhase price for calves /4.171/;
scalar PCa  price of cattle per animal unit /7.70/;

Variables
  h(t,i)    State variable for animal i at time t
  Buy(t)    Purchases of cattle calves at time t
  Sales(t)  Sales of cattle at time t
  eff(t,i)  Effort devoted to harvest of species i at time t
  z         Net present value from game ranching;
Positive variables h, Buy, Sales, eff;
h.fx('0','Gr')=401*au('Gr');
h.fx('0','Th')=166*au('Th');
h.fx('0','Gi')=58*au('Gi');
h.fx('0','Or')=185*au('Or');
h.fx('0','Zb')=149*au('Zb');
h.fx('0','Wb')=858*au('Wb');
h.fx('0','Ko')=679*au('Ko');
h.fx('0','Im')=69*au('Im');
h.fx('0','Ca')=1874*au('Ca');
h.lo('30','Gr')=401*au('Gr');
h.lo('30','Th')=166*au('Th');
h.lo('30','Gi')=58*au('Gi');
h.lo('30','Or')=185*au('Or');
h.lo('30','Zb')=149*au('Zb');
h.lo('30','Wb')=858*au('Wb');
h.lo('30','Ko')=679*au('Ko');
h.lo('30','Im')=69*au('Im');
h.l(t+1,'Gr')=401*au('Gr');
h.l(t+1,'Th')=166*au('Th');
h.l(t+1,'Gi')=58*au('Gi');
h.l(t+1,'Or')=185*au('Or');
```

```
h.l(t+1,'Zb')=149*au('Zb');
h.l(t+1,'Wb')=858*au('Wb');
h.l(t+1,'Ko')=679*au('Ko');
h.l(t+1,'Im')=69*au('Im');
eff.fx('30',i)=0;
h.l(t+1,'ca') = 1370*au('ca');
Buy.l(t) = 99;
Sales.l(t) = 983;
eff.fx(t,'Ca')=0;
equations
   NPV          Objective function in Kenyan shillings
   growth(t,i)    growth of animals over time
   cattle(t)     cattle equation of motion
   catt2(t)      restriction on cattle sales in each period
   catt3(t)      carrying capacity of cattle restriction;
NPV..           z =e= sum(t, rho(t)*(PCa*Sales(t)
                -pur*Buy(t)))
                 +sum(t, rho(t)*sum(i,p(i)*h(t,i)*
                 (1-exp(-e(i)*eff(t,i)))))
                 -cc*sum(t,rho(t)*
                 sum(i,eff(t,i)$(not(cat(i)))));
growth(t+1,i)$(not(tfinal(t))and (not(cat(i))))..
             h(t+1,i) =e= h(t,i)+g(i)*h(t,i)*
             (1-(sum(j, a(i,j)*h(t,j)))/(d(i)*rain))
             -h(t,i)*(1-exp(-e(i)*eff(t,i)));

cattle(t+1)$(not(tfinal(t)))..
             h(t+1,'Ca') =e= 1.0222*h(t,'ca')+Buy(t)
             -Sales(t);
catt2(t)..   Sales(t) =l= h(t,'Ca');
catt3(t)..   h(t,'Ca')+Buy(t) =l= 2253;
Model range /all/;
solve range using nlp maximizing z;
display h.l, Buy.l, sales.l, eff.l, h.m,  Buy.m, sales.m, eff.m;
```