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Improving Access to Livestock Markets for Sustainable Rangeland Management

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Abstract

Productivity of rangelands in Kenya is affected by increasing crop farming especially in more fertile range areas. Among the key factors driving the encroachment of crops on rangelands are the changing opportunities brought about by markets. We hypothesize that the existing market inefficiencies characterizing livestock markets, especially the price disincentives that livestock producers face, are major risks rangelands face. To analyze the effect of livestock market conditions on rangeland management, we draw on household survey and economic modeling tools. We find that traders' rent seeking behavior and high transport costs act as disincentives to livestock producers' participation in livestock markets and influence their decisions in seeking alternative rangeland uses to sustain livelihoods. However, improved livestock market access enhances livestock producers' livelihoods and the stewardship of the ecosystems thus reducing pastoralists' vulnerability to ecological climate variability associated with rangelands.

Keywords: Extensive livestock production, market access, ecological-economic model, positive mathematical programming (PMP) model, Kenya

JEL codes: Q13; Q15; Q24

Highlights

- Encroachment of crop farming on Kenya's semi-arid rangelands occurs as producers seek higher financial gains for sustaining livelihoods.
- The condition of livestock markets is viewed to be a major risk rangelands face.
- Traders' rent seeking behavior and high transport costs act as disincentives to market participation and sustainable rangeland management.
- Re-apportioning value-added in livestock marketing chains and reduced transport costs complement efforts of manage rangelands sustainably and improve livelihoods.

1 Introduction

Livestock production is a key component of Kenyan rangelands and indeed for rangelands in Sub Saharan Africa found in the Arid and Semi-Arid Lands (ASALs). About 70% of the nation's livestock is found in the ASALs, valued at about Kshs. 70 billion (GOK, 2012a). Livestock production also plays a key role in the economic development and welfare of the county. Recent estimates indicate that the value added by livestock to the agricultural GDP is about US$4.54 billion, slightly less than that from arable agriculture with a contribution of US$5.25 billion (Behnke and Muthami, 2011; GOK, 2012a). Livestock production also provides a source of livelihood to about 14 million people residing in the ASALs and millions of others through backward and forward linkages (GOK, 2012a).

Extensive systems of livestock production prevail in the ASALs where pastures provide the main feed for livestock as well as other herbivores found in the rangelands. This highlights the need to maintain the productivity of the grazing systems with regard to the role they play in livestock production. However, rangelands in the country are being impaired by degradation manifested in the form of soil erosion, vegetation cover conversions, and salinity (Greiner et al., 2013; Odhengo et al., 2012; Flintan, 2011; Pickmeier, 2011; Maitima et al., 2009; Harding and Devisscher, 2009; Gomes, 2006; Mugai, 2004; Duraiappah et al., 2000; Olang, 1988). Among the resulting consequences of degradation are the declining productivity of the ecosystems with negative effects on livelihoods.

Numerous studies have been carried out identifying the driving forces of the observed biophysical changes in rangelands in the country (Pickmeier, 2011; Harding and Devisscher, 2009; Mwangi, 2009; Gomes, 2006; Campbell et al., 2005; Amman and Duraiappah, 2004; Mwagore, 2003; Lambin et al., 2001; Duraiappah et al., 2000; Rutten 1992). The majority of the above studies are mainly qualitative, and only a few studies discuss the drivers of rangeland degradation in light of how different socio-economic, political, and biophysical factors influence each other and the resulting effect on the productivity of the ecosystems (Campbell et al., 2003; Campbell et al., 2005). In addition, despite the scant empirical literature on the sustainability of rangelands in the country, there is little information available on how the factors interplay and their impact on the ecosystem.

Serneels and Lambin (2001), focusing on the proximate causes of land use change, show that mechanized and smallholder agriculture replace rangelands in higher potential areas.

Butt (2010) analyzed the relationship between vegetation variability, cattle mobility, and density in Kenya. The author identifies that cattle intensively utilize different parts of the landscape at different times, showing the implications that sedentarization and reduced cattle mobility are likely to have on vegetation. Maitima et al. (2009) similarly focused on the relationship between land use change, biodiversity, and land degradation. The study indicates that land use changes not only reduce the quality and abundance of species of

conservation concern, but also lead to a significant decline in soil nutrients. Though they present important findings, these studies are hardly sufficient to inform policy makers about how drivers of rangeland degradation come to play, how they affect each other, and their effect on the sustainability of the ecosystems. The present study contributes in filling this important gap in this field of research.

From the literature review, a large share of the drivers of rangeland degradation relates to land use/land cover changes. Among the key factors influencing LULCC in global livestock grazing systems are the changing opportunities brought about by markets (Lesslie et al., 2011; Fox and Vogler, 2005; Hazell and Wood, 2008; Sternberg, 2008; Hu et al., 2008; Baldi and Paruelo, 2008; Lambin et al., 2003). This study seeks to offer evidence that inefficient livestock markets, in the face of developing national and international markets for crop commodities, may have externalities to a number of factors driving rangeland degradation. The study postulates that inefficient livestock markets may lead to conversion of grazing areas to competing land uses. Conversion of grazing vegetation to other land use/land covers limits access to wider grazing options that provide important ecological functions for rangelands in ASALs. In addition, loss of grazing areas limits the mobility of livestock and increases grazing pressure of livestock in confined areas. This is likely to have negative impacts on the sustenance of the ecosystems, leading to productivity losses. Less grazing areas and less productivity of the ecosystems is likely to have negative impacts on incomes as well as an increase in vulnerability of rural households to the variable climate characterizing rangelands. This indicates that livestock market inefficiencies may have far-reaching side effects on other drivers of rangeland degradation and consequently on rural livelihoods.

In Kenya as well as in many other developing countries, semi-arid grazing lands are more prone to being developed as a consequence of conversion and intensification processes in response to market triggers (Lambin et al., 2001). The analysis of the study is therefore based on semi-arid rangeland environments within the country. The study is organized as follows: Section 2 provides a description of the case study area and data. Here we also discuss in some detail the factors driving rangeland degradation and the ways in which inefficient livestock markets contribute to degradation. Section 3 describes the rangeland model, while Section 4 presents the results. A discussion of the modeling results drawing policy implications is presented in Section 5, and Section 6 provides the conclusion.

2 Case Study Area, Rangeland Management, and Livestock Markets

2.1 Study Area

The study area, Narok County, is a semi-arid agro-pastoral region located in southwestern Kenya, inhabited by the pastoral Maasai community. Narok County primarily supports extensive livestock operations and wildlife. The principal livestock found in the region are cattle, sheep, and goats. Characterized by an average rainfall ranging from 500 to 1,800 mm annually, the region seems promising to agricultural neighbors, but most of the suitable areas only lie along the borders. The center of the region is either very dry with very unreliable rainfall, or the soils are infertile and shallow (Jaetzold *et al*., 2009).

Despite some differences in the challenges affecting rangeland areas, the semi-arid lands in Kenya face similar challenges regarding the loss of grazing lands to other land uses, mainly crop farming. Based on these similarities, the data availability, and the accessibility of the rangelands, the study used Narok County to achieve its objectives.

2.2 Rangeland Conversions and Modifications

Maps of land degradation patterns by Le et al. (2014) and Waswa (2012) identify Narok as one of the country's degradation hot spots - findings which were supported by field observations. Recent scientific research provides various narratives regarding the key drivers of rangeland degradation in Narok as well as other ASALs in Kenya (Duraiappah, 2000; Campbell et al., 2005; Kameri-Mbote, 2005; Mwagore, 2003; Rutten, 1992; Harding and Devisscher, 2009; Pickmeier, 2011; Gomes, 2006; Homewood, 2012; Flintan, 2011; Campbell et al., 2003). A key driver of rangeland degradation in semi-arid areas has been LULCC (Cheche et al., 2015; Maitima et al., 2009; Kiage et al., 2007; Serneels and Lambin, 2001). These land use/land cover changes are often associated with the loss of natural vegetation, biodiversity loss, and land degradation (Maitima et al., 2009; Kiage et al., 2007). The pressure points which have had the greatest impact on land use/land cover changes in Narok County as well as other semi-arid rangelands in the country have been the changing crop market conditions mediated by land reforms (Campbell et al., 2003; Campbell et al., 2005; Duraiappah et al., 2000; Serneels and Lambin, 2001; Temper, 2012; Pickmeier, 2011; Amman and Duraiappah, 2004). Increasing opportunities for commercial arable farming created by the development of both local and international markets act as pull factors leading to LULCC in better-watered grazing areas (Campbell et al., 2005; Duraiappah et al., 2000; Serneels and Lambin; 2001;Temper, 2012; Pickmeier, 2011). The facilitating land reforms constitute the redefinition of land use arrangements from communal ownership to exclusive property rights (Mwangi, 2009; Meinzen-Dick and Mwangi, 2009; Duraiappah et al., 2000; Campbell et al., 2003; Kameri-Mbote, 2005; Mwagore, 2003).

Selective conversion of grazing areas to other land uses such as cropping leads to fragmentation of land, a key driver of rangeland degradation (Flintan, 2011; Rutten, 1992; Galaty and Ole Munei, 1999; Amman and Duraiappah, 2004; Hobbs et al., 2008). Fragmentation of the grazing ecosystems leads to flexibility losses and the opportunistic spread of grazing pressure that occurs with the seasonal movement of livestock, subjecting rangelands to environmental degradation (Mireri et al., 2008; Mwagore, 2003; Flintan, 2011; Boone and Hobbs, 2004; Hobbs et al., 2008; Meinzen-Dick and Mwangi, 2009). This undermines the capacity of pastoral communities to sustainably use the ecosystems as well as deal with risks such as drought.

2.3 Livestock Markets

Feasible markets for livestock and livestock products serve as engines for drawing surplus herds from grazing areas to consumption points and the attraction of investments such as SLM technologies (Hurrissa and Eshetu, 2002). The ability of rural livestock producers to raise their incomes also depends on their ability to compete in the market effectively (Markelova et al., 2009). Despite livestock production being key in Narok County, markets for livestock in the region, as well as in other parts of the country, are faced with significant market price disincentives. The market price disincentives arise from issues related to market inefficiencies such as middlemen rent-seeking behavior, government taxes and fees imposed on cattle trekkers, high transport costs, lack of market infrastructure, financial and technical service constraints, and market information system constraints, among others (Makokha et al., 2013; Muthee, 2006; Ahuya et al., 2005; Aklilu, 2002). High exploitation by traders/middlemen and high transport costs represent the largest shares of these inefficiencies (Makokha et al., 2013; Muthee, 2006). The numerous challenges that hinder smooth trade in livestock markets may explain the apparent limited price responsiveness of pastoralists in the country to livestock markets (Ng'eno et al., 2010). Given the challenges facing livestock markets and in the face rural households' need to increase their incomes and improve their livelihoods, rural households are likely to explore more profitable rangeland uses such as conversion to crop farming, land leases, or sales to immigrant crop farmers.

Drawing from the above discussions, the drivers of rangeland degradation emerge to be highly interrelated, with externalities running from one factor to another. We postulate that, with low benefits from livestock production, the need to internalize potential economic benefits with alternative uses of rangelands has led to evolving property rights in the area. With property rights reforms, significant spatial expansion of cropping lands occurs with the increasing market opportunities for crop production both for local consumption and for export. However, these changes in land use/land cover occur at the expense of pastoralists and sustainable rangeland use.

Theoretical models support the above discussion. The demand-led model states that redefinition of property rights mainly follows the need to internalize externalities resulting from increasing market opportunities and population growth. This implies that property rights in pastoral areas evolve when the benefits of pursuing private rights exceed the costs (Kamara et al., 2004). Similarly, Anderson and Hill (1975) state that competitive forces lead to the erosion of institutions that no longer support economic growth. Changes in market conditions and the potential economic benefits that can be exploited motivate adjustments to existing property rights structures. According to the new institutional economic theory, competition, such as that between conflicting land uses, is stated to be the key to institutional change (North, 1995).

The study further employs Hertel's (2011) partial equilibrium model of a profit-maximizing farm to illustrate land supply in response to commodity prices. According to the model, change in agricultural land use can be determined as follows:

$$q_L^* = \left[\frac{\Delta_A^D + \Delta_L^S - \Delta_L^D}{1 + \frac{\eta_A^{S,I}}{\eta_A^{S,E}} + \frac{\eta_A^D}{\eta_A^{S,E}}} \right] - \Delta_L^S \qquad (1)$$

where q_L^* is the long run equilibrium change in agricultural land use. The key determinants of q_L^* are:

Δ_A^D = Change in demand for agricultural output due to exogenous factors

Δ_L^S = Change in supply of agricultural land due to exogenous factors

Δ_L^D = Exogenous yield growth

η_A^D = Price elasticity of demand

and the aggregate agricultural supply response to output price comprising of:-

$\eta_A^{S,I}$ = Intensive margin of land supply

$\eta_A^{S,E}$ = Extensive margin of land supply

The study focuses on the size of the intensive margin of land use relative to extensive margin of land use $\left(\frac{\eta_A^{S,I}}{\eta_A^{S,E}} \right)$. This ratio captures the incentives to expand at the intensive margin (Stevenson et al., 2011). It indicates that agricultural output can either expand with increase in yields (at the intensive margin) or with physical expansion of area (at the extensive margin) (Stevenson et al., 2011). When the ratio is high, the size of the denominator in

equation (1) increases leading to fall in equilibrium agricultural land use. In regard to rangelands, an increase in the size of the ratio leads to less natural grazing lands being converted to agricultural land, mainly cropping land. This occurs when the opportunity cost of converting grazing areas is high and producers are encouraged to increase crops yields from existing cropping areas so as to increase output. However, when the opportunity cost of conversion is relatively low, a positive shock in crop commodity prices is likely to lead to increased crop production at the extensive margin (physical expansion of cropping areas). Agricultural encroachment would result in loss of natural grazing cover.

Loss of rangelands to other land uses can be minimized by increasing value/competitiveness of livestock production. A viable method is to enhance the productivity and profitability of the livestock production with well-established linkages to markets (improved market access). Incorporating livestock producers directly into the value-addition chain and linking them to existing terminal markets would loosen the grip of the livestock traders and improve pastoralists' and other livestock producers' margins. In addition, adoption of efficient methods of transporting livestock at the prevailing road infrastructure conditions is likely to generate higher margins for producers. Higher profitability of livestock production provides an avenue through which rangeland conversion processes can be minimized. In addition, efficient livestock markets are capable of facilitating the destocking of animals during periods of low rainfall, such as drought years, thus relieving grazing pressure on the rangelands. Some of the suggested initiatives have been rolled out, but on a small scale (CARE- Livestock marketing and enterprise project, Garissa, Kenya), and thus it is important to evaluate their effect for policy advice. With the underutilization of the existing meat processing facilities (Ng'eno et al., 2010) and the country serving as a net importer of red meat (Muthee, 2006), the study assumes a ready market for livestock in the country. We evaluate the effect of the identified options on land use/land cover changes on rangelands and their subsequent effect on the sustainable management of the ecosystems.

2.4 Data

Among the key reasons for selecting this case study area for rangeland modeling was the opportunity to verify the land conversions and degradation processes as shown on the maps by Le et al. (2014) and Waswa (2012). The area is also characterized by different pastoral systems (pastoral leasing, agro-pastoral, pastoral) forming a good representation of the pastoral systems found in the country. The Kenya integrated household budget survey (KIHBS) 2005/06 provided detailed data on agriculture holdings, agriculture input and output, and livestock information for a period of 12 months, covering all possible seasons (KNBS, 2005/06c). The rich dataset provided crucial data for our model. Data on livestock marketing costs is obtained from the detailed study on livestock market value chains by

Muthee (2006). The GlobCover 2005 was employed to obtain land cover estimates in the area (Bicheron et al., 2006).

3 The Rangeland Model

3.1 Model Description

There is growing literature on the use of dynamic ecological-economic rangeland models to assess the impact of alternative policies on the management of the natural rangeland resources (Moxnes et al., 2001; Hein, 2006; Hein and Weikard, 2008; Kobayashi et al., 2007). Among the potential benefits of these models is their ability to integrate the feedback effects between natural resources and human activity. This is particularly important in rangeland studies, as human rangeland use decisions may have long-term effects on the productivity of the ecosystem.

I present here the basic structure of the dynamic ecological-economic rangeland model1. The model is adapted from Hein (2006) and Hein and Weikard (2008) and has been applied in several empirical studies (see Weikard and Hein, 2011; Hein, 2010; Kobayashi et al., 2007). The novelty of the model presented lies in the introduction of stochastic rainfall realizations in the analysis. In addition, an extension of the model is made to enable calibration of the model to the actual land use activities in the study area using Howitt's (1995) positive mathematical programming (PMP) model. The model is implemented using GAMS software with nonlinear programming solver CONOPT3, with 20 repetitions characterized by different rainfall realizations. Fig. 1 provides an illustration of the main elements and structure of the model.

1 The model is dynamic in the sense that it will be able to determine a dynamically optimal series of actions (controls) at every time in response to states prevailing then.

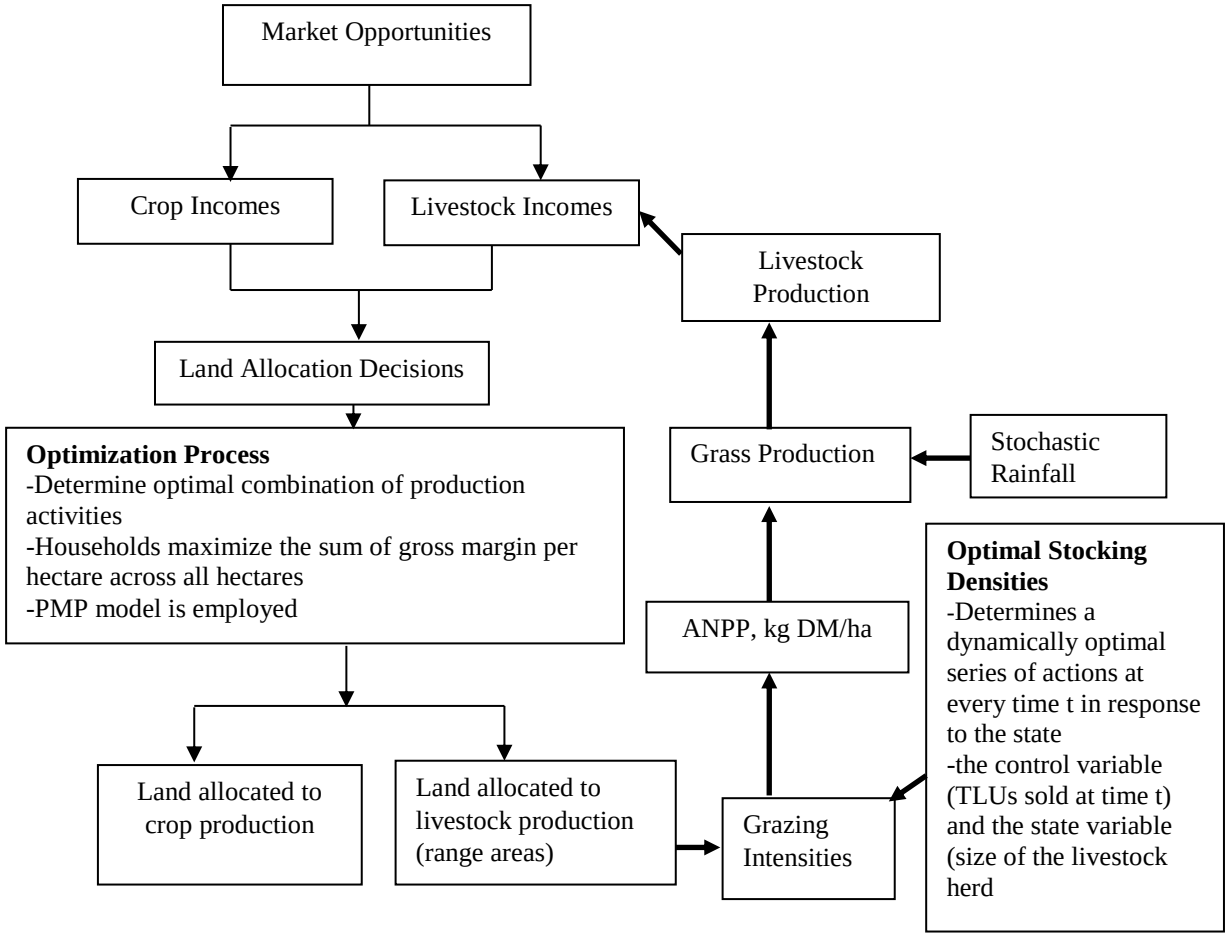

Figure 1: Main components of the ecological-economic rangeland model

Source: Adapted from Hein (2010) with modifications by the author

3.2 Optimization Problem

Households are assumed to maximize the sum of gross margin per hectare across all hectares subject to production constraints. In the study area context, there are five main possible production activities: four different crops (wheat, maize, beans, and potatoes) and grass, representing pasture areas. The optimal combination of production activities is solved using the PMP approach with a nonlinear land cost function 1(Mérel and Howitt, 2014; Howitt, 1995).

For $i =$ wheat, maize, beans, potatoes, and grass; the optimization problem is defined as:

$$Max \sum_i p_i y_i l_i - (\alpha_i + 0.5\gamma_i l_i) l_i - \sum_{j=2}^{n} w_j a_{ij} l_i$$

$$\text{s.t. } Ax \leq b \qquad (2)$$

1 Heterogeneous land quality results in the marginal cost per unit of output increasing as more land is converted to croplands.

where a_{ij} is a matrix of technical coefficients of resource requirements, l_i is the land allocated to the crop which yields y_i, α_i and γ_i are respectively the intercept and slope of the cost function per unit land, w_j is the cost per unit of the j^{th} input, A is a matrix with elements a_{ij}, and b is a vector of resource constraints. Land is the binding constraint for calibration. Observed data is used to calibrate the model to replicate initial land allocation conditions.

3.3 Crop production

The study adopts a constant elasticity of substitution (CES) production function for each crop. The production function allows for substitution between production inputs1. Constant returns to scale (CRS) regarding CES production function is assumed for Narok County. The parameters of the CES are solved following Howitt (2005). Crop yields are assumed to be fixed2 while the prices are exogenous. The output of crops is determined by the number of acres of land allocated to each crop.

3.4 Rangeland Productivity/Degradation Assessment

Prolonged grazing pressures, with loss of grazing areas, leads to poor protective cover of the soils. This increases the vulnerability of soils to degradation. Reduced vegetation cover coupled with intense animal tracks from trampling exposes the grazing areas to soil erosion, among other forms of degradation. Soil erosion leads to the loss of nutrient rich topsoil and exposure of vegetation roots, thus affecting the productivity of the soils. The above process informs the choice of the study's indicator of rangeland degradation/productivity as aboveground net primary production (ANPP).

ANPP, or its quotient to the corresponding precipitation, rainfall use efficiency (RUE), are two ecological parameters commonly used for assessing the rangeland ecosystem state (Le Houérou 1988; Hein, 2006; Hein and de Ridder, 2006; Hein and Weikard, 2008; Ruppert et al., 2012; Snyman and Fouché 1991). The principal ability of ANPP to assess an ecosystem's state (including degradation and desertification) has been widely confirmed (Bai and Dent, 2006; Sala et al., 1988; Snyman and Fouché, 1991; Prince et al., 1998; Diouf and Lambin, 2001; Holm et al., 2003; Buis et al., 2009; Ruppert et al., 2012).

1 With a lack of substitution elasticity available from existing studies and lack of data to estimate, the study fixes the CES value equal to 0.6 for all inputs. This allows for limited substitution between the production inputs as observed from farmer production practices.

2 The focus of the model is on health of grazing areas (represented by area covered by grass).

Studies on the relationship between grazing biomass and rainfall in ASALs in East Africa demonstrate biomass production to be a linear function of rainfall (De Leeuw and Nyambaka, 1988; De Leeuw et al., 1991). Sites used to measure the relationships were either protected or located in low grazing areas (De Leeuw and Nyambaka, 1988). To model biomass productivity, the study adopts from the work of De Leeuw et al. (1991) the linear relationship between median rainfall and annual aboveground net primary productivity (ANPP, kg DM/ha). The relationship is measured in a neighboring region with similar characteristics as the study area.

Following Hein (2010) and Hein and Weikard (2008), the model in this study is formulated to account for the feedback effects of grazing intensities on biomass production, where grazing limits biomass growth and the marginal reduction increases with high stocking rates (Hein and Weikard, 2008). The model also incorporates the effects of uncertain rainfall events on biomass production. In semi-arid areas, rainfall occurrence is primarily bimodal with two distinct rainy seasons: short rains (October to December) and the long rains (March to May) (Biamah, 2005). Four possible rainfall realizations for each season (very low, low, fair, and high) are considered. A time series of stochastic rainfall realizations is obtained from scenarios of possible combinations of short and long rains, together with the probability of their realization. Land users make decisions ex ante in view of the risks and encounter the 'realized' stochastic value of rainfall ex post (Domptail and Nuppenau, 2010).

3.5 Available Forage

Unlike the high-potential areas, pastures are the main source of livestock feed in ASALs. About 90% of the livestock diet in rangelands is composed of natural pastures1. Crop residues constitute negligible components of livestock feed, while fodder crops are hardly grown in the dry lands. Total available livestock forage in the model is formulated as being governed by biomass productivity by hectare (ANPP, kg DM/ha) and pasture/grazing area. A 'proper-use factor' forage allowance is made where the standard 50% (or "take half, leave half") rule of thumb in range management is employed. An adjustment factor for biomass share available for livestock use is also made as some of the biomass produced is consumed by other herbivorous animals among other uses.

3.6 Optimal Stocking Levels

Livestock producers' current decisions do have an effect on the long-term productivity of rangelands. Successful decisions should therefore constitute an optimal sequence of actions based on the level of state variables in each period. This is achieved by adopting the value

1 Statement made from field observations as well as calculations from the 2005/06 KNBS survey

iteration approach that solves the Bellman equation (Judd, 1999; Howitt 2005; Kobayashi et al., 2007). The livestock producer's problem is presented as follows:

$$\underset{c}{Max}\left[E_0\left\{\sum_{t=0}^{\infty}\beta f\left(c_t\right)\right\} \mid \mathrm{x}_{t+1} = \mathrm{x}_t - c_t + g(\mathrm{x}_t;\theta_t)\right] \tag{3}$$

where x_t is the state variable (the size of the livestock herd measured in Tropical Livestock Units) c_t is the control variable (TLUs sold at time t), $E_0\{.\}$ is the expectation operator, $f(.)$ is the current profit equation; β is the discount factor; $g(.)$ characterizes net livestock herd size expansion. It also constitutes the equation of motion1; and θ_t is the level of stochastic forage production2.

Equation (3) presents an infinite-horizon problem where livestock producers aim at maximizing the current and future profits. As stated earlier, current decisions do have an impact on the long-term productivity of the ecosystems. Optimal livestock producers would therefore consider the state of forage production in each time period when making decisions. A closed-loop system is therefore defined where feedback occurs from information obtained on the level of state variables in each time period (Kobayashi et al., 2007).

The livestock producer's problem is then presented using the Bellman equation as follows:

$$V(x_t;\theta_t) = \underset{c_t}{Max}\left\{f\left(c_t\right) + \beta E_{\theta_{t+1}}\left[V(x_{t+1};\theta_{t+1})\right]\right\} \tag{4}$$

where $V(.)$ is the value function and $E_{\theta_{t+1}}[.]$ represents the expectations formed on forage production in period $t+1$. The Bellman equation expresses the value function as a combination of a current payoff and a discounted continuation payoff. The forward solution of the equation is such that the sum of the maximized current payoff and the discounted or carry-over value maximize the total value function (Howitt 2005).

The livestock sale control is represented as follows:

$$c_t = x_t + g\left\{x_t;\tilde{\theta}_t\right\} - x_{t+1} \tag{5}$$

where $\tilde{\theta}_t$ is the realized forage production.

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1 We can logically assume that $g(.)$ is concave in x i.e. $g'_x > 0$, $g''_x < 0$

2 Because future rainfall events are unknown, the model incorporates uncertainty with the help of probability distribution.

Using equation (5), the control variable (C_t) can be expressed in terms of the optimal herd size in the next period (x_{t+1}) (Kobayashi et al., 2007). Equation (4) can then be rewritten as:

$$V\left(x_t;\tilde{\theta}_t\right) = \underset{x_{t+1}}{Max}\left\{ f(x_t + g(x_t;\tilde{\theta}_t) - x_{t+1}) + \beta E_{\theta_{t+1}}\left[V(x_{t+1};\theta_{t+1})\right]\right\} \tag{6}$$

Rewriting equation (6) using $\Phi(.)$ and substituting the next period's value function gives:

$$V\left(x_t;\tilde{\theta}_t\right) = \underset{x_{t+1}}{Max}\left\{\Phi(x_t, x_{t+1};\tilde{\theta}_t) + \beta E_{\theta_{t+1}}\left[\underset{x_{t+2}}{Max}\{\Phi(x_{t+1}, x_{t+2};\theta_{t+1}) + \beta E_{\theta_{t+1}}\left(V(x_{t+2};\theta_{t+2})\right)\}\right]\right\} \tag{7}$$

The first order condition of equation (7) (w.r.t. x_{t+1} in time t) gives us the Euler condition:

$$-\frac{\partial\Phi(x_t, x_{t+1};\tilde{\theta}_t)}{\partial x_{t+1}} = \beta\left[\frac{\partial\Phi(x_{t+1}, x_{t+2};\theta_{t+1})}{\partial x_{t+1}}\right] \tag{8}$$

Equation (8) defines the condition for intertemporal optimality (Kobayashi et al., 2007). The left-hand side gives the marginal cost, where the marginal cost is measured by potential marginal payoffs foregone in period t, while the right-hand side gives the discounted marginal payoffs in period $t+1$.

Following Judd (1999), Howitt (2005) and Kobayashi, et al. (2007), the study employs a Chebychev Polynomial to obtain a continuous approximation to the value function. The approximation is given as:

$$V(x) \approx \hat{V}(x) = \sum_{j=1}^{n} \alpha_j \phi_j\left(\hat{x}\right) \tag{9}$$

Where α_j is the coefficient of the j^{th} polynomial term $\phi_j(.)$ and $\hat{x}$ is the state variable mapped onto [–1, 1] interval on which Chebychev polynomial functions are defined.

3.7 Herd Dynamics

Following Hein (2010), to model livestock dynamics, the livestock herd is assumed to follow a logistic growth process:

$$\Delta x_t = LAM * (1 - (x_t / MTLU_t)) * x_t \tag{10}$$

where x_t are the tropical livestock units (TLU) 1 in the current period, Δx_t is the change in TLU, LAM captures the potential natural growth in livestock, and $MTLU_t$ is the maximum grazing capacity of the grazing areas.

Livestock in the next period (x_{t+1}) are determined by the livestock growth process defined in Eq. (4.10) above and the number of sales (c_t) as shown below:

$$x_{t+1} = x_t + (LAM * (1 - (x_t / MTLU_t)) * x_t) - c_t \quad (11)$$

Livestock sales are considered to be the key source of livestock production revenue in the grazing areas. The prices/costs incorporated in the model are assumed to be deterministic. The detailed model is presented in the appendices (see Appendices A-C).

1 1 TLU = 1.43 cattle or 10 sheep or goats

4 Results

4.1 Base Specification

A brief summary of the survey data observations and results are presented in Table 1. The base land allocations in Narok County between the four major crops grown and range areas (grass) are illustrated in Table 1, column 1. Using the PMP model, we are able to replicate the land allocations as observed on ground as shown in Table 1, column 2. While the majority of the land appears to be grazing/pasture areas, most fertile former rangelands have been converted to cropping farming leading to undesirable effects on the remaining rangelands especially in the dry periods (Osano et al., 2012; Mundia and Murayama 2009; Homewood et al, 2001; Serneels and Lambin, 2001).

Table 1: Survey data and model results

	Survey (data 2005–2006)	**Modeled results**			
	Initial observations (Average Sample)	**Model Validation**	**Base Scenario**	**Scenario 1**	**Scenario 2**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Land Allocations '000'Ha:					
Wheat	82.75	82.75	82.75	77.39	76.45
Maize	316.44	316.44	316.44	297.23	293.86
Beans	94.41	94.41	94.41	-	-
Potatoes	30.30	30.30	30.30	14.68	11.94
Grass(Range areas)	974.43	974.43	974.43	1,109.04	1,116.08
Average Margin (KSH. per TLU)	10,526.23		10,526.23	15,461.98	16,110.40
Average herd size (TLU, '000')*	610.0		583.01	531.87	535.15
Stocking density (TLU/ha)*	0.63		0.60	0.480	0.479
Optimal stocking densities*			0.467	0.447	0.449
Optimal stocking levels*			455.5	495.8	502.0
Average sales volume (TLU'000')*	78.56		80.08	115.60	116.17
Average net returns over variable costs per ha:	KSH. per ha				
Wheat	27,175.98				
Maize	28,749.02				
Beans	4,906.84				
Potatoes	6,631.80				

*For modeled results: Results are an average of 20 repetitions per scenario characterized by different rainfall realizations

For Survey data: Source: KIHBS 2005/06 survey data

Average exchange rate: 1 USD ≈ 75 KES[1]

1 Source: https://www.centralbank.go.ke/index.php/rate-and-statistics/exchange-rates-2?

In the base scenario, at the existing market conditions, the modeled stocking density, average herd size, and average sales volume are similar to the observations on the ground from the sample data (Table 1 column 3). The consistency of the results of the base model with sample observations suggests that the model accurately depicts the conditions on the ground.

A plot of net primary productivity against the median rainfall from our baseline information reveals an almost one to one relationship between ANPP and rainfall (Fig. 2).

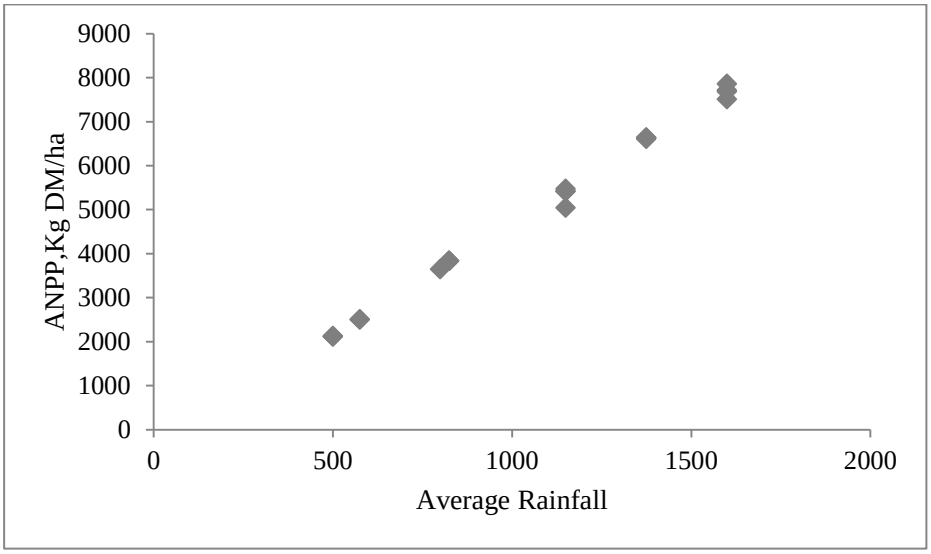

Figure 2: Relationship between ANPP, kg DM/ha and rainfall

However, ANPP, kg DM/ha is also affected by grazing intensity, as shown in Fig. 3.

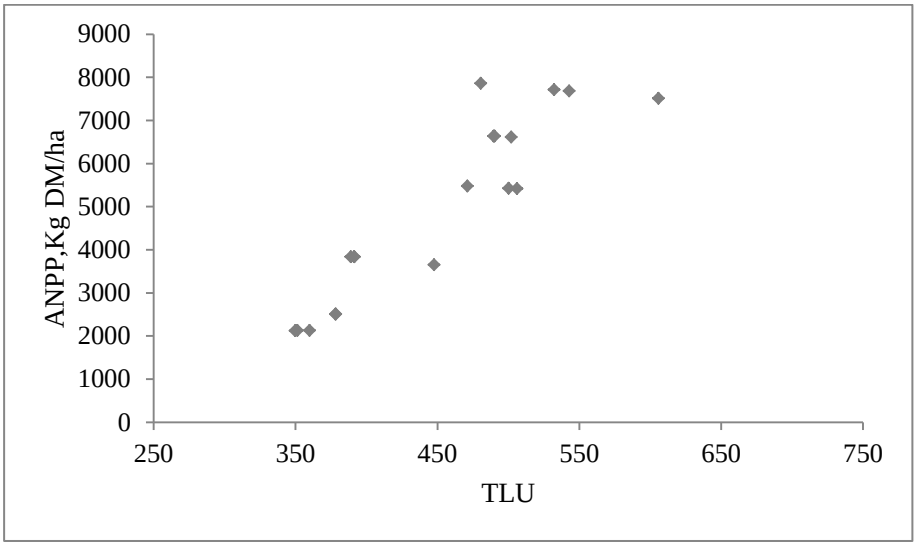

Figure 3: Relationship between ANPP, kg DM/ha, and TLU in the baseline scenario

Grazing pressures beyond the ecologically sustainable level leads to the declining productivity of land. This is shown by the decline in ANPP, kg DM/ha, with increasing flock

sizes beyond a certain level. The turning point of the relationship between ANPP, kg DM/ha, and herd size gives us the optimal stocking density, beyond which increasing grazing intensities will have a negative effect on the ecosystems. At the base level, the optimal herd size of 455.5 TLU yields an optimal stocking rate of 0.47 TLU/ha, which is significantly below the observed current stocking rates of 0.63 TLU/ha and the modeled 0.60 TLU/ha (Table 1). The results indicate that the current grazing-livestock population exceeds the total grazing capacity in the area.

4.2 Re-apportioning value-added in the livestock marketing chain: Incorporating livestock producers directly into the value-addition chain and linking them to existing terminal livestock: Scenario 1

The detailed study on livestock market value chains in the country by Muthee (2006) is used to estimate changes in producers' benefits from incorporating livestock producers directly into the value-addition chain and linking them with the buyers at the terminal market. The above concept has been employed, on a small scale, by organizations such as CARE Kenya[1], thus ensuring its practicability. The approach involves establishing a market-based intervention whereby the pastoralists are organized into producer associations and enabled to participate in the value-addition chain (fattening of animals before sale) and linked to the livestock terminal markets (McKague et al., 2009; Muthee, 2006). Strengthening vertical linkages between fattening camps and livestock producers improves the live weight of livestock, enabling the producers to receive better margins, unlike in cases in which livestock is sold to middle men at the primary markets. On the other hand, linking livestock producers to existing terminal markets would minimize the exploitation by middlemen and further improve the livestock producers' margins.

The purpose of organizing producers into groups is to improve cooperation among pastoralists, reduce transport costs and consolidate supply, and improve the collective bargaining power of the livestock producers (McKague et al., 2009). As in the case of CARE Kenya, existing producer associations, such as water users associations commonly found in pastoral and agro-pastoral areas, can be used as a basis of these producer-marketing groups. The use of existing groups limits the transaction costs of forming new associations. From the above, this study is based on the assumption that there are existing producer associations which would act as the basis of the above market base intervention. Hence, no transaction costs associated with forming new associations are incurred.

This market-based intervention also requires the help of a value chain actor/market facilitator, whereby the role can be played by either the government, or, as in the case of

1 A non-governmental organization involved in creating market linkages to livestock farmers by enabling them to become involved in the value chain itself charging a small fee for operational costs

CARE Kenya, by an NGO. The work of the value chain actor is just to provide support, meaning they are not involved in buying or selling but mainly assist in removing obstacles that limit livestock producers from participating in the terminal markets (McKague et al., 2009). The related costs of the intervention, such as the transport costs to the terminal markets and the costs of facilitating contracts at the terminal markets, fattening fees at fattening camps, among other costs, are provided in detail in the study by Muthee (2006) (Table 2). It is on the basis of the existing work on livestock market value chains and market facilitation processes that the study evaluated the effects of re-apportioning value-added in the livestock marketing chain.

Table 2: Value chain facilitation

Margins in Marketing Immatures/Head	**KSH**
Buying Price (Price received by livestock producers from middlemen)	6,500
Marketing Costs	2,220
Terminal Market Facilitation Fee (5 percent of Selling price[1])	906.25
Total Costs	9,626.25
Selling Price	18,125
Margin (Excesses that are extorted by middlemen)	8498.75
Margin as a Percent of Selling Price	0.4689
Breakdown of Marketing Costs	
Broker Fees	100
Trader Costs	65
Loading	30
Branding	5
County Fee	40
Permits	100
Veterinary Costs	100
Transport	850
Loader	20
Fattening Fee	480
Herder Fee	60
Transport to Slaughter	120
Trader Costs	150
Boma Fee/others	100

Source: Values from Muthee (2006)
Average exchange rate: 1 USD ≈75 KES[2]

1 Additional costs that producers would incur if directly linked to terminal markets (logistical support and facilitation expenses)
2 Source: https://www.centralbank.go.ke/index.php/rate-and-statistics/exchange-rates-2?

Linking livestock producers to the end market and involving them in the livestock value addition is estimated to increase the producers' margin by 46.89% (Table 2). With the increased benefits associated with livestock production, land allocation moves in favor of livestock production (grass). Higher producer margins lead to land allocated for livestock production increasing from 974,431ha to 1,109,041ha, confirming that land allocations are driven by the benefits the land users expect to derive from the land (Table 1, column 4). The reallocated land is crucial as it represents the regaining part of former fertile rangelands. Higher allocation of land for grazing purposes is likely to facilitate livestock mobility and access to wider pasture areas. We further evaluate the effect of increased land allocation to land management and livelihoods (Fig 4).

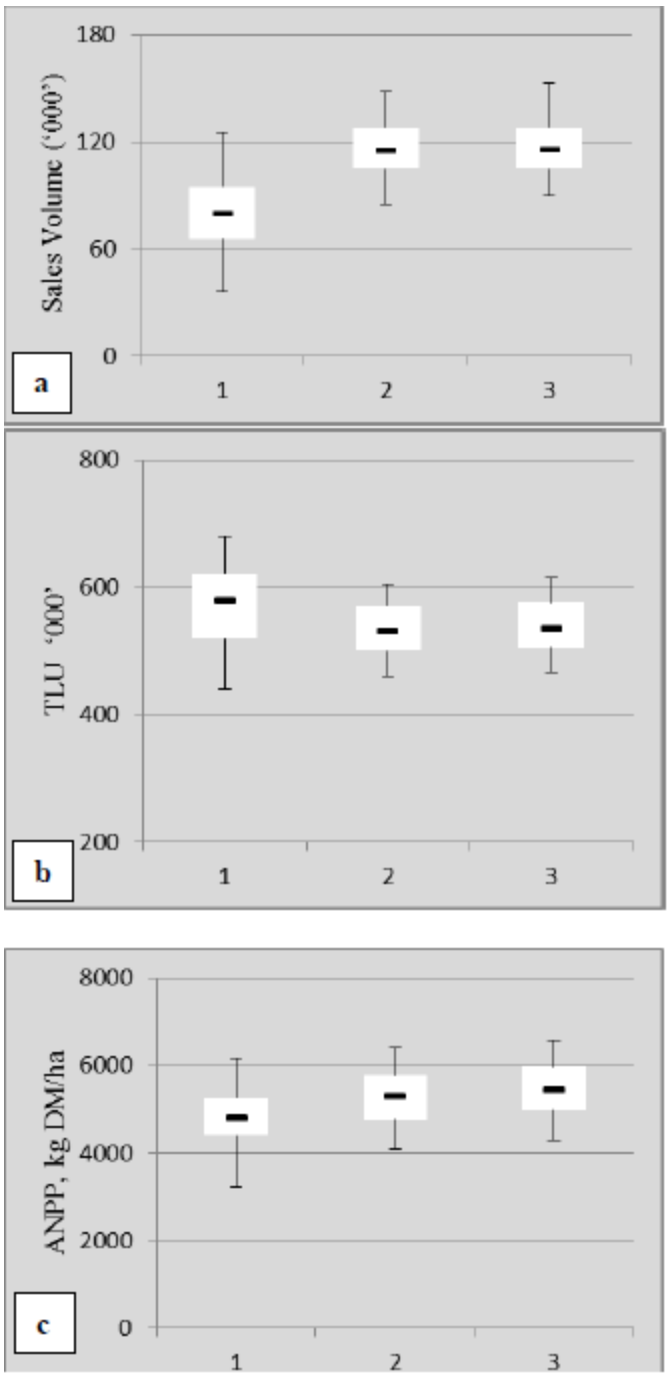

Figure 4: Plots of model output results. The results are an average of 20 repetitions per scenario characterized by different rainfall realizations. Legend: 1=Baseline Scenario; 2=Scenario1; 3=Scenario 2.

With the re-apportioning of value addition and links to terminal markets, we observe the increased livestock sales levels compared to the base average sales level (Table 1, column 4 and Fig. 4, a). With livestock sales as the control variable in the dynamic livestock model, increased livestock sales indicate that livestock producers are able to utilize markets more in taking action (livestock sales) in every time period in response to the state of the rangelands. This leads to better management of land as productivity increases and is less variable compared to the base scenario (Fig. 4, c). In addition, compared to the optimal stocking density of 0.45 TLU/ha1 in Scenario 1, the stocking density of 0.48 TLU/ha indicates better management of land, given its close proximity to the optimal level and also compared to the Base Scenario stocking density of 0.60 TLU/ha (Table 1, column 4).

1 Obtained at the turning point of the relationship between ANPP, kg DM/ha and herd size as shown in Fig. 3

Given the higher off-take levels, as expected, the herd size in Scenario 1 is lower compared to that of the base scenario (Table 1, column 4 and Fig. 4, b). While this might not look appealing at first sight; Scenario 1 presents a better strategy, as it involves fewer variations in herd sizes. With livestock as important assets for pastoralists, Scenario 1 presents more stable wealth levels for the livestock producers (Fig. 4, b). In addition, fewer variations in livestock levels indicate that the producers are less likely to face drastic reductions in livestock compared to the base scenario. The live weight of livestock is also expected to be better in Scenario 1, given the higher productivity levels compared to the base scenario.

4.3 Efficient livestock transportation means: Efficient livestock transportation means in addition to re-apportioning value-added in the livestock marketing chain: Scenario 2

Similarly to the value addition and terminal market scenario, all the transports costs (trucking of livestock) were obtained from the detailed livestock market study by Muthee (2006). Transport costs constitute a large share of livestock marketing costs in the country, going as high as 65% of the total marketing costs in some parts of the country (Muthee, 2006). In Narok, trucking/trekking costs constitute about 40% of the total marketing cost (Muthee, 2006). Trucking vehicles are normally hired and the associated costs charged per livestock head (transport, loading, and off-loading). With the aim of mitigating the high transportation costs, the study evaluates the effects of adopting efficient transportation means at the prevailing road infrastructure conditions. The use of a double-decker trailer as a transport means is assessed as a possible means of reducing transportation costs. A standard double-decker transporter has the capacity to carry 26 cattle and 70 shoats (Muthee, 2006). We assess the benefits/savings made by transporting shoats alongside cattle in a double-decker cabin versus transporting the shoats separately (see table in Appendix B).

Use of a double-decker truck increases the producers' margin further by 6.16%, leading to land allocations as shown in Table 1. Higher producer margins have the potential of increasing land allocated to pastures to 1,116,076 ha (Table 1).

Similar to Scenario 1, the higher producer margins with the use of a double-decker truck are associated with higher livestock sales levels compared to the base average sales level (Table 1, column 5 and Fig. 4, a). This indicates the use of efficient transport not only facilitates movement of livestock to the terminal markets but also that producers are able to save on transportation costs. As highlighted earlier, increased sales levels indicate the ability of livestock producers to utilize livestock markets more in taking action (livestock sales) in response to the state of the rangelands. With higher ability to take action in response to the state of the land, productivity of the rangelands increases and is less variable compared to

the base scenario and Scenario 1 (Fig. 4, c). Similar to Scenario 1, the optimal stocking density in Scenario 2 is given as 0.45 TLU/ha1. The stocking density of 0.475 TLU/ha indicates better management of land compared to the Base Scenario and Scenario 1 (Table 1, column 5)

Increased participation in livestock markets leads to lower livestock levels in Scenario 2 compared to the Base Scenario but higher compared to Scenario 1 due to more land allocations for grazing purposes (Table 1, column 5, and Fig. 4, b). Scenario 2 is also associated with higher and more stable wealth levels compared to Scenario 1 and the base level. This is from the higher herd sizes compared to Scenario 1 and stable livestock levels compared to the Base Scenario (Fig. 4, b).

1 Obtained at the turning point of the relationship between ANPP, kg DM/ha and herd size as shown in Fig. 3

5 Discussion and policy Implications

Competing land use options in rangelands are likely to lead to the conversion of grazing vegetation to other land uses/land covers with subsequent consequences on the health of the ecosystems. The increasing practice of crop cultivation on the rangelands is identified as a serious threat to future livestock production and rangeland management (Solomon et al., 2007). Expansion of crop farming curtails the traditional adaptive strategies of pastoralists and limits the mobility of livestock and access to key resources in particular during dry seasons (Butt, 2010). This leads to concentrated livestock densities above optimal levels on the rest of the rangeland, as shown in the initial observations (Table 1). The key consequence of rangeland losses is restricted access and mobility of livestock (Flintan, 2011), leading to high livestock densities and unsustainable production on the rest of the rangeland. This is demonstrated by the effect of large herd sizes on the productivity of rangeland (ANPP,Kg DM/ha) beyond the optimal level (Fig. 4, c).

Indeed, while crop farming may provide an alternative to pastoralism, especially in the wetter semi-arid areas, the associated costs, in the mid- to long term, appear too great to bear (Davies and Bennett, 2007). With lower productivity of the grazing areas (ANPP, kg DM/ha) and high livestock densities (0.6 TLU/ha), communal pastoralists become more vulnerable to the ecological climate variability of rangelands resulting in larger livelihood impacts (Fig. 4, b). This is in line with observations of Banks (2003), stating that the opportunity costs of disrupting the traditional operations of rangelands are overlooked, while the benefits may be overstated. Among the overlooked costs are the effects of rangeland use changes on biological diversity and the ability of biological systems to support human needs (Maitima et al., 2009). The effect of the loss of rangelands on the sustainability of the ecosystems is further exacerbated by low take-off rates of livestock. Well-established markets could greatly facilitate the movement of livestock from areas of forage scarcity, thereby regulating livestock densities and minimizing the ecological vulnerabilities of the dry lands (Turner and Williams 2002).

To understand the driving forces of the observed transformations in rangelands, emerging now is the acknowledgement of the presence and interaction of both equilibrium and non-equilibrium factors in the dynamics and the paths of rangeland degradation (Vetter, 2005; Domptail, 2011). Responses to emerging economic opportunities, facilitated by institutional factors, are driving the observed rangeland uses (Lambin et al., 2001). Rangeland users in the region, as with other developing countries, no longer live outside the cash economy (Davies and Bennett, 2007). Expected economic gains have been observed to influence their land use decisions. This is shown by the land allocation decisions in response to changes in returns realized from the current land uses. For instance, Table 1 shows how land allocations to various land uses differ from the base land allocations in response to the increased benefits associated with livestock production. The reverse, as has been the case, can also

occur as shown by Tiffen et al. (1994), where expansion of the area under cultivation occurs in a semi-arid area with increased crops marketing opportunities and a decrease in livestock prices.

In their study, Tiffen et al. (1994) show that the progress of rural farmers can be facilitated by raising producers' prices through transport improvements and minimization of marketing costs. However, livestock markets function poorly with high marketing costs and high reliance on itinerant traders with whom they often have poor bargaining power to sell stock; this finding corroborates with that of McDermott et al. (2010), Makokha et al. (2013), and Muthee, (2006). The inefficiencies characterizing the livestock markets affect the benefits that livestock producers receive and drive rangeland use changes where opportunities prevail.

In addition to sustaining livelihoods, improved livestock marketing may have significant opportunities for improving environmental management (Frost et al., 2007). Ecological research shows that, with erratic rainfall characterizing rangelands in ASALs, the design of marketing systems should be such that they absorb fluctuations in marketed livestock. Among the components of such marketing systems identified is access to the largest markets and improved transport infrastructure (Behnke, and Kerven, 1994). Similar to Turner and Williams (2002), we found that livestock markets are capable of facilitating the destocking of animals leading to better productivity of land (Table 1; Fig. 4). Improving market access through the creation of opportunities for pastoralists to sell livestock more profitably and lower transportation costs increases the benefits associated with rangelands, leading to higher land allocations to grazing purposes (Table 1). Our analysis concurs with previous empirical work by Barrett and Luseno (2004), highlighting the main factors affecting livestock producers' earnings in the country as transportation costs and lack of competition within the marketing channel which create an unattractive marketing environment for pastoralists. Price fluctuations in the terminal market provide little empirical justification to worry about (Barrett and Luseno, 2004). Improved earnings associated with range areas are also observed to stabilize wealth of households (Fig. 4 c). This is expected to have direct positive effects on the livelihoods of rural rangeland users and less vulnerability to the variable ecological climate characterizing ASALs.

Currently, the existing national policy for the sustainable development on ASALs, titled, "Releasing our full potential," entails a key number of objectives aimed at achieving the sustainable use of rangelands while improving livelihoods. Among the elements include 1) the development of an enabling environment for accelerated investment in foundations to reduce poverty and build resilience and growth; 2) a responsive government to the uniqueness of arid lands which include ecology, mobility, population distribution, economy, and social systems; and 3) climatic resilience (GOK, 2012a). Our findings could prove useful if brought into play by Kenyan ASALs policy planners. The findings suggest that policy measures to attain the stated objectives should include efforts to minimize barriers limiting

livestock producers' participation in value-added livestock production and access to high-value markets such as terminal markets. This can be achieved, as illustrated in the study, by minimizing/eliminating the price market disincentives currently characterizing rangelands. Second, community participatory approaches, such as producer groups, could be used as market-based interventions for livestock producers. Policy action promoting collective action at the grass-roots levels is therefore likely to have positive effects not only on improving livelihoods but also on the sustainable management of rangelands.

The study acknowledges that additional policies should go hand in hand with efforts to make livestock markets serve as mechanisms of destocking livestock, especially during periods of low biomass production as well as promote sustainable rangeland management. Although pastoralists have been shown to be generally open minded, capable of producing livestock optimally (Kimani and Pickard, 1998; Mwangi and Meinzen-Dick, 2009), and in great need for stronger links to the outside world, such as with improved livestock market access (Coppock, 1994), more incentives may be required for active participation in markets and sustainable rangeland management practices. An existing initiative that would complement the improved access to livestock markets would be the expansion of the index-based livestock insurance (IBLI). Insurance of livestock would be a critical concept encouraging livestock producers to participate in livestock markets. Insurance would enable the producers to stabilize their livestock accumulation, making them less likely to face drastic reductions in livestock, with increased offtake levels, in the event of a shock from the risky climatic conditions characterizing range areas. In addition, improved access to livestock markets coupled with IBLI is likely to lead to crowding in of finance to provide the much-needed credit for the economic development of the rangelands.

In addition, the livestock production associations can further be used to foster cooperation among pastoralists, for example, with regard to how much of the grazing areas should be unaltered and also on livestock production strategies, such as stocking levels. Such cooperation among pastoralists currently exists, as observed in the case of conservancies, where land use regulations have contributed to numerous ecosystem benefits (Osano et al., 2013). Producer associations therefore present a viable option to foster sustainable management practices in semi-arid grazing lands as a complement to market-based interventions. Further research work may address other possible synergies between improved livestock incomes and sustainable rangeland management.

6 Conclusions

Livestock production plays a key role in the economic development and welfare of the county. In spite of their significant role, rangelands in the country are being impaired by factors related to LULCC. Among the key factors driving conversion of rangelands to other land use/land covers are the changing opportunities brought about by markets. This study explores the linkages between improved livestock market access, rangeland use change, and livestock producers' livelihoods in the semi-arid Narok County of Kenya. In an effort to realize potential economic benefits with rising domestic and export markets for crops, fertile rangelands are observed to be increasingly converted to crop farming in the country. Among the resulting consequences of the declining range areas are degradation of rangeland ecosystems leading to negative effects on the social and economic security of the remaining livestock producers.

This study shows that improved livestock market access affects the economic returns of producers, which in turn affects rangeland management decisions. Improved market access in the study is sought through the creation of opportunities for pastoralists to sell livestock more profitably by re-apportioning value-added in the livestock marketing chain, linking them with terminal markets and through reduced livestock transportation marketing costs. Livestock producers' margins improve with re-apportioning value-added and reduced livestock marketing costs. Increased benefits associated with livestock production, on the other hand, lead to fewer conversions of former rangelands to crop farming, stabilizes herd levels, and increases market participation among livestock producers. The livelihood of livestock producers improves with better earnings and stabilized assets levels. In addition, livestock producers' vulnerability to ecological climate variability characterizing rangelands is reduced with better productivity of the ecosystems. From the study findings, national policy on improved livelihoods of pastoral communities should therefore entail efforts to include pastoralists in value-added livestock production and also access to high-value markets.

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Appendices

Appendix A: Parameters used to calibrate the biomass production equation

Parameter	Description	Value	Source
β	Biomass production slope	7.5	De Leeuw et al. (1991)
α	Biomass production intercept	-1000	De Leeuw et al. (1991)
LAM	Herd growth rate (logistic function)	0.6	Estimated using KIHBS 2005/06 data set
PH	Feed required for the maintenance of a TLU(kg DM/TLU per year)	6.25 kg of forage dry matter daily	De Leeuw et al. (1991)
BINS	'Proper-use factor' forage allowance	0.5	Sedivec (1992) ; Gerrish and Morrow (1999)
BOSH	Share of biomass available for livestock after other users/uses have received their share (e.g. feed for other herbivores and non-feed uses such as thatching) (Domptail and Nuppenau, 2010).	0.7	
INTERCEPT	Livestock demand function intercept	201,312.24	Estimated using parameters from Karugia et al. (2009) and Mose et al. (2012).
SLOPE	Livestock demand function slope	0.12	

Appendix B: Adoption of efficient transport system: Double decker truck

Costs Margins in Marketing		With Double Cabin	Without Double Cabin
Selling Price: (Price at the terminal market)			
	Goat	2,067.00	2,067.00
	Sheep	1,933.00	1,933.00
Total Costs			
	Goat	1,818.00	1,941.00
	Sheep	1,652.00	1,775.00
Margin			
	Goat	249	126
	Sheep	281	158
Increase in margin as a percent of Selling Price			
	Goat	5.95	
	Sheep	6.36	
Average increase in margin as a percent of Selling Price per Shoat (Average of Sheep and Goat)		6.16	
Breakdown of Marketing Costs of shoats			
Production costs:			
	Goat	1850	1850
	Sheep	1650	1650
Broker Fees@		50	50
Trader Costs@		55	55
Loading@		5	5
Branding@		10	10
County Fee@		20	20
Permits@		50	50
Transport@		**7**	**130**
Off-loading@		5	5
Boma Fee@		40	40
Others@		10	10

Source: Values from Muthee (2006).

*Table presents the savings made by transporting shoats together with livestock by use of a double decker truck

Average exchange rate: 1 USD ≈ 75 KES[1]

1 Source: https://www.centralbank.go.ke/index.php/rate-and-statistics/exchange-rates-2?

Appendix C: Detailed lists of sets, parameters, scalars, variables, and equations in the model.

PMP MODEL

SETS

I	PRODUCTION PROCESSES
II(I)	INTENSIVE PRODUCTION
J	RESOURCE SUB SET
R(J)	LAND INPUT
P(J)	CROP RESOURCE SUB SET
ITEMS	ITEMS INCORPORATED IN THE SIMULATION
ALIAS (J,L)	

PARAMETERS

PRI(I)	CROP PRICES (KSH PER KG)
Y(I)	CROP YIELD (KG PER HECTARE)
TABLE C(I,J)	COST (KSH PER UNIT) OF FIXED PRODUCTION FACTORS
TABLE A(I,J)	A MATRIX OF TECHNICAL COEFFICIENTS/ QUANTITY OF INPUTS (J) THAT TRANSLATE INTO PHYSICAL OUTPUT PER HECTARE
XBASE(I)	BASE/INITIAL LAND ALLOCATIONS
B(J)	RESOURCE CONSTRAINTS
XB(I,J)	TOTAL BASE QUANTITY OF RESOURCES USED
	XB(I,J) = A(I,J) * XBASE(I) ;
REV(I)	REVENUE
	REV(I) = PRI(I)* Y(I) ;
CSL(I)	LINEAR COST:
	CSL(I) = SUM(J, C(I,J)*A(I,J));
NET(I)	NET RETURN:
	NET(I) = REV(I)- CSL(I);
PERDIFF1(I)	DIFFERENCE BETWEEN LINEAR PROGRAM LAND USE AND BASELINE OBSERVATIONS
	PERDIFF1(I)$XB(I,"LAND") = ((LX.L(I)- XB(I,"LAND"))*100)/ XB(I,"LAND") ;
SUB	ELASTICITY OF SUBSTITUTION
ADJ	ADJUSTMENT FOR MARGINAL CROPS
	ADJ = RESOURCE.M("LAND") * ADJFACT;
OPP(J)	OPPORTUNITY COST OF LAND
	OPP(J)= RESOURCE.M(J) ;
	OPP("LAND")= RESOURCE.M("LAND") - ADJ;
LAM(I,J)	PMP DUAL VALUE ON LAND
	LAM(I,"LAND") = CALIB.M(I) + ADJ ;
TOT(I)	TOTAL OUTPUT
	TOT(I) = Y(I)*XB(I,"LAND") ;
CST(I,J)	COST OF FIXED PRODUCTION FACTORS PLUS OPPORTUNITYCOST
	CST(I,J) = C(I,J) + OPP(J) + LAM(I,J) ;
ETA(I)	FUNCTION OF ELASTICITY OF SUBSTITUTION

```
                    ETA(I) = (SUB - 1)/SUB ;
THETA               MINUS ONE OVER ELASTICITY OF SUBSTITUTION
                    THETA = -(1/SUB) ;
BETA(I,J)           SHARE PARAMETERS
                    BETA(II,J)$(SW(J) EQ 1) = 1/( SUM(P, (CST(II,P)/CST(II,J)) *
                    ( XB(II,J)/XB(II,P))**THETA ) + 1 ) ;
                    BETA(II,J)$(SW(J) EQ 2) = 1 - SUM(L$(SW(L) NE 2), BETA(II,L) ) ;
                    BETA(II,J)$(SW(J) EQ 0) = SUM(R,BETA(II,R))*(CST(II,J)/ SUM(R,CST(II,R)))*
                    (SUM(R, XB(II,R))/XB(II,J))**THETA ;
CN(I)               SCALE PARAMETER
                    CN(II) = TOT(II) / (SUM(J, BETA(II,J)*
                    ((XB(II,J)+0.0001)**((SUB-1)/SUB )))** (SUB/(SUB-1))) ;
NI(J)               RESOURCE COUNTER
                    NI(J) = ORD(J);
MARPRO2(I,J)        MARGINAL PRODUCT
                    MARPRO2(II,J) = BETA(II,J)*(CN(II)**ETA(II))* (TOT(II)/XB(II,J))**(1/SUB) ;
VMP2(I,J)           VALUE MARGINAL PRODUCT
                    VMP2(II,J) = MARPRO2(II,J)* PRI(II) ;
ALPH(I)             COST INTERCEPT
                    ALPH(I) = C(I,"LAND") - LAM(I,"LAND")
GAM(I)              COST SLOPE
                    GAM(I)$(LAM(I,"LAND") NE 0 ) = (2* LAM(I,"LAND"))
                    /XBASE(I)
PMPTEST(I)          TEST VALUE FROM PMP
                    PMPTEST(I) = ALPH(I)+ GAM(I)*XBASE(I) ;

PMPDIFF(I)          PERCENT DEVIATION IN PMP
                    PMPDIFF(I)$LAM(I,"LAND") = (( PMPTEST(I)- LAM(I,"LAND"))*100)/
                    LAM(I,"LAND")

VMPDIFF(II,J)       VALUE MARGINAL PRODUCT CHECK
                    VMPDIFF(II,J)$CST(II,J) = (( VMP2(II,J)- CST(II,J))*100)/ CST(II,J);
PERDIF2(I,J)        PERCENT DIFFERENCE BETWEEN CALIBRATED NON-LINEAR MODEL INPUT
                    ALLOCATION AND OBSERVED BASE INPUT ALLOCATION
                     PERDIF2(I,J)$XB(I,J) = (XC.L(I,J) - XB(I,J)) * 100 / XB(I,J) ;
```

SCALAR

EPSILON	ROUNDING ERROR ALLOWABLE IN THE RESOURCE AND CALIBRATION CONSTRAINTS
ADJFACT	ADJUSTMENT FACTOR FOR MARGINAL CROPS
NJ	NUMBER OF INPUTS
	NJ = SMAX(J, NI(J)) ;

VARIABLES:

VARIABLES USED IN THE PMP CALIBRATION PROCESS

LX(I)	LAND ALLOCATED IN THE LINEAR PROGRAM
LINPROF	LINEAR PROGRAM PROFIT

VARIABLES USED IN THE CALIBRATED MODEL

XC(I,J)	RESOURCE ALLOCATION
TPROFIT	NON-LINEAR TOTAL PROFIT FUNCTION (CALIBRATED);

EQUATIONS:

CONSTRAINED RESOURCES

RESOURCE(J).. SUM(I,A(I,J)*LX(I)) =L= B(J) ;

UPPER CALIBRATION CONSTRAINTS

CALIB(I)… LX(I) =L= XB(I,"LAND") * (1+EPSILON) ;

LINEAR PROGRAM OBJECTIVE FUNCTION

LPROFIT... SUM((I), LX(I)*(PRI(I)* Y(I)- SUM(J, C(I,J)*A(I,J)))) =E= LINPROF;

CALIBRATED MODEL RESOURCE CONSTRAINTS

INPUT(J)… SUM(I, XC(I,J)) =L= B(J);

NON-LINEAR PROFIT FUNCTION IN THE CALIBRATED MODEL

NONLINPROFIT… TPROFIT =E= SUM((II), PRI(II) * (CN(II)* (SUM(J, BETA(II,J)* ((XC(II,J) +0.0001)**((SUB-1)/SUB)))** (SUB/(SUB-1)))))+ XC("GRASS","LAND") *(Y("GRASS")*V("GRASS"))-SUM(I, ALPH(I) *XC(I,"LAND") + 0.5* GAM(I) * SQR(XC(I,"LAND"))) - SUM((I,P), C(I,P)*XC(I,P)) ;

RANGE PRODUCTION

SETS

T	YEARS
P	PRECIPITATION LEVELS
K	TIME PERIODS
W	RAINY SEASONS
BASET(K)	FIRST PERIOD

ROOT(N)	THE ROOT NODE
KW(K,W)	RELATING TIME PERIODS TO RAINY SEASONS
N	NODES: DECISION POINTS OR STATES IN SCENARIO TREE
KN(K,N)	MAP NODES TO TIME PERIODS
ANC(CHILD,PARENT)	ANCESTOR MAPPING
NP(N,P)	MAPS NODES TO PRECIPITATION LEVEL
LEAF(N)	
ITER	MAX NUMBER OF ITERATIONS
I	NODES AT WHICH VALUE FUNCTION IS EVALUATED
ALIAS	(N,PARENT,CHILD)
ALIAS	(I,J)

TABLE

RAINFALL(W,P)	RAINFALL AMOUNT FOR EACH SEASON

PARAMETERS

PR(P)	PROBABILITY DISTRIBUTION OVER RAINFALL LEVELS
NPROB(N)	PROBABILITY OF BEING AT ANY NODE
NDELTA(N)	RAINFALL AT EACH NODE
R(T)	RAINFALL SCENARIOS (AMOUNTS AT THE NODE OF SCENARIO TREE FORM THE RAINFALL SCENARIOS)
DEF	DEFAULT VALUE
BETA(T)	DISCOUNT FACTOR BETA(T) = 1/(1+ IR)**ORD(T); BETA(T) = BETA("1");
TLU0	TROPICAL LIVESTOCK UNITS IN PREVIOUS PERIOD TLU0 = STOCK(I) ;
BETA0	CURRENT BETA BETA0 = BETA("1");
RAIN	RAIN IN CURRENT PERIOD
X(I)	NODE VALUE FOR THE STATE VARIABLE ON THE UNIT INTERVAL X(J) = COS(ARG(J)) ;
IN(I)	INDICES TO CALCULATE THE ARGUMENT OF THE COSINE WEIGHTING FUNCTION IN(I) = ORD(I); IMAX = SMAX(I, IN(I)) ;
AOLD(J)	PREVIOUS POLYNOMIAL COEFFICIENT VALUE FOR LOOP CONVERGENCE CHECK AOLD(I) = ACOEF(I);
STOCK(J)	STOCK LEVEL VALUE AT NODE J FOR GRID POINT CALCULATION STOCK(J) = (L+U+(U-L)*X(J))/2;
VAL(J)	STORES THE VALUE OF THE VALUE FUNCTION FOR LOOP CALCULATION
PHIBAR(I,J)	POLYNOMIAL TERMS USED IN THE LOOP CONVERGENCE CALCULATION

PHIBAR("1",J) = 1;
PHIBAR("2",J) = X(J);
LOOP(I$(ORD(I) GE 3), PHIBAR(I,J) = 2*X(J)*PHIBAR(I-1,J)-PHIBAR(I-2,J)) ;

ARG(J) ARGUMENT OF THE COSINE WEIGHTING FUNCTION
ARG(J) = ((2*IN(J)-1)*PI)/(2*IMAX)

ACOEF(I) INITIAL POLYNOMIAL COEFFICIENT VALUES FOR VALUE FUNCTION
ACOEF(I) = 0;
ACOEF(I)$SUM(J,SQR(PHIBAR(I,J))) = SUM(J, VAL(J)*PHIBAR(I,J)) / SUM(J,SQR(PHIBAR(I,J))) ;

DIFF(ITER) DEVIATION OF CHEBYCHEV COEFFICIENTS FOR EACH VALUE ITERATION
DIFF(ITER)= TEST;

CPOLY(ITER,I) CHEBYCHEV POLYNOMIAL COEFFICIENTS AT EACH ITERATION
CPOLY(ITER,I)= ACOEF(I);

CVALUES(ITER,I,*) COEFFICIENT VALUES FOR CHEBYCHEV POLYNOMIALS
CVALUES(ITER,I,'CERROR') = DIFF(ITER) ;
CVALUES(ITER,I,'CCOEF_VALUEFCN') = CPOLY(ITER,I);

SCALAR

LAM GROWTH RATE OF LIVESTOCK HERD

AREA RANGE AREA IN HA

PH FEEDING REQUIREMENTS OF A TLU KG DM/TLU PER YEAR

VC VARIABLE COST PER TLU (INPUT COSTS TO MAINTAIN THE HERD)

IR THE DISCOUNT RATE

BOSH 'PROPER-USE FACTOR' FORAGE ALLOWANCE

BINS ADJUSTMENT FACTOR FOR BIOMASS SHARE USED BY OTHER LIVESTOCK AND NON-LIVESTOCK USES

TEST TEST FOR CONVERGENCE
TEST = SUM(I,(ACOEF(I)-AOLD(I))*(ACOEF(I)-AOLD(I)));

TOL TOLERANCE FOR CONVERGENCE

IMAX LARGEST INTEGER IN SET I

PI $\pi = 3.14...$;

U UPPER LIMIT ON CARRY-OVER STOCK

L LOWER LIMIT ON CARRY-OVER STOCK

VARIABLES

CVB CURRENT VALUE BENEFIT

PHI(J) NODAL APPROXIMATIONS OF VALUE FUNCTION

VALUEFCN VALUE FUNCTION

SL OPTIMAL SALES

ANPP ABOVEGROUND NET PRIMARY PRODUCTIVITY (ANPP, KG DM/HA)

SRATE STOCKING DENSITY

TLU TROPICAL LIVSTCK UNITS IN NEXT PERIOD

MTLU MAXIMUM GRAZING CAPACITY

FOD FODDER
PROFIT TOTAL CURRENT PROFITS

EQUATIONS

ABOVEGROUND NET PRIMARY PRODUCTIVITY (ANPP, KG DM/HA)
RUEEQN.. ANPP =E=-1000 + 7.5*RAIN-SRATE*(-1000+7.5*RAIN) ;
STOCKING DENSITY
STOCKEQN.. SRATE =E= TLU/ AREA
LIVESTOCK DYNAMICS
TLUEQN.. TLU=E= TLU0+(LAM *(1-(TLU0/MTLU))*TLU0)- SL;
MAXIMUM GRAZING CAPACITY
MAXEQN.. MTLU =E= FOD/PH ;
FODDER PRODUCTION
FODEQN.. FOD =E= (ANPP* AREA*BOSH)*BINS ;
CURRENTPROFITS
PROFITEQN.. PROFIT =E= SL*(INTERCEPT- SLOPE *SL)-SALES *VC;
POLYNOMIAL RECURSION EQUATION 1
PHI1.. PHI("1") =E= 1 ;
POLYNOMIAL RECURSION EQUATION 2
PHI2.. PHI("2") =E= ((TLU-(L+U)/2)/((U-L)/2)) ;
POLYNOMIAL RECURSION EQUATION 3
PHI3(J)$(ORD(J) GE 3).. PHI(J) =E= 2*((TLU-(L+U)/2)/((U-L)/2))*PHI(J-1)-PHI(J-2) ;
VALUE FUNCTION FOR SIMULATION STAGE
VFN.. VALUEFCN =E= SUM(J, ACOEF(J) * PHI(J)) ;
PRESENT VALUE BENEFIT FUNCTION WITH CHEBYCHEV APPROXIMATION
CVBFCN .. CVB =E= PROFIT + BETAO*VALUEFCN.