# Sustainable Livestock Management in the Kalahari: an Optimal Livestock Rangeland Model (OLR)

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**Abstract**

Special tariffs on beef imports by the European Union, together with wealth created by the diamond industry have provided both the incentive and the means for Botswana to embark
upon an ambitious programme of livestock expansion into the Kalahari, an arid savanna system in Botswana. The result has been changing rangelands as well as a drastic reduction in the size of the Kalahari's migratory wildlife populations. Existing studies have tended to be simplistic and have not integrated the economic and ecological driving forces and feedback loops. We have attempted to address this shortcoming by developing a model that integrates two sub-models in some detail; one ecological and the other economics. The ecological aspects are captured firstly by considering the piosphere effect which is driven by borehole and livestock density, and then modeling the overgrazing which is determined largely by the economics of the livestock sector. The model not only captures the browse-grass dynamics but also the inter-temporal spatial dynamics of this interaction. The model uses non-linear programming techniques provided by the General Algebraic Modeling System (GAMS) to solve the model. Preliminary results from the OLR (Optimal Livestock Rangeland) model suggest that the price of cattle together with rainfall play crucial roles in governing the grass-browse interactive dynamics. Furthermore, the important role browse plays in the livestock sector is highlighted and is a component which cannot be ignored in rangeland management.

**Resumen**

Los aranceles preferenciales a la carne de res importada a la Unión Europea, sumados a la riqueza proveniente de la industria del diamante, le han entregado a Botswana el incentivo y los medios para iniciar un ambicioso programa de expansión de ganadería en el Kalahari, un sistema de sabanas áridas. Como consecuencia de esto, se ha observado un cambio en los pastizales y una disminución drástica en la población migratoria de fauna. Los estudios realizados tienden a ser simplistas al no integrar las fuerzas económicas y ecológicas ni a los circuitos de retro-alimentación.

Los autores del presente estudio han intentado corregir esta limitación mediante la creación de un modelo que integra dos sub-modelos con cierto grado de detalle: uno ecológico y otro económico. El efecto ecológico se mide teniendo en cuenta el efecto de piosfera producido por densidad en la ganadería y en los pozos, (el efecto de piosfera sobre los arbustos y pastos que rodean a un pozo es directamente proporcional a la densidad de ganado y a la proximidad entre los pozos). Luego se modela el pastoreo excesivo que depende de factores económicos del sector de la ganadería. El modelo representa, por un lado, la respuesta del pasto y el follaje del desierto ante cambios en variables como la lluvia, la densidad del ganado, y el precio del mismo. Y, por otro, modela la dinámica espacial y temporal de la interacción entre pasto y follaje. Para resolver el modelo se utilizan las técnicas de programación no lineales que ofrece el Sistema General de Modelaje Algebráico (SGMA). Algunos resultados preliminares del modelo OPG (optimización de pastizales para ganadería) sugieren que la lluvia y el precio del ganado influyen en forma fundamental sobre la dinámica interactiva entre pasto y follaje. Además, se destaca el papel que juega el follaje en el sector de la ganadería, poniendo de relieve que es un componente esencial en la gestión de pastizales.

Des taxes spéciales perçues sur les importations de viande bovine par l'Union européenne, ainsi que la richesse engendrée par l'industrie du diamant, ont fourni au Botswana tant l'incitation que les moyens lui permettant de se lancer dans un programme ambitieux d'expansion de l'élevage au Kalahari, système de savane aride de ce pays. En sont résultés des changements affectant les terres de parcours ainsi qu'une spectaculaire réduction de la taille des populations de faune migrante. Les recherches déjà effectuées tendent

au simplisme et ne pratiquent pas l'intégration des forces motrices d'ordre économique et écologique et des boucles de rétroaction. Nous avons tenté de pallier à ce défaut en élaborant un modèle qui en intègre deux autres - un sous-modèle écologique et un autre, économique - de manière assez détaillée. Les aspects écologiques sont pris en compte, d'abord en considérant l'effet de biosphère engendré par la densité des forages et du bétail, puis en procédant à la modélisation du surpâturage, largement déterminé par l'économie de l'élevage. Le modèle ne se contente pas de prendre en compte la dynamique brout-herbe mais aussi la dynamique spatio-intertemporelle de cette interaction. Pour sa résolution, le modèle fait appel aux techniques de programmation non-linéaire mises à disposition par le Système général de modélisation algébrique (*General Algebraic Modeling system, GAMS*). Les résultats préliminaires du modèle d'optimisation des rapports bétail-terres de parcours suggèrent que les prix du bétail tout comme les précipitations, jouent un rôle crucial de détermination de la dynamique d'interaction brout-herbe. Qui plus est, l'importance du rôle joué par le brout dans l'élevage est mise en lumière: il constitue une composante de la gestion des terres de parcours qu'on ne saurait ignorer.

# Contents

# Introduction

Economically beef farmers in Botswana have benefited under the European Union Beef Protocol Agreement which, since the early 1970s, has paid above world prices for Botswana's beef. Coupled with the advent of deep borehole drilling technology and a run of 'good' rainfall years in the 1970s, the Protocol Agreement provided considerable impetus to the expansion of permanent livestock keeping into Kalahari pastures (Cooke, 1985). Consequently the last two decades have seen extensive areas of the Kalahari move from low density usage by hunterer-gatherer populations to borehole-centred livestock keeping (Perkins,1996). It is a change that has raised the spectre of widespread range degradation and resulted in the substitution of domestic stock for formerly large herds of wild ungulates over large areas (Perkins and Ringrose, 1996).

Today, important questions surround the future of livestock-keeping in the Kalahari of Botswana. The Beef Protocol Agreement is due to be phased out in 2004 with largely unknown implications for the economic viability of the livestock sector, while growing demands for livestock rearing is placing unprecedented pressure on land use planners to increase borehole densities and so enable new ranches to be established. Consequently it is important to understand the ecological consequences of inter-related changes in borehole densities and stocking rates and the implications of reduced beef prices upon the economics of beef production. To do so, requires an integrated model which fully captures the essential ecological and economic forces that drive the system, and upon which meaningful policy solutions may be formulated.

Carrying capacities have been the central concept used in determining optimal stocking rates for livestock. However, using a static concept to illustrate a dynamic system can be misleading and provide erroneous rangeland management policy prescriptions. The major issue with rangelands is not one of degradation but of species composition change (Abel 1997). The two principal categories of primary biomass critical in determining rangeland carrying capacity are grass and browse. However, the composition mixture of the two relies on many factors and the composition is far from static. Therefore, to determine the adequate carrying capacity of the rangelands, the composition mixture between grass and browse must be tracked through time; in order to do this, the factors determining each species must be captured explicitly. Existing studies have tended to be simplistic and have not integrated the economic and ecological driving forces and feedback loops. We have attempted to address this shortcoming by developing a model that integrates two sub-models in some detail; one ecological and the other economics. The ecological aspects are captured by firstly considering the piosphere effect which is driven by borehole and livestock density, and then modeling the overgrazing which is determined largely by the economics of the livestock sector.

The paper is presented as follows: in the next section, an overview of the complete model is presented. Two sections follow this, the first discussing in detail the economics module while the second focuses on the ecology of the system. Preliminary results are presented in the fifth section. The paper ends with some concluding remarks.

# Modeling Scope

The model is formulated as a deterministic dynamic optimisation problem in which net revenue accruing from livestock production is maximised. The endogenous variables in the model are grass and browse availability, borehole densities, livestock stocking rates, livestock off-take rates, and the rate of bush encroachment. Grass and browse availability is captured through the spatial dynamics in the model which keeps track of not only the number of sacrifice, bush encroached and grazing reserve zones in each time period but also the grass-browse composition within the respective zones. The zones and the grass-browse composition over time, or in other words the bush encroachment factor, are in turn influenced by borehole density and livestock stocking rates; all these variables as explained earlier are determined within the model solution process. Prices and rainfall enter the model as parameters. Sensitivity or range analysis is used to investigate how uncertainty in these parameters will affect final results.

Before we present the equations of the model, a brief introduction to the nomenclature used in the model is provided below. This will help the reader follow the use of subscripts in the mathematical model.

Model Nomenclature

Set C Commodities
Elements of Set C are: Grass, Browse, Cattle, Goats

Sub-Set {PB(C)} Non-Market Commodities Primary Biomass
Elements are: Grass, Browse

Sub-Set { DH(C)} Market Commodities Domestic Herbivore
Elements are: Cattle, Goats

Set Z Zones
Elements are: SC- Sacrifice ,BEZ-bush encroached ,GRZ-grazing reserve

Set P Periods
Elements are: Wet, Dry

Set T Time Periods
Elements are: 1,2,3,4,5

# The Economic Module

A net benefit maximisation problem is pursued.  Benefits accrue solely from livestock - cattle and goats.  Cattle and goats provide two categories of benefits- flow and stock benefits.  The former captures primarily the slaughter of cattle and goats for commercial sale.  The latter, stock benefits, relate to benefits accrued by keeping livestock, mainly milk, draught power and prestige.

Similar to benefits, costs were categorised into flow and stock costs.  However, a further distinction is necessary to elucidate the various cost components.  These were, in the case of flow cost, direct and indirect cost while for stock cost, fixed and variable cost.  The detailed description of the various cost items within each category is given in the next section.

**Benefit function**

The benefit function is comprised of four components.  We make a distinction between benefits accrued from stocks as well as flows.  The flow benefit comes from the sale of cattle for slaughter.  The benefit accruing from the stock of domestic herbivore arises primary from the use of these herbivore for draught power, milk and hides as well as a prestige component.

**Flow Benefit from domestic herbivore**

$$fb_t^{cdh} = \sum_p \sum_{c \in cdh} p_{c,t} s_{c,p,t}^h \qquad \forall t \in T \tag{1}$$

Flow Benefit is equal to revenue generated by sale of domestic herbivores. Revenue is equal to price multiplied by harvest levels.  Price is exogenous in this model.  Note that the benefits are added over two seasons for a time period, which in this case is a year.

**Stock Benefit from domestic herbivore**

$$sb_t^{cdh} = \sum_p \sum_{c \in cdh} l_c s_{c,p,t} \quad \forall t \in T \tag{2}$$

The stock benefit comes from the milk and draught power cattle provide.  We assume goats do not have any stock benefits.  The alpha coefficient was estimated using results from previous valuation studies.  The coefficient is based on a livestock unit (LSU), where values vary from 1.2 LSU for a bull, to 0.1 LSU for a calf, with a cow that is four years and older being 1.0 LSU (Carl Bro, 1982). In this version, we assume all cattle to be equivalent to 1 LSU and goats to be 0.1 LSU.

**Direct Flow Cost from livestock**

$$dfc_t^{cdh} = \sum_p \sum_{c \in cdh} \left(w^{tr}\right) s_{c,p,t}^h \qquad \forall t \in T \tag{3}$$

The direct flow cost comes from the transportation cost incurred while shipping the animals from the boreholes (ranch) to the abattoirs. Omegak is the unit cost or cost/LSU. It is logical to assume that the harvest level is the number transported.

**Indirect Flow Cost from Livestock**

$$idfc_t^{cdh} = \sum_p \sum_{cdh} l_c s_{c,p,t}^h \qquad \textbf{(4)}$$

Indirect flow cost from livestock comes from the opportunity cost of milk and draught power which is lost from stock harvested. Note that we use the same price we used in computing the stock benefits.

**Fixed Stock Cost for Livestock**

$$fsc_{"dry",t+1}^{cdh} = \left[h_{"dry",t+1} - h_{"wet",t}\right] w^k + \sum_{c \in CDH} s_{c,"wet",t}^{rstck} p_c^{rstck} \quad t \in T \qquad \textbf{(5)}$$

$$fsc_{"wet",t}^{cdh} = \left[h_{"wet",t} - h_{"dry",t}\right] w^k + \sum_{c \in CDH} s_{c,dryt",t}^{rstck} p_c^{rstck} \quad t \in T \qquad \textbf{(6)}$$

Fixed stock costs are comprised of two items: (1) borehole investment costs; and (2) animal restocking costs. In order to compute borehole investment costs incurred in each season, we need to take the difference or the increase in the number of boreholes between subsequent periods. Because of the unique structure of this model, we need to link two seasons within a time period and two seasons across two time periods. For example, in this model we start in the wet period in time period one. In order to compute time varying variables, we need to specify the level of certain variables for the dry period in time period one. It is for this reason, we need to specify for certain relationships two equations, one for the wet and another for the dry season explicitly. If we look at equation five, we notice that we use a t+1 subscript for the dry seasons instead of just t as in the wet season. This is as we had mentioned earlier; we use the wet period as the point of departure. The equations themselves state that fixed stock cost is equal to borehole investment cost plus restocking costs.

**Variable Stock Costs for Livestock**

$$vsc_{c,t} = \sum_{p \in P} w^e e_{c,t} + \sum_{p \notin P} h_{p,t} w^h + \sum_{p \in P} s_{c,p,t} w^{\sup p} \quad c \in CDH, t \in T \qquad \textbf{(7)}$$

The variable stock cost is equal to labour cost, borehole maintenance costs and cattle food supplement costs. Borehole maintenance is for all existing boreholes. Labour cost is equal to wage rate multiplied by effort level. Supplement costs is equal to cost/LSU multiplied by herd size[1].

[1] No significant economies of scale were detected to warrant the use of herd size dependent unit cost coefficients.

**Effort Level**

$$e_{c,p,t} = e_c s_{c,p,t} \quad \forall c \in dhb, p \in P, t \in T \qquad \textbf{(8)}$$

Effort is a simple linear function whereby epsilon is man-hours/LSU.

**The borehole accumulation equation**

$$\begin{aligned} h_{"dry",t+1} &\geq h_{"wet",t} \qquad t \in T \\ h_{"wet",t} &\geq h_{"dry",t} \qquad t \in T \end{aligned} \qquad \textbf{(9)}$$

In defining the number of boreholes present in each season, we assume that once a borehole has been drilled, it is effectively in place and in operation. No disused boreholes are allowed in this version of the model. We model this assumption by making sure that the number of boreholes in the next period is always equal to or greater than the number of boreholes in the existing period. This equation does not however determine the actual number of boreholes which should be put in place. That is determined in the next equation.

**Boreholes Investment Decision Equation**

$$s_{"cattle",p,t} \leq h_{p,t} w^{\max}_{"cattle"} \qquad \textbf{(10)}$$

In the above equation we link the number of livestock, in this case only cattle. to the number of boreholes. The a omega coefficient indicates the number of cattle a borehole can support. Now, if cattle stock is to be increased, then boreholes must be drilled.

**Upper bound on number of boreholes**

$$h_{p,t} \leq 1000 \qquad t \in T \qquad \textbf{(11)}$$

An upper bound was imposed on the maximum number of boreholes which can be drilled in the total area considered. The upper bound is closely related to the ecological piosphere effect which is set into motion by boreholes. The reason for the upper bound is provided in the explanation of the piosphere effect as outlined in the next section on the ecological components.

# The Ecological Module

Ecologically the OLR model is founded upon the well established relationship between average annual rainfall and primary production (Coe *et al*, 1976) and the fundamental importance of the piosphere effect (Lange, 1969; Andrew, 1988) in determining the quantity and quality of forage available to large herbivores in semi-arid environments. Although neither concepts are new, such explicit modeling of the spatial and temporal variability of forage production or its broader linkage with the primary economic determinants of livestock production in the Kalahari has not been attempted before. Past models of the livestock sector in Botswana have either been entirely sectoral or have attempted to model the ecology on the basis of average stocking rates and carrying capacities as detailed by Field (1977). Consequently, the piosphere effect as the dominant factor shaping the impact of livestock upon semi-arid rangelands and critical management decisions relating to the optimal density of boreholes are entirely overlooked. As a result, important and well-documented changes in semi-arid savannas, such as the opening up of sacrifice zones and the spatially more widespread loss of graze via the process of bush encroachment are rarely captured.

The inclusion of browse in the primary and secondary production equations is therefore regarded as an important step forward and an essential deviation from earlier models. Whilst recognised as an important source of forage, browse is typically ignored (Le Houerou, 1980), despite the fact that within a piosphere context it is the most accessible to livestock, particularly during the critical dry season period. Most ecological models therefore fail to capture effectively the paradox of the piosphere effect, whereby large quantities of good quality graze available at some distance from the borehole remain unutilised because of the energetic costs attached to its utilisation. The drilling of more boreholes does open up these pastures, but also results in an absolute reduction in available grass biomass because of the establishment of new sacrifice and bush encroached zones.

Moreover, if Walker *et al's* (1991) assertion that is the 'unpalatable grazing reserve' that confers resilience to the ecosystem is correct, then increasing borehole densities is likely to result in the livestock populations displaying little constancy. Increased borehole densities could therefore act to accentuate the 'boom and bust' variability inherent in the natural rainfall cycle, with the troughs and peaks of drought-related mortality and above average growth of herds in a run of wet years, respectively, ever more accentuated. This has been observed in some wildlife populations around waterpoints in protected areas in South Africa (Walker *et al,* 1987) and has led to ecological guidelines on their spacing and operation (Owen-Smith, 1996).

A dilemma therefore emerges, with the obvious range conservation policy response of a ceiling on the number of boreholes diametrically opposed to prevailing socio-economic and political factors that are placing increasing demands on any such limitations to be lifted.

Before discussing the results obtained from the OLR model, each component is briefly outlined below.

### Rainfall and Primary Production

The long established predictive relationship between rainfall and primary production (Walter, 1954; from Coe, 1990) was investigated in the western Kalahari sandveld of Botswana by Skarpe (1986) and in the Kalahari Gemsbok Park of South Africa by Knight (1991). Skarpe's equation was found by Lindsay (1992) to provide more accurate predictions of grass biomass production in the Central Kalahari Game Reserve of Botswana in 1989-90 and so is used by the OLR model to generate biomass estimates from Kalahari rainfall data.

Grass production is therefore linearly correlated with annual rainfall, with most workers, while recognising the importance of browse as a source of fodder for domestic herbivores, tending to ignore it. Within the context of piosphere related bush encroachment (see below) and the progressive substitution of graze by browse over time, this is a major oversight. An attempt is therefore made to capture browse production, which was estimated by Skarpe (1986) to be of the order of 100-330 kg/ha in the western Kalahari (see also browse section below).

Rainfall in Botswana is concentrated in the summer months from November to April (the wet season) and is highly variable in both space and time. Analysis of the limited rainfall records for the region (Tyson, 1986) has shown the existence of a pronounced quasi-eighteen-year oscillation (9 below-average years followed by 9 above average years), within which a typical three to four year succession of good or bad years is common (Bhalotra, 1987). Droughts are therefore endemic, with the 'wet' years of the 1970s contrasting dramatically with the severe 1982-86 drought.

We begin by defining two seasons, a dry and a wet season. We also define three zones surrounding each borehole. The size or area of each zone will be based on its radius. To prevent the double counting of over-lapping regions, we impose a maximum number of boreholes so that no over-lap occurs - equation 11.

We distinguish two type of primary biomass, grass and browse. We also identify four levels of stocks for each of the primary biomass. These are growth stock, available stock, used stock, and leftover stock. We begin with the wet season.

### Primary Biomass Growth Equation in Wet Season in tons/sqkm

$$b^{growth}_{pb,p,t} = \left[ i_{pb,p} + w^{slope}{}_{pb,p} RAIN_{p,t} \right] \qquad pb \in PB, p \in P, t \in T \qquad \textbf{(12)}$$

The growth of grass and browse is a linear function of rain. We not only differentiat between browse and grass but also across seasons. Grass grows well in the wet season but very poorly in the dry season. Browse on the other hand does well in both seasons– browse is taken to refer to leaves, twigs and seed pods of both deciduous and evergreen species.

### Primary Biomass in the respective zones in Wet Season

$$b^{ava}_{pb,z,"wet",t} = b^{growth}_{pb,"wet",t} a^{pb}_{pb,z,"wet",t} + b^{left}_{pb,z,"dry",t} w^{co}_{pb,"dry"} \qquad pb \in PB, z \in Z \quad t \in T \qquad \textbf{(13)}$$

The amount of primary biomass available is the amount of growth per square kilometer (SqKm) multiplied by total area The second term in equation 13 represents the carryover from the previous period, which in this case is the dry season but within the same year. As these are perennials, we have a larger fraction of carryover from the wet to the dry than from dry to wet. A further distinction is made between grass and browse. The assumption used is that browse has a large carryover fraction even from dry to wet. Another factor added is the area differentiation. We have now introduced the concept of zones.

**Primary Biomass in zones in the respective zones at Beginning of Dry Season**

$$b^{ava}_{pb,z,"dry",t+1} = b^{growth}_{pb,"dry",t+1} a^{pb}_{pb,z,"dry",t+1} + b^{left}_{pb,z,"wet",t} w^{co}_{pb,"wet"} \qquad b \in PB, \; z \in Z, t \in T \qquad \textbf{(14)}$$

Equation 14 is identical to equation 13. The difference lies in the linking subscripts between the seasons and time periods. In this case, we have a link between the wet period in time t and the following dry period which is in the next time period. Irrespective of the sequence of the wet and dry seasons, there will always be a connection link whereby one season links to the next which is in the following time period.

**Primary Biomass Available after trampling effects**

$$b^{avt}_{pb,z,p,t} = b^{av}_{pb,z,p,t}\left(1 - ti_{z,pb,p,t}\right) \qquad pb \in PB, z \in Z, p \in P, t \in T \qquad \textbf{(15)}$$

In equation 15, we start modelling the first process of the piosphere effect. The trampling intensity decreases as we move away from the borehole. The forage which is available for the livestock is only what is left after the trampling has taken place. The zone differentiation now becomes a crucial factor in determining the final supply of forage available.

**Primary Biomass finally available for herbivore consumption**

$$b^{avm}_{pb,z,p,t} = b^{avt}_{pb,z,p,t} w^{access}_{pb} w^{conv}_{pb} \qquad pb \in PB, z \in Z, p \in P, t \in T \qquad \textbf{(16)}$$

Once we have the total forage available for livestock, we need to do two things. First, we have to compute the accessibility of the forage to the livestock. This is necessary because browse, due to its properties is not 100 percent accessible. Grass on the other hand is more easily accessible. The second and final step is the conversion of the forage availability in tons to energy units. Again, the difference in the forages is crucial and is picked up by this parameter. Grass is more energy efficient than browse.

**Trampling Intensity**

$$ti_{z,pb,p,t} = \frac{s_{"cattle",p,t}}{h_{p,t}} w^{tramslop}_{z,pb} \qquad z \in Z, pb \in PB, p \in P, t \in T \qquad \textbf{(17)}$$

Trampling intensity is dependent on the herd density, which is computed by dividing the total number of livestock by the total number of boreholes. Through the necessity to reduce the modeling complexity the herd density is therefore reduced to an average, whose impacts are nonetheless mediated through the piosphere effect. The a coefficient was computed based on existing data and studies (Perkins 1991, Perkins and Thomas, 1993a; 1993b), which found 'trampling intensity' as measured through by the number of cattle tracks across a set distance, to be the most effective index of floristic variation within piospheres. The coefficient is differentiated across the zones and biomass. In other words, the impact per LSU is different in the different zones and the impact on the forage is also different with larger destructive effects on grass vis-à-vis browse.

**Demand for Primary Biomass by each User**

$$d_{c,p,t} = s_{hb,p,t} w_c^{mit} + \sum_z \sum_{pb} \frac{b_{c,pb,z,p,t}^{used}}{b_{c,pb,z,p,t}^{used} + 0.001} DIST_z w_{c,p}^{walk} s_{c,p,t} \quad c \in CDH, p \in P \quad t \in T \tag{18}$$

The demand for forage is dependent on two factors, namely the amount of livestock and the distance they walk to obtain their food supply. The former is captured by the first term. MIT is the forage necessary for the maintenance of one LSU. The second term while appearing complicated simply captures the extra forage needed if a cow walks a bit further to get its forage requirements. The $b^{used}$ variable indicates the amount of forage taken, differentiated by type and zone. Therefore, once $b^{used}$ is triggered, then DIST is triggered and that computes the distance walked corresponding to the zone in which the forage is taken. The omegawalk coefficient tells us the extra energy required for walking unit distance.

**Upper Bound on Browse use by Cattle**

$$\sum_z b_{"cattle","browse",z,p,t}^{used} \leq 0.3\left(d_{"cattle",p,t}\right) \tag{19}$$

This equation was included after preliminary runs highlighted a slight inconsistency in forage use by the cattle. In the earlier models, the demand for food intake by cattle was completely met by supply from browse in order to conserve the grass cover which in turn is needed to reduce the encroachment by bush. However, it is not possible for cattle to substitute browse for grass by 100 percent. Although browse has a high protein content, tannins and related polyphenolics have negative effects on palatability and digestibility, with many actually being poisonous (Woodward and Reed, 1989). In order to reduce this effect and produce more reasonable forage intakes, we imposed an upper bound of 30% of total forage demand which can be met by browse, based on cattle digestive habits and tolerance levels for browse.

**Upper Bound on Livestock Herd Size**

$$\sum_z \sum_{pb} b_{c,pb,z,p,t}^{used} = d_{c,p,t} \quad c \in CDH, p \in P, t \in T \tag{20}$$

The above equation can be seen as meeting a demand constraint. The equation stipulates that demand for primary biomass by livestock must be met. If there is insufficient supply, demand will be adjusted, ie, livestock will be reduced. Therefore, unlike traditional economic models where prices are used to adjust demand and supply, here quantity (ie, livestock levels) is used as the clearing mechanism. Turning our attention to the summation operators, we observe that the total amount of energy used by each category of livestock that is sourced from the two types of forage and across all zones in each season in each time period must be equal to the demand.

**Primary Biomass Material Balance Equation**

$$b^{avm}_{pb,z,p,t} \geq \sum_{c \in CDH} b^{used}_{c,pb,z,p,t} \quad pb \in PB, z \in Z, p \in P, t \in T \qquad \textbf{(21)}$$

Although equation 21 appears similar to equation 20, it captures another dimension of the supply-demand balance. In this equation, we say that the total amount of a particular forage type used in a zone must be less than the amount available. This must hold true for each season in each time period.

**Primary Biomass Left over**

$$b^{left}_{pb,z,p,t} = \frac{b^{avm}_{pb,z,p,t} - \sum_{c \in cdh} b^{used}_{pb,z,p,t}}{w^{conv}_{pb}} \qquad b \in PB, z \in Z, p \in P, t \in T \qquad \textbf{(22)}$$

In order to link the biomass supply between seasons and time periods, we need to compute the biomass left over in each season in each zone. The residual of supply and demand gives us the level and by dividing the amount by the conversion factor, we get back to forage leftover in tons. Again, the need to convert tons to energy units, kilojoules (KJ), is due to the differences in the energy content of the two forage types.

**Primary Biomass left over per unit area**

$$b^{lefta}_{"grass",z,p,t} = \frac{b^{left}_{"grass",z,p,t}}{a^{pb}_{"grass",z,p,t}} \qquad z \in Z, p \in P, t \in T \qquad \textbf{(23)}$$

The final step in the primary biomass computations is the calculation of the critical load in the respective zones. The critical load is defined as the minimum grass density which is needed to prevent bush encroachment. Once the grass cover falls below this amount, the bush takes over. The area is a variable itself and thus forage intensity can change by two ways: (1) increasing the bleft level; and/or (2) reducing the area under grass in the respective zones.

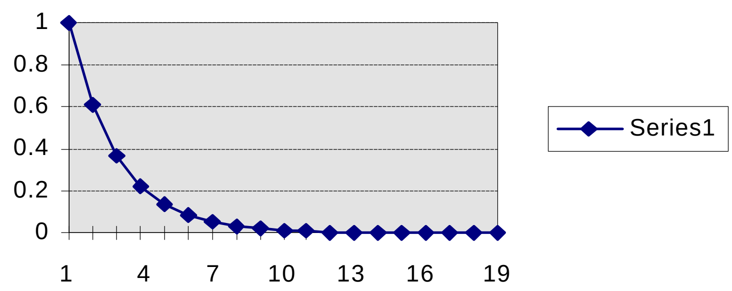
**Bush Encroachment Factor**

$$bef_{z,p,t} = e^{\frac{b^{lefta}_{"grass",z,p,t}}{w^{b\min}}} (2.71825) \qquad \textbf{(24)}$$

The bush encroachment factor is modeled as an exponential decay function. Existing data on the threshold levels in the different zones (Perkins, 1991, 1996) were used in calibrating the exponential function as shown in figure two below. The $\omega^{bmin}$ coefficient is the minimum grass cover density before bush encroachment starts. The $\omega^{grad}$ coefficient represents the degree of decay, which occurs when the maximum grass cover at which bush encroachment does not take place is 200 tons/sqkm.

**Figure 1. The exponential bush encroachment function**

The vertical axis represent the percentage encroachment while the horizontal axis denotes the amount of grass cover.




**Herbivore Herd level at end of season in each time Period.**

$$s_{c,"wet",t} = \left[s_{c,"dry",t} + s^{a}_{c,"wet",t}\right] - s^{h}_{c,"wet",t} \quad c \in CDH, t \in T \qquad \textbf{(25)}$$
$$s_{c,"dry",t+1} = \left[s_{c,"wet",t} + s^{a}_{c,"dry",t+1}\right] - s^{h}_{c,"dry",t+1} \quad c \in CDH, t \in T$$

We now turn our attention to the livestock growth and accumulation functions. The level of livestock available at the end of each season in each time period is equal to the level present at the end of the previous season plus the amount added in the present season (through growth plus restocking) minus the amount harvested.

**Stock additions in each season in each time period**

$$s^{a}_{c,"wet",t} = s_{c,"dry",t} w^{growth}_{c,"wet"} + s^{rstck}_{c,"wet",t} \quad c \in CDH, t \in T \qquad \textbf{(26)}$$
$$s^{a}_{c,"dry",t+1} = s_{c,"dry",t+1} w^{growth}_{c,"dryt"} + s^{rstck}_{c,"dry",t+1} \quad c \in CDH, t \in T$$

The stock addition is equal to an intrinsic growth rate plus the possibility of restocking from external sources, ie, by purchasing livestock from other regions.

**Upper bounds on Harvest levels in Dry Period**

$$s^{h}_{c,"dry",t+1} \leq s_{c,"dry",t+1} - s^{a}_{c,"dry",t+1} - s^{a}_{c,"wet",t} \qquad c \in CDH, t \in T \qquad \textbf{(27)}$$

$$s^{h}_{c,"wet",t} \leq s_{c,"wet",t} - s^{a}_{c,"wet",t} - s^{a}_{c,"dry",t} \qquad c \in CDH, t \in T$$

We impose a bound on the level of harvest which can occur in any one season. The constraint is such that all additions to the herd either through intrinsic growth rates or restocking in the last two seasons cannot be harvested. There must be a year lag before they can be sent for harvesting.

**Area under Sacrifice and Bush zones**

$$a_{z,p,t} = w^{a}_{z} h_{p,t} \quad z \in ZA, p \in P, t \in T \qquad \textbf{(28)}$$

Due to the concentric nature of the piosphere effect, we divide the zones into three. The first two are calculated on the basis of their radii from the borehole and these are in turn derived from data (Perkins 1991; Perkins and Thomas, 1993a and 1993b; Perkins, unpublished data). These constitute omega. As these are dependent on boreholes with more zones opening up as more boreholes are put in place, we aggregated the total area under each zone across all the boreholes into one single figure. This was done to ease the work of tractability. It would not have been a trivial task keeping track of each of the three zones for each borehole drilled. It is a simplifying assumption but one which we are confident will not have any significant impacts on the end results.

**Area under the grazing Zone**

$$a_{"grz",p,t} = L - \sum_{z \notin ZA} a_{z,p,t} \qquad p \in P, t \in T \qquad \textbf{(29)}$$

The land under grazing reserve is just the residual of the total land available and land under the other two zones. L here is the total land under consideration. The second term is computed from equation 28.

**Grass Browse Cover in each Zone**

The following set of equations relate to the spatial changes which are caused by the piosphere effect. The equations track the grass-browse composition within each zone. The mixture is, to a large extent, dictated by the number of boreholes while the grass:browse ratio is determined by the bush encroachment factor. The equations also need to capture the temporal changes. Therefore separate equations are formulated for linking the seasons and the time periods
.

$$a^{pb}_{"grass","bez","dry",t+1} = \left(1 - bef_{"bez","wet",t}\right) a^{pb}_{"grass","bez","wet",t} + \left(a_{"bez","dry",t+1} - a_{"bez","wet",t}\right) \qquad t \in T \qquad \textbf{(30)}$$

$$a^{pb}_{"browse","bez","dry",t+1} = a_{"bez","dry",t+1} - a^{pb}_{"grass","bez","dry",t+1} \qquad t \in T$$

In equation 30, forage composition changes for the bush encroached zone are formulated. It states that the area under grass in the dry periods is equal to what is left from the previuos period minus the land lost to bush encroachment plus new land being reclassified as bush encroached zone due to new boreholes being put in place. These by default will be grass covered as what is being brought under the zone will be grass land from the grazing reserve.

$$a^{pb}_{"grass","bez","wet",t} = \left(1 - bef_{"bez","dry",t}\right) a^{pb}_{"grass","bez","wet",t} + \left(a_{"bez","wet",t} - a_{"bez","dry",t}\right) \quad t \in T$$
$$a^{pb}_{"browse","bez","wet",t} = a_{"bez","wet",t} - a^{pb}_{"grass","bez","wet",t} \quad t \in T \qquad \textbf{(31)}$$

Equation 31 is identical to equation 30 but is for the wet period.

The next set of equations capture the amount of land which has been added to the first two zones. In other words, we are computing the amount of land that is lost from the grazing reserve.

$$\Delta a_{z,"dry",t+1} = a_{z,"dry",t+1} - a_{z,"wet",t} \quad z \in ZA, t \in T$$
$$\Delta a_{z,"wet",t} = a_{z,"wet",t} - a_{z,"dry",t} \quad z \in ZA, t \in T \qquad \textbf{(32)}$$

Equation 32 states that the change in land in zones in set ZA (in this case the first two zones) is equal to the difference between two seasons. Please note that we do not make a distinction here between grass and browse. This is based on the implicit assumption that all new land brought into the zones comes from the grass covered section of the grazing reserve.

$$a^{pb}_{"grass","grz","dry",t+1} = \left[a^{pb}_{"grass","grz","wet",t} - \sum_{z \in ZA} \Delta a_{z,"dry",t+1}\right]\left(1 - bef_{"grz","wet",t)}\right) \quad t \in T \qquad \textbf{(33)}$$
$$a^{pb}_{"browse","grz","dry",t+1} = \left[a^{pb}_{"Grass","grz","wet",t} - \sum_{z \in ZA} \Delta a_{z,"dry",t+1}\right] - a^{pb}_{"grass","grz","dry",t+1} + a^{pb}_{"browse","grz","wet",t} \quad t \in T$$

In equation 33, we state that the land under grass in the grazing reserve at the end of each season is equal to the amount of land under grass in the previous season minus the total amount of land lost to the other two zones in this period minus the amount of land lost to bush encroachment in this period. In the case of browse coverage, we first need to deduct the land that is lost to the other zones, after which we need to deduct the amount of land that is still under grass. This is finally added to the previous season's land under browse coverage.

$$a^{pb}_{"grass","grz","wet",t} = \left[a^{pb}_{"grass","grz","dry",t} - \sum_{z \in ZA} \Delta a_{z,"wet",t}\right]\left(1 - bef_{"grz","dry",t}\right) \quad t \in T \qquad \textbf{(34)}$$
$$a_{"browse","grz","wet",t} = \left[a^{pb}_{"grass","grz","dry",t} - \sum_{z \in ZA} \Delta a_{z,"wet",t}\right] - a^{pb}_{"grass","grz","wet",t} + a^{pb}_{"browse","grz","dry",t} \quad t \in T$$

Equation 34 is identical to equation 33 but is for the wet season.

The final equation of the model is a terminal condition. If we do not impose an appropriate terminal condition, we can get some unrealistic results towards the end of the model. For example, cattle stocks can be driven to zero so as to maximise profits which in turn could results in massive degradation of the biomass as there is no need to conserve once the time horizon is completed.

$$s_{"cattle","wet",tt} \geq s_{"cattle","dry","0"} \quad \textbf{(35)}$$

Equation 35 states that the amount of cattle at the end must be at least as large as the amount which was started with (TT is terminal period)

$$a_{z,"dry","0"}$$
$$a^{pb}_{pb,z,p,t}$$
$$b^{left}_{pb,z,"dry","0"}$$
$$h_{"dry","0"}$$
$$s_{cdh,"dry","0"}$$

Initial conditions are necessary for a temporal model. The following conditions were used in the model. The first condition states the amount of land allocated in each zone. The second condition gives the forage composition in each zone. The third condition gives the amount of biomass available for carryover to the next season. The fourth condition gives the staring number of boreholes while the last initial condition gives the livestock levels. This brings us to the last specification we need before the model is complete. The objective function we use in this model is net benefit and this is maximised in the optimisation process.

$$NB = \sum fb^{cdh}_t + sb^{cdh}_t - dfc^{cdh}_t - idfc^{cdh}_t + fsc^{cdh}_t vsc^{cdh}_t \quad \textbf{(36)}$$

We maximise the net benefit function, which is a summation of all benefits minus all costs. In the optimisation procedure, the trade-offs in terms of benefits and costs will be done. The constraint is the ecological system of the rangelands. For example, if the price of beef is high, then the benefits from livestock increases. But the decision-maker has to weigh the pros and cons of increased livestock production. First, increased livestock populations would imply higher capital costs in terms of boreholes and wages. But increased boreholes would imply higher utilisation intensity which in turn implies less forage conservation and thus a limit to livestock maintenance. From the dynamics, the continual degradation of the rangelands would imply lower benefits in the future and a trade-off has to be made between environmental degradation in the form of lower productivity versus immediate gains from increased livestock production.

# Results

OLR differs from other range models through its explicit attention to the spatial and temporal dynamics of piospheres Its ability to capture the competitiveness between browse and graze layers through piosphere mediated processes is its major strength over existing models. Integrating the piosphere process within an economic decision making framework allows us to observe crucial variables, ecological and/or economic, which drive the system. This information can then be used to develop management strategies to ensure the optimal use of the rangelands.

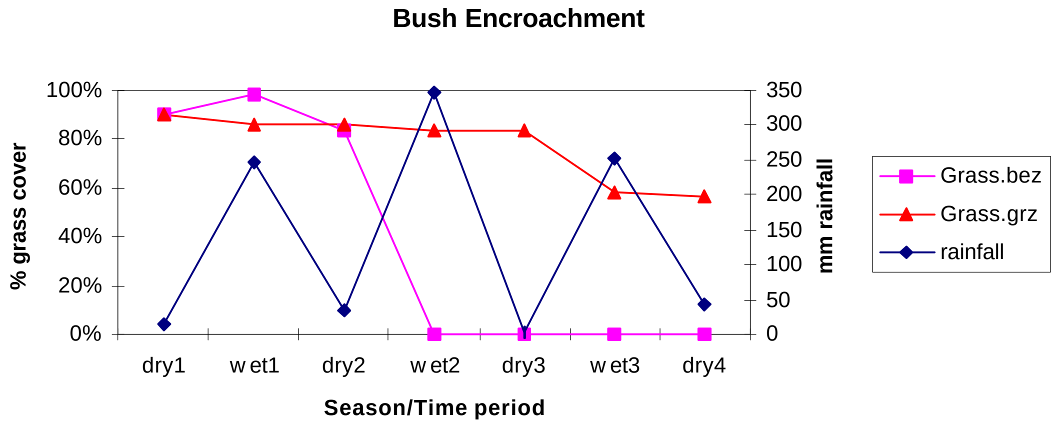
Most critically there is no exogenously derived 'proper use factor' that so characterises other rangeland models and is explicitly built in to provide a link with sustainability (for example, Toxopeus *et al*, 1994; Wiijngaarden, 1985; Braat and Opschoor, 1990). Indeed, such factors are based upon a rather narrow view of carrying capacity, that has been heavily criticised in the literature (Mace, 1991). Instead, OLR derives a limit to livestock numbers endogenously based upon the essential dynamics of semi-arid ecosystems, the piosphere effect and the objectives of commercial beef production.

Intuitively, different time horizons may be appropriate to the economic and ecological processes respectively. For example, five years may be appropriate for economic planning horizons in the Kalahari but ten years or longer would be more appropriate for ecological sustainability. We begin by establishing a Base run on a five-year period as this would be the economic planning horizon of most range users. Towards the end of this section, however, we produce results where we compare this with a ten-year time scale to explore the longer-term implications of range management decisions.

We begin by running what we call the "Base" run. In this simulation, economic data that most closely reflects the present situation is used. Initial levels for boreholes, cattle and goats of 50, 20,000, and 6,250 were used respectively. The 20,000 herd size was based on an average of 400 cattle per borehole, which is the present recommendation (Tsimako, 1991). The first version of the model was run over five time periods - a total of ten seasons.

A number of interesting results were observed. First, as Figure 2 shows, the grass cover in the bush encroached zone had totally disappeared within the third season while grass cover in the grazing reserve saw a steady decline until a 60% coverage was reached.

**Figure 2. Bush Encroachment in Base Run**

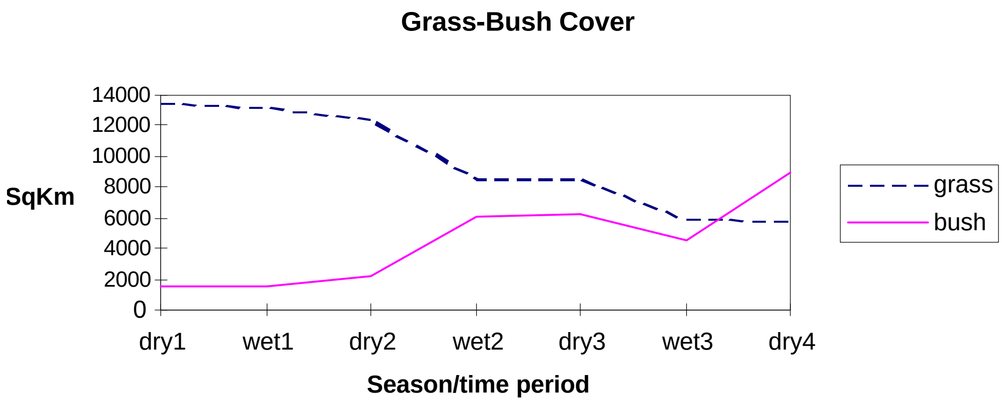



There is a slight increase in grass cover in the bush zone in the first wet period. This is caused by an increase in the total area classified as bush encroached zone. This reclassification is caused by an increase in the number of boreholes. Note, as more boreholes are put in place, more sacrifice and bush encroached zones appear. These come at the expense of the grass covered grazing reserve.

Empirical evidence suggests that a herd intensity as low as 30 cows is sufficient to start destroying grass cover in the sacrifice zone and a herd size of 80 is sufficient to destroy all grass coverage, in this spatially limited zone. In the bush encroached zone, because of the distance away from the borehole and thus a larger area, the upper and lower thresholds are slightly different. Trampling starts to have an impact with 150 cows and is maximised at 750. The third zone of course is the least affected and has the capacity to support a much larger herd size before trampling effects set in. It is estimated that the grazing zone is able to support 670 cows before the effect starts and is maximised at 2000.

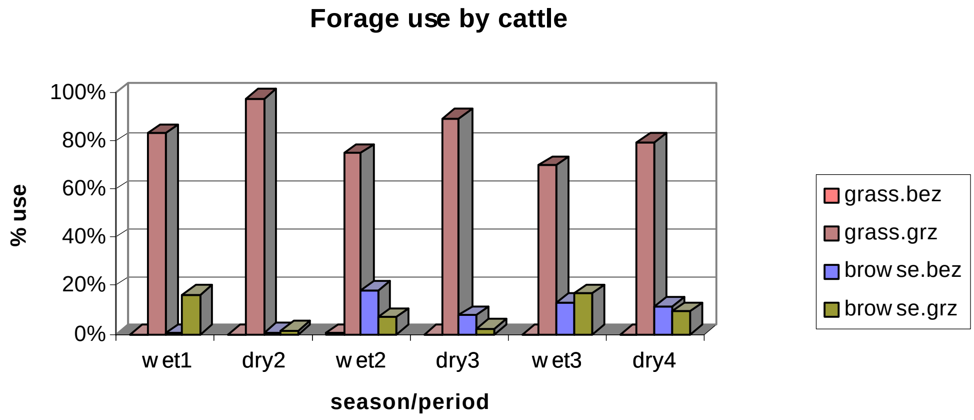
The herd intensity in the base run was 677. It apparently seems logical to have such a high herd density in spite of the damage it causes in the bush encroached zone. It would seem that the economics of the cattle industry dictate such a management strategy. In terms of the grass-browse ratio over the total area, it can be observed from Figure 3 that grass is slowly replaced by browse with a take over between the third wet and the fourth dry season.

**Figure 3. Grass bush cover**



Another interesting result is the feeding strategy. Figure 4 below suggests that the optimal strategy requires the herd to source its forage demand in the wet season from a combination of grass and browse. As the grass supply in the bush encroached zone is completely removed by the second wet season, all grass intake is now taken from the grazing reserve. The feeding strategy is implicitly driven by an analysis of trade-offs in the background. First, to walk to the grazing reserve requires more energy that in turn implies a higher demand for forage. However, as there is insufficient grass in the bush encroached zone and only 30 percent of total demand can be met by browse, the herd has no other choice but to walk to the grazing reserve.

**Figure 4. Forage use by cattle**

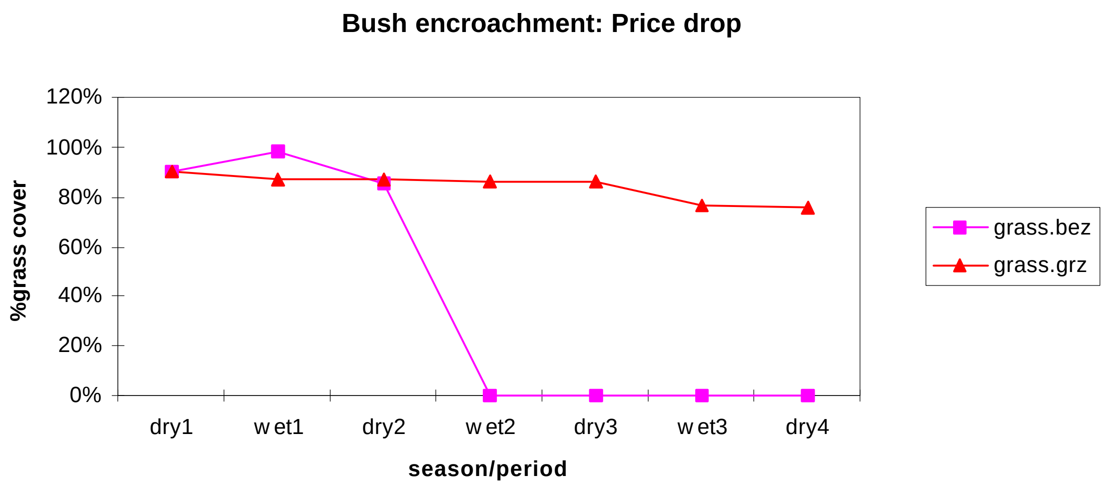



It is at the grazing reserve where some crucial dynamics are at play. During the wet season, the herd meets its forage demand by a combination of grass and browse. In fact, the herd takes in browse to the maximum allowed - 30%. The remainder is met by grass from the grazing reserve. This is primarily for two reasons. First, grass needs to be conserved in the wet season to ensure adequate supply for the dry season when there is very little growth. Second, if the grass is grazed below the critical threshold level, bush encroachment is set into motion and the availability of grass for the critical dry season is lowered.

The next few experiments investigate the sensitivity of the results to two key economic factors, the price of cattle and the cost of borehole investment, and one ecological factor, namely rainfall. Of the factors considered, two had significant effects on the end results. Reducing the price of cattle by approximately 20%, the rate and degree of bush encroachment was observed to be much slower. Although the grass cover in the bush encroached zone was wiped out by the second wet season, incidentally the same as in Base, the encroachment in the grazing reserve is lower as shown in the diagrams in figure six below. This occurs for two reasons. First, the number of boreholes put in place dropped from 385 in the Base to 295. This meant that the number of sacrifice and bush encroached zones opened is lower. Second, although from table one we see that the herd intensity was higher than in Base, the impact in the grazing reserve is minimal[2]. In essence, the marginal benefits of cattle outweigh the marginal cost incurred from the loss in grass cover in the grazing reserve. We can also infer that lower bush encroachment is a direct result of lower number of boreholes.

[2] Note: the minimum number of cattle needed before trampling intensity starts is if there is a herding intensity of 670 and above.

**Figure 5. Bush Encroachment when there is a price drop in cattle**



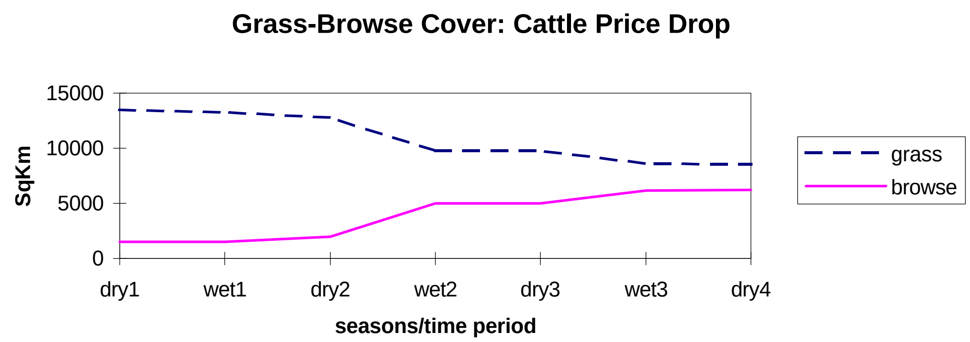




**Table 1. Summary of key results for sensitivity analysis**

| | Base | Price of cattle drop | Borehole cost drop | Dry spell |
|---|---|---|---|---|
| No of boreholes | 385 | 295 | 387 | 277 |
| Herd size | 649 | 674 | 670 | 674 |
| Area/lsu (ha/lsu) | 6 | 7.5 | 5.7 | 8 |

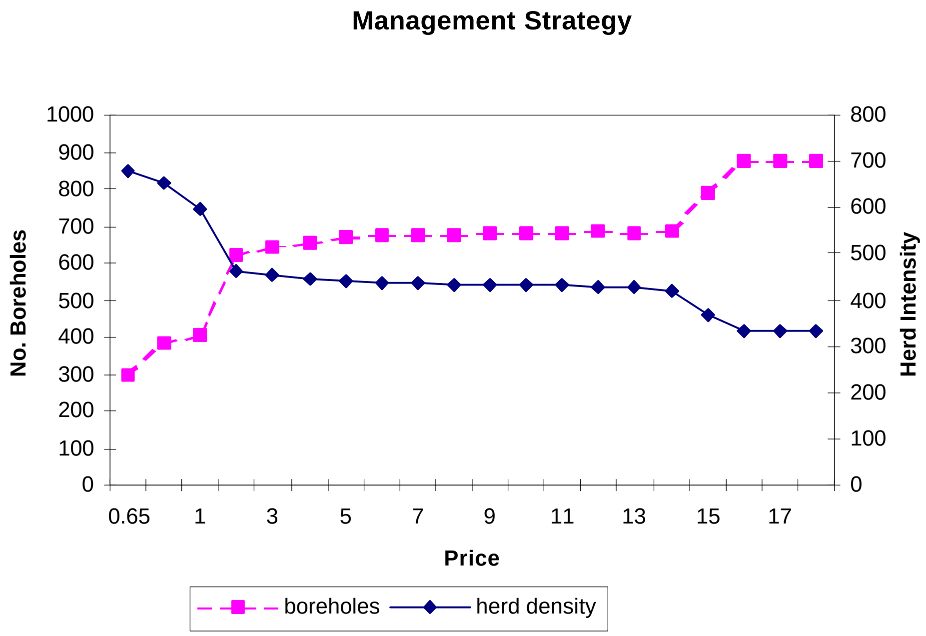
Table 1 above summarises the main indicators from the various sensitivity experiments. Logically, the dry spell run returns the lowest number of boreholes. At first glance the reader may be surprised at the herd size of 674. But on closer scrutiny, this is a credible strategy. The maximum number of cows that the grazing reserve can hold before trampling intensity starts is 670. Therefore, based on a cost-benefit analysis, a trade off is done between herd size and graze damage and the end result is a trampling intensity of 0.33 (33% damage) versus a drop in net benefit of 13 percent.

What comes clearly across from these results is that if the time planning horizon is five years, then the best strategy in the event of price or rainfall uncertainties is to drill between 275 to 300 boreholes and with a herd size of between 670 to 674. The results suggest that price of cattle has a significant impact on management options while domestic subsidies to reduce costs have very little impact on management strategies.

We now turn our attention to ecological limits and management strategies. The question we want to answer is whether there is a limit to the number of boreholes and cattle which the rangeland can sustain? To answer this undertook the following experiment. From the previous experiments, it was found that the price of cattle was a key economic factor determining borehole investment as well as stocking rates. We therefore began with the following assumption: if the price of cattle is increased, then logically, more cattle will be stocked and inadvertently more boreholes. The above question was rephrased to the following. is there an upper limit on the number of cattle that can be stocked no matter how much the price is increased?

In Figure 6, we have mapped the trend of boreholes and herd density. The maximum number of boreholes the site can sustain is 877. However, linked to this number is the herd intensity; 877 boreholes together with the presently recommended number of cattle of 400, would not be a sustainable strategy. The herd density or intensity as we have seen repeatedly in the previous experiments plays a crucial role in the bush-grass cover dynamics.

**Figure 6. Range Management Strategies**




The herd density associated with the maximum number of boreholes stabilises at approximately 350. Surprisingly, both indicators reach critical limits at the same point. Looking at Figure 6, we can distinctive phases. From a price of 0.65 per cow (650 Pula) to 3, the number of boreholes increases exponentially, after which it tapers off till a price of 13.

After 13, there is another slight jump and then levels off at 16. The herd density follows an identical but inverse path to that of the boreholes.

A couple of pointers to be aware at this point. First, the 877 borehole and 350 herd density is not an economically sustainable strategy; it is an ecologically sustainable level. Of course, if the price reaches 16 per cow, then the economic and ecological sustainable strategies coincide. Second, this carrying capacity is of course only valid for the rainfall patterns as used in the simulations. As clearly illustrated earlier, rainfall is the other critical factor determining strategies and if rainfall patterns change, so do the economic and ecological sustainable strategies.

There were many instances where issues relating to the length of the time horizon were raised. In order to investigate the influence time has on the results, we lengthened the time horizon in the model from five to ten periods. The baseline data were used in order to ensure consistent benchmarks for comparison. The rainfall data we used followed a similar pattern to those of the baseline with wet and dry years spread randomly. Extending the time period does impact on management strategies. In the base line scenario, the number of boreholes put in place increases from 385 in the short run case to 523 in the long run (Table 2).

**Table 2**

| | **Base short** | **Base long** | **Price drop short** | **Price drop long** | **Dry spell short** | **Dry spell long** |
|---|---|---|---|---|---|---|
| Boreholes | 385 | 523 | 295 | 403 | 277 | 496 |
| Herd density | 649 | 471 | 674 | 522 | 674 | 380 |
| Area/lsu (ha/lsu) | 6 | 6 | 7.5 | 7 | 8 | 8 |

A common trend is seen across all experiments. The herd density had dropped with an associated increase in the number of boreholes. A plausible explanation is that when faced with a longer time horizon and the need to ensure a sustainable stream of benefits, the strategy is to put in place more boreholes to reduce the trampling intensity. Although more sacrifice and bush encroached zones are opened up, it would seem that the cost associated with this trend are far outweighed by the cost incurred by trampling. However, the area per LSU does not change with the different time horizons. In other words, the number of livestock on the average remains the same irrespective of the time period but the management strategy is dependent on the time profile. This brings us to the end of the results[3].

[3] Refer to Figure 3 for a comparison to the Base case scenario

The present position of the Botswana Government is that there is rangeland degradation and it is caused primarily by the existing but ill-defined property rights regime. Consequently, policy

degradation in Botswana has been seriously challenged (Sandford, 1983; Abel and Blaikie, 1989), particularly in the Kalahari where the low relief and deep sand cover precludes soil

There is no doubt that shifts in vegetation composition and structure have been coincident with livestock keeping in the Kalahari, and that such changes are focused around surface

borehole spacing, stocking rate limits and herding strategies will always dictate the precise nature of the ecological impacts that occur and so need to be explicitly addressed by policy.

ii) a recommended stocking rate of 16ha/LSU; and iii) a desire by the Government to set up turnkey ranches. However, only the limit on borehole density is enforced with very little

contributed to the rapid change in forage composition. What is needed is an approach which addresses all three dimensions in order to optimise the use of the rangelands.

The obvious policy solution to increased demands for livestock grazing land is to increase borehole density. In fact there is an ongoing initiative to reduce borehole spacing, or in other

possibility of overlapping bush encroached zones and the widespread loss of grazing reserve areas. Under such a scenario of overlapping piospheres, drought related mortalities are likely

totals, likely to be both steeper and longer lasting.

In this manner, the widespread conversion of grassland to bush encroached savanna may well

economic viability of beef production on Kalahari pastures. However, increasing borehole density is a viable option and is, in fact, recommended when the time horizon is extended to 10

this policy, if adopted, must be accompanied by the recommendations on stocking rate and herd management which vary significantly for different bore hole densities. Failure to do so

affect beef production.

**Stocking Rate**

Previously, livestock policies have consistently failed to enforce recommended stocking rates on rangeland. Indeed, while Field's (1977) recommended stocking rate is 400LSU per borehole, Perkins (1991) found the range to be extreme in the eastern Kalahari, from 50 to 1000 LSU per borehole (n=143)[4]. Significantly, results from OLR suggest the existence of critical thresholds of borehole density, with increases acceptable only in conjunction with reductions in overall herd sizes. The existing failure of policy to control the latter therefore suggests that borehole spacing should be explicitly regarded as the critical variable by which livestock impacts upon Kalahari pastures can be regulated.

Although the forage requirements of domestic stock does not change over time, their ability to meet them does. In particular, the replacement of grass by woody biomass around the borehole (ie, . bush encroachment) results in livestock having to forage over greater distances to meet their energy requirements. The critical interplay is therefore between changing grass and browse ratios as determined by both the number of boreholes and the number of livestock that they carry. These two factors remain the only ones that can be addressed by policy, with borehole densities perhaps more critical and more realistically controlled by legislation than stocking rates.

**Herding Strategy**

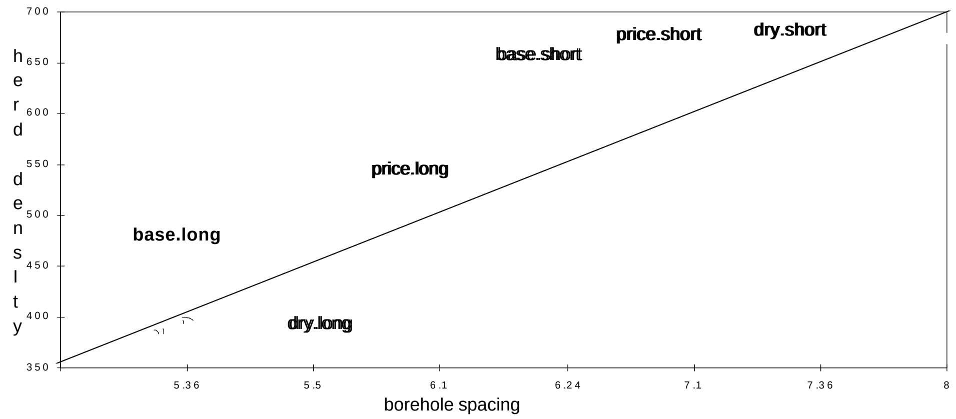
It should be emphasised that increasing the number of boreholes, particularly in the absence of controls on livestock numbers per borehole, is undoubtedly a risky strategy. The key to increased beef production, without damaging sustainability is probably a strategy that enables increased utilisation of the grazing reserve without damaging its integrity – through the imposition of sacrifice and bush encroached zones. In this respect Nicholson's (1987) recommendations made for Zebu cattle in Ethiopia apply with equal prescience to the Kalahari of Botswana. That is strategies of increased herding and reduced frequency of watering (e.g a 3-day cycle), that enable more distant pastures to be reached (Nicholson, 1987), are likely to lead to greater flexibility in the number of livestock the rangelands can support, than increasing borehole density.

'Drought relief' boreholes, that are in the grazing reserve and can only be utilised during a drought, are another alternative. However, in light of the fact that this was the idea behind the first boreholes in the eastern Kalahari, which subsequently moved to permanent utilisation, sets a precedent which makes this strategy unsustainable.

[4] n=143 reflects the sample size used in the study.

*y*

and herd density. A 45 degree line is drawn and we contend that scenarios below the line are with higher borehole spacing, the piosphere effect is minimised and, coupled with a lower herd illustrated by the dry.long point in the graph which corresponds to the dry scenario with a 10 long run experimental runs; the long run results always tend to move downwards and leftward term.



# Conclusion

There are a number of range management, and therefore policy, implications that arise from OLR. One of the most critical questions currently facing land use planners in Botswana, and particularly the eastern Kalahari study area, is 'what borehole density and stocking rates are sustainable?' Currently in the eastern Kalahari boreholes are spaced an average of about 8kms apart, with there being tremendous pressure to drill boreholes in between to accommodate the demand for ranches. This would result in ranches being an average size of 16km$^2$, which corresponds almost exactly with the maximum ecologically sustainable figure of 877 boreholes, generated by the OLR model (where the area of concern is 15,000 km$^2$). It should be noted however, that this borehole density corresponds with an average of 350 LSU/borehole, which is less than the currently recommended 400LSU.

Perkins (1991) found considerable variation in eastern Kalahari herd sizes on the 143 boreholes for which veterinary data existed in 1988. Then the maximum number of cattle on a borehole was found to be almost 1500 (or 1000LSU), and the minimum 77 (or 58 LSU), although it should be noted herd sizes were probably still somewhat depleted after the 1982-86 drought, which decimated the country's livestock population. OLR fails to capture this spatial variation in stocking rates simply because of the complexities of such modeling. Nevertheless, under the current situation of an almost 'laissez-faire' approach to permissible stocking rates per borehole, despite loan approvals being conditional on acceptance of the recommended 400 LSU, it would be unwise to suggest an increase in borehole densities would be ecologically sustainable. There is also a need to lengthen the time span over which such a scenario is ran, and experiment further with the effect that rainfall variations have upon OLR.

However, it is particularly revealing that the 8km 'rule of thumb' borehole spacing, which appears to based upon how far cattle can reasonably walk from the water point appears to be an ecologically sound recommendation. It corresponds with 234 boreholes in the study area modeled by OLR, a number that is conservative compared to those generated, from even the most unfavorable conditions. That such a ruling, apparently from colonial times, can withstand scrutiny under today's knowledge of rangeland dynamics and animal production is noteworthy.

Even so, in conclusion it should be emphasised that increasing the number of boreholes, particularly in the absence of controls on livestock numbers per borehole is undoubtedly a risky strategy. The key to increased beef production, without damaging sustainability is probably one that enables increased utilisation of the grazing reserve without damaging its integrity – through the imposition of sacrifice and bush encroached zones. In this respect Nicholson's (1987) recommendations for Zebu cattle in Ethiopia apply with equal prescience to the Kalahari of Botswana. That is strategies of increased herding and reduced frequency of watering (e.g a 3-day cycle), that enable more distant pastures to be reached (Nicholson, 1987), are likely to lead to greater flexibility in the number of livestock the rangelands can support, than increasing borehole density.

'Drought relief' boreholes, that are in the grazing reserve and can only be utilised during a drought, are another alternative. However, in light of the fact that this was the idea behind the

first boreholes in the eastern Kalahari, which subsequently moved to permanent utilisation, sets a precedent, which makes this strategy unsustainable.
There may be some concern by those working in livestock management in rangelands that OLR does not report mortality levels among livestock. We should like to point out here that in the first version of OLR, we decided to assume that optimality conditions imply no mortalities explicitly. The inclusion of mortality implies risk analysis and modeling risk analysis is a non-trivial task. It is however, an area for potential future work.

OLR in the present version, in-spite of certain stringent assumptions, can be used as a planning tool for Kalahari rangelands. Perhaps, somewhat ominously the results suggest that there will be a trend of increasing borehole densities under the current economic climate. The need for Botswana to seriously question the benefits of the EU beef subsidy and the sustainability of cattle keeping on Kalahari rangelands has never been greater.

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