Final Technical Report (FTR)

Environmental variability and productivity of semi-arid grazing systems

A.W. Illius, I.J. Gordon[1], J.F. Derry, Z. Magadzire[2] & E. Mukungurutse[2]

Institute of Cell, Animal and Population Biology, University of Edinburgh, Kings Buildings, Edinburgh, EH9 3JT, Scotland, UK. [1]Macaulay Institute, Craigiebuckler, Aberdeen, AB9 2QJ, Scotland, UK. [2] Matopos Research Station, Zimbabwe

Executive Summary

A very brief summary of the purpose of the project, the research activities, the outputs of the project, and the contribution of the project towards DFID's development goals. (Up to 500 words).

Climatic variability is the single largest cause of poverty in pastoral societies, resulting in increased livestock mortality and low productivity. Browse can be a major constituent of livestock diets throughout the year, but is especially important during the dry season, during droughts, and under most communal grazing conditions. However, little was known about what constrains its productive potential. The project sought to develop techniques for assessing the productive capacity of rangeland in relation to climatic and other environmental variability; to identify production constraints and analyse management strategies which address the temporal and spatial variation in the productivity of rangeland systems; to develop a decision-support system to assist policy scenario analysis.

We showed that flexible stocking strategies alone are not likely to be successful in coping with droughts. For subsistence pastoralists, the traditional policies of maintaining the maximum number of breeding stock, and of hoping that most of them will survive drought, may be as close as 'opportunistic' management can get to dealing with climatic variability.

We also showed that, in seasonally variable environments, the supply of dry-season forage determines the numbers of livestock that can be carried. Wet season resources may be important for production, but maintaining livestock numbers depends on dry-season nutrition. Browse could make a significant contribution here.

Browse is a dependable forage that is available over a longer growing season than grass. Its production may equal or exceed that of grass, and it may be the only forage available in heavily-utilised areas. Assessment of browse biomass is quite easy and methods of estimation we developed could be used as a rapid means of field assessment of range capacity.

In an investigation into ways to manage browse resources, we showed that lopping branches in the late dry season can provide valuable forage, particularly as a source of N, at a critical time of year. Lopping stimulates re-growth and appears not to affect the survival of tree.

We showed that cattle and goats use different forms of browse, with cattle selecting predominately the large-leaved species, while goats can make efficient use of the small-leaved species as well. There is little competition between the two livestock species. Mixed grazing and matching the ratio of animal species with forage resources would, therefore, be advantageous for livestock keepers in semi-arid regions where grass biomass has been depleted by high stocking rates.

Background

Information should include a description of the importance of the researchable constraint(s) that the project sought to address and a summary of any significant research previously carried out. Also, some reference to how the demand for the project was identified.

Semi-arid environments are prone to a high degree of climatic variability and low primary production, with the result that pastoralism is the principal form of land-use. Climatic variability is the single largest cause of poverty in pastoral societies because: (1) droughts that cause livestock mortality result in the destruction of wealth and loss of potential output; (2) climatic variation causes the long-term stocking rate to be lower than could be maintained under more reliable climatic conditions, because livestock populations take time to rebuild after die-offs. Clearly, ways need to be found of combating the economic and social effects of drought.

Browse can be a major constituent of livestock diets throughout the year, but is especially important during the dry season, during droughts, and under most communal grazing conditions. Although browse is a significant and comparatively (cf grasses) dependable component of forage resources, the assessment of its productive capacity for livestock and wildlife has been hampered by the very limited knowledge of browse production, its seasonality, its response to rainfall, and its acceptability to and proportion utilisable by different classes of livestock. This is a severe constraint on effective land use planning.

Development of effective management strategies for responding to climatic variability is impeded by lack of a systems framework for analysing livestock stocking policies and management practices. Effective decision-making requires that the important biological components of rangeland systems (ie the response of woody and herbaceous components of rangeland to rainfall and of animal responses to vegetation composition) are quantified and analysed in a systems context.

In June/July 1995 we held meetings with members of five rangeland extension agencies in Zimbabwe and Botswana (Zimbabwe: Agritex, ARDA, DRSS; Botswana: APRU and Range Ecology Section, Min of Agriculture) and asked what they perceived as needs for research in semi-arid rangeland. Strategies for dealing with drought, and better range management and assessment techniques, especially taking account of browse, featured prominently. Matching animal and vegetation resources was a related theme. Staff at Agritex and DRSS stressed that the production and utilization of browse was the largest unknown factor, yet it was obviously an important part of forage resources. Their views formed the basis of our research project.

Project Purpose

The purpose of the project and how it addressed the identified development opportunity or identified constraint to development.

To develop techniques for assessing the productive capacity of rangeland in relation to climatic and other environmental variability; to identify production constraints and analyse management strategies which address the temporal and spatial variation in the productivity of rangeland systems; to develop a decision-support system.

Research Activities

This section should include detailed descriptions of all the research activities (research studies, surveys etc.) conducted to achieve the outputs of the project. Information on any facilities, expertise and special resources used to implement the project should also be included. Indicate any modification to the proposed research activities, and whether planned inputs were achieved.

The project had three parts:

1. It evaluated the seasonality and variability in **browse production** in relation to the main environmental factors: rainfall, soil type and grass cover. It also measure browse harvest and re-growth under a range of lopping regimes.
2. It examined **browse utilisation** by foraging cattle and goats, especially during nutritional bottlenecks.
3. The **model** was developed into a prototype decision-support system for analysis of management options and assessment of rangeland capacity.

1. Browse production

(a) Field experiment. The study was carried out at Three Sisters, a part of the Department of Research and Specialist Services (DRSS) Matopos Research Station, 28 km S of Bulawayo, SW Zimbabwe (20° 23'S 28° 31'E) at an altitude of 1430m. The site has a mean annual rainfall (40 year average, 1931-1971) of 586 mm, which falls mostly between November and March.

Two soil types, a clay soil and a sandy soil are present at the site, separated by a stream. Two sites were located on either side of the stream and about 100 m from it. The land slopes up from the stream at about 2°, and two further sites were located higher up this catena on either side, and between 200 and 500 m from the stream. Thus the study comprised four sites, two on the clay soil and two on the sandy soil, and at either near the bottom or mid-way up the catena. The vegetation of the site is semi-arid savanna, with predominant herbaceous species: *Heteropogon contortus, Aristida* spp, *Rrynchelytrum nerviglume, Digitaria pentzii, Cynodon dactylon,* and forbs; and predominant tree species: *Acacia karoo, A. nilotica, Combretum apiculatum, Rhus pyroides* and *Ziziphus mucronata*. Tree density was greater at the sites near the base of the catena, and they are thus referred to as either Sand or Clay High Tree Density, whereas the sites further up the catena had low tree density. At each site, four 20 x 40 m plots were established and fenced. Grass basal cover was reduced on half the plots by herbicide.

Over four growing seasons, (1998/9 – 2002) grass and browse production were measured on the plots. Shoot growth was measured on marked trees. Water balance was measured by neutron probe (data still being analysed).

(b) Estimating range resources. We developed a method of estimating browse production using indirect measurement. Calibrations for estimating browse leaf, current season's twig and wood mass in relation to tree height, basal diameter and canopy volume were established for the seven major browse species at the end of the growing season in 1999, 2000, 2001 and 2002. A total of 143 trees were harvested and the dry mass of their separate components determined.

(c) Controlled studies of water use. To complement the field study, two experiments to estimate water use efficiency in browse *(Colophospermum mopane, Dichrostachys cineria, Acacia karroo, Combretum apiculatum*) and grass (*Aristida barbicolis, Cymbopogon plurinoides, Heteropogon contortus, Themeda triandra)* species were conducted. Plants were grown in 1 m plastic pipes either in a sandy or clay soil and watered to field capacity either every 2, 4 or 6 weeks. Water use and biomass production were measured.

(d) Management of browse resources for dry-season fodder in Communal Areas. At the first workshop, stakeholders and farmers identified lopping of branches of *Colephospermum* *mopane* and *Combretum apiculatum* as a means of producing browseable material in October, when other forages are in critically short supply. In a pilot experiment, initiated in Bidi communal area, we examined browse yields and regrowth at three severities: the removal of 0.25, 0.5, 0.75 or none of the canopy, at the beginning of November in each season. After the lopping treatments were applied the following tree measurements were taken: height, basal circumference and canopy volume. Four shoots on each tree were marked and length measurements taken and the number of leaves counted. At the end of each growing season in April, tree and shoot measurements were repeated and the amount of regrowth that had accumulated on each tree was quantified. Treatments were repeated in two subsequent years, and production and survival of the trees monitored.

2. **Browse utilisation**

(a) Field experiment on browse utilisation by cattle and goats. We wished to determine how livestock respond to changes in the relative and absolute abundance of browse and grass. The experiment was carried out in April 1999, Sept. 1999 and July 2000. Six paddocks of 50 x 365 m (1.875 ha) were established, and pre-grazed or pre-browsed to alter the forage availability. Forage biomass was estimated before and after each intensive study period, which consisted of estimating diet selection and forage intake by groups of six goats and six steers. Each study group was allowed a week in each paddock to acclimatise before observations were made over the following week, and each paddock was used twice, in rotation. Foraging time and plant selection were estimated by scan and focal sampling, and diet selection and food intake estimated by the alkane technique.

(b) Controlled studies to evaluate browse species intake rates by cattle and goats, and comparison with grass. To compare intake rates in cattle and goats, we offered branches of eight important browse species and patches of five grass species separately to four animals of each species. Each animal was allowed to feed for a few minutes or until about half of the forage offered had been consumed. The number of bites and time taken were recorded and bite mass was estimated from weight loss of the forage, corrected for DM. To examine what limits intake rate of browse plants we manipulated their characteristics by removing thorns and reducing the number of leaves of branches offered to goats and cattle.

(c) Use of browse resources in Communal Areas. This work was also initiated as a result of discussions at the first workshop. PRA was used to learn about farmers' perceptions of browse resources used by cattle and goats. Direct observation was used to determine the utilisation of browse by cattle and goats by season on communal rangeland and to determine the activity pattern of cattle and goats in mixed-species grazing. The work was conducted in Bidi during 1999 and 2000, with three observations of one week's duration in the dry season: March, June, and September of each year. Focal and scan sampling of village livestock during their normal foraging routine was used to describe diet selection. Forage abundance was estimated.

3. **Decision support modelling of semi-arid rangeland.** This consisted of modelling the effects of climatic and spatial variation on livestock systems, in order to conduct policy analysis. The model runs on daily rainfall data, and calculates daily vegetation growth and its allocation to plant parts, the selection and intake of these by animals, the animals' consequent energy and protein balances, body growth, reproduction and mortality. It therefore simulates animal population dynamics by coupling them to vegetation biomass dynamics, allowing the underlying mechanisms to dictate the performance of the system over the chosen time scale. We developed all aspects of the existing model: the soil-water-plant component, the prediction of foraging behaviour and diet selection, and by explicit treatment of spatial variation. The model was developed to allow spatial heterogeneity to be represented by a chosen number and size of cells in a grid. For each cell, soil, vegetation and altitude can be specified, and a water point can be located.

The user interface was upgraded by collating the input parameters into a file system. A report-generating module was written to summarise the output data in a number of flexible ways. The GIS interface was upgraded to allow binary IDRISI raster images or ascii files of soil, topography and vegetation cover GIS layers to be input to the program. A module was developed that makes the necessary interpolations between these data inputs and the additional inputs needed by the program (*eg*, soil depth, tree and grass biomass).

The latest version is SimSAGS 3.1 (SimSAGS stands for Simulation of Semi-Arid Grazing Systems). Its strengths lie in its adaptability as a prototype decision support simulation tool in application to real world scenarios. The user can specify a wide range of inputs, such as land type and area, rainfall, etc, then run the simulation for a given number of years. Specified model outputs can be graphed and recovered from file for analysis.

These are some of the features introduced during development of the current version of SimSAGS:

- Attractive user definable graphical user interface (stores window sizes and positions)
- Automated screen capture for graphs and grids
- Extensive data output filing system
- Unlimited user defined data output file (choice of over 500 variables)
- Summary statistics of user defined data output file

- Unlimited numbers of plant and animal types can be added
- Established soil water balance model
- Alternative non-spatial model (retained earlier version)
- User definable livestock watering point location
- Text file daily rainfall data input
- Fully randomised rainfall sequence re-sampling
- Support for simulation replicates

- GIS import control for rainfall, wind speed, landscape topography, soil fertility, soil depth, vegetation height, and plant initial biomass
- IDRISI raster binary GIS layer compatible
- Text flat-file GIS alternative

- Intuitive model parameter structure
- One-click access to model parameters
- Model parameter search mechanism
- Quick access model parameter group buttons
- Easy editing of model parameters with automatic data type recognition.
- Browse prompts for file/folder locations; easy "yes/no" responses
- Active and passive edit alerts for data type changes
- History list for model parameter locations
- Edit undo / redo mechanisms
- Low committal model parameter update avoiding full simulation
- Data protection lock during update / simulation

Two studies were completed, examining the effects of (a) temporal and (b) spatial variation in primary production on livestock population dynamics.

Outputs

The research results and products achieved by the project. Were all the anticipated outputs achieved and if not what were the reasons? Research results should be presented as tables, graphs or sketches rather than lengthy writing, and provided in as quantitative a form as far as is possible.

1. Browse production

(a) Field experiment. Browse and grass production data are summarised in Table 1 and Fig 1. Grass and browse had similar inter-annual variability. Annual production of wood was more variable, due to mortality of trees in some years and on some plots being recorded as negative production. Grass and browse had similar responses to rainfall (Fig 1). The high rainfall in 1999/0 lead to runoff losses and flooding, and so shows lower rain use efficiency. Years of moderately high rainfall may have a carryover effect on browse production in the following year.

Table 1. Annual production of grass, browse and wood (kg DM/ha) over four years on sand and clay sites

Site		1998/9	1999/00	2000/01	2001/02	Mean	Inter-annual cv
Soil	**Tree density**	**Grass**					
Sand	Low	626	1116	740	634	779	0.296
	High	993	1278	1738	1238	1312	0.237
Clay	High	1573	2060	2962	1700	2074	0.302
	Low	683	1207	1699	1037	1157	0.365
Mean		**969**	**1415**	**1785**	**1152**	**1330**	**0.266**
		Browse (leaf + twig)					
Sand	Low	823	1443	1748	1151	1291	0.307
	High	635	1920	1468	1462	1371	0.391
Clay	High	988	2045	1563	1525	1530	0.283
	Low	960	2043	1913	1499	1604	0.304
Mean		**851**	**1863**	**1673**	**1409**	**1449**	**0.303**
		Wood					
Sand	Low	270	532	450	209	365	0.413
	High	402	639	859	56	489	0.704
Clay	High	846	1406	1766	262	1070	0.615
	Low	299	814	671	251	509	0.545
Mean		**454**	**848**	**936**	**194**	**608**	**0.570**
		Rainfall (mm)					
		422	915	629	516	621	0.345

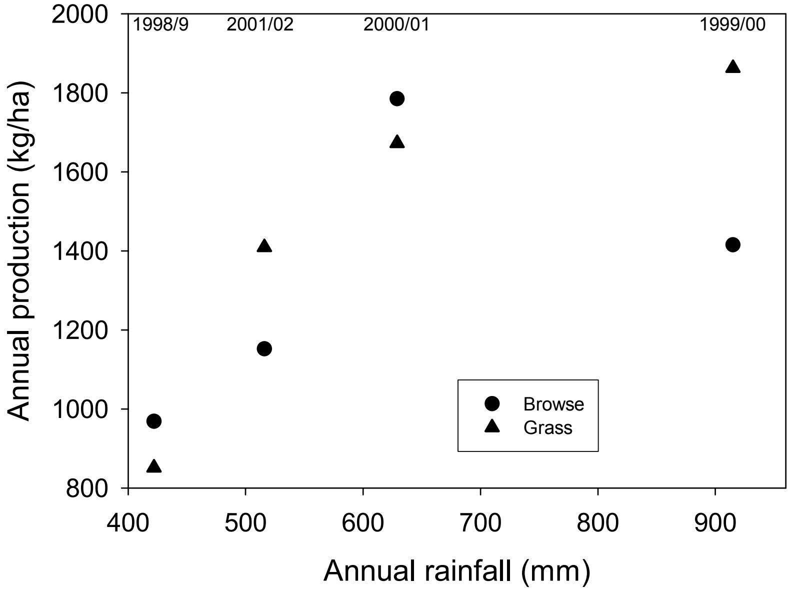

Fig.1 Rainfall affects annual production of grass and browse.

Message: Browse may constitute 20-70% of forage resources in savannas, and may be virtually the sole resource in heavily-grazed areas. Rainfall is the main environmental influence on annual primary production, and its response to rain does not differ much from that of grass. Grass cover and soil type have relatively minor effects.

1 (b) Estimating range resources. For the estimation of browse biomass, we developed prediction equations for estimating browse leaf, current season's twig and wood mass in relation to tree height, basal diameter and canopy volume. The simplest measure to estimate tree production is height. Good predictions of the tree production parameters were made after accounting for height and species. Equations that incorporated both height and diameter reduced the standard error of the prediction as a proportion of the mean, giving the best estimate.

Table 2. Biomass estimates in savanna trees. Accessible browse is the browseable current season's growth that is within 1.5 m of the ground. Wood is total dry mass of the remainder of the tree.

	Accessible browse (leaf+twig, kg)				Wood (kg)			
Tree ht (m):	1	2	3	4	1	2	3	4
Acacia karroo	0.08	0.35	0.51	0	0.15	1.42	5.23	13.24
Acacia nilotica	0.10	0.46	0.65	0	0.17	1.57	5.80	14.66
Acacia rhemanniana	0.08	0.34	0.50	0	0.11	1.08	3.98	10.07
Combretum hereroense	0.10	0.46	0.67	0	0.13	1.23	4.56	11.55
Rhus pyroides	0.04	0.17	0.24	0	0.07	0.65	2.41	6.09
Terminalia sericea	0.08	0.37	0.54	0	0.10	0.95	3.53	8.93
Ziziphus mucronata	0.06	0.25	0.35	0	0.12	1.14	4.23	10.70
Mean	**0.08**	**0.34**	**0.50**	**0**	**0.12**	**1.15**	**4.25**	**10.75**

Tree diameter, height and species accounted for most of the variation in the mass of current season's twig, number of shoots and leaf produced, but after fitting these, there were significant annual differences in these variables. There were no significant annual differences in wood and total biomass after accounting for height, diameter and species. Replacing height by volume did not improve the leaf and current season twig biomass estimate. Table 2 illustrates the results obtained: an average sized tree yields about 1/3 kg of browse. Tree density in savannas is obviously highly variable, but a hectare might typically contain about 3000 trees >1m high, and about 500 trees of 1-2 m and >2 m high.

Message: When combined with an estimate of tree density, rapid field assessment of the forage contribution of browse trees can now made.

1 (c) Water Use Efficiency. Controlled studies provided evidence of water use efficiency (WUE) that is vital to modelling semi-arid grazing systems. Plant growth was affected, as expected, by watering frequency treatments, but WUE was similar across treatments. Although both browse and grass species showed significant diversity in growth, in biomass partitioning between above- and below-ground parts, and in water use efficiency, the similarities between plant types is more striking (Table 3). In general, browse species were affected by soil type but grasses were not.

Table 3. Water use, plant growth and Water Use Efficiency in savanna browse and grass tabulated by species and by soil type (mean of watering frequency treatments).

	Water use (kg)	Above-ground production (g DM/plant)	Above ground WUE (g/kg)	Root growth* (g DM)	Total WUE (g/kg)
Browse:					
A. karroo	10.9	16.5	1.55	26.6	3.96
C. mopane	9.1	9.4	1.06	33.4	4.82
C. apiculatum	8.7	11.1	1.31	21.0	3.57
D. cineria	10.6	18.6	1.76	26.5	4.42
Clay	11.2	16.7	1.49	30.5	4.21
Sand	8.4	10.9	1.30	23.3	4.07
Mean	**9.8**	**13.9**	**1.42**	**26.9**	**4.19**
Grass:					
A. barbicolis	8.2	9.4	1.16	4.1	1.68
C. plurinoides	9.5	10.7	1.14	28.8	4.19
H. contortus	9.9	17.4	1.76	36.3	5.56
T. triandra	9.6	11.9	1.26	32.3	4.68
Clay	9.6	12.7	1.32	25.9	4.02
Sand	7.2	9.6	1.33	19.9	4.10
Mean	**9.29**	**12.4**	**1.33**	**25.4**	**4.03**

*Total root biomass for grasses rather than growth over the measurement period.

Trees growing on clays used more water than those growing on sand. *A. karroo* and *D. cineria* used up about 26 percent more water on clay than *C. mopane* and *C. apiculatum.* There were no significant differences in water use between species when growing on sands. *A. karroo* and *D. cineria* growing on clays produced significantly more biomass than *C. mopane* and *C. apiculatum* but the differences in production between the four species on sands was not significant. The species performed differently on the different soil types. *A. karroo* had the highest total growth on clays and *C. mopane* yielded highest on sands. Grass growth and water use were not affected by soil type.

Message: The similarities between browse and grass species in growth, in biomass partitioning, and in water use efficiency, are greater than diversity within and between plant types.

1 (d) Management of browse resources for dry-season fodder in Communal Areas. Significantly more shoot material was harvested on *C. mopane* than *C. apiculatum* trees and on clay soils than on sands. Shoot biomass harvested from the trees depended on the lopping level with trees that had 75 percent branches lopped yielding highest . The harvested shoot material increased as the years went by and the highest yield was in the third season (2000/01).

The amount of re-growth that accumulated on the tree increased with severity of lopping. Re-growth material out-yielded the shoot material that was harvested (671, 999 and 1053 g DM harvested and 765, 2807 and 4632 re-growth accumulated from the 25, 50 and 75 percent lopping levels respectively). More re-growth grew on trees found on clay soils than on sandy soils and on *C. apiculatum* than on *C. mopane* trees and the highest yield was in 1999/00 and the least in 1998/99 (2750 and 1463 g DM respectively). Re-growth material did not yield any fruits, even on the three year old branches, but carried more green material into the dry season, and lopped *C. mopane* trees carried leaf material until the end of the dry season.

Shoot growth was stimulated by lopping, and this effect increased with the severity of the lopping regime. The shoot length changes were 6, 9 and 12 cm for the 25, 50 and 75 percent lopping levels respectively. The stimulatory effect of lopping on shoot growth was carried over from one season to the next and was 4, 7, and 13 cm for 1998/99, 1999/00 and 2000/01 seasons respectively.

Table 4. Amount of browse harvested and regrowth (g DM/tree) under three severities of lopping trees in communal rangeland.

Treatment:		25%		50%		75%	
Year	**soil**	harvest	regrowth	harvest	regrowth	harvest	regrowth
		C. apiculatum					
1998/99	**sand**	28	88	60	2188	74	11742
1999/00		81	740	139	2120	160	4009
2000/01		985	482	1557	2417	1658	2691
1998/99	**clay**	58	171	126	738	168	1894
1999/00		150	1354	250	3874	288	10876
2000/01		758	1612	1446	4903	1203	5765
Mean		**343**	**741**	**596**	**2707**	**592**	**6163**
		C. mopane					
1998/99	**sand**	66	25	131	257	154	292
1999/00		224	574	317	1734	257	2672
2000/01		1176	322	1993	405	1848	467
1998/99	**clay**	245	810	428	1513	383	3681
1999/00		625	2383	971	8140	641	5530
2000/01		3655	620	4542	5394	5807	5964
Mean		**999**	**789**	**1397**	**2907**	**1515**	**3101**

harvested material: s.e.d. species=40.7, lopping level =47.0 soil=33.3 year=40.7
regrowth: s.e.d. species=357.2, lopping level =505.1 soil=357.2 year=437.4

The lopping treatments had no effect on tree girth increment whereas tree height was stimulated by lopping. The more severe the lopping the more height that was accrued. *C. mopane* trees had a higher mean height change than *C. apiculatum* trees. Tree canopy volume change was negatively affected by lopping with trees that had 75 percent of branches lopped, accumulating the least canopy volume and those that had 25 percent of their branches lopped accumulating more canopy volume. The amount of volume accumulated varied with season and in the 2000/01 season trees accumulated the highest volume and the least was in 1999/00.

Message: Feeding new tree shoots to livestock as a dry season supplement could improve livestock productivity in semi-arid communal areas at a critical stage in the season. Cutting of tree branches induced the re-growth of material that can be consumed by livestock. Over the course of the experiment, tree survival appears not to have been affected and the amount of material harvested and the re-growth accumulated on the trees was greatest when 75% of the canopy was lopped for fodder.

2 Browse utilisation

(a) The field experiment conducted in April 1999 show that both cattle and goats increased the amount of browsing in paddocks that had been treated to reduce grass abundance by pre-grazing with cattle, and decreased browsing in paddocks pre-browsed by goats (Fig. 2). Cattle spent up to 20% of their time browsing when grass was depleted, compared with nearly 70% by goats.

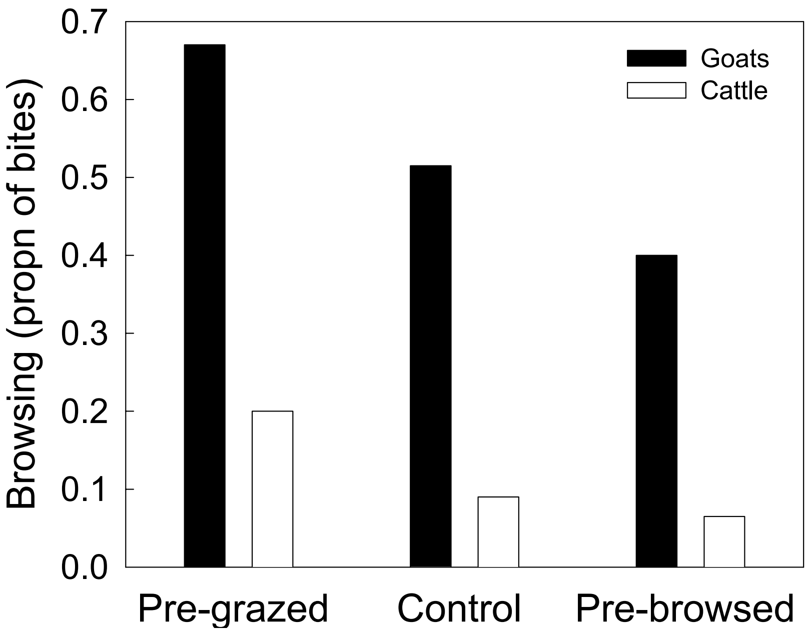

Fig.2 Browsing increases or decreases in response to resource depletion, especially in goats.

Similarly, in the dry season of 2000, goats had higher proportions of browse in their diets, and responded to depletion either of grass or both grass and browse by increasing the use of browse. Cattle, on the other hand, made little use of browse, even when grass was depleted (Table 5).

Table 5. Proportion of browse and grass in the diets of cattle and goats during the dry season of 2000.

Animal species	Treatment	Browse	Grass
Cattle	Low-browse	0.01	0.99
	Low-grass	0.11	0.89
	Low-grass-browse	0.05	0.95
Goats	Low-browse	0.15	0.85
	Low-grass	0.25	0.75
	Low-grass-browse	0.37	0.63

In general, cattle and goats responded to different cues in their feeding environment. Cattle responded to changes in grass biomass while goats responded to changes in browse biomass. Therefore, the cues were based on the preferred resources, and were related to their feeding habits. Goats were more flexible than cattle in their behavioural responses at the spatial scale of the experiment. Cattle used broad-leaved browse species, while goats were not limited in the types of browse species they used. This resulted in a low diet overlap, removing the potential for competition and supporting the case for mixed species grazing which would enhance resource utilisation.

Message: Browse is an important resource in the feeding strategy of goats. In the presence of declining quantities of grass and browse, goats can expand their diet breath to mitigate the effects of low quantity and quality in food resources. There is little competition for browse resources between cattle and goats, though both take substantial proportions of grass in the diets when it is available. Cattle are less adaptable to seasonal changes in resource availability.

2 (b) Intake rate whilst browsing and grazing. Detailed comparison of feeding mechanisms of cattle and goats clearly shows that, because bite size is similar for the two animal species when browsing (unlike when grazing), intake rate per unit metabolic body mass is much lower in cattle when browsing than in goats (Table 6). This suggests reasons why cattle are less inclined to browse than goats. Goats showed quite similar intake rates of browse and grass.

In general, cattle had higher instantaneous intake rates on grass than browse, but only came close to matching the intake rates they achieved on grass when they browsed on broad-leaved thornless species. Goats were equally efficient on grass and browse, and had higher intake rates per metabolic body weight than cattle. Therefore, instantaneous intake rate measured under controlled conditions predicted that cattle should select broad-leaved browse species in preference to species with small leaves and thorns. This concurs with the results of the cattle in the field experiment and the communal area study.

Table 6. Foraging behaviour of cattle and goats when feeding on browse and grass.

	Bite rate (min^{-1})		**Bite mass (g DM)**		**Intake rate (g/min/kg $W^{0.75}$)**	
Browse species	**Cattle**	**Goats**	**Cattle**	**Goats**	**Cattle**	**Goats**
Acacia karoo	16	40	0.4	0.3	0.1	1.3
Acacia geradii	21	40	0.4	0.3	0.1	1.3
Combretum apiculatum	16	14	2.3	0.8	0.5	1.0
Dichrostachys cinerea	19	33	1.1	0.7	0.3	2.5
Grewia monticola	22	15	1.8	0.7	0.5	1.0
Rhus pyroides	18	17	1.2	0.9	0.3	1.6
Securinega virosa	23	24	0.8	0.4	0.2	1.0
Ziziphus mucronata	15	20	0.7.	0.7	0.1	1.4
Browse mean	**18.8**	**25.4**	**1.1**	**0.6**	**0.3**	**1.4**
Grass species						
Cymbopogon plurinodis	11	9	5.2	1.3	0.7	1.0
Chloris virgata	10	10	8.3	1.1	1.0	1.0
Heteropogon contortus	7	7	9.4	2.1	0.8	1.1
Panicum maximum	11	8	6.1	3.1	0.9	2.0
Themeda triandra	10	10	5.0	1.9	0.7	1.5
Grass mean	**9.8**	**8.8**	**6.8**	**1.9**	**0.8**	**1.3**

Reducing the leaf density of browse plants lowered the intake rate in cattle, while removing thorns increased it (Table 7). Intake rate in goats was not significantly affected by leaf density or thorns. This shows that cattle are more sensitive to browse plant characteristics, and that goats are highly adaptable browsers.

Table 7. Intake rate per metabolic body weight (mg/s/kg $W^{0.75}$) of browse by cattle and goats in relation to browse characteristics.

Treatment	**Log intake rate**		**Untransformed intake rate**	
	Cattle	Goats	Cattle	Goats
Reduced leaf density	0.2802	1.1726	1.9	14.9
Remove thorns	0.5432	1.2420	3.5	17.5
Control	0.4207	1.2251	2.6	16.8
s.e.d.	0.04799			

Message: Cattle cannot make good use of browse because they have low intake rates, particularly when browsing species with thorns and small leaves, such as the *Acacias*. Goats, on the other hand, have high intakes when browsing a wide range of species, as well as when grazing.

2 (c) Use of browse resources in Communal Areas. We conducted a PRA with local livestock keepers to learn about what they recognise as important browse resources. Results from PRA and direct observation are given in Tables 8, 9 and 10 below.

Table 8: Farmers' ranking of preference of browse by cattle and goats.

Ranking	Species preferred by cattle	Species preferred by goats
1	*Combretum apiculatum*	*Acacia tortilis*
2	*Grewia monticola*	*Boscia albitrunca*
3	*Combretum herrerense*	*Ziziphus mucronata*
4	*Strychnos innocia*	*Colophosperum mopane*
5	*Lonchocarpus capassa*	*Combretum herreroense*
6	*Colophosperum mopane*	*Grewia monticola*

Table 9: Calendar of use of browse by goats from January to December.

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Acacia tortilis	L	LW	LW	LW	LW	LW	LP LD	LW P	LW P	LW P	LW P	LW P
Boscia Aaitrunca	LW	LW	LW	LW	LD	LD	LD	LW	LW	LW	LW	PW
Colophosperum mopane	LW	LW	LW	LW	LD	LD	LD	LD	LD	LW	LW	LW
Grewia monticola	LW	LW	LW	LW	LD	LD	LD	LD	LD	LW	LW	LW
Ziziphus mucronata	LP W	LP W	LP W	LP W	LW PD	LW PD	LW PD	LW PD	LW PD	LW PD	LW PD	LW PD
Combretum herreroense										LW	LW	LW

KEY: L = leaves; P = pods; W = wet (fresh); D = dry.

Table 10: Calendar of use of browse by cattle from January to December

SPECIES	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Combretum apiculatum	LW	LW	LW	LW	LW	LD	LD	LD	LD			
Combretum herrerpemce	LW	LW	LW	LW	LW	LD	LD	LD	LD			
Colophosperu mopane	LW	LW	LW	LW	LW	LD	LD	LD	LD			
Grewia monticola	LW	LW	LW	LW	LW	LD	LD	LD	LD	LW	LW	LW
Lonchocarpus capassa										LW	LW	
Strychnos innocia	LP W	LP W	LP W	LP W	LP W	LP W	LP W	LP W	LP W	LP W	LP W	LP W

Direct observation of free-ranging cattle and goats on communal rangeland was used to determine the utilisation of browse by cattle and goats. Browsing took up only a small proportion of the time of cattle in the communal area study (Table 11). It increased from March to June because in March, grass, the preferred resource, was still available. By June, the fields were open to livestock and they had access to stover and this took up a large proportion of their time. In September, there was very little browsing because leaves from Mopane trees had been consumed by Mopane worm and farmers started supplementing with stored stover. Cattle offered stover in the morning attempted to graze (mainly grass stems) later, as browse was limited.

Table 11: Percentage of observation time spent on each activity by cattle and goats when not in kraals.

	Cattle			**Goats**		
Activity	**March**	**June**	**Sept.**	**March**	**June**	**Sept.**
Browsing	1.4	4.5	0.9	45.5	56.5	58.5
Grazing	59.0	28.0	59.7	30.8	6.7	11.4
Stover		35.1	4.0		5.3	0.7
Chewing			0.4			
Ruminating	14.4	5.4	2.2		7.0	6.3
Walking	15.8	12.5	18.1	13.4	17.1	14.9
Watering		1.1	1.3	3.3	4.3	2.1
Standing	2.2	4.2	10.2	2.0	2.1	4.2
Playing		1.4	1.3			
Disturbance		0.3	0.9			
Lying down	7.2	7.4	0.9	5.0	1.1	2.1

In all the months, goats spent more time on feeding activities than cattle. Browsing took up about half of the time of goats. In March, the goats grazed for a significantly longer period of time but this fell sharply in June, picking up a little in September. Stover is not an important food resource for goats, but they use it when the fields are first opened.

Cattle use a much narrower range of browse species than did goats (Table 12). This could partly be explained by the fact that goats travel more than cattle and, therefore, increase their access to other resources. Cattle walked between 2.6 and 5.1 km/day, and goats between 6.2 and 9.0 km/day.

Table 12: Species selection of grass and browse by goats in 1999 (expressed as percentage of total species counts made).

	Cattle			Goats		
	March	**June**	**Sept**	**March**	**June**	**Sept**
Browse:						
Acacia erubescens					4.0	20.8
Azanza gackiana				0.9	1.6	5.8
Acacia galpini						13.3
Acacia nilotica				4.4	3.2	1.7
Acacia tortilis				15.9	7.1	1.7
Boscia albitrunca					0.8	0.0
Combretum apiculatum			2.8		13.5	2.5
Combretum hereroense						4.2
Combretum imberbe					1.6	4.2
Dichrostachys cinerea					0.8	
Grewia monticola					0.8	
Lonchocarpus capassa		1.3				0.8
Cassia abbreviata					2.4	
Colophospermum mopane	3.4	4.6	1.4	16.8	27.0	4.2
Euclea divinorum						0.8
Gardenia spatulifolia					0.8	1.7
Peltophorum africana					0.8	
Sclerocarya birrea				8.0	3.2	
Strychnos madagascariensis	0.0	0.4	0.7		1.6	
Terminalia sericia					1.6	
Ziziphus mucronata						18.3
Forbs				12.4	7.1	0.0
Unknown species						1.7
Grasses:						
Aristida barbicollis	25.3	14.6	75.0	25.6	1.6	5.0
Cynodon dactylon	35.6	12.6	1.4			2.5
Chloris virgata	13.8	5.4			2.4	
Dichanthium papillosum			12.5			
Eragrostis rigidior	16.1	9.2	0.0	8.0	0.8	1.7
Heteropogon contortus	4.6					
Panicum coloratum	1.1			7.1	2.4	1.7
Panicum novemnerve					0.8	
Unknown spp				0.9	0.8	6.7
Solanum incanum					4.8	
Stovers:						
Groundnut leaves		0.4				
Bamara nuts					0.8	
Maize		51.5	6.3		0.8	
Millet					1.6	
Sorghum					5.6	0.8

Grass biomass and species diversity is low in this communal rangeland, despite the large area covered by the work. In June and September, the range of species of grass which were selected by cattle declined as grass biomass became depleted In September, *Aristida barbicollis* and *Dichanthium papillosum* became important because they are the most abundant and are not consumed as much after the rains when more preferred species are available.

Out of the large selection of browse species available, cattle choose only a few, the common factor being that the tree species selected are all broad-leaved. *Lonchocarpus capassa* is considered as a ‘reserve’ by the farmers because it is evergreen and too tall for goats (and cattle) to reach. Although *Combretum apiculatum* and *Strychnos* were not defined as a reserve, the trees of this species in the area are generally tall and the former is also almost evergreen.

Goats used a wide range of trees. Some, such as *Strychnos*, *Gardenia* spp and *Lonchocarpus* are consumed as fallen leaves because the browse on these trees is out of the reach of goats. *Sclerocarya birrea* has fruits which the animals consume whole, although the hard seed appears not to be digested. Forbes form an important part of the goat diet even when they are dry. There is a wide range of species, especially in fallow lands.

Livestock have resource niches which they use when forage becomes scarce. For example, *Cynodon dactylon* is found next to the dam and is green when other grasses are dry (but there is a limitation to its intake because it forms a carpet making it difficult to bite). Other niches include the stover in the fields, as well as the grass which grows on the contours. In the same fields, some farmers allow trees to grow (rather than stumping them) because they know the value of them to their livestock. Most of the *Strychnos* is found in the fields and fallow lands. Species such as *Acacia tortilis* do not grow beyond about a metre in height, but would be more productive if they were allowed to grow in the protection of the fields.

The selection pattern of the animals is not fixed. Although data collected in September 2000 are not presented, they show that there was more grass in 2000, following the heavy and prolonged rains of the wet season. Cattle therefore grazed most of the time and farmers were not supplementing with stovers. Farmers who tried supplementing noticed that the animals rejected the stovers (they were rained on heavily, so probably the quality was too poor). There were still some areas with green grass and sedges. Mopane still had green leaves, and for the goats, there were a lot of green forbs.

The observed diets (Table 12) may be compared with the ranking given by farmers in a PRA conducted in 1998 (Table 8).

Message: The dry season strategy of goats consisted of increasing browsing and expanding their diet breath, while cattle depended more on stover in the fields as a forage supplement in the dry season. Key resources such as grass on contour bunds, riverine areas and fallow fields were also important, at the large scale. In both the field experiment and the communal area study, cattle and goats had low diet overlap indices, particularly for browse because cattle avoided species with thorns and selected broad-leaved species.

3 Decision support modelling of semi-arid rangeland. The results of the model (Fig 3) show that rainfall, which is known to be the primary determinant of livestock abundance, can be used to predict vegetation growth and hence animal population dynamics. The predictions are quite close to observed carrying capacity, and in fact this model still maintains a world lead in its predictive ability.

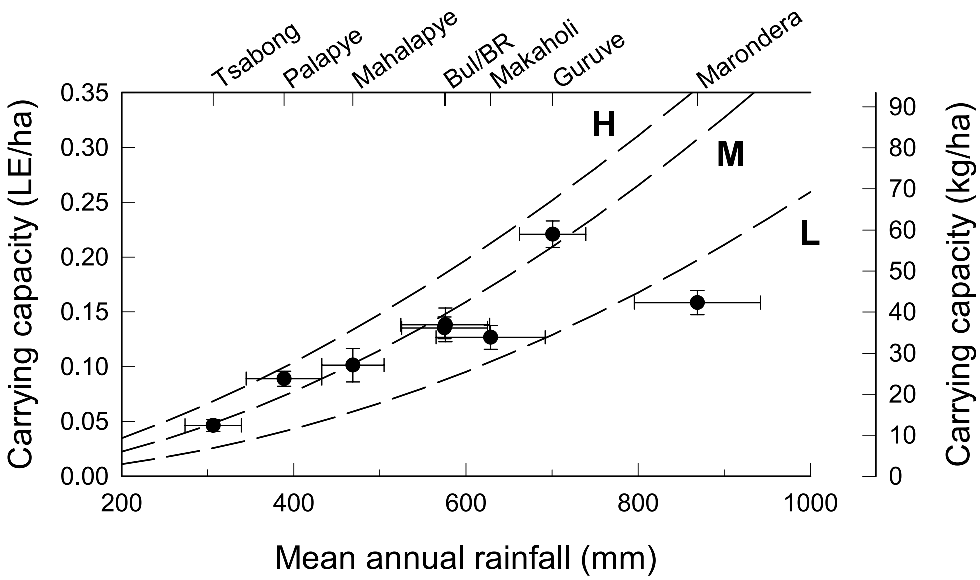

Fig 3. The symbols show model predictions of the 20-year mean ecological carrying capacity (± se) in relation to the rainfall at 7 locations from SW Botswana to NE Zimbabwe (Tsabong, Palapye, Mahalapye, Bulawayo and Buffalo Range, Makaholi, Guruve, Marondera). The model was run at high soil fertility. For comparison, the curves (right axis) show the carrying capacity observed by Fritz & Duncan (1994) in relation to rainfall at sites of high, medium or low soil nutrient availability (H, M, L, respectively). One Livestock Equivalents (LE) is the metabolic liveweight of an animal with mature size 450 kg.

Fritz, H. & Duncan, P. (1994). On the carrying capacity for large ungulates of African savanna ecosystems. *Proceedings of the Royal Society, London, Series B,* **256**, 77-82.

Message: Modelling can be used to predict the long-term mean carrying capacity of semi-arid rangeland in relation to rainfall.

3. (a) Livestock offtake strategies under climatic variability. Ways of 'tracking' environmental fluctuations could be of value in limiting drought-induced mortality and increasing output. We examined a range of tracking policies, designed to tackle climatic variation, using a simulation model of a semi-arid grazing system. These compared annual sales designed to limit stocking rate, pre-emptive sales triggered by insufficient rainfall, and variable sales and stocking-rate regimes determined by the current season's rainfall. The policy against which they were compared was one where only animals in excess of a target stocking rate were sold, with sales occurring at the end of the wet season. The target stocking rate was defined as that maximising mean long-term output.

Although the flexible stocking strategies did reduce mortality losses, compared with fixed stocking, they did not increase average annual sales. The main reasons for this are that major losses of stock are associated less with one-year than with two-year droughts, which are difficult to track, and that de-stocking can be really effective only if the productive potential of the herd can be re-established more rapidly than is possible from depleted herd resources. Tracking policies also increased inter-annual variability of sales and hence cash-flow (Table 13).

Table 13. Mean annual sales and the mean inter-annual CV of sales, derived from 25 replicates runs of 20 years.

	No Female sales		**With Female sales**	
	No re-stocking	**With re-stocking**	**No re-stocking**	**With re-stocking**
Policy	**Sales (kg live weight/ha)**			
Fixed stocking	13.5	15.3	19.2	19.6
Pre-emptive sales in Dec	13.4	15.9	19.5	20.0
Pre-emptive sales in Feb	13.2	15.6	19.3	19.9
Tracking, basic	15.0	17.1	17.9	18.2
Tracking, capped @ 0.3 LE/ha	15.4	16.8	17.9	18.4
Tracking, capped ∝ rainfall	15.2	15.2	14.2	14.5
Mortality tracking + fixed stocking	12.9	14.1	16.1	17.8
Mortality tracking + variable stocking	14.3	14.8	16.7	18.4
Mean	14.1	15.6	17.6	18.3
	CV of sales (%)			
Fixed stocking	102	85	66	63
Pre-emptive sales in Dec	101	80	66	62
Pre-emptive sales in Feb	106	84	66	63
Tracking, basic	121	104	150	149
Tracking, capped @0.3 LE/ha	109	98	144	143
Tracking, capped ∝ rainfall	99	99	144	140
Mortality tracking + fixed stocking	99	90	88	76
Mortality tracking + variable stocking	115	112	157	140
Mean	106	94	110	105

The main effect on the sales performance of the various strategies is due to the option allowing the sale of breeding females in order to meet the objective of reducing stocking rate. Without female sales, the stocking rate reduction was often not achieved, leading to lower sales, and tracking policies had a slight advantage over more rigid policies. But large increases in output could be achieved by allowing female sales, thereby achieving a mean stocking rate nearer to the optimal rate. Then, fixed and pre-emptive sales policies had the lowest inter-annual variability in sales. Policies designed to track climatic variation had minimal advantage in terms of sales and yet had about twice the inter-annual variability. A cv of 140% implies zero sales in nearly one year in four. Inter-annual variability in sales is an obvious consequence of policies that aim to track climatic variation by varying stocking rate.

We extended this study in a collaboration with Tarr & Hearne (University of Natal), who were studying rangeland policy in Namibia. One possible criticism of the original study is that some of the sales policies ended up reducing average stocking rate below what we had previously estimated to be optimal (*ie*, sales-maximising). To address this, we estimated the optimal stocking rate for each policy, and ran the simulations at the stocking rate appropriate for each policy. We also introduced a new policy, 'Tracking, lower bound' in which stocking rate was adapted to the current season's rainfall, up to an upper limit, plus sales included only suitable animals (ie of sufficient weight). The results were an even more striking lack of advantage of flexible policies over fixed stocking, although they still had the marked disadvantage of higher inter-annual variance in output (Table 14).

Table 14. Re-assessment of the effects of stocking/offtake policy on mean stocking rate and hence performance, for a Namibian site. Prices in Namibian $.

Policy	Net Income (M$/y)	Income CV(%)	Mortality (%)	Stocking rate (LE/ha)
(a) Policies compared at *target* stocking rate = 0.08 LE/h				
Fixed stocking	1.26	41	21	0.093
Pre-emptive sales	1.25	42	23	0.093
Tracking	0.74	119	4	0.06
Mortality tracking	0.74	119	3	0.06
Tracking, lower bound	0.76	107	6	0.07
P	<0.01	<0.01	<0.01	
(b) Policies compared at local optimum stocking rate				
Fixed stocking	1.26	41	21	0.093
Pre-emptive sales	1.25	42	23	0.093
Tracking	1.28	106	22	0.11
Mortality tracking	1.28	105	20	0.11
Tracking, lower bound	1.15	103	22	0.10
P	<0.05	<0.01	=0.5	

Message: Flexible stocking strategies alone are not likely to be successful in coping with droughts. For subsistence pastoralists, the traditional policies of maintaining the maximum number of breeding stock, and of hoping that most of them will survive drought, may be as close as 'opportunistic' management can get to dealing with drought.

3 (b) The role of 'key resources' in maintaining livestock populations. It has been suggested that climatic variation has the effect on the dynamics of arid and semi-arid grazing systems of reducing animal numbers below the level at which they have much impact on vegetation or soils, and that spatial heterogeneity in resource availability serves to buffer herbivores against climatic variation. Modelling was used to test these hypotheses and to examine the interacting effects of temporal and spatial variability in plant production on animal population dynamics and defoliation intensity. The model distinguishes areas of the range that are accessible during wet and dry seasons, and examines the effect of seasonal restrictions in foraging area.

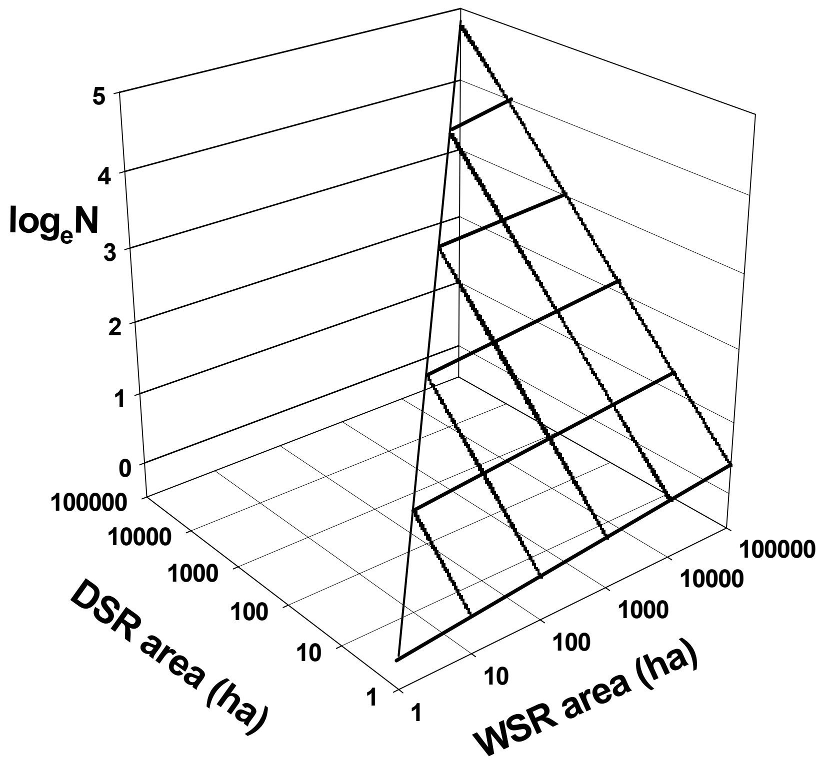

Fig.4 Mean animal abundance ($\log_e(N)$, mean of 100-year simulations) in response to increasing availability of dry season range (DSR) and of wet season range (WSR). Animal numbers are rather insensitive to WSR area, but respond sharply to availability of dry season resources.

It was established that the animal population is in long-term equilibrium with dry-season resources (so-called 'key resources'), on which it depends for survival. As the abundance of key resources is increased, so animal numbers increase. In contrast, the size of the available wet-season range had very little effect on year-round carrying capacity (Fig. 4). Increasing degrees of variability in primary production on areas used by animals for surviving the dry season increased the annual variation in livestock numbers and reduced the mean (Fig. 5).

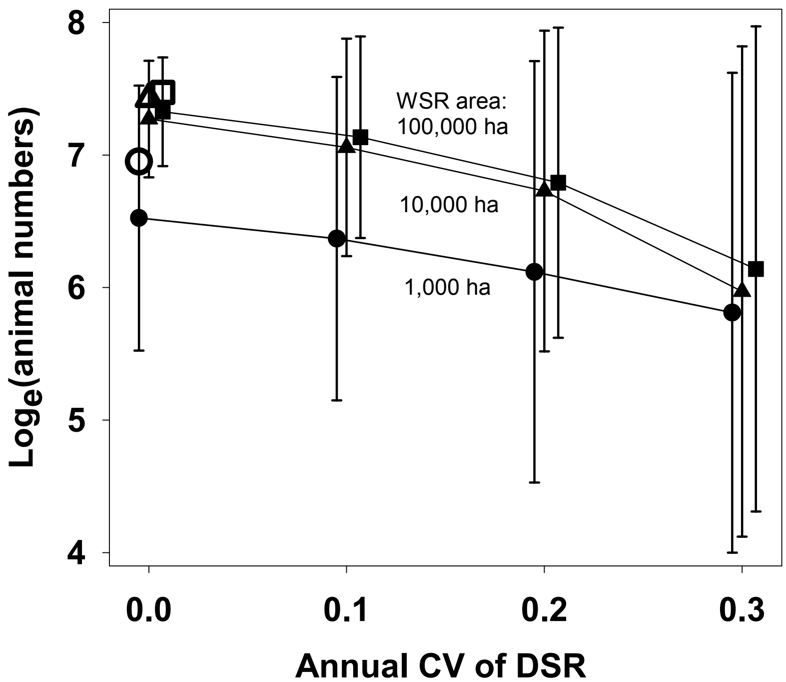

Fig 5. Mean animal abundance ($\log_e(N)$, mean of 100-year simulations) in response to increasing variability of primary production in the dry season range (DSR) and with wet season range (WSR) area of 1,000 ha (●), 10,000 ha (▲), or 100,000 ha (■). DSR range area was 1,000 ha, and WSR cv of primary production was 0.3 throughout. The error bars show the mean inter-annual SD of $\log_e$(N). Open symbols show $\log_e(N)$ predicted by the model when it was run without climatic variation.

By comparison with a stable environment, for which the model predicts virtually stable animal numbers and constant, low defoliation intensity, variation in annual rainfall causes wide fluctuations in animal numbers and defoliation intensity. Under climatic variation, animal numbers can build up enough to impose much higher defoliation intensities than under a constant regime. Periodic intense defoliation is a consequence of climatic variability which is likely to make these environments more, not less, prone to ecological change. A high ratio of dry season to wet season resources may support a sufficiently large animal population to impose non-trivial defoliation impacts on the outlying range.

Message: The carrying capacity of rangelands is very largely governed by the availability of dry-season forage resources.

Contribution of Outputs

Include information on how the outputs will contribute towards DFID's developmental goals and the identified promotion pathways to target institutions and beneficiaries. What follow up action/research is necessary to promote the findings of the work to achieve their development benefit? This should include a list of publications, plans for further dissemination, as appropriate. For projects aimed at developing a device, material or process specify:

Climatic variability is the single largest cause of poverty in pastoral societies, for two reasons. First, droughts that are severe enough to cause livestock mortality result in the destruction of wealth and loss of potential output. Second, climatic variation causes the long-term stocking rate to be lower than could be maintained under more reliable climatic conditions, because livestock populations take time to rebuild after die-offs. Environments which are arid or semi-arid are prone to a high degree of climatic variability and low primary production, with the result that pastoralism is the principal form of land-use. Clearly, ways need to be found of combating the economic and social effects of climatic variability and drought.

1. We showed that flexible stocking strategies alone are not likely to be successful in coping with droughts. For subsistence pastoralists, the traditional policies of maintaining the maximum number of breeding stock, and of hoping that most of them will survive drought, may be as close as 'opportunistic' management can get to dealing with climatic variability.
2. We also showed that, in seasonally variable environments, the supply of dry-season forage determines the numbers of livestock that can be carried. Wet season resources may be important for production, but maintaining livestock numbers depends on dry-season nutrition.
3. Browse is a dependable forage that is available over a longer growing season than grass. Its production may equal or exceed that of grass, and it may be the only forage available in heavily-utilised areas.
4. Assessment of browse biomass is quite simple and methods of estimation we developed could easily be used as a rapid means of field assessment of range capacity.
5. We showed that cattle and goats use different forms of browse, with cattle selecting predominately the large-leaved species, while goats can make efficient use of the small-leaved species as well. Browse is of more use to goats than to cattle.
6. There is little competition for browse between the two livestock species. Mixed grazing and matching the ratio of animal species with forage resources would, therefore, be advantageous for livestock keepers in semi-arid regions where grass biomass has been depleted by high stocking rates
7. In evaluating the potential nutritional contribution of browse, emphasis should be given to which species are and can actually be used by particular livestock species, rather than only regarding the nutritional value of browse species.
8. Lopping branches in the late dry season can provide valuable forage, particularly as a source of N, at a critical time of year. Lopping stimulates re-growth and appears not to affect the survival of tree.

a. What further market studies need to be done?

b. How the outputs will be made available to intended users?

We are preparing dissemination materials on the assessment and utilisation of browse resources in semi-arid rangeland. The focus is on meeting livestock nutrient requirements in the late dry season, which we have shown is the critical time for sustaining livestock numbers.

c. What further stages will be needed to develop, test and establish manufacture of a product?

The scope for this type of model is, we believe, as a decision tool for use by experts/consultants, rather than as a desk-top aid for more widespread use. The model should be developed from the prototype stage to be readily useable for policy analysis and the prediction of carrying capacity. This would involve developing a comprehensive Help System, with quick links to the help system and to a user support website; literature archives of relevant project publications and background information; and a guidance system that would walk users through the type of investigation they want to conduct.

d. How and by whom, will the further stages be carried out and paid for?

Unknown at this time.

Publications:

Reference Type	Citation Details
peer reviewed journal paper	Illius, A.W., Derry, J.F. & Gordon, I.J. (1998) Evaluation of strategies for tracking climatic variation in semi-arid grazing systems. *Special Issue on Drought, Agricultural Systems* **57,** 381-398
peer reviewed journal paper	ILLIUS, A.W. and O'CONNOR, T.G. (1999) On the relevance of nonequilibrium concepts to semi-arid grazing systems. *Ecological Applications,* **9**: 798-813
peer reviewed conference paper	ILLIUS, A.W. and O'CONNOR, T.G. (1999) When is grazing a major determinant of rangeland condition and productivity? *Proceedings of the VI Intl Rangelands Congress,* **1**: 419-423 and The Stobbs Memorial Lecture
peer reviewed journal paper	ILLIUS, A.W., DERRY, J.F. and GORDON, I.J. (2000) *Corrigendum* - Evaluation of strategies for tracking climatic variation in semi-arid grazing systems. *Agricultural Systems*, **63**: 73-74.
Peer reviewed journal paper	ILLIUS, A.W. and O'CONNOR, T.G. (2000)) Resource heterogeneity and ungulate population dynamics. *Oikos* **89**, 283-294
Edited proceedings	ILLIUS, A.W., DERRY, J.F. and GORDON, I.J. (1999) A re-assessment of the value of strategies for tracking climatic variation in semi-arid grazing systems. *Proceedings of the VI Intl Rangelands Congress,* **1**: 504-505.
Edited proceedings	Illius, A.W. (1998) Browse in semi-arid communal livestock systems: synopsis of group discussions. DFID/DRSS 1st Workshop Report, Matopos
conference proceedings	Illius, A.W. & O'Connor, T.G. On the relevance of nonequilibrium concepts to semi-arid grazing systems. 'Policy-making for the Sustainable Use of Southern African Communal Rangelands', South Africa., 1998 (Abstr)
conference proceedings	Illius, A.W., Derry, J.F. & Gordon, I.J. Evaluation of strategies for tracking climatic variation in semi-arid grazing systems. 'Policy-making for the Sustainable Use of Southern African Communal Rangelands', South Africa, 1998 (Abstr)
Open day	MAGADZIRE, Z. and MUKUNGURUTSE, E. (1999) Browse production and utilisation. Agritex Livestock Specialists Annual General Meeting (National). Matopos Research Station, 20 May.
Public seminar	MAGADZIRE, Z. and MUKUNGURUTSE, E. (1999) Browse production and utilisation. Monthly seminar attended by stakeholders, farmers, Agritex, Station staff. Matopos Research Station, July.
Workshop	MAGADZIRE, Z. and MUKUNGURUTSE, E. (1999) Browse production and utilisation. Annual Review Meeting of Livestock and Pastures, Department of Research and Specialist Services Matopos Research Station, 1 -2 November
Oral presentation	MAGADZIRE, Z. and MUKUNGURUTSE, E. (1999) Browse production and utilisation. Visit of four Zambian Livestock Research Specialists. 18 November
Oral presentation	MAGADZIRE, Z. and MUKUNGURUTSE, E. (1999) Browse production and utilisation. Visit by Agriculture Students from Namibia. 18 October.
Workshop and Proceedings	ILLIUS, AW, MAGADZIRE, Z. and MUKUNGURUTSE, E. (2000) Browse production and utilisation. Annual Review Meeting of LPP projects. Matopos Research Station, 26-28 Sept
Open day	MAGADZIRE, Z. and MUKUNGURUTSE, E. (2000) Browse production and utilisation. Agritex Livestock Specialists Annual General Meeting (National). Matopos Research Station, 20 May.

Public seminar	MAGADZIRE, Z. and MUKUNGURUTSE, E. (2000) Browse production and utilisation. Seminar attended by stakeholders, farmers, Agritex, Station staff, Open University staff. Matopos Research Station, 29 June
Workshop	MAGADZIRE, Z. and MUKUNGURUTSE, E. (2000) Browse production and utilisation. Annual Review Meeting of Livestock and Pastures, Department of Research and Specialist Services Marondera Research Station, 30 Oct.
Oral presentation	MAGADZIRE, Z. and MUKUNGURUTSE, E. (2000) Browse production and utilisation. Visit of 30 farmers from Gwanda (SDARMP) 16 May
Oral presentation	MAGADZIRE, Z. and MUKUNGURUTSE, E. (2000) Browse production and utilisation. Visit of Mkoba Teachers College 28 July
Oral presentation	MAGADZIRE, Z. and MUKUNGURUTSE, E. (2000) Browse production and utilisation. Visit of AGRITEX officers from Manicaland Province and SEDAP Masvingo Provincial management team (Tsododo) 21 Sept
Oral presentation	J W Hearne, K J Koch and A Illius, 'On some aspects of grazing dynamics',1999 World Conference on Natural Resource Modelling, Halifax, Canada, June , 1999.
Oral presentation	J W Hearne, H Tarr, A Illius, and J Derry, 'Determining Cattle Management Strategies for Regions of Namibia', 15th Triennial Conference of The International Federation of Operational Research Societies, Beijing, China, August, 1999
Public lecture	Illius, A.W. 'New perspectives on range ecology in variable environments.' *E.J. Dyksterhuis Distinguished Lecture Series, Texas A & M University,* April 2000.
Oral presentation	A Illius, H Tarr, J W Hearne, and J Derry. 'An analysis of cattle offtake strategies under climatic variability'. 2000 World Conference on Natural Resource Modelling: The Ecology of Scale. Wageningen, Holland June, 2000
Poster	Mukungurutse, E. (2002) Effects of lopping Colophospermum mopane and Combretum apiculatum trees in order for livestock to access shoots and leaves on a semi-arid savanna site. In: *Responding to the Increasing Global Demand for Animal Products*: Programme and Summaries 60, pp. 131. BSAS
Poster	MAGADZIRE, Z., GORDON, I.J. and ILLIUS, A.W. (2002) Foraging strategies of cattle and goats during the late-wet and dry seasons in Southern Zimbabwe. In: *Responding to the Increasing Global Demand for Animal Products:* Programme and Summaries 58, pp. 127-128 BSAS
Seminar	Magadzire, Z. 2003 Foraging behaviour of free-ranging cattle and goats: Implications for management – BIDI. Matopos Research Station.
Thesis	Magadzire, Z (2001) *Foraging strategies of cattle and goats in mixed-species grazing systems*. PhD Thesis, University of Edinburgh
Thesis	Mukungurutse, E. (2002) "*Browse production in semi-arid grazing systems* MPhil Thesis, University of Edinburgh