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Anticipating vulnerability to climate change in dryland pastoral systems: using dynamic systems models for the Kalahari

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Abstract

It is vitally important to identify agro-ecosystems that may cease functioning due to changing climate or land degradation. However, identifying such systems is confounded on both conceptual and methodological grounds, especially in systems that are moving towards thresholds, a common trait of dryland environments. This paper explores these challenges by analysing how a range of external pressures affect the vulnerability of dryland pastoral systems in the Kalahari. This is achieved by employing dynamic systems modelling approaches to understand the pathways by which communities became vulnerable to drought. Specifically, we evaluate how external pressures have changed: (1) different agro-ecosystems abilities to tolerate drought (ecosystem resilience); (2) rural communities' abilities to adapt to drought (mediated via their access to assets); and (3) the ability of institutions and policy interventions to play a role in mediating drought related crises (socio-political governance). This is done by re-analysing ecological and participatory research findings along with farm-scale livestock offtake data from across the Kalahari in Botswana. An iterative process was followed to establish narratives exploring how external drivers led to changes in agro-ecosystem resilience, access to assets and the institutional capacity to buffer the system. We use "causal loop diagrams" and statistical dynamic system models to express key quantitative relationships and establish future scenarios to help define where uncertainties lie by showing where the system is most sensitive to change. We highlight that greater sharing of land management knowledge and practices between private and communal land managers can provide 'win-win-win' benefits of reducing system vulnerability, increasing economic income and building social capital. We use future scenario analyses to identify key areas for future studies of climate change adaptation across the Kalahari.

Keywords: Dynamic systems modelling, vulnerability pathways, Kalahari, Botswana, pastoral farming, climate change, drought sensitivity.

INTRODUCTION

The purpose of this paper is to apply dynamic system modelling tools to investigate food system vulnerability to both climate change and land degradation, with a focus on drought sensitivity in the pastoral Kalahari region of Botswana. To do this, we draw on published data and field ecological and participatory research findings to generalise factors that influence how the agro-ecosystem responds to droughts. These factors are linked to key components of the pastoral system using a dynamic systems model, which explores a series of quantifiable future scenarios. The paper's empirical contribution is to develop and provide a detailed analysis of the pastoral system to answer two key research questions:

1. Is there evidence that the Kalahari pastoral-based food system is becoming more or less vulnerable to drought?; and
2. What policy "leverage points" are there to reduce vulnerability in this dynamic agro-ecosystem?

The paper also makes a theoretical contribution by providing a case study to evaluate the strengths and weaknesses of using quantitative dynamic systems modelling to assess dryland pastoral system vulnerability. To date, livelihoods research in this region on this issue has been based primarily on field-based research (e.g. Sporton and Thomas 2002, Chanda et al. 2003, Rohde et al. 2006, Reed et al. 2008, Sallu et al. 2009) and quantitative modelling that links socio-economic and biological factors has not been attempted. This case is interesting more broadly as it focuses on a pastoral system, typical of many of the most climatically marginal African drylands that have always suffered recurring droughts and food shortages (Lane 1997), but are often ignored in development debates that focus on food security in terms of crop production (e.g. Parry et al. 1999, FAO 2006, IPCC 2007). Furthermore, pastoral societies across dryland Africa face a range of changes in their farming systems and thus present difficult research, management and policy challenges (Reynolds et al. 2007). Partly this is due to land tenure reform that has undermined traditional livestock management (Toulmin and Quan 2000), as well as increased rainfall variability over the last 50 years across Southern Africa (Tennant and Hewitson 2002) and Sub Saharan Africa more widely. Therefore, both the academic literature (e.g. Warren 2002, Reynolds et al. 2007) and in global policy statements via the United Nations Convention to Combat Desertification (UNCCD) now recognize integrated research (based on global change and sustainability science) is needed to provide more policy- and development-relevant outputs for drylands. However, the specifics of how this is best achieved in case study regions remains largely unexplored.

RESEARCH DESIGN AND METHODS

This paper significantly extends previous field-based studies from this region by developing and applying a four-stage dynamic systems modelling exercise where we re-interpret data and interview information from a decade of multi-disciplinary research. Work involves four methodological steps taking us from the initial integration of local and scientific knowledge all the way to a quantitative vulnerability analysis capable of modelling different proposed management, market and policy options under two future climate scenarios. The outline methods are presented below (with specific details in the sections that follow):

1. We use expert opinion, derived from researchers who have worked on ecological and socio-economic studies across the region for over 15 years to develop conceptual models of agro-ecosystem functioning. This was combined with a re-analysis of land user interview transcripts to establish a *background narrative* that describes the livelihoods system and its social, institutional and ecological context (Section 3);
2. We use economic livestock data from a local (ranch/village) level to refine the narrative and establish the *conceptual model* of the system, focusing on three dimensions of vulnerability (agro-ecological, household assets, and institutional factors - as per Fraser 2007 – see Section 4);
3. We then conduct a *qualitative vulnerability analysis* of this system by using the conceptual model and narrative to show how these three dimensions of vulnerability have changed through time (Section 5); and
4. We conduct a *quantitative vulnerability analysis* by expressing key relations in the conceptual model mathematically using VENSIM, a software tool for dynamic systems modelling (Section 6). We run different management, market and policy simulations to examine how the model is sensitive to assumptions made in developing the conceptual model. This leads us to establish a series of hypotheses about which system elements are most influential in changing future vulnerability.

Taking the final quantitative step in this process, which entails making assumptions about the nature and strength of relations, is a key aspect of this study and one which we explicitly discuss the value of (and potential problems with) in our analysis and in the discussion.

BACKGROUND NARRATIVE

Lying in the semi-arid interior of Southern Africa, approximately 80 % of Botswana is covered with Kalahari sand soils and savanna ecosystems that support both commercial and communal livestock systems, as well as National Park and Wildlife Management Areas. The climate is typified by a mean annual rainfall varying from less than 200 mm p.a. in South West to 650 mm p.a. in North East with an inter-annual variability of *c*. 40 % (Bhalotra 1987). Despite significant economic growth (based largely on diamonds), 47 % of Botswana's population lives under the UN's two US dollars/day poverty line (CIA 2009). In Botswana, pastoral agriculture represents the chief source of livelihood for over 40 % of the nation's 1.8 million residents (FAO 2006) and cattle represent an important source of status and wellbeing for the vast majority of Kalahari residents (White 1993). Beef sales constitute *c.* 5 % of national exports and 1.5 % of GDP (Hitchcock 2002).

The food production and livelihood system of the Kalahari remains predominantly a pastoral system with savanna ecosystems utilised for both cattle and smallstock (mainly goats and sheep) in proportions dependent on the land tenure system (communal or private) and on the environmental characteristics of forage availability (notably the ratio of bush to grass and the availability of palatable grass species). Traditional systems are transhumant, with a high degree of herd mobility to respond to the patchy nature of rainfall and forage (Sporton and Thomas 2002) with *c*. 70% of the country still under customary communal land tenure (Clover and Eriksen 2009). These systems have been constrained in places by fencing and privatisation of large areas supported by a series of national agricultural policies and international trade agreements (e.g. Lomé Convention 1972) that provide tariff-free access to international markets for beef (the EU in this case) dependent on disease control measures. As such, private-owned ranch farming systems have developed that are increasingly sedentary and commercialised with former communal rangeland being privatised and fenced. This has led to absentee owners who employ a few local residents to manage their land and livestock (Adams et al. 2002) and is restricting the land available to communal systems that support residents of settlements across the Kalahari where few other livelihood options exist (Ringrose et al. 1996, Hitchcock 2002). Rural poverty, AIDS-HIV and growth in the mining and urban economies have also led to a decline in rural labour and farming as a way of life (Twyman et al. 2004).

Within pastoral Kalahari systems, ecological resources and their dynamics are critically important for livelihoods (Sallu et al. 2009). In terms of food provision, the reliance on livestock means that milk and meat are important for daily diets and these are often supplemented by wild fruits. It also means that there is a heavy reliance on food imports, notably maize meal (with some millet / sorghum) that is a staple food despite there being only limited production of these crops. This cereal production is itself threatened by climatic changes (Chipanshi et al. 2003) and soil degradation (Dougill et al. 2002) so maize meal is predominantly imported from South Africa and sold in local markets, or provided *in lieu* of cash for labour by wealthy land owners. In times of drought (which is designated most years by the Government of Botswana), jobs are offered by Government to enable families to earn wages for maize purchase. This offers a safety net that has thus far minimised the numbers of drought-induced cases of famine and malnutrition in Botswana.

Real concerns exist over the dual threats of poverty and land degradation as they increase the vulnerability of pastoral communities to environmental change (Thomas and Twyman 2004) and reduce the resilience of the rangeland ecosystem (Thomas et al. 2000). In some parts of Botswana, land degradation has led to extensive areas of thorny bush encroachment, which cannot be accessed by cattle (Moleele et al. 2002) reducing the economic returns from rangelands. In the drier southwest of Botswana, land degradation has also led to the mobilisation of dune fields (Reed et al. 2008). Pastoralists use a wide range of indicators to recognise and monitor land degradation processes, most of which are supported by empirical ecological assessments (Reed et al. 2008). For example:

> "Staying in an area too long is like wearing the same dress for years; it gets worn out."

Female communal farmer, age 65

> "The veld (rangeland) is like a person: there are fat and thin people and no matter how much you feed some people, they remain thin. If the soil is poor, no matter how much it rains, nothing will grow."

Male communal farmer, age 82

The National Action Programme to Combat Desertification (Republic of Botswana 2006) has been drafted and approved as required for inclusion in the UNCCD and associated funding negotiations. However, many uncertainties remain on the accuracy and legitimacy of this report that emphases soil erosion and is questionable given the weight of environmental research focusing on ecological change and the lack of in-depth participatory consultation to the village level. There is also uncertainty on how best to implement policies aimed at providing environmental and food system resilience at a local and district level (as per broader discussions across Southern Africa outlined by Stringer et al. 2007). These uncertainties mean the policy needs greater guidance to help reduce agro-ecosystem vulnerability. It is to this end that the stages in this research are guided.

BUILDING OF CONCEPTUAL MODEL

The building of the conceptual model was initially undertaken by one of the authors with no research experience in the study region to avoid subjective bias in analysis of expert interviews. A series of 12 one-on-one interviews were held with the two authors who have worked extensively across the study region and who have previously published ecological conceptual models of the rangeland system (Dougill et al. 1999, Dougill 2002, Reed et al. 2008). These interviews developed a more holistic conceptual model of the farming system and identified socio-economic, environmental and political driving forces for change, drawing on both ecological research outputs and from interviews undertaken with pastoralists, extension workers and policy-makers. The authors field experience focuses in Kgalagadi District (around Bokspits, Tsabong and Tshane), Central District (Makoba Ranch Block) and Ghanzi District (Ncojane Ranch Block) and thus the model presented is viewed as applicable to these Kalahari rangeland systems (Figure 1). Indeed, we stress that studies conducted further north in mopane woodland and pan systems of the mid-Boteti District find significantly different indicators of degradtion (Reed et al. 2008).

Following these interviews, an expert workshop involving eight participants (who all have worked in semi-arid livelihoods systems) was held where the conceptual model was presented, discussed, and refined. Finally, further refinements were undertaken following interviews with 6 researchers and policy makers with extensive research experience from the region, including staff from the Government of Botswana. The first interviews were semi-structured (to identify major drivers and outputs) and resulted in the narrative presented above. Subsequent interviews and the workshop were designed to develop and refine the conceptual model and included discussions of institutional, social and ecological subsystems. Over a period of 8 months and 15 iterations, the background narrative was turned into a dynamic systems model flow chart (Figure 2) that identifies the feedback loops and highlights indicators of vulnerability that are assessed in subsequent qualitative and quantitative analyses.

QUALITITATIVE STAGES OF MODEL BUILDING

Part I: Changes in capacity of agro-ecosystem to remain productive in drought

In terms of the capacity of the agro-ecosystem to remain productive during a drought (variables inside circles in Figure 2), a number of major environmental changes suggest that the region is losing some of its agro-ecological resilience:

- Reduction in the cover of perennial (palatable) grass species and their replacement by annual (less palatable) grasses (Thomas et al. 2000);

- Increases in the proportion of thorny bush cover increasingly spreading to cover wide areas due to fire suppression and the maintenance of intensive grazing through droughts (Dougill et al. 1999);
- Increased spatial heterogeneity and patchiness of key soil nutrients (N & P) linked to landscape-scale grazing patterns and associations of microbial soil crusts with encroaching bush species (Berkeley et al. 2005);
- Climate variability remains high, though as yet hard to associate any definitive changes in farming practice or yields caused directly by global-scale climate change processes (Washington et al. 2005);
- Borehole water depths are increasing and in the more arid areas (e.g. SW Botswana near Bokspits) where very little or no potable water is now found. In addition, there are concerns that ancient stable dune systems will become active here (Thomas et al. 2005).

These changes threaten agro-ecosystem resilience due to the reliance on livestock as the dominant income source for supporting livelihoods. The loss of perennial and palatable grass species has a direct impact on the size and viability of cattle-keeping and has, in many areas, led to a significant shift to the keeping of sheep and goats as the main livelihood activity (Rohde et al. 2006, Sallu et al. 2009). In a few commercial, privately owned, ranches, a shift has been made to farm game species (e.g. springbok, gemsbok, ostrich) though this is not widespread compared to that in South Africa (Milton et al. 2003) and Namibia (McGranahan 2008). In areas where thorn bush stands extend extensively over many kilometres (or tens of kilometres as around Kgalagadi District settlements (Chanda et al. 2003)), forage availability and diversity is reduced to the extent that traditional pastoral systems become vulnerable and non-natural resource based livelihood options become vital. In these areas, residents are seeking alternative livelihood options (or are migrating to urban centres) or depend on Government support (e.g. pensions and drought relief support) with rangelands no longer being the major source of livelihood for many residents (Chanda et al. 2003). The existence of these support systems, and improved access to regional markets, mean that rural communities remain in the Kalahari. However, they are increasingly vulnerable to environmental changes (whether ecological or climatic) and it is recognised that current policy arrangements are inadequate (Stringer et al. 2007) given projected climatic changes.

Part II: Changes in capacity of individuals to adapt to drought

In terms of the capacity of individuals to adapt (variables inside squares in Figure 2) to droughts, communities across the Kalahari span a range of ethnic (principally Tswana, Herero and Basarwa/San groups), cultural and socio-economic histories and characteristics (Sporton and Thomas 2002). This makes it difficult to generalise the nature of a socio-economic 'community structure', with many now stressing that within-community dynamics need to be considered more explicitly (e.g. Twyman et al. 2002, Sallu et al. 2009). The largest single ethnic group are the Tswana who first introduced cattle into the Kalahari over 2,000 years ago and now make up the majority of Botswana's population (Hitchcock 2002). Indigenous tribal groups (e.g. the Basarwa/San) have been working in cattle-keeping societies for many centuries and the populist image of isolated bushmen as pristine historical artefacts living a hunting-gatherer existence is a mis-representation of complex inter-dependent systems. What has developed is a hierarchy with Tswana political dominance despite international campaigns to restore some land and power to indigenous groups.

Tswana society is itself hierarchical and cattle-keeping is culturally important. Strong community structures exist through tribal chiefs and elders who make up village courts (*kgotla*) in every community. The power of traditional community systems has declined as greater influence is felt from national and District-level Government structures, dominated by the main Tswana political party (the Botswana Democracy Party – BDP) that has ruled Botswana since independence in 1966. In both Tswana and Herero households, livestock are an important source of capital, being saved for key events such as weddings, funerals and paying school fees, as well as having value from milk and meat in the food system. It is normal that the majority of households own some animals, even if this is only a small number of sheep or goats. Indeed, recently Government support programmes have provided support for smallstock rearing as a route to help poorer households through times of drought.

With increasing national wealth, there is a growing divide between rich and poor (international measures show that Namibia, South Africa and Botswana have the most iniquitous distribution of wealth of any countries calculated by the Gini index – CIA, 2009) and this drives increasing pressures for private land ownership. Within individual villages, this has marginalised women, the young and Basarwa tribal groups (Hitchcock 2002). Both out-migration from rural areas and increased mortality rates (due to the HIV-AIDS pandemic) are also affecting rural community structures. This is leaving many societies with a lack of fit working age people, with grandparents left to run households with young children and significant numbers of orphans. The strength of extended family and ethnic groups remains a strong binding agent. However, with out-migration this is threatened and could reduce system resilience associated with the ability to move livestock across an area (which is also curtailed by disease related controls). Physical capital is increased through Government provision of infrastructure (roads, health centres etc.), as is the human capital through the enhanced knowledge base provided through free primary schooling (though this reduces access to labour). This means that for many (especially those without livestock) declines in access to financial capital is the real problem in securing adequate food supplies and is leading to an increasing reliance on Government support (Sallu et al. 2009) and/or overseas aid (Rohde et al. 2006).

Part III: Changes in the collective capacity to respond to droughts

The collective capacity of pastoral communities to respond to droughts (variables inside hexagons in Figure 2) is based on the nature and effectiveness of formal or informal institutions, including social networks (Twyman et al. 2002). In this regard, land is either communally owned and managed through traditional tribal systems at a village scale or privately owned by individuals or syndicates (Adams et al. 2002). Within both systems, there is strong national control of livestock sales (through the Botswana Meat Commission (BMC) a para-state organisation that controls over 90 % of the nation’s cattle) and movements through controls on the provision of borehole water sources. The single parastatal set-up of the BMC offers the potential for Government to help to set-up emergency livestock marketing interventions, of buying livestock rapidly at the onset of droughts. However as yet, no such co-ordinated actions have been undertaken by the BMC.

Throughout the late twentieth century, there has been a move away from traditional tribal and village institutional systems (Sporton and Thomas 2002). This move away from local decision-making and control is now recognised as a regional problem (Rohde et al. 2006). As such, mechanisms are slowly being put in place to support traditional systems and to bridge between Government support (e.g. from Agricultural Extension Workers) and local traditional systems. Given that droughts tend to occur at a District (or national) scale, the greater role of district and national institutions offers greater capacity to respond.

Link to vulnerability assessment models

From the above commentary, based on literature review and interview re-analysis, it seems that there are two broad vulnerability pathways (shown on Figure 3) through the vulnerability space as developed by Fraser (2007). The first path is for the "wealthy" private ranchers who have lost out in terms of ecological resilience, but gained in terms of collective and individual capacity to respond to a drought. The other pathway is for the "poorer" communal pastoralists who have seen their vulnerability increase in all three dimensions (Figure 3).

QUANTITATIVE VULNERABILITY ASSESSMENTS

Part I: Expressing relations mathematically

To assess how policy impacts on vulnerability to drought in the Kalahari, we re-visited and analysed the interview insights from participatory research to mathematically express the relations in the conceptual model. Given the system complexity and the limited empirical research on relationships recording and explaining yields / livestock production, it is as yet impossible to use quantitative methods to test relationships and establish sophisticated linear or polynomial relations that can withstand the full rigour of academic analysis. However, there is a need for some scenario forecasting based on best available knowledge even though the datasets required to make realistic projections remain many years away across Sub-Saharan Africa (Thompson and Scoones 2009). It is however important to go through these mathematical steps (using best available estimates) to enable quantification of future scenarios.

We used both expert opinion, local stakeholder insights (from the iterations of interviews), and analysis of livestock offtake data obtained at District, village and ranch scales (Reed and Dougill 2008 and Figure 4 as an example) to determine which of the relationships were positive or negative (as marked on Figure 2) and their relative strengths for scenario modelling. For example, it was possible to trace changes in livestock offtake to changes in land ownership at a local village / ranch scale and to assess existing relations between rainfall trends and offtake for different management types and ecological changes through time. We used this mix of expert insight and yield analysis to determine if relationships were linear, a sigmoid, or if they follow a u-shaped path and then made estimates as to the slope of the different relationships. We then used these assumptions as the basis for a series of hypotheses and expressed these as simple equations that posited how each variable was related. Only once the model was expressed in this way, did we run a baseline scenario and different policy, management and market scenarios to see how the vulnerability to drought was sensitive to different interventions.

In all, we developed four different scenarios based on: (1) projected levels of climate change, (2) the effects of agricultural best management in reducing rates of land degradation, (3) the effect of a Government policy that slows the rate at which communal land is privatized; and (4) the effects of changes in the price for cattle. Each of these four scenarios was parameterized by creating a "best-case" and a "worst-case" situation that reflected the range of conditions deemed likely from the literature (summarised in Table 1). These best-and-worst case variants of each scenario were combined, giving 16 variants using the VENSIM software. The combinations of climate, land management, market and policy scenarios provide a range of plausible futures that allow modelling of how overall system behaviour changes in response to these factors. We stress that these remain only sketchily checked in relation to economic yield data due to the limitations in the quality of this data (Figure 4). In particular, cattle statistics nationally and price statistics across southern Africa (from FAOStat 2009) show huge inter-annual variability that is hard to capture in simplified market price scenarios at a coarse-scale.

It is also important to note that even with this scenario-based approach, it was not possible to express all the possible relations using mathematical functions. In some cases, our confidence in data was weak. In other cases, the factors were inherently qualitative. In particular, we found it impossible to quantify institutional/collective aspects of vulnerability (y-axis on Figure 3). As such, this research focused on changes to income based on herd size changes (a proxy for the individual's ability to adapt to drought) on a regional scale. Such analysis cannot account for the wider social, cultural and biodiversity impacts of changes in land ownership that have been highlighted by many assessing the shift to greater private land tenure across the Kalahari (see Sporton and Thomas 2002).

Part II: Where are leverage points that could reduce vulnerability*?*

Illustrative outputs from the dynamic systems model under modelled scenarios are displayed in Figures 5 - 7, separated to show the impacts of different management scenarios (Figure 5), market scenarios (Figure 6) and policy options (Figure 7). Figures 5 and 6 display the modelled outputs (over 100 model iterations / years) for the relative economic output from the total value of cattle held on private land (Figure 5a and Figure 6a) and on communal land (Figure 5b and 6b) under different degradation and climate change scenarios under the rate of land conversion seen today. Finally, Figure 7 displays the impact on the total relative value of cattle on private and communal lands that would result from changes in the rate of land tenure conversion from communal to private ownership.

In our assessments of these modelled future scenarios, the following key implications are drawn from the modelled outputs within the confines of our selected variables:-

- The impacts of climate change (as per IPCC predictions) have the largest economic impact on the future value and economic viability of pastoral systems. As such, efforts at the local and regional level will not have as large an economic impact as global influences of future climatic changes, notably desiccation of the semi-arid system as predicted by regionally downscaled climate models (e.g. Thomas et al. 2005, Hewitson and Crane 2006).

- The positive benefits of improved management (guided by holistic rangeland management guides – such as from Tainton 1999 and Reed and Dougill 2010 - are apparent under all cases. The extent of the 'best' management impacts are greatest under private land ownership and for the first 20 years of modelled iterations showing that this is capable of absorbing much of the economic impacts associated with climate change (Figure 5a).
- Market growth scenarios would not be sufficient to alleviate the economic losses seen from the communal sector associated with continued rapid rates of land conversion to private ownership (Figure 6b). As such, policy leverage to support market price rises for livestock would preferentially favour the private sector that is more efficient in producing cattle for sale on national / international markets (Figure 6a). Such support would therefore not address the poverty alleviation needs of communal pastoralists.
- Policy interventions aimed at changing the rate of land conversion from communal to private land ownership when assessed in a solely economic manner display that continued rapid rates of land privatisation can help to increase the overall value of cattle regionally and buffer some of the impacts of climate change and/or degradation (Figure 7).

When assessing these modelled outputs, it is important to note that they only display the predicted economic impacts of different scenarios solely for the pastoral system and not the more diversified livelihood options practiced. As such, these model outputs fail to capture important impacts on social capital, community cohesion, equality / poverty levels and biodiversity or carbon storage declines that have important economic value and implications, but which remain difficult to feed into policy-making nationally. The need to value these broader ecosystem services is a vital next step required for research in this region, as in other drylands (Turner and Daily 2008). It is also important to note that results remain far from definitive (due to the problems of data parameteristaion of models given the limited quantitative livestock data available). Therefore, these results should be treated as hypotheses requiring further testing and as a guide to focus future research design rather than as firm conclusions. As such, before any policies are developed, there needs to be a further empirical research involving local scale quantitative yield assessments to test the validity of these claims.

DISCUSSION

This paper provides an extension of farming systems research that is based on field data into a dynamic conceptual model and then a quantitative dynamic system model informed by livestock yield data. The quantitative scenario-based approach has the potential to enhance the communicative power of vulnerability assessments including the graphical representation of economic impacts of different management, market and policy futures (Figures 5 - 7). In following such a quantitative approach, we can provide further insights into the farming system under consideration, in terms of factors affecting its vulnerability to future droughts. In particular, the findings highlight the following empirical findings:

1. That cattle herds and associated incomes are likely to continue declining in communal lands under most scenarios. This is due to the effects of ongoing land degradation and will be exacerbated by climate change and fast rates of land tenure conversion to private ownership. Improvements in rangeland management practices are, as yet, only making small improvements to the income that can be derived from communal herds. One-way to view such findings is that further land privatisation will help enhance national income but needs to be complemented with support directed at communal area residents. However, when combined with field research from communal rangelands (e.g. Reed et al. 2007, Sallu et al. 2009), the potential for learning about management practices (e.g. mix of cattle breeds, rotational grazing, controlled burning and drought feed supplements) offers a route to improving livestock yields from communal lands and enhancing system resilience. Adopting best-practices on communal lands will require community-based management at a village level as seen to provide wider social, cultural and economic benefits in other dryland pastoral regions (e.g. Klintenberg et al. 2007, Oba et al. 2008). Empowering village level committees thus should be a priority to enable 'win-win-win' benefits that could span environmental, economic and societal aspects of the dryland pastoral system.

2. Differences in the factors affecting the magnitude of future livestock income / offtake projections for private and communal lands further stresses the need to treat these as different farming systems (as per Thomas and Twyman, 2004) even though they share the same climatic and ecological settings. The vulnerability pathway mapping (Figure 3) enables us to generalise factors contributing towards the vulnerability pathways of each land tenure system, which is useful for identifying policy leverage points and likely impacts. By linking dynamic system models with ecological state and transition models it will be possible to explore causes and timings of thresholds that control system vulnerability to droughts.

3. A final indicative finding is the portrayal of the greater impact that global climate change and international market drivers have compared to improvements in land management practices. Whilst long-term benefits have been shown from local-level shifts in grazing management practices (Reed and Dougill 2010), the lack of immediacy and limited extent to which this benefits income explains some of the difficulties in encouraging changes to management practices (Reed et al. 2008).

In terms of policy guidance aimed at developing projects or policy at the District or National level to reduce vulnerability to climate change, our analysis suggests:

1. There remains a need for greater encouragement of, and support for, improved rangeland management approaches, notably in sharing lessons between management practices from private ranches to communal rangelands. Improved rangeland management involves better matching of grazing intensities with fodder availability (e.g. Joubert et al. 2008). This may result from either local-scale rotational grazing practices or District level schemes to support landscape-scale movement of cattle in response to changes in fodder availability. Such regional movements have long typified the Kalahari pastoralists drought coping strategies and is formalised traditionally through the *mafisa* livestock movement system, where friends and family exchange livestock over hundreds of kilometres, enabling herds to track forage resources at a landscape scale. This would require the introduction of improved

national marketing systems to facilitate rapid destocking at the onset of drought as seen in Namibia (Katjiua and Ward 2007). Barriers include the increasing numbers of absentee livestock owners (Perkins 1996) and continued privatisation of communal areas that reduces the extent of traditional grazing reserves during drought (Twyman et al. 2002).

2. A combination of land privatization, together with establishment and empowerment of formal communal village committees and market price increases represents the most significant opportunities to sustainably increase herds and incomes (Figure 6a), and hence reduce the vulnerability of the system to future climate change. In this regard, the more nuanced portrayal of vulnerability pathways provided here and the risks of increasing vulnerability in both private and communal systems provide guidance on routes to reduce vulnerability.

3. Increasing market accessibility (at the household, community or private ranch level) will increase incomes obtained from the farming system as a whole, whilst not increasing the system vulnerability to droughts. This is especially true for communal systems, where it would be beneficial for the Government to focus on providing the routes to market (via the Botswana Meat Corporation) in as fair and equitable a manner as possible. Such a shift would enable sharing of the benefits currently seen on private land to communal rangelands. Experiences from the establishment of ranch-owning syndicates and from communities where community-based rangeland management initiatives have taken root firmly (e.g. Namibian case outlined in Klintenberg et al. 2007) suggest that such community-wide mechanisms offer a route to enable economic gains, whilst avoiding many of the equality and marginalisation concerns with the move away from communal ownership.

4. The enhanced support of local extension services, and their ability to outline the long-term benefits of improvements in agricultural management practices (such as those in locally-developed management guides), is essential in realising the benefits that shifts in agricultural practice can lead to. This is especially so in the face of significant additional economic and environmental pressures associated with regional climate change predictions.

Finally, we re-emphasise that this policy guidance is based on outputs from a model that is based on expert judgements and preliminary economic appraisals only. As such, the findings reflect the biases and assumptions of those who built the model and the limited data available to parameterise this. Representing these judgements mathematically is controversial because numerical outputs such as Figures 5-7 can give an illusion of certainty and authority that may be misleading. We stress that dynamic systems modelling offers a rapid, transparent and systematic approach to capture and use expert knowledge to understand how complex systems might work. In contrast to the way quantitative models from the reductionist school are communicated with error-bounded certainty, dynamic systems models fit more comfortably in an interpretativist school, where there are just different interpretations by different people in different contexts. In this context, rather than shying away from quantifying models based on expert opinion, this paper uses the heuristic power of a tool from which both researchers and decision-makers can learn.

In terms of the theoretical contribution this paper has made to vulnerability debates, key insights from this case study include:

1. That re-analyzing data using a pre-determined framework has allowed us to highlight vulnerability pathways (Figure 3) that can then be quantified (Figures 5-7) to allow for comparability with qualitative field-based research.
2. The hypothesis that there may be generic vulnerability trajectories that are common to a range of different situations and that common policy strategies may be suitable for each type of trajectory.
3. In terms of developing the mathematical formulae in the dynamic systems models, we feel that this approach has merits in that it created a visual representation that allows the explanation of system behaviour. The act of programming the dynamic system was also useful in exposing and quantifying the assumptions we made in the narrative and scenario building (Table 1).

CONCLUSIONS

This paper increases our understanding of dryland pastoral systems and how they are vulnerable to climate change using reflections and re-analysis of a substantive body of research from across the Kalahari. The largest threat to the economic viability of the pastoral food system is shown as regional climate change, highlighting that all routes to enhance resilience to future droughts must be considered seriously. The qualitative aspect of our analysis shows that Government land privatization policy has helped wealthier ranchers, but has increased the vulnerability of poorer communal pastoralists (Figure 3). Privatization does however remain a route to enhance resilience at a national and District scale as the wealthier, private land-owning group has become less vulnerable to drought, due to this group's ability to purchase food and leverage help from institutions (Chanda et al. 2003) and to undertake a wider range of management options. Poorer communal pastoralists, however, have lost assets and experienced significant rangeland degradation. Their vulnerability to drought has increased so that even small droughts can have larger livelihood impacts.

The quantitative aspect of our analysis suggests that increasing access to markets and improving the access and empowerment of poorer communal farmers (through community-based management committees or formal syndicates) can reduce system vulnerability more than programmes designed to improve land management within 'loose' communal land management structures. Greater sharing of management knowledge and practices between private and communal land owners offers the best opportunity for 'win-win' benefits of reduced system vulnerability and redressing some of the inequalities in poverty and livelihood status across the Kalahari. To achieve this, will involve formalisation of management structures at a village level, community engagement in developing and using locally appropriate rangeland monitoring and evaluation tools and institutional support to empower community groups to function both for the community and between communities. This would allow community groups to share knowledge and allow livestock movements in response to fodder availability patterns as required for efficient use of dryland fodder resources.

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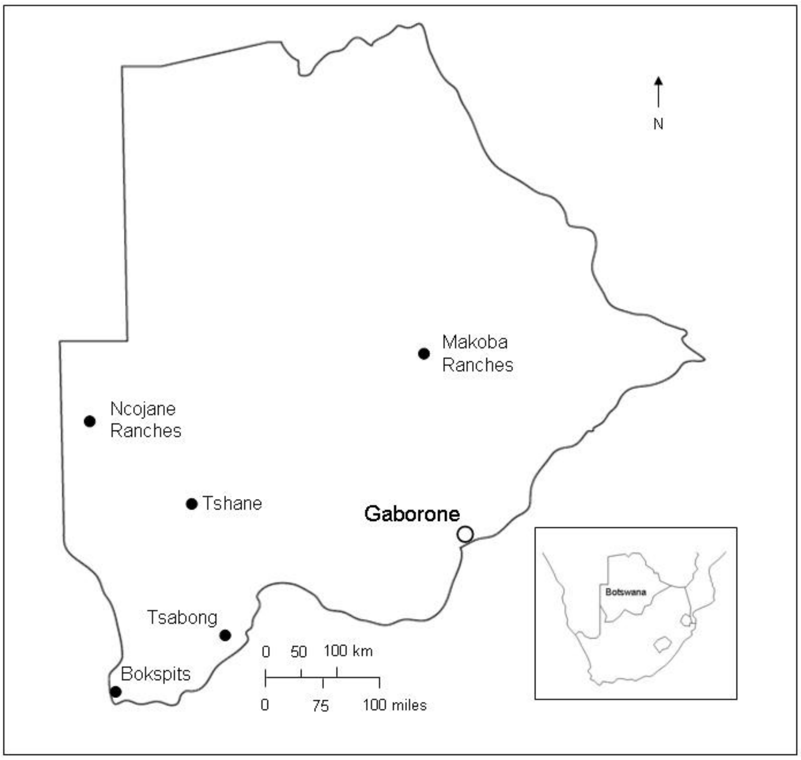
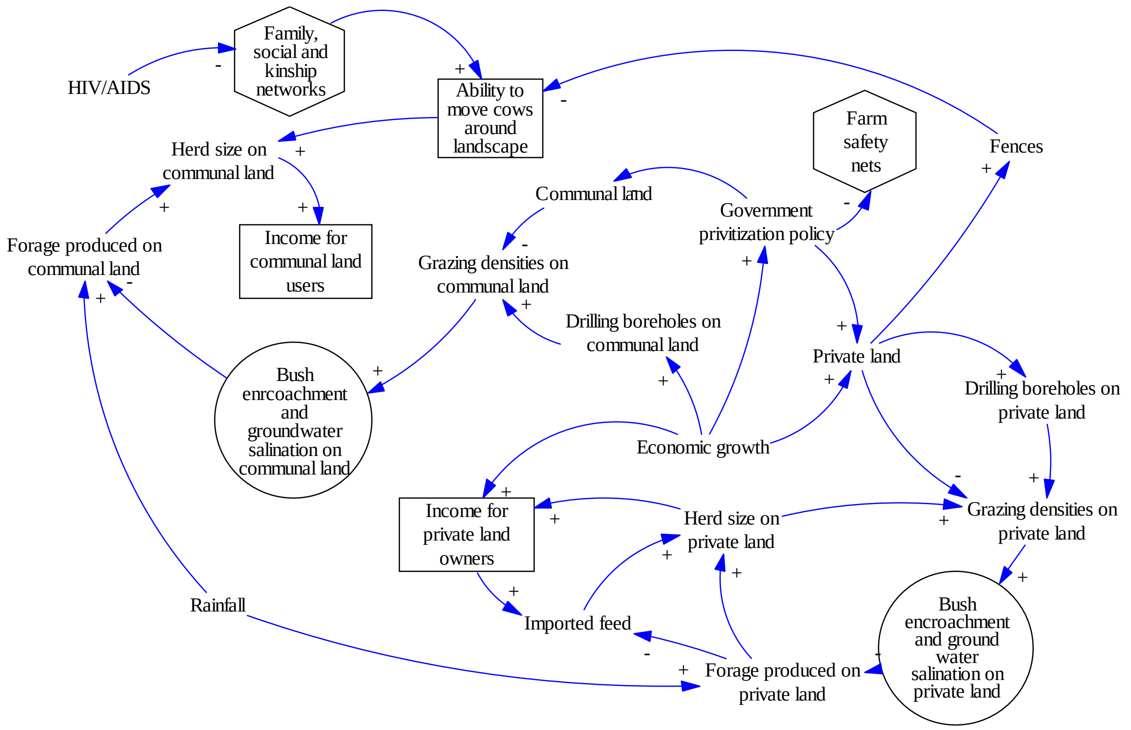


Figure 1. Location of research sites upon which expert knowledge and farmer interviews are based.



Variables with circles around them refer to the capacity of the agro-ecosystem to remain productive during a drought (x-axis of Figure 3).

Variables inside boxes refer to the capacity of individuals to adapt to a drought based on the assets they possess (y-axis of Figure 3).

Variables inside hexagons refer to the capacity for collective solutions based on institutional capacity (z-axis of Figure 3).

Open text = Identified drivers of system change

Figure 2. Dynamic systems model of the agro-pastoral food system of southern Botswana based on expert interviews, ecological surveys, and government data. Each variable in this model emerged from expert opinions, and the sign next to each arrow (+ or -) indicates whether the relation is positive or negative as classed from interviews and/or available data analysis.

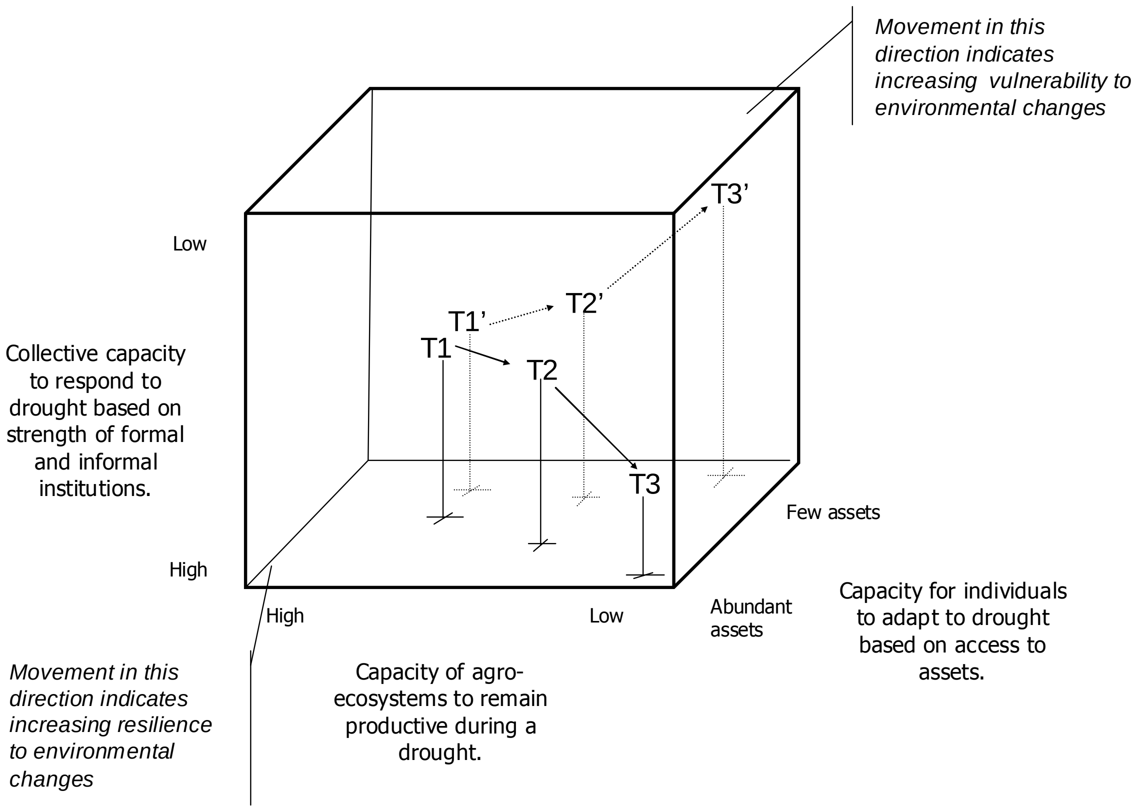


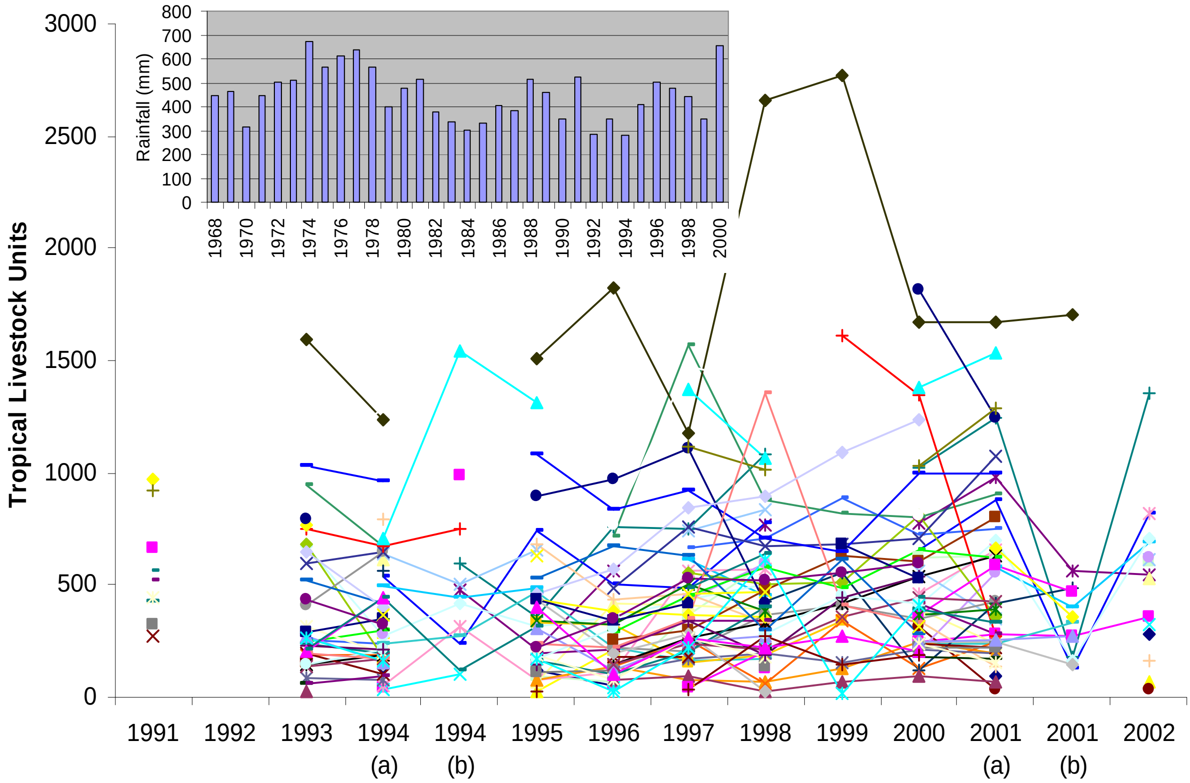
Figure 3. Heuristic depiction of changing levels of vulnerability to drought for southern Botswana pastoralists over the past 30 years.

T1, T2 and T3 refers to wealthy ranchers who raise cattle on private land.

T1', T2' and T3' refer to poorer pastoralists on communal land.

Figure 4. Communal land livestock holdings for a.) an example 10 villages in Southern Kgalagadi District and b) Southern Kgalagadi District. Source: Republic of Botswana; Department of Agriculture Statistics.

a.



b.

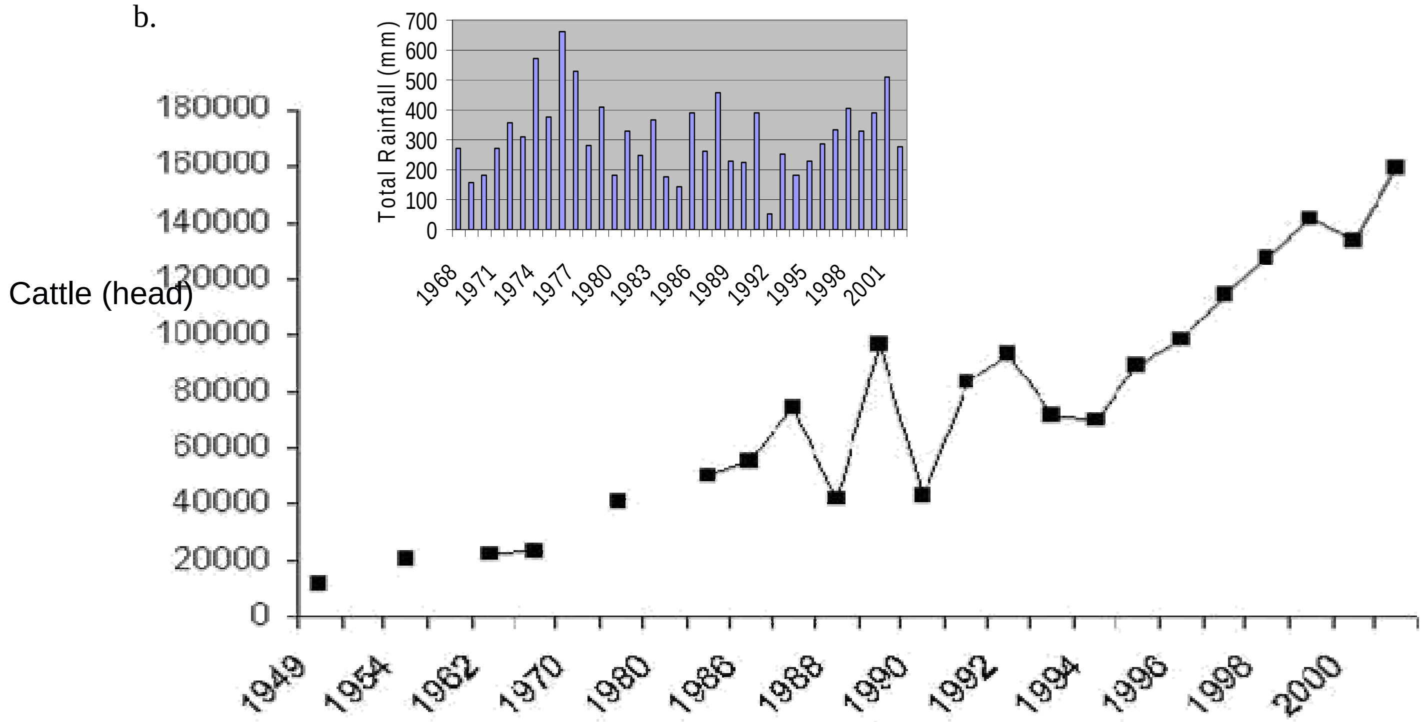
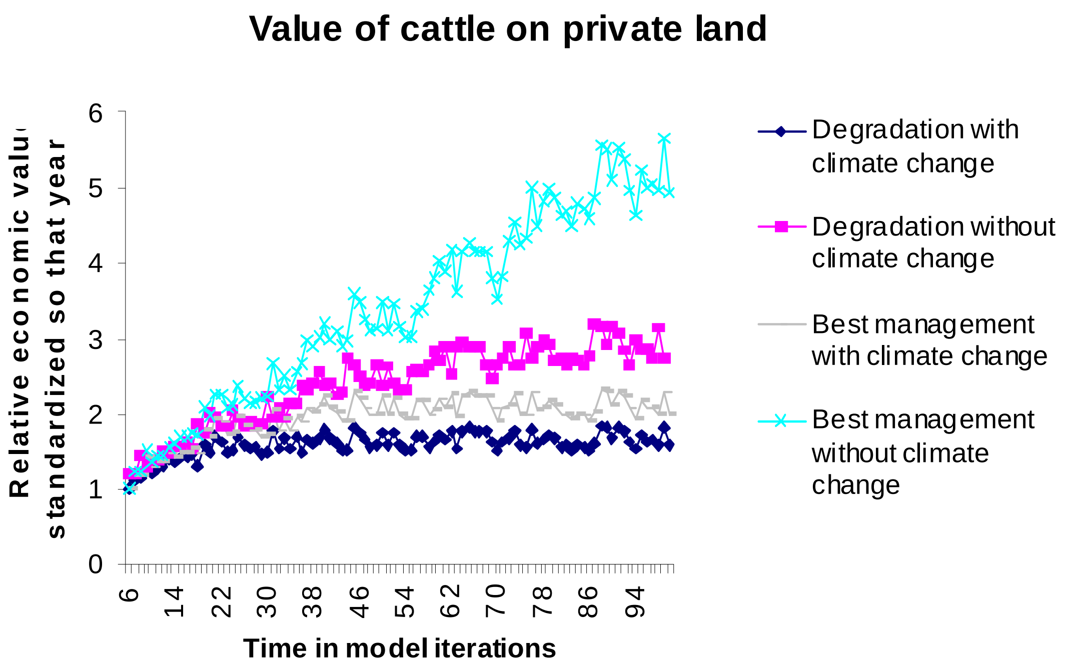


Figure 5. Management scenario options and their impacts on the value of cattle on a. private land and b. communal land across Southern Botswana (as per scenario assumptions in Table 1).



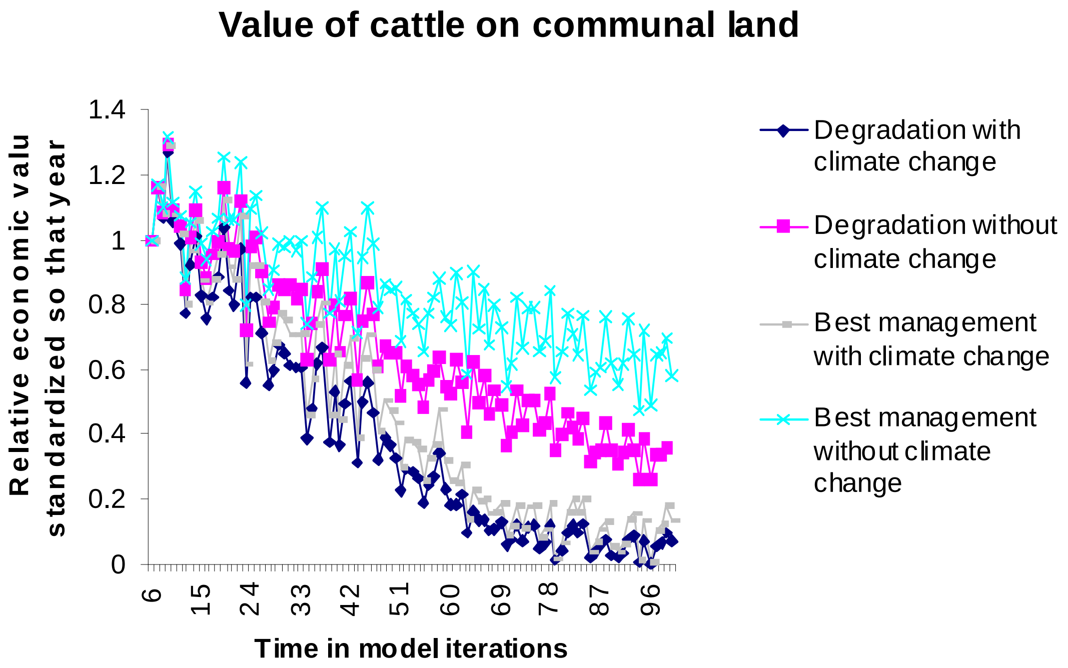
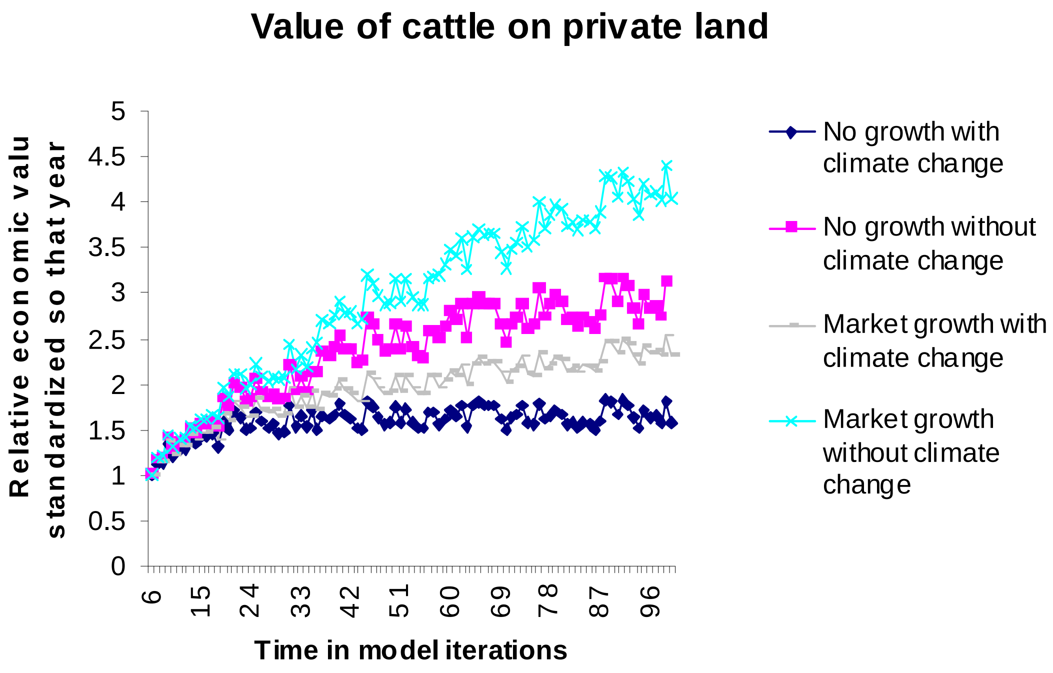


Figure 6. Market scenario options and their impacts on the value of cattle on a. private land and b. communal land across Southern Botswana (as per scenario assumptions in Table 1).



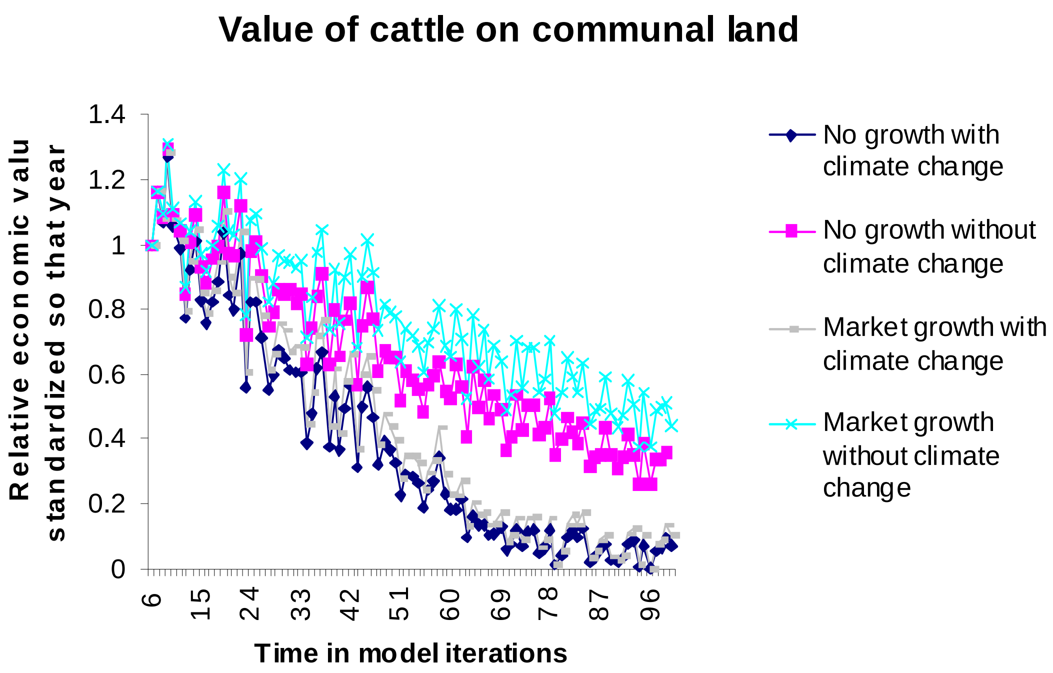
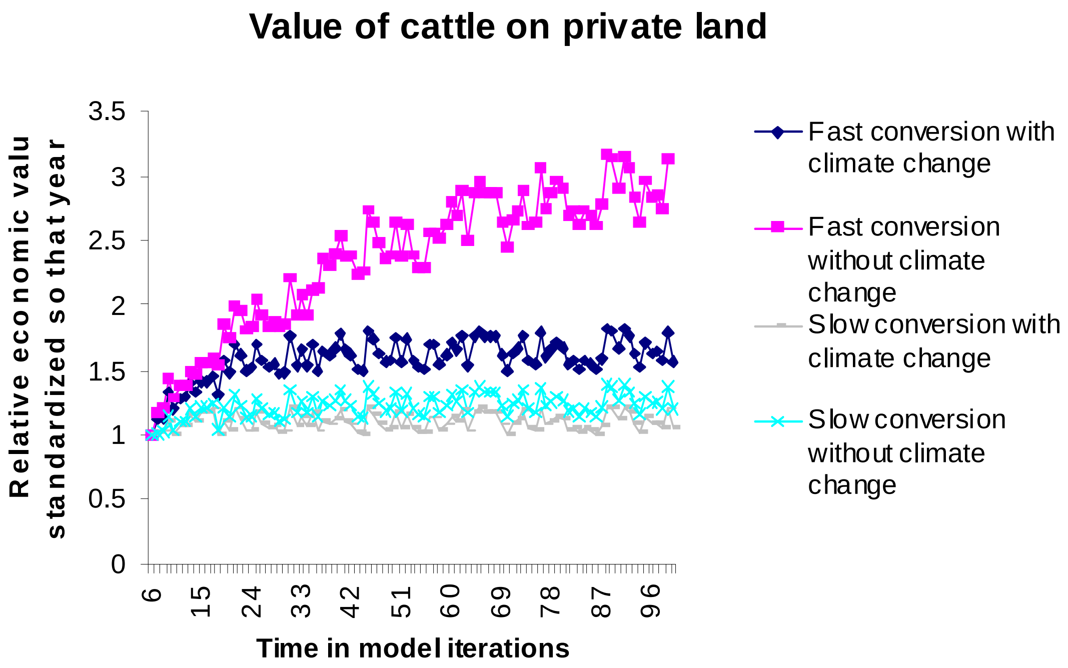
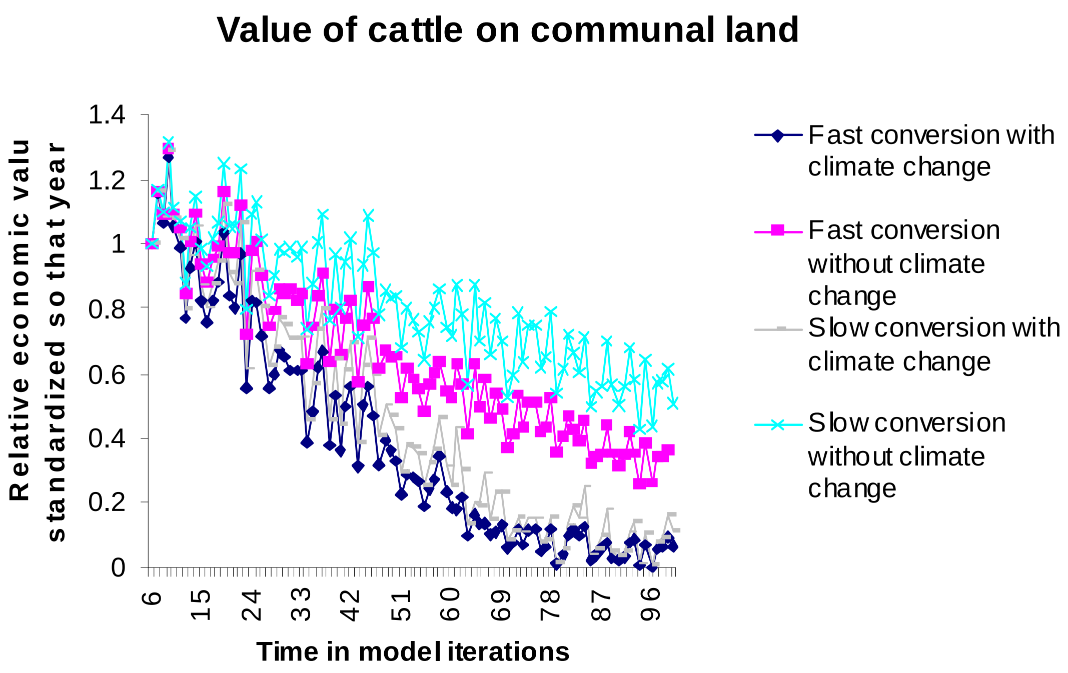


Figure 7. Policy scenario options and their impacts on the value of cattle on a. private land and b. communal land across Southern Botswana (as per scenario assumptions in Table 1).





Scenario name	Description	Lower estimates	Upper estimates
Climate change	This scenario determines what effect climate change might have on the value of communal and private cattle herds and is based on IPCC rainfall projections and a historic analysis of rainfall variability.	40% inter-annual variability and no long-term change in rainfall.[1]	40% inter-annual variability and a 0.1% p.a decline in average rainfall.[1]
Environmental management	This scenario determines to what extent agricultural best management practices might reduce the effects bush encroachment and is based on the ecological literature on the effects of bush encroachment.	Improved management leads to increases of 1 % p.a. (for 10 years) on private land prior to or 0.1 % p.a. for 20 years on communal land.[2]	Bush encroachment leads to a 0.05 % p.a. decline over the full model run period for both private and communal herders.[3]
Land tenure policy	This scenario simulates the effects of a governmental policy that slows the rate at which communal land is privatized and is based on the effects of similar policy in neighbouring countries.	A 'slow conversion' rate from communal to private ownership of 0.1 % p.a. based on Botswana's relatively high proportion of "tribal" lands as compared with neighbouring countries.[4]	0.5% p.a. of communal land is converted is privatized based on high rates of private lan holdings in neighbouring countries.[5]
Market conditions	This scenario determines how changes in the price of cattle may affect the value of communal and private cattle herds and is based on long term cattle price trends.	0.05 % p. a. increase in the price of cattle could occur from greater market access or higher market prices (either internationally or from greater national control / price guarantees to pastoralists).	10% annual variability in price but no long term changes because historic analysis of price does not show significant rises or falls in adjusted cattle price over past 40 years.[6]

Table 1. Summary of scenarios developed to quantify relative impact of different drivers on the value of cattle herd for private and communal herders in southern Botswana. The key references used to parameterize the scenarios are: (1) Christensen et al. 2007; (2) Quan et al. 1994 & Reed and Dougill 2008; (3) Dougill et al. 1999 ; (4) Adams et al. 1999 ; (5) Adams, 2001; (6) FAOSTAT & Perrings and Stern 2000.