# Drought, change and resilience in South Africa's arid and semi-arid rangelands

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**Droughts can have serious ecological and economic consequences and will pose an increasing challenge to rangeland users as the global climate is changing. Finding ways to reduce ecological and economic impacts of drought should thus be a major research thrust. Resilience, defined as the amount of perturbation a social or ecological system can absorb without shifting to a qualitatively different state, has emerged as a prominent concept in ecosystem ecology and more recently as a conceptual framework for understanding and managing complex social-ecological systems. This paper discusses the application and relevance of resilience to understanding and managing ecosystem change, and enhancing the capacity of land users to adapt to droughts. Drought can trigger vegetation change and factors such as grazing management can influence the likelihood of such transitions. Drought can cause differential mortality of perennial plants and this could provide an opportunity for rangeland restoration by opening up establishment sites for desirable species. The capacity of land users to cope with drought is influenced by the resilience of their agro-ecosystems, the diversity of livelihood options, access to resources and institutional support. By these criteria, current agricultural development approaches in South Africa, particularly in communal rangelands and areas of land reform, are unlikely to enhance land users' resilience to drought and other perturbations.**

**Key words**: adaptive capacity, alternative stable states, desertification, restoration, thresholds

## Introduction

Droughts are a frequent occurrence in South Africa's arid and semi-arid rangelands and can have severe ecological and economic consequences.[1] While these may be short-term and followed by recovery during subsequent years of higher rainfall,[2] in some cases droughts can trigger substantial and irreversible ecological and socio-economic changes. Desertification, in the form of reduced perennial vegetation cover, increased bare ground, soil erosion and reduced rain use efficiency, is thought to occur in steps which can be triggered by extreme climatic events such as drought.[3] Each step to a more transformed state comes with a higher cost to land users in the form of lost production, higher input costs and escalating costs of restoring lost function.[4,5] Some droughts have had catastrophic effects on whole societies, leading to economic collapse and mass migration.[6,7] Prolonged severe droughts can trigger socio-economic declines from which many people are unable to recover when normal climatic conditions return, and economic and ecological crises are often closely linked. For example, the Dust Bowl in the Great Plains of the U.S.A. during the 1930s led to the loss of several billion tons of topsoil and the displacement of some 3.5 million people, a third of the population in affected areas.[8]

Examination of past droughts shows that their ecological or economic impact is not always proportional to the severity of the climatic event, including its duration and rainfall deficit. In some cases relatively mild droughts have had surprisingly large ecological and socio-economic effects.[9] This suggests that some social and ecological systems display greater resilience than others, and raises the question as to which attributes enable a social or ecological system to retain its essential structure and functioning through disturbances such as drought. The links between drought, land management and desertification have been highlighted in the research literature and government policies and legislation.[1,10] Yet despite substantial (if sporadic) government investments in drought research, policy and action plans, our predictive understanding of the effects of drought on rangeland systems is limited and people living in these areas remain vulnerable to the ecological and economic effects of droughts. This is a cause for concern as the world is entering a period of unprecedented climate change, which is predicted to result in higher average temperatures, changes in precipitation patterns, increased risk of drought over many land areas and more frequent extreme weather events.[11] Models predict that reductions in mean annual rainfall, increased inter-annual variation and more frequent droughts will lead to disproportionately large impacts on livestock production.[12] Growing human populations, rising food and fuel prices, political changes and uncertainties around land reform add to the challenges of coping with droughts and climate change in South Africa's arid and semi-arid rangelands.

Resilience has become a prominent research topic in the context of achieving sustainability.[13,14] Since the idea of alternative stable ecosystem states, thresholds and resilience emerged in the early 1970s,[15] there has been an exponential growth in the number and diversity of publications on resilience, accompanied by an increasingly broad and ambiguous use of the concept.[16] Initially defined as the time it takes an ecosystem to recover from disturbance, resilience has become more commonly viewed as the amount of perturbation a social or ecological system can absorb before it shifts to a qualitatively different state, including its essential structure, processes and functions.[17] Two main lines of resilience research and literature have emerged, which use the concept of resilience in different ways.[16] The first focuses on the functioning of ecosystems and is concerned with the identification of alternative stable states, the nature of the thresholds between them, the mechanisms by which switches are triggered and the attributes that make ecosystems susceptible or resilient to such regime shifts.[18] The second applies resilience as a conceptual framework for sustainability that links production of knowledge, social learning and adaptive management to an underlying theory of complex adaptive social-ecological systems shaped by cross-scale interactions, nonlinear feedbacks and uncertainty.[14,17] While both applications of the concept are relevant to understanding the effects of drought on rangelands, conceptual clarity and practical relevance are lost if these descriptive and normative aspects of the concept of resilience are not clearly distinguished.[16]

## Drought and ecosystem resilience

Observations that vegetation responses to grazing, drought and fire are often discontinuous and difficult to reverse have led to the suggestion that thresholds exist between different range-

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land states,[19] and to the development of state-and-transition models.[20] These incorporate multiple successional pathways, multiple stable states, thresholds of change, and discontinuous and irreversible transitions.[21] Rangelands can exist in alternative vegetation states characterised by dominance of different functional groups such as trees, shrubs, perennial or annual grasses and herbs. Usually the structure, biomass and percentage cover of the vegetation differs noticeably between states. Alternative states are also characterised by different processes and altered relationships between state variables, e.g. between rainfall and primary production[22] or between stocking rate and animal performance.[23] The ecosystem states are separated by critical thresholds and often the state change is difficult to reverse due to the presence of strong internal feedbacks which maintain an ecosystem state.[24]

Transitions between alternative stable states may be triggered in two main ways.[25] The first occurs via altered biotic interactions (e.g. grazing, competitive dynamics) which provide sufficient perturbation to force the state to cross a threshold. In the widely used ball-in-cup analogy, this corresponds to the ball crossing a hill in a constant landscape. Alternatively, changes to the abiotic conditions (rainfall, soil nutrients) of a site may lower the threshold, analogous to the hill eroding, thus lowering the magnitude of perturbation required to move the ball across.[25] Drought represents the latter type of trigger, which can act in concert with the first kind (e.g. particular grazing regimes) to effect a system switch. Thus drought can lower the threshold to a different state such that a particular amount of perturbation (e.g. grazing) is sufficient to trigger a transition during drought.

Ecosystem resilience can be viewed as the strength of the negative feedbacks which return state variables such as livestock populations or plant composition to equilibrium after a perturbation.[26] Thresholds can be exceeded when these feedbacks weaken and are replaced by positive feedbacks which destabilise the system, rendering it susceptible to factors such as droughts which can trigger a sudden regime shift.[26,27] This could occur when negative feedbacks between grazers and vegetation become asymmetric. For example, when dry season fodder is provided, the impact of herbivory on the vegetation is increased whereas the negative feedback of the vegetation on the herbivores is reduced. There is evidence that provision of large amounts of supplementary feed in North Africa, the Middle East and Central Asia has led to rangeland degradation.[28,29]

Undesirable ecosystem states, such as compacted or eroding bare soil or rangelands that are densely bush encroached, can be highly resilient and require considerable management inputs to initiate the transition to the more desirable state.[20] Restoration of degraded rangelands or mined areas is often slow, difficult and unpredictable. This results from ecological constraints that create internal feedbacks, such as soil changes, altered hydrology, presence of alien plant species which alter ecosystem processes, changed microclimate or the loss of native seed banks and other sources of propagules.[24] The loss of shrubs or bush clumps, which create fertile islands by accumulating nutrients and organic matter under their canopies, can lead to landscape-level nutrient losses.[30,31]

## Drought, vegetation change and management opportunities

Vegetation change is an outcome of the differential mortality and recruitment of different plant species in response to drought, defoliation and other forms of stress and disturbance.[32] Knowledge of the response of different plant groups to high and low rainfall events, including critical thresholds for seedling recruitment and adult mortality, can help predict vegetation change and allow opportunistic interventions to prevent or promote vegetation change.[33]

Vegetation change triggered by drought often results in reduced agricultural productivity, for example a loss of perennial shrubs or grasses.[34] Heavy, continuous grazing is thought to be a major factor which increases the likelihood of drought causing such a switch.[3] Selective herbivory increases mortality of palatable plants by reducing their ability to accumulate stored resources and reduces their fecundity by decreasing their size or destroying reproductive structures.[35,36] In systems dominated by perennial grasses, high grazing pressure can exacerbate drought mortality of grass tussocks and hinder post-drought establishment of seedlings.[37,38] Compositional changes and local extinction of palatable grass species such as *Themeda triandra* following drought are greater under heavy grazing than under light or no grazing.[39,40] In subtropical thicket, heavy continuous browsing by goats breaks up bush clumps and results in the formation of a pseudo-savanna of scattered trees and an ephemeral field layer.[41] Rates of tree mortality in this pseudo-savanna exceed recruitment and this unstable state thus represents a transition to a desertified state dominated by annual grasses and forbs. Heavily-utilised thicket can also become dominated by karooid dwarf shrubs.[42] In the Karoo, heavy continuous grazing and drought lead to a loss of palatable shrubs and increased dominance by unpalatable woody species and annuals.[3,35]

Vegetation in arid areas can have very little plant turnover for extended periods, punctuated by large recruitment or mortality events in high-rainfall and drought years respectively.[33,34,43] This is especially the case when the dominant species are long-lived.[44] In such systems extreme climatic events provide rare opportunities for manipulating vegetation change to restore rangelands[45] or to avoid undesirable change. Bush encroachment in arid savannas is largely constrained by seedling recruitment. This in turn depends on water availability, which is mainly a function of the magnitude and timing of rainfall events, but is modified by competition from grasses and established trees.[46] Drought mortality prior to a high-rainfall event may create favourable conditions for tree recruitment by causing grass mortality. Prevention of bush encroachment requires interventions to avoid a release of the recruitment bottleneck, for example by ensuring high grass biomass during rainfall events rather than allowing grazers to reduce it.

The important role of high-rainfall events for plant recruitment and the opportunity this presents for rangeland restoration is now well recognised,[45] but the potential role of droughts in improving rangeland condition has been less explored. Seedling recruitment in arid shrublands is limited by rainfall but also by the availability of establishment sites and competition from established plants.[33,47] Drought mortality reduces competition from adult plants and thus creates favourable conditions for seedling establishment.[33] Faster growing, palatable shrub species are less susceptible to drought mortality than slower growing, more defended shrubs under light grazing.[48] Managers could time restoration interventions to take advantage of such an opportunity. The success of this would depend on the rainfall after a drought, the amount of drought mortality and hence the availability of open space, the availability of safe sites (nurse plants or artificially created microhabitats) and grazing pressure. Recruitment after a drought relies on a source of propagules in the form of a seed bank, or dispersal from surviving plants. Perennial grasses invest less in reproduction from seed than do annual grasses,[38] and palatable shrubs often have low seed production under heavy grazing.[35] Their dispersal, recruitment and establishment is therefore often seed limited, and open space created by drought is often colonised mainly by ruderals.[49] Restoration interventions are therefore likely to require the introduction of seeds or other suitable propagules.

## Detection of thresholds and assessment of ecosystem resilience

Because of the high inherent rainfall and vegetation variability in arid rangelands, thresholds can be difficult to detect. Over time scales typical of most rangeland research (i.e. less than a decade), rainfall and other abiotic drivers are often found to be stronger determinants of primary production than grazing effects.[50,51] Data over longer time scales are required to detect long-term change because inter-annual and cyclical rainfall variation can obscure longer-term trends.[52] Assessment of directional change is further complicated by the fact that vegetation change is spatially heterogeneous. Some areas are more resilient to transformation than others, either because herbivores cannot access them for prolonged periods (e.g. annual grasslands, grazing areas far from permanent water) or because the dominant plant species are tolerant of heavy defoliation (e.g. stoloniferous grasses). Nutrients, water and plant propagules lost from degrading patches may also be deposited and concentrated elsewhere in the landscape with little net loss in productivity.[52,53] The effects of vegetation transformation on secondary production tend to be masked by this spatial heterogeneity[54] and during periods of favourable rainfall.[52] Since long-term changes can take place over time scales much greater than those at which management decisions are made, land users often do not perceive degradation as a concern.[5]

Whether a change is perceived as gradual or sudden can depend on the scale of observation. Alternative states are often present as patches in the same landscape and fairly abrupt changes at the patch scale can result in more gradual change at the landscape level. Such processes have been modelled as patch dynamics in mosaics with two or more phases (e.g. bush vs. grass, or grass, bare and degraded states) using cellular automata.[33,55] Recent literature suggests that strong self-organisation and scaling of vegetation elements occurs in arid and semi-arid ecosystems.[55,56] Size class distributions of patch sizes have been found to closely follow a power law (with many small and fewer large patches) in a range of research sites including a rainfall gradient across the Kalahari[57] and Mediterranean shrublands.[58] These relationships can be mimicked closely by models which include strong positive interactions between plants at small spatial scales and overall large-scale density dependence based on resource (usually water) limitation. Positive interactions between plants within patches have been widely documented in arid ecosystems, as vegetation patches increase runoff capture, nutrient enrichment and water infiltration, reduce soil erosion and create favourable microclimates for plant establishment.[27,55] A loss in the spatial structure of patchiness may serve as an indicator of imminent desertification.[55–58]

Evidence for the existence of alternative stable states requires demonstration of at least two states which are locally stable and which persist after the perturbation that caused the switch has ceased.[25] Vegetation under different grazing management usually differs noticeably in composition, structure, diversity and forage production potential.[35,59] One way to determine whether these alternative states are stable is to experimentally change their management by excluding grazers from heavily grazed vegetation or monitoring vegetation changes after changes to lighter or heavier utilisation. Large areas in South Africa are currently undergoing land-use change from commercial livestock farming to wildlife conservation or as a result of land reform. This land-use change provides a wealth of opportunities to study the nature of the changes that occur, whether there is evidence of threshold behaviour, and what attributes and processes characterise systems as they approach a threshold.

Examples of state shifts in rangelands have been documented for a range of ecosystems.[60] But while it is possible to demonstrate the existence of alternative stable states, it is difficult to test whether all systems work that way as the absence of state transitions in any given system does not prove that they cannot occur. The question remains whether all rangeland systems have the potential for alternative stable states under current and likely land use and climatic scenarios and whether rangeland states in some ecosystems are more generally continuous and reversible. Objective and critical meta-analyses of case studies and long-term data sets in different systems are required to determine which systems exhibit catastrophic shifts, whether different management actions increase or decrease the likelihood of drought-induced transitions and whether any common patterns can be detected that signal a regime shift. Even then, alternative explanations of the dynamics cannot always be ruled out,[61] but few experimental studies have been done to examine the existence of alternative stable states in rangelands. A review of 35 manipulation experiments[61] to test for evidence of alternative stable states included only three experiments conducted in natural grasslands. Two of these were found to be of an unsuitable design to deduce the existence of alternative stable states, while the third found no evidence for alternative stable states.

## Drought as driver of socio-economic change

Rangelands are complex systems characterised by linkages and feedbacks between ecological and social processes across a range of temporal and spatial scales.[5] The effects of droughts in rangelands are an outcome of the interplay between climatic events, plant-herbivore interactions and human management decisions. The latter are determined by the opportunities and constraints presented by various ecological, economic and political drivers, which in turn often originate at higher levels of organisation (e.g. national legislation and policy, global commodity prices) than the scale at which management takes place.[52] To understand the response of rangelands to drought, assessments thus have to be integrated across disciplines and also across different spatial and temporal scales.

The Sterkspruit (formerly Herschel) District in the Eastern Cape illustrates the role of drought in ecological and economic collapse, but also the apparent resilience of a degraded system.[62] Up to the early 1870s, various visitors to the district reported high levels of agricultural productivity and a prosperous population, but historical accounts suggest that a transition to a degraded and less productive state took place in the last decades of the 19th century and that a drought in the late 1870s and early 1880s appeared to have been the turning point.[63] Droughts, locusts and rinderpest between 1895 and 1899 and in 1903 further devastated agricultural production, forcing many people to sell their livestock and to seek employment. Reports from the following years show increasing reliance on migrant labour and food sources from outside the district.[63] Since the 1920s, Sterkspruit has been rated repeatedly as one of the most severely degraded districts in South Africa.[10,64,65] Records spanning the twentieth century show no decline in livestock numbers, even though soil erosion has increased in severity and extent during that period.[66] Livestock are now increasingly supported by feed inputs.[62] The human population has grown exponentially, from 24 000 in 1895 to 130 000 in 1991,[62] and average livestock holdings per household have decreased correspondingly. All this suggests a system with declining ecological and social resilience which may be nearing the threshold of agricultural collapse, yet the district continues to export wool and livestock numbers remain high. Other communal rangeland systems have shown similar persistence despite predictions of imminent collapse.[67]

### What makes social-ecological systems resilient, and is this supported in South African rangelands?

Resilience requires the capacity to absorb change or to adapt.[14] Analyses of vulnerability to drought and climate change in rural or agricultural systems show that adaptive capacity depends on the resilience of their agro-ecosystems, opportunities for changing and diversifying income streams, institutional support and access to resources.[9,68] The sustainable livelihood framework[69] measures vulnerability in terms of five classes of 'livelihood assets': human capital such as health, education and skills; natural capital such as access to ecosystem services and products; social capital including social and kinship networks and support; physical capital such as infrastructure and housing; and economic capital including income, savings and access to credit. Households with a higher and more diverse endowment of these different forms of capital are more capable of coping with perturbations and adapting to change. Access to market information, climate forecasts and other information can also increase the ability to anticipate and cope with drought.

In South Africa resilience thinking has become influential in the management of many conservation areas, where the emphasis has shifted from preventing change and reducing the effects of environmental variability to managing for heterogeneity and complexity with an aim to enhancing the resilience of these ecosystems.[70] Nevertheless, building adaptive capacity among land users is not the primary goal of conservation agencies and conflicts between conservation and human development needs remain a challenge. Agricultural research and development have generally remained focused on sustainable yields and reducing the effects of environmental variability, and agricultural policies and interventions in South Africa still lack an integrated approach which incorporates ecological and social dimensions of rangelands use. A case in point is agricultural policy and government support for communal rangelands and beneficiaries of land reform.[71] Rural livelihoods are derived from diverse sources of income and there is a high dependence on employment, pensions and other state grants, while farming serves primarily as a safety-net against unemployment and makes a relatively small contribution towards day-to-day household subsistence.[71,72] People in rural areas also rely on a range of natural products to meet energy, food and other needs.[72] This diversity of income sources is an adaptive response to variable and unpredictable biophysical and socio-economic environments, but despite this many households in rural areas are chronically poor.[71] Land reform aims to enhance land-based livelihoods, to improve the food security of the poorest households and to promote the emergence of black full-time commercial farmers.[71,73] Lack of support, capital and infrastructure have led to the failure to achieve these aims in most cases. The South African Department of Agriculture has adopted an approach geared to commercialising livestock production in the commons, despite the fact that few current or prospective livestock owners have the intention or capacity to give up other sources of income and enter full-time commercial farming.[74] At a time when many established commercial farmers are giving up farming or diversifying their sources of income in the face of economic, political and climatic uncertainty, reducing the diversity of livelihood options among poorer and emerging farmers reduces their ability to cope with drought and other pressures.

### Conclusions

Droughts will pose an increasing challenge to rangeland users in the future, and finding ways to reduce their ecological and economic impacts should be a major research thrust. This requires rigorous ecological research to understand rangeland responses to drought and other drivers, as well as an integrated trans-disciplinary framework for supporting and developing complex rangeland systems. The research challenges involved in understanding resilience are considerable. Resilience theory, with its ball-and-cup analogies and metaphors of 'bouncing back' can be deceptively simple and intuitive. This has made it a useful concept for fostering communication across disciplines and between science and practice,[16] but this accessibility brings with it the risk of oversimplification and uncritical acceptance of some of its associated hypotheses.

Research to investigate resilience and thresholds in relation to drought needs to be long term, flexible and opportunistic to capture slow and stochastic processes. This poses obvious challenges. Funding cycles and the typical time spans of postgraduate degrees are shorter and less flexible than such research requires. This places the onus on research institutes and initiatives such as the South African National Rangeland Monitoring Programme to ensure such data are collected in the long term with the strategic objective of understanding long-term variability and change. Given the closely-linked ecological, social and economic impacts of droughts, research and monitoring programmes need to integrate these different dimensions in their design, execution and outputs.

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