CEPF SMALL GRANT FINAL PROJECT COMPLETION REPORT

I. BASIC DATA

Organization Legal Name: Arid Zone Ecology Forum

Project Title (as stated in the grant agreement): Drought in the Succulent Karoo – Increasing the Awareness of Stakeholders Through a Better Understanding of the Physical, Ecological, and Socioeconomic Effects, Interactions, and Responses

Implementation Partners for This Project:

Project Dates (as stated in the grant agreement): July 1, 2007 – February 28, 2008 (Extended to June 30, 2009)

Date of Report (month/year): 06/2009

II. OPENING REMARKS

Attached to this document are two reports of workshops held during this project. The first relates to a farmers' workshop held in Sutherland in September 2007, and the second a Land managers' workshop held in Noep in May 2009.
Also attached are 7 pdf files which were produced thanks to funding from CEPF for the AZEF 2007 meeting which focused on drought in South Africa's arid zones, with a focus on the Succulent Karoo. These are peer-reviewed papers published in the *South African Journal of Science* 105 (1/2) Jan/Feb, 2009, and are also publicized on the AZEF website (www.azef.co.za).

III. NARRATIVE QUESTIONS

1. What was the initial objective of this project?

The project aimed to disseminate scientific research to civil society, through farmers and land manager workshops and publications in the *South African Journal of Science* and popular press. The AZEF has a long history of helping young scientists to launch their conference-going careers, and to this end, the project aimed to benefit young scientists through the conference experience, the positive young role models and the opportunity to participate in the peer-reviewed publication process.

The specific outputs related to this funding application achieved by June 2009 are:

1. Presentations by six invited speakers on drought in the arid areas of South Africa, including the Succulent Karoo, exploring physical, ecological and sociological effects, interactions and responses;
2. A farmers' workshop, where management responses to drought were discussed and explored;
3. A land managers workshop, where ecological function, ecosystem services and restoration were discussed, and practical in-field assessment techniques were trialed;

4. The publication of six papers, and a synthesis paper to be in the South African Journal of Sceince;
5. Published popular articles in *Farmers' Weekly* and *Landbouweekblad* summarizing the major outcomes of the conference;
6. Published electronic abstracts of the conference available through the AZEF web site along with the publications emerging from this meeting.

2. Did the objectives of your project change during implementation? If so, please explain why and how.

Objectives have not changed. All six papers were published (see attached). One of our key speakers, Susi Vetter, was interviewed for an article in the *Farmers' Weekly* (see attached).

3. How was your project successful in achieving the expected objectives?

The farmers' workshop was a great success – see attached evaluation by Rhoda Louw, based on interviewing both farmers and scientists on the day of the workshop. The conference was very interesting, and the papers on drought and resilience, and the importance of biodiversity to these are now published. The land mangers workshop was also a fantastic success, with a total of thirteen managers trained. Attached is a report detailing the training activities carried out, coordinated and presented by Dr. Peter Carrick.

4. Did your team experience any disappointments or failures during implementation? If so, please explain and comment on how the team addressed these disappointments and/or failures.

Weaknesses related to the farmers' workshop are reported in Rhoda Louw's evaluation, but as you will see, none of these were major. In fact, one criticism from the farmers was that they wanted the workshop to be longer, they felt they had learnt a lot but wanted more. The conference itself was a success, all the invited speakers presented good, relevant and interesting papers, with interesting results emerging, particularly about South African policy (e.g. that 6 of the 12 proposed Accelerated and Shared Growth Initiative for South Africa (ASGISA) projects that government has planned will not be viable, given the shortage of fresh water in this country). The journal papers did take a while to collect, review, and go to press, and could only be published in January 2009. This type of delay is typical for peer-reviewed papers, however, as reviewing papers is an "extra" that scientists do, and not "core" business. The additional land managers workshop was also very successful, however, and although we had the capacity to train 20 people, only 13 were prepared to take time off to be trained. Motivating people to attend training workshops is a serious challenge, and one we are as yet unable to address. Hopefully, those who did attend will share their knowledge and motivate others to attend in future, should such opportunities arise.

5. Describe any positive or negative lessons learned from this project that would be useful to share with other organizations interested in implementing a similar project.

Again, Rhoda Louw's evaluation is useful here, but the most important points are:

- We think we would advertise more in advance, making it clear that the presentations would be in the farmers' home language (some farmers had reservations about attending as they thought it would be in English).
- We would also include a land-user demonstration of best practices, perhaps as a field trip.
- Adjusting the programme to accommodate people who wanted to/could only attend certain sessions would have been a good idea.
- A need for closer partnerships between land-users and researchers was identified
- Rely on a local contact person to gain access to farmers who might be interested in attending these meetings. Was helpful to have someone "on the ground" – a resident of the Sutherland area, to invite people and to help explain the aim of the workshop.
- Difficulties associated with producing a special journal edition is that people are interested but are time constrained
- It is very difficult to get land managers to attend courses, however smaller-sized groups allowed for focused interaction and discussion on a subject, and a reasonably fast pace of learning.

6. Describe any follow-up activities related to this project.

The farmers' workshop was such a success that we have in the interim carried out more, firstly at out joint conference in Oudtshoorn with the Fynbos forum in August 2008, and then in the Land managers' course at Noep in the Succulent Karoo, utilizing the remainder of the CEPF funds. It is hoped that the experience and skills generated will lead to more farmers and land managers workshops being conducted in association with AZEF in future.

7. Please provide any additional information to assist CEPF in understanding any other aspects of your completed project.

IV. ADDITIONAL FUNDING

Provide details of any additional donors who supported this project and any funding secured for the project as a result of the CEPF grant or success of the project.

Donor	Type of Funding*	Amount	Notes
National Research Foundation	B	$ 5 600	Running costs of the conference itself, not including guest speakers, etc.
BIOTA Southern Africa	B	$14 000	Financial support for needy students and land managers to attend the conference

***Additional funding should be reported using the following categories:**

- ***A*** *Project co-financing (Other donors contribute to the direct costs of this CEPF project)*
- ***B*** *Complementary funding (Other donors contribute to partner organizations that are working on a project linked with this CEPF project*
- ***C*** *Grantee and Partner leveraging (Other donors contribute to your organization or a partner organization as a direct result of successes with this CEPF project.)*
- ***D*** *Regional/Portfolio leveraging (Other donors make large investments in a region because of CEPF investment or successes related to this project.)*

V. ADDITIONAL COMMENTS AND RECOMMENDATIONS

VI. INFORMATION SHARING

CEPF is committed to transparent operations and to helping civil society groups share experiences, lessons learned and results. One way we do this is by making programmatic project documents available on our Web site, www.cepf.net, and by marketing these in our newsletter and other communications.

These documents are accessed frequently by other CEPF grantees, potential partners, and the wider conservation community.

Please include your full contact details below:

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Resilience: *managing shifting sands*

The finalists in the Eastern Cape Conservation Farmer of the Year competition are farmers who effectively manage change by establishing sustainable farming practices, says judging panellist **Dr Susi Vetter**. This, as **Roelof Bezuidenhout** reports, is known as resilience.

- Resilience enables a system to survive and persist during change.
- All finalists applied conservation farming principles and were involved in their communities.
- Extreme climatic conditions have resulted in some societies collapsing while others survived.

WE'RE SEEING YEAR-TO-YEAR climatic variations and experiencing social, economic and political change at various scales. Regarding climate, we have to start asking what the long-term effects of global warming will be and if ecosystems and people are resilient enough to cope with them. That's according to Dr Susi Vetter of Rhodes University's Department of Botany who delivered a keynote address at the recent Arid Zone Forum congress held in Sutherland.

"Resilience is the ability of a system to survive and persist in the face of disturbance by maintaining and reorganising its key attributes," Vetter says. "Building resilience into human-environment systems will help us to handle change. This is particularly true for arid regions which are marked by high variability, low fertility, sparse populations, remoteness, and distance from decision-makers."

Ecological change can occur slowly and, at first, go unnoticed. But Vetter warns that when bush encroachment has taken hold it's not easy to reverse without drastic steps. "We don't really know how to tell when an ecological shift is imminent and when a threshold will be crossed into the next state," she says. "Often, fluctuations obscure trends as a system nears a switch to less favourable conditions. So far, management has focused on preventing or slowing down

What a resilient farm looks like

DR SUSI VETTER AND PIETER CONRADIE OF the Dohne Agricultural Research Station describe their tour of the five farms that reached the finals for the Peter Edwards Award (**see box: Peter Edwards Award**) for conservation farming, and what they have in common.

The farms lie in diverse agro-ecological areas, from Karoo veld with an annual rainfall of less than 300mm to climax mountain veld with an annual rainfall of over 1 000mm.

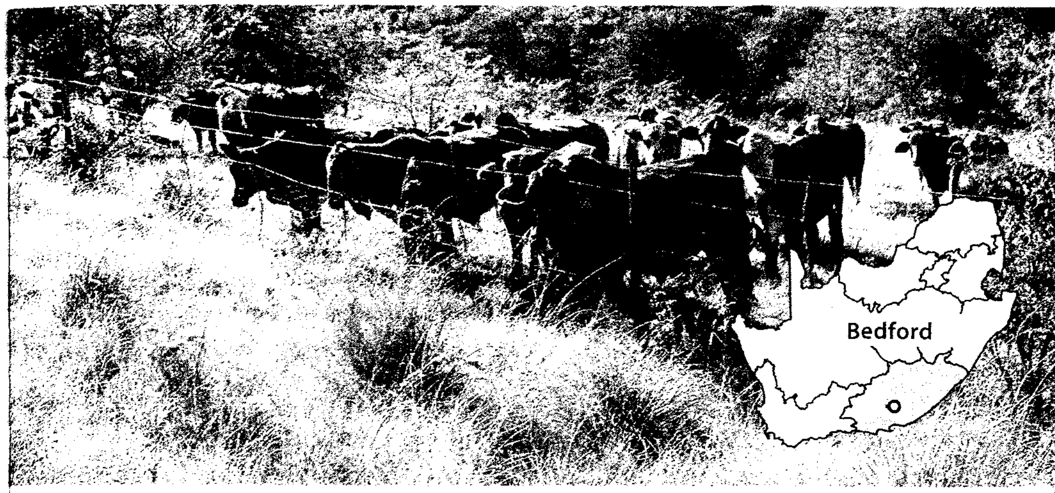
While the Karoo farms had last seen rain in November 2006 at the time they visited, the farms around Bedford and Grahamstown had had record rainfall in 2006 and early 2007. The challenge there was coping with the prolific grass growth before it became tough and unpalatable. All finalists showed great commitment and creativity, applied sound conservation farming principles and were actively involved in their communities. All farmers had identified a veld management system suited to their resources and adapted their livestock production systems accordingly. All farmers felt the effects of lower or unstable meat and wool prices, higher input costs and tougher labour laws and thus cut costs by eliminating unnecessary activities. Only one regularly provided supplementary feed – the others rarely, if ever, did. Instead, they adjusted animal numbers to match the productivity of their veld.

All finalists had a small but stable staff component of between four and eight workers – a third of the size a decade ago. This illustrates the efficient manner in which these farming systems are run. Two of the farmers had established farm schools, one encouraged workers to keep livestock on the farm and all provided reliable and serviced housing for their staff.

Future of agriculture in South Africa

The finalists agreed that conservation farming is a long-term commitment.

There has also been a massive shift to game ranching, driven in part by very high prices offered for land by buyers from cities and overseas. While this is good news for biodiversity and tourism, it also raises the question of the future of farming as more and more farming infrastructure is removed, farming communities and their social and educational facilities become thinner and conflicts between farmers and game reserves become more common.



Lochart Ainslie of Glen Gregor Farm employs patch burning and grazing by mature oxen to control his *Cymbopogon*-dominated veld.

observable changes rather than assessing and maintaining resilience. In the face of economic, political and environmental change and unpredictability, we should shift the focus of management from maintaining stability to ensuring that we can deal with, adapt, and learn from change."

Link between people and ecology

Vetter believes the resilience of ecological and social processes are linked. "Farming is a prime example of this. It would be interesting to know the effects of extreme climatic events and climate change on societies in the past and what allowed some to cope better than others, and if ecological resilience had anything to do with it," Vetter says. "Extreme climatic events have resulted in some societies collapsing while others survived. Climate reconstructions show that between 1500 and 1800 there was a long period during which Southern Africa was considerably dry and cold. But while the archaeological record from Namibia shows a decline in settlements, in other parts of Southern Africa there was an expansion."

The Ethiopian famines in the 1970s and 1980s were devastating and thousands of people died or were displaced. Yet, Vetter says from a climatic perspective, these were not particularly extreme droughts. "The problem was that there was a civil war and the northern parts of the country – where the famine hit hardest – were cut off from alternative means of obtaining food or income," Vetter says. "Government responded by mass resettlement, which

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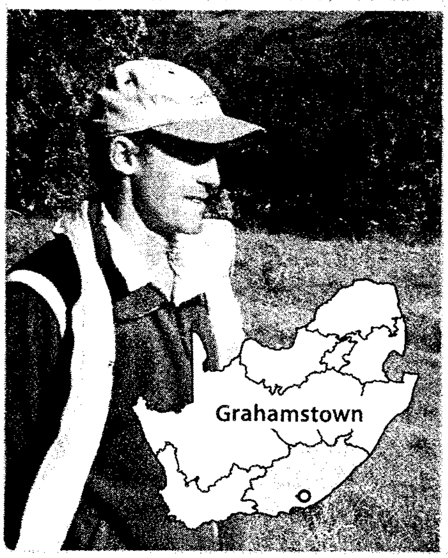
John and Richard Gush: Beacon Hill Farm



The farm Beacon Hill in Grahamstown is owned and run by John Gush and his son Richard. They too have been active members of the conservation committee and the local study group. They maintain meticulous records of all enterprises on the farm – cattle, sheep, game and ecotourism. Conservation works erected by John's father have seen previously eroded areas stabilised and covered by bush and grass. The farm has *Themeda*-dominated veld maintained by judicious grazing management and burning. When Richard, a civil engineer, came to the farm in the late 1990s he realised the need for additional enterprises. In 2001 Amakhala Game Reserve was established together with five fellow farmers as partners. Amakhala is now one of the premier private game reserves in the area and remains family-run.

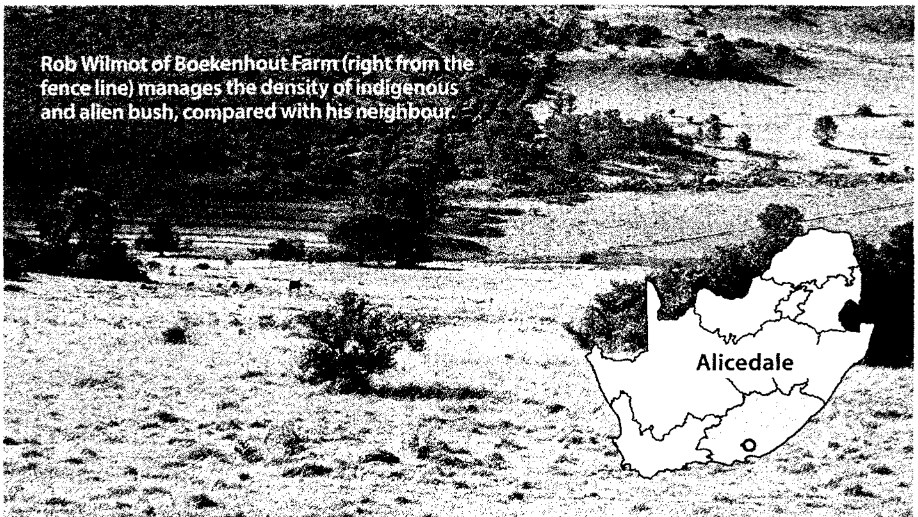
Lochart Ainslie: Glen Gregor Farm

The farm Glen Gregor, belonging to Lochart Ainslie of the Kowie Valley near Bedford, has been in his family since 1837, with Lochart representing the fifth generation. His son Hugh recently joined the farming venture, which consists of cattle, while hunting is a sideline.

As pioneer in the battle against *Acacia karoo* encroachment, which is a major challenge in the lower-lying sweetveld parts of the farm, he has hosted symposia on the subject and is actively combating encroachment using mechanical clearing plus herbicide, fire and a flock of 1 000 Boer goats. He also keeps some Dorpers.

The higher parts of Glen Gregor represent a different challenge with *Cymbopogon*-dominated climax mountain veld. Lochart uses patch burning and grazing by mature oxen which utilise and control this resource. As a result he has seen improved basal cover and species composition, reduced abundance of *Cymbopogon* and an increased carrying capacity of 600 large stock units (LSUs).

Lochart is an active member of the local soil conservation committee and farmers' association, and established the Mill Cricket Ground on his property as a venue for local and international cricket matches, while the historical mill serves as the clubhouse.



Rob Wilmot of Boekenhout Farm (right from the fence line) manages the density of indigenous and alien bush, compared with his neighbour.

further disrupted agriculture and displaced people. Farming ecosystems are often sensitive to environmental change because they rely on a low diversity of often poorly adapted species, breeds or cultivars. Farmers also become vulnerable if they are unable to divert or diversify sources of income, and if institutions do little to ease adverse impacts," Vetter says. "The Irish potato famine, for example,

'We should ask if land reform will increase the resilience of emerging farmers.'

left two million people to starve or emigrate when *Phytophthora* caused two consecutive harvests to fail. The reason for the devastation was the complete reliance on a single variety of one crop and no other sources of income to switch to."

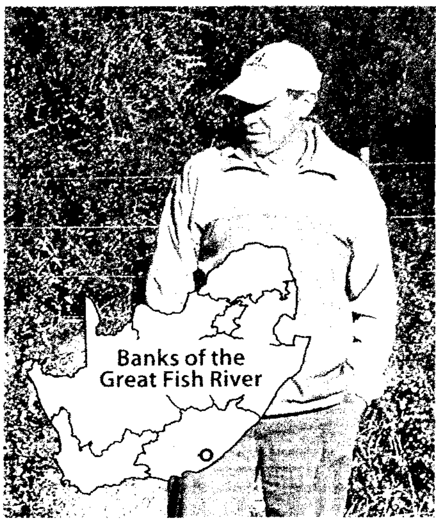
How resilient are South African farmers?
Records from Herschel's communal district in the Eastern Cape show that there has been no decline in livestock numbers over 100 years, despite severe and increasing soil erosion. Research shows that livestock are increasingly maintained by feed inputs and animal purchases while the human population continues to grow. Vetter says this suggests declining ecological and social resilience. The question is whether this system is nearing a threshold to collapse, or if it actually is in a resilient state that people have been able to maintain through adaptation and diverse sources of income.

"We should ask if land reform will increase the resilience of emerging farmers. Land

Rob Wilmot: Boekenhout Farm

Rob Wilmot of the farm Boekenhout near Alicedale is one of the few farmers in the area still successfully farming with sheep, of which there is a long and proud history in his family. Much of the farm is on grassy fynbos and the challenge is to prevent fynbos shrubs' dominance and utilise a grass sward which grows quickly and becomes unpalatable when not managed well.

There's a noticeable difference in the density of indigenous and alien bush between Rob's and his neighbouring property. Nevertheless, there are scattered clumps of indigenous bush on the farm which add shelter for sheep and plant diversity. A number of rare species such as *Oldenburgia grandis* (donkey ears) are well preserved. Boekenhout has been used by the Eastern Cape Department of Agriculture as a benchmark for Grahamstown False Macchia veld type. Rob has served as chairperson of the local farmers' association and Albany Conservation Committee, and was recently chosen to serve as a mentor to developing farmers on the revived conservation committee for Albany.



Tony and Lynn Phillips: Bucklands Farm

Tony and Lynn Phillips farm on Bucklands along the Great Fish River. The farm is now almost completely surrounded by conservation areas, including the Great Fish River Reserve, which has increased the challenge posed by ticks and jackals. The vegetation type is Valley Bushveld with an impressive component of *spekboom* and excellent grass cover. This is in considerable contrast to the neighbouring conservation area.

Tony and Lynn started out as teachers but made a career change and studied at Grootfontein Agricultural College. They keep cattle (Bonsmara stud), Angora goats and purebred Dorpers. Grazing is done first intensely with cattle for two weeks, followed by goats for two weeks and then 11 months' rest. Water provision has been a big challenge but all of the many camps have good water points which, despite the intensive short duration grazing system, were surrounded by a dense grass sward. Lynn developed ecotourism on the farm, although the presence of hippo soon stopped the river rafting activities.

The winners: Trenly and Wilmari Spence

The winners – by a narrow margin – were Trenly and Wilmari Spence of Kriegerskraal near Graaff-Reinet. Trenly took over the farm in his early 20s after the death of his father and developed its infrastructure, dividing the large and heterogeneous grazing camps into a system of nearly 150 small camps which are intensively used. He developed underground water to provide permanent and sufficient water to all camps and extended his father's irrigated lucerne lands to 30ha, which he now mainly uses as a cash crop providing a buffer in extreme years.

Despite no rain in nearly eight months, and while his neighbours had been feeding their livestock for two months, Trenly still had ample grazing reserves and did not anticipate the need for supplementary feed.

He was the first farmer to introduce Nguni cattle to the area in 1997, and has since served as chairperson for the Nguni Stud Breeders' Association. He now keeps equal proportions of Nguni cattle, Angora goats and Dorper-Damara sheep which he runs in mixed herds. This has proved to be effective in fully utilising the veld during short, intensive three-day grazing spells, and reduced the vulnerability to jackal predation. Despite criticism from many of his peers, Trenly developed, maintained and adapted his intense short-duration grazing system.

He regularly monitors his veld, measuring shrub and grass cover, and keeps photographic records. Through this he has documented improved plant cover and composition, and has increased livestock productivity from 28ha/LSU to 9ha/LSU over 20 years of farming. He credits the full and non-selective utilisation followed by very long recovery periods which prevent the loss of palatable perennial shrubs and grasses in this arid environment. He has also undertaken veld reclamation in eroded areas using a butting plough and introducing preferred grass species. Trenly and Wilmari are active in the local study group.

Trenly Spence developed a system to use underground water in his camps, ensuring grass cover despite eight months without.

PHOTOS: PIETER CONRADIE

reform models that push for commercial farming with limited livelihood options and weak institutional support are unlikely to leave the recipient in a resilient position to cope with economic and climate change," Vetter says. "Often the amount of land per farmer is small, making the system ecologically and economically vulnerable as there is little spatial buffering and stocking rates are often too high to get enough return. Cutting ties with the communal areas also means abandoning social support networks which help to maintain resilience."

Learning from others

Vetter believes people can learn about resilience from farmers who have managed to stay successful despite economic and political change, as well as an unpredictable climate. "Many such farmers have systems that are ecologically well adapted, matching breeds of livestock to their environment, using grazing systems that work for the veld type and reducing reliance on inputs," Vetter says. "They have also diversified sources of income, and can draw on good institutional support.

"To plan for the future we need objective and critical analyses of case studies in different systems to see how many exhibit catastrophic shifts and what they have in common. We'll need to know what alternative system behaviours are and what distinguishes systems with gradual, abrupt and regime shift responses. Most importantly, we should identify indicators of vulnerability for low resilience, ecological and social. This is a challenge given the unpredictable nature and long time scales of many of the processes involved, which are often not picked up in research typically funded for three to five years."

Managing for resilience must include maintaining and enhancing livelihood options. But this should happen at different levels and requires commitment and resources from all roleplayers.

- *Call Dr Susi Vetter on (046) 603 8595.* |fw

The 2007 Peter Edwards Award

The Peter Edwards Trophy (Peter Edwards was a local pasture scientist) is awarded at the annual Grassland Society of SA (GSSA) Congress to a land user in the province in which the congress is held. Presented in recognition of sound application of the principles of range and forage science and conservation, the trophy was first awarded in 1981 when the GSSA Congress was also hosted in the Eastern Cape. Since then, many outstanding livestock farmers and game ranchers have been added to the list of recipients.

The 2007 adjudication was done during late June, which is the driest and most challenging time of the year and a good time to visually appraise the five farms that entered the competition. The panel consisted of Tony Palmer (ARC, Livestock Business Division), Pieter Conradie and Susi Vetter.

Nurture
Restore
Innovate

"Ecological solutions for landscapes and livelihoods"

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Report on the Field-Based Training Course on Ecological Functioning, Management and Restoration for Land-Managers in the Namaqualand Region.

7 – 8 May 2009

Presented by:

AZEF (Arid Zone Ecology Forum)
&
NRI (Nurture Restore Innovate)

With support from:

ARC (Agricultural Research Council)
&
CI (Conservation International)

Report by:

NRI (Dr Peter Carrick)

28 May 2009

Background

The Arid Zone Ecological Forum funded the training of a group of 13 individuals on ecological functioning of the veld, its management and restoration. The training was open to those that manage areas of land in various ways in Namaqualand, e.g. farmers, municipal and government officers with responsibility for veld management, ecotourism operators and others that conduct projects that impact natural landscapes and biodiversity (this training session was not aimed at the mining sector as the NRI has conducted a number of training sessions with the mining sector already). A complete list of participants is provided in Appendix A, and further information on each of the trainees can be found in the supporting documents.

The NRI followed a process to advertise and invite applications to the land-manager training course. An advert was placed in a newspaper with good coverage of the regionl, 'Die Namakwalander' (Appendix B). The course was also advertised through the appropriate forums and networks of the NRI and supporting organisations (in particular, the LED training project of CI). Applicants had to submit a one-page application in order to attend the course, which included personal details, their background and reasons for attending the course (see Appendix B and supporting documents). In addition, participants had to provide for their own transport to Koingnaas / Noup (indicating their motivation and commitment to the training), but one there all training, training materials, accommodation and meals were provided at no cost to the participants. No applicants were turned away. Unfortunately no farmers applied to attend the course, despite concerted efforts from all the organisations involved. Trainees included: five land-mangers from the CI's LED training project; five land-managers who responded independently to the newspaper advertisement (all involved in developing their own landscape or biodiversity based project, in addition one was natural science, high school teacher); and three individuals from the supporting organisations who run projects aimed at improved biodiversity land-management in Namaqualand but who do not have a background in ecology.

Dr Peter Carrick and Mr Andre Meyer of the NRI ran this training course, with training support from Mr Clement Cupido of the ARC, and logistical support from CI (in particular, CI and partners funded the accommodation and catering for the course at Noup). The course took place on the 7th and 8th of May 2009, in the mining area of Koingnaas (of De Beers Namaqualand Mines) and surrounds. This area was chosen so that land-managers could see what can be achieved through restoration, and inspire a realisation that degraded areas (e.g. overgrazed water points) can be returned to productive ecosystems. Restoration areas also provide an excellent learning environment for understanding the components of the ecosystem that together provide sustainability and resilience to the ecosystem. Training centred on actively comparing degraded, restoring and pristine sites to gain an improved understanding of the ecosystem: how it functions, how it is degraded and how it can be restored.

Training

‘Learning in the field, while doing’ was the idea around which the training was structured. Participants arrived at the training venue between 10am and 11am on the 7th of May, from all over Namaqualand (e.g. Springbok, Garies, Calvinia), and enjoyed a welcome morning tea.

Andre Meyer started with an introduction to the environmental and land-use drivers of Namaqualand ecosystems, providing a national and regional context for the Namaqualand ecosystems. Clement Cupido’s presentation started discussion of the broad building blocks of ecosystems, from water and soil to plants and micro and macro fauna.

After lunch Peter Carrick had the participants learning to identify 12 different functional groups that cover all the plant types in the Succulent Karoo, and understanding the different roles that the functional groups play in the ecosystem. Thereafter the participants split into two groups, each with two subgroups, and began a formal assessment of different ecosystems. Each group assessed a degraded site (previously mined) and a pristine site by analysing a 100m transect at each site. The groups scored their site according to a system which allocates points for perennial plant abundance, functional groups, species and reproduction. Through this process trainees learned to analyse the ecosystem not only by differentiating among the above components, but by counting the appropriate components (some functional groups are not counted), and the spatial interaction between them. The groups returned to the training venue to consolidate their scores, and to enjoy supper and the beauty of land- and seascape around the accommodation at Noup.

The next morning started early with breakfast at 7am, and the trainees were then led by Peter through a calculation of the scores for each of the groups transects, and an understanding of what the scores indicate about each of the sites (i.e. a discussion of the assessment of each component of the ecosystem). Peter and Clement then led lectures and discussions on the ecological condition of veld (including briefly: sustainability; resilience; and ecosystem services) and the ecological impacts of different sorts of degradation (overgrazing, cropping / ploughing, surface mining). The training alternated between powerpoint presentations and activities and discussion in the veld, and focussed on the spatial interactions among ecosystem components and on the role of soil (including a practical exercise with biological and chemical crusts).

After tea and collecting lunch packs the participants entered the Koingnaas mining area on a De Beers bus, with a security escort. Peter and Andre led a tour of sites within the mining area which covered a range of ecological conditions (e.g. no topsoil, topsoil not stabilised, topsoil stabilised, differences in soil types, reintroduction of species and spatial interactions etc.), building throughout on the practical experience the participants now had in understanding and assessing components and interactions between soil and plant components of ecosystems. The tour finished with a visit to a severely degraded site that lacked topsoil, but had been actively restored over the last 18 months by a local Namaqualand restoration business, using the ecological components and spatial dynamics that participants had focussed on during the training, and again emphasising the value of this understanding in practice.

Conclusions

There was sufficient capacity to train around 20 participants on this course, and the absence of farmers highlights the difficulties in getting this group of land-managers to devote time to courses such as this (the arrival of the seasons first rains a week or two before did however mean that farmers had many demands on their time). All the participants were strongly engaged in all aspects of the course, including the practical component (which provides opportunities that are not self-motivated to disengage from the activities). All the participants were motivated by a need or desire to better understand ecological functioning, and were there for no other purpose. In addition the group had a similar, and a high capacity, to engage with the substance of the course, and the smaller size of the group allowed for focussed interaction and discussion of the subject, and a reasonably fast pace of learning. Everyone in the group had responsibilities for land-management, had experience of the need for understanding, and achieving results. They were serious about the training and feedback indicates not only that they learned a lot, but that the understanding gained was ‘down to earth’ and that some of their understanding of ecology and ecological principles that had been abstract became practical, through the course.

The Koingnaas areas provided an ideal learning experience, as trainees could then see restoration in action, and understand the components of the ecosystem building at different sites. One can not get this understanding across nearly as effectively in a classroom environment, or even in one area of uniform veld. I believe the higher objectives of the training were also reached, namely: to initiate a basic level of ecological understanding for land-managers within the Namaqualand area; giving them a hands on experience in assessing and valuing veld condition; and to start interpreting ecosystem service changes that result from different land-uses and levels of degradation.

Appendix B:

Arid Zone Ecology Forum and
Nurture Restore Innovate
Bied aan:

Informele Kursus in Basiese Namakwalandse Ekologie en Veld Restourasie

7-8 MEI 2009
KOINGNAAS

Eie vervoer benodig.
Verblyf, etes en kursus materiaal voorsien.

Persone wat sou voordeel trek sluit in bv. staatsbeamptes, boere, ekotoerisme operateurs, ens.

Belangstellendes moet asb afskrif van ID en kontakbesonderhede fax na: 086 524 8711 of e-pos na: andre.meyer.eco@gmail.com met antwoorde op die volgende vrae voor
1 Mei 2009:
Hoekom stel u belang om die kursus by te woon?
In watter area van Namakwaland werk u?
Watter tipe grondbestuur maak deel van u werk uit; bv. boer, meentbestuurder, ontwikkelingsbeampte?

Suksesvolle applikante sal gekontak word.
Vir meer inligting skakel Andre by: 079 518 9907

Agriculture production's sensitivity to changes in climate in South Africa

James Blignaut[a*], **Liza Ueckermann**[b] **and James Aronson**[c]

South Africa in general has been approximately 2% hotter and at least 6% drier over the ten years between 1997 and 2006 compared to the 1970s. The use of water has also increased greatly over this same period. By 2000, 98.6% of that year's surface water yield and 41% of the annual utilisable potential of groundwater was allocated to use. Irrigation agriculture, comprising 60% of total consumption, is by far the largest single consumer of water. Given these climatic and water use changes as a backdrop, we employed a panel data econometric model to estimate how sensitive the nation's agriculture may be to changes in rainfall. Net agricultural income in the provinces, contributing 10% or more to total production of both field crops and horticulture, is likely to be negatively affected by a decline in rainfall, especially rain-fed agriculture. For the country as a whole, each 1% decline in rainfall is likely to lead to a 1.1% decline in the production of maize (a summer grain) and a 0.5% decline in winter wheat. These results are discussed with respect to both established and emerging farmers, and the type of agriculture that should be favoured or phased out in different parts of the country, in view of current and projected trends in climate, increasing water use, and declining water availability.

Key words: agriculture production, rainfall, drought, climate change, water scarcity

Introduction

This study focused on the impact of changes in climatic conditions on agriculture: it is motivated by the fact that agriculture is the mainstay of rural economies in South Africa, and indeed throughout much of Africa. Agriculture's importance cannot be overemphasised from a food security perspective, or from its vital role in assisting the country to enhance and maintain political stability through successful land reform. Understanding changes in agriculture already taking place, or likely to take place in the near future, in response to climate change is therefore of utmost importance.

To map the historic changes in rainfall and temperature with changes in agriculture production in South Africa we were constrained to using existing provincial data, rather than biome-level data, which would have been preferable, but were unavailable. In addition, we had to limit ourselves to the period for which relevant data were available, i.e. from 1970 onwards. This of course affects the predictive powers of the models. Notwithstanding these limitations, some valuable insights were gained as to the relationships, and the challenges ahead, concerning the links between climate and agriculture.

We first consider recent changes in climatic conditions in South Africa's nine provinces, and then discuss the use of water based on a panel data econometric analysis of the relationship between rainfall and various components of agricultural production. We conclude with an assessment of the impact of rainfall specifically on field crops, as they are most likely to be adversely affected by sudden or gradual changes in climatic conditions.

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Changes in climatic conditions

It is widely assumed that ongoing changes in climatic conditions will have an adverse effect on agricultural production in Africa.[1–3] While the impact of climate change is felt by farmers predominantly through changes in the timing, frequency and intensity of rainfall events, and in the distribution of these events within a season of growth, most macroeconomic and agricultural production data are only available as annual averages. Yet annual numbers and averages for level of, or changes in, temperature and rainfall do not provide an adequate indication of the impact of such variations from the mean on a specific farm. Given this limitation, it should be noted that this study was not an investigation into climate change *per se,* even though we did analyse and discuss the data used in determining the impact of changes in climate on agriculture. A further limiting factor is that, when dealing with annual numbers, one is strictly speaking not dealing with drought as defined by McKee,[4] who indicated that a drought occurs when the Standardised Precipitation Index over 12 months is continuously negative and reaches a value of –1 or less. We therefore did not consider the impact of individual drought events on agriculture, but rather the gradual drying trend on agricultural production as a whole. Our aim was to analyse the available data to examine whether changes in the variance from the mean for rainfall and temperature had indeed occurred.

Materials and methods

To address the broad-scale impact of climate change on agriculture, we considered rainfall and temperature data from 1970 to the present for South Africa's nine provinces. For rainfall (in mm), the annual sum of the provincial monthly average was used (Appendix 1 online). The data received were, in all cases, provided in a ready-to-use format and were not manipulated in any way. The temperature data (Appendix 2 online) consist of the annual averages of the daily maximum temperatures, in either two or three towns or cities per province. In general, daily minimum temperatures are considered a better indicator of climate change *per se,* but here we use daily maximum temperatures since it is these changes that are likely to have an impact on agriculture production in South Africa. The data received consisted of monthly averages of the daily maxima and, from these, we computed the annual averages.

First, the nine provinces of South Africa were clustered together in four broad climatic areas in terms of their average rainfall and temperature data (Table 1). Thereafter, we calculated the changes in the average rainfall and temperature, and the changes in the variance from the mean and the covariance (Table 2). This summary contains the results for the nine provinces for the periods 1970–1979 and 1997–2006, as well as 1970–1989 and 1990–2006. The data set was split into these four separate time periods to ascertain whether there are distinct differences between

Table 1. Clustering of South Africa's nine provinces based on temperature and rainfall data, with percentage changes between 1970–1979 and 1997–2006 (source: own analysis of data from Appendices 1 and 2).

Mean annual rainfall by region		Mean annual temperature by region		Final clustering	% Change in rainfall	% Change in temperature
<550 mm	Northern Cape	>25°C	Limpopo	**Hot and arid**		
	North West		North West	Northern Cape	–21.4%	1.7%
			Northern Cape	North West	–11.3%	2.3%
550–700 mm	Western Cape	24.5–25°C	Western Cape	**Hot and semi-arid**		
	Free State		Free State	Limpopo	–1.4%	3.8%
	Limpopo		Mpumalanga			
	Eastern Cape			**Temperate & semi-arid**		
				Western Cape	0.3%	1.5%
>700 mm	Gauteng	<24.5°C	KwaZulu-Natal	Free State	–3.5%	1.7%
	Mpumalanga		Gauteng	Mpumalanga	–5.7%	–2.1%
	KwaZulu-Natal		Eastern Cape			
				Temperate & non-arid		
				Gauteng	–7.1%	4.0%
				Eastern Cape	–4.8%	2.8%
				KwaZulu-Natal	–5.8%	2.1%
				South Africa	**–6.0%**	**2%**

the levels of rainfall and temperature among the various periods, and how weather patterns may have changed.

Results

Temperature

Several observations can be made from the results displayed in Tables 1 and 2. With the exception of a temperature decline at Mpumalanga, all the other areas showed a considerable increase—in places as much as 4%. For South Africa as a whole, the last 10 years have been on average 0.5°C—or 2%—hotter than the 1970s. The variance increased during the same period, implying that changes in temperature became less predictable, but were consistently higher in absolute terms and increased steadily over the entire period studied.

Rainfall

All but one of the nine provinces received progressively less rainfall since 1970. The exception was the Western Cape, which, on average, received consistent annual rainfall over the entire study period (Table 1). The Northern Cape and the North West provinces have in general been the most affected, both in terms of percentage change (Table 1) and absolute change (Table 2). South Africa as a whole received on average 40 mm less rain per annum over the last 10 years than during the 1970s, which means 6% less average rainfall. However, the deviation from the mean for all the hot and arid areas was less during the last ten years than during the 1970s. The variance from the mean has increased for other less arid areas, indicating increasing unpredictability and occurrence of extreme events.

In sum, South Africa has been hotter during the last 10 years compared to the first 10 years of the study period, and with more variation from the mean. Additionally, average annual rainfall was less during the last decade than during the 1970s. The variance around these lower rainfall numbers is declining for the two westernmost provinces, implying more predictability at low and declining levels of rainfall for the hottest, most arid regions. Variance, however, is increasing for the other areas, implying increasing unpredictability.

Covariance of rainfall and temperature

The relationship between rainfall and temperature was analysed using ANOVA for the individual provinces of South Africa, yielding the results shown in Table 2 and Fig. 1. For both periods studied and for all areas, the covariance of rainfall and temperature was very significantly negative ($P < 0.001$) for most provinces. Indeed, with the exception of the arid areas, the covariance observed between temperature and rainfall has actually become stronger over the last decade: the hotter it gets, the less rainfall there is in all regions. Should the evidence produced here signal a lasting trend, then the prevailing adverse climatic conditions are likely to persist and possibly deteriorate further. In the next section we will consider how changing climate, especially reduction in rainfall, may affect agriculture.

Water use in agriculture in South Africa

Given that South Africa, overall, is getting hotter and drier, the question is, how big is the buffer? How much surplus water does South Africa have, who is using it, and can the trend be changed in view of the declining supply? The South African Department of Water Affairs and Forestry[5] estimates that in 2000 South Africa had a total reliable surface water supply of 13 226 million m^3. In the same year, the nation used 13 041 million m^3, leaving a surplus of only 186 million m^3, or 1.4% of the supply (at 98% assurance of supply) for that year. Additionally, 12 of the country's 19 water catchments reported water deficits, which were only partially offset by an intricate system of inter-basin water transfer schemes. These statistics are supported by the water resource accounts, produced by Statistics South Africa.[6] In theory, as the remaining annual supply of a vital natural resource approaches zero—crossing clearly identifiable thresholds of scarcity—the marginal value of that resource approaches infinity.[7] This implies that the economic value of the last 1.4% of unutilised water resource is very high, far exceeding that of the prevailing bulk water tariff. Matters are complicated by the fact that, as water supply is annually recharged through precipitation, it does not imply that only 1.4% is available into perpetuity, but rather that for the year 2000, specifically, only 1.4% of the water supply was unallocated or not used. This implies that should the water demand grow by more than 1.4%, the only way to accommodate such growth is by reducing water use in some of the currently water-intensive sectors, which in turn implies that some tough decisions have to be made.

Moreover, the meagre water reserve mentioned above includes the water imported from neighbouring Lesotho. Unutilised domestic sources of water are limited to two river catchments in

Table 2. Changes in climatic conditions, as indicated by changes in temperature and rainfall, for South Africa's nine provinces: 1970–2006 (source: own analysis of data from Appendices 1 and 2).

	Temperature				Rainfall: changes in mm				CoVAR 1st period	CoVAR 2nd period	CoVAR Dif
	Difference between 1970–1979 & 1997–2006		Difference between 1970–1989 & 1990–2006		Difference between 1970–1979 & 1997–2006		Difference between 1970–1989 & 1990–2006				
	Average change in °C	VAR	Average change in °C	VAR	Average change in mm	VAR	Average change in mm	VAR			
Hot and arid											
Northern Cape	0.43	−0.14	0.11	0.05	−67.4	−12357	−35.8	−7159	−34.35	−11.33	23.02
North West	0.59	0.17	0.30	0.00	−70.7	−2767	−34.9	−3308	−79.68	−67.45	12.23
Hot and semi-arid											
Limpopo	1.01	0.30	0.83	0.18	−9.3	52021	−4.9	37254	−43.33	−113.67	−70.34
Temperate & semi-arid											
Western Cape	0.37	−0.05	0.07	0.11	1.7	−9118	0.9	−4583	−6.10	−18.69	−12.59
Free State	0.42	0.49	0.26	0.29	−21.3	3477	−22.7	3092	−58.21	−86.34	−28.13
Mpumalanga	−0.52	−0.02	−0.37	0.24	−49.3	28267	−39.3	23343	−23.56	−68.69	−45.13
Temperate & non-arid											
Gauteng	0.93	0.10	0.58	0.02	−53.2	17011	−3.9	13916	−34.20	−76.18	−41.98
Eastern Cape	0.65	0.17	0.38	0.09	−32.4	2856	−24.2	−1165	−12.53	−26.98	−14.44
KwaZulu-Natal	0.51	0.14	0.28	0.17	−56.3	9799	−73.3	2893	−9.80	−56.88	−47.08
Total South Africa	**0.49**	**0.08**	**0.27**	**0.07**	**−39.8**	**5758**	**−26.5**	**6951**	**−22.82**	**−47.33**	**−24.51**

the ecologically-sensitive and relatively undeveloped Eastern Cape province. Water-supply constraints are therefore an issue with unparalleled economic development implications. Further supply options are limited, but include further water importation from Lesotho, and, additionally from the distant Congo River, and/or desalination of seawater. All three of these options are costly and capital intensive and their implementation would have a significant effect on water tariffs with the result of making drinking water less accessible to those who are most in need. In other words, only 1.4% of South Africa's water yield is currently available to address the demands of the poor, most of whom who do not have any access to potable piped water currently. But has the market reacted to these changes? Have water use extraction and allocation trends already changed?

Surface water use

Irrigation agriculture is by far the largest single surface water user, consuming 60%, with agriculture in general consuming 65% of total available water.[6] Use of surface water for irrigation has also increased steadily from 7630 million m^3 in 1995 to 7921 million m^3 in 2000, an increase of 291 million m^3, or 4%. This use represents 160% of the total water surplus remaining at the end of 2000. The official water use for 2005 has not yet been released, but if the volume of water used for irrigation increased by the same margin, without any compensatory reduction in water use by other sectors having taken place, there must have been a deficit for the country as a whole. Furthermore, the total increase in water consumption for all sectors from 1995 to 2000 was 348 million m^3, which implies that irrigated farming's share of the increase was 84%.

Groundwater use

Surface water use is increasing rapidly, with no signs of a decline in use in any sector. Use of groundwater is increasing rapidly as well.[8,9] Vegter[8] estimates that by 1999 there were approximately 1.1 million water boreholes in the country, compared to only 225 000 recorded on the National Groundwater Database. From drilling data and agricultural records, Vegter[8] calculates that the groundwater use in 1999 was about 3360 million m^3 per year and is increasing at, on average, approximately 3.4% per year. The estimated use at the end of 2001 was approximately 3850 million m^3, or 49% of the surface water usage. The exploitable groundwater usage for 2000 is estimated[6] at 9500 million m^3, which implies that groundwater usage at that stage was about 41% of the potential. This allows room for some further development, but clearly the surplus is dwindling fast. In fact, water abstraction of both surface and groundwater has increased so quickly in recent years, being used primarily to drive the development of agriculture, mainly in the horticulture and animal production sectors.

Water: The limiting factor

Water is therefore one of the main, if not the, limiting resource upon which intelligent, sustainable economic investments should be concentrated.[10–13] Water use, given the supply constraints, cannot continue to grow at current rates. This situation is exacerbated by the likely decline in the water availability due to changes in climatic conditions, and socio-economic and demographic pressure to increase the use of potable water for domestic use and to allocate water to higher value added industries. Another complicating factor is the plausible introduction of a wide-scale biofuel programme and its plausible impact on future water demand.

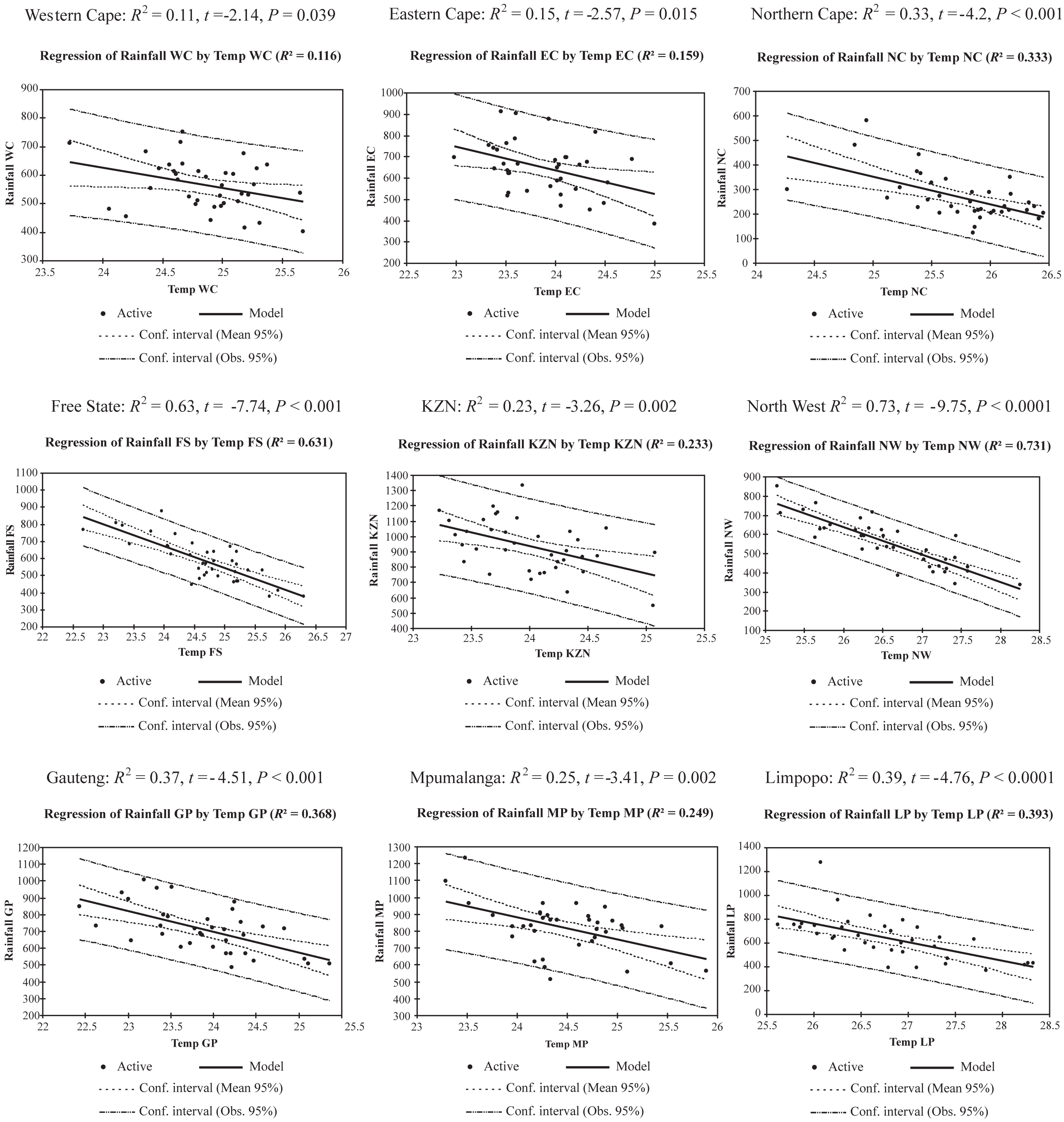

Fig. 1. The statistically-significant relationship between rainfall (mm) and temperature (°C) in South Africa from 1970 to 2006 (source: own analysis of data from Appendices 1 and 2 in online supplement).

Quantifying rainfall's contribution to agriculture

Model

We developed a Seemingly Unrelated Regression (SUR) model (Appendix 3 online), using a three-dimensional panel data set, to quantify the contribution of rainfall to agriculture. Hsiao[14] defines a panel data set as one that follows a given sample of individuals—provinces in this case—over time, and thus provides multiple observations on each individual in the sample. Here the dimensions are time, geographic area (nine provinces), and a series of variables. From a modelling perspective, panel data is therefore very powerful, as it combines regular time-series and cross-sectional regressions, and has numerous other advantages.[14–16]

Data

We gathered data for each province over the period 1970–2006, for gross income from agriculture (subdivided into three sectors: field crops, horticulture, and animal production), expenditure on intermediate goods and services, labour and other expenditures, net income, and contribution to GDP. It was not possible to allocate the cost items to specific agricultural sectors since no method to do so exists. To estimate provincial shares, we used data from unpublished sources, mostly from the archives

Table 3. Results of the SUR model for field crops, horticulture, and animal production

	Field crops			Horticulture			Animal production		
	Coeff.	s.d.	% Contrib. to SA prod. 2006	Coeff.	s.d.	%Contrib. to SA prod. 2006	Coeff.	s.d.	% Contrib. to SA prod. 2006
Input	–0.263***	(0.055)		–0.451***	(0.053)		–0.212***	(0.039)	
Wages	–0.304***	(0.053)		–0.322***	(0.060)		–0.542***	(0.036)	
Contribution to GDP	0.391***	(0.021)		0.175***	(0.034)		0.252***	(0.018)	
Productivity	0.215***	(0.015)		0.120***	(0.013)		0.267***	(0.007)	
Temperature	–0.054*	(0.030)		–0.012	(0.045)		–0.064**	(0.023)	
Rain – Western Cape	–0.024***	(0.022)	8%	0.043***	(0.041)	42% (x)	–0.006***	(0.015)	17% (x)
Rain – Eastern Cape	–0.045***	(0.037)	1%	0.021***	(0.052)	6%	0.019***	(0.025)	10% (x)
Rain – Northern Cape	–0.007***	(0.023)	6%	–0.002	(0.047)	7%	0.006***	(0.023)	7%
Rain – Free State	0.031***	(0.031)	31% (x)	–0.039***	(0.055)	4%	–0.007***	(0.021)	15% (x)
Rain – KwaZulu-Natal	0.017***	(0.034)	17% (x)	–0.032***	(0.059)	4%	–0.008**	(0.025)	13% (x)
Rain – North West	0.028***	(0.027)	15% (x)	–0.048***	(0.047)	3%	0.003	(0.0254)	10% (x)
Rain – Gauteng	–0.026***	(0.045)	2%	–0.007	(0.058)	6%	0.033***	(0.029)	12% (x)
Rain – Mpumalanga	0.021***	(0.036)	16% (x)	0.007	(0.064)	11% (x)	–0.020***	(0.026)	9%
Rain – Limpopo	–0.010**	(0.044)	5%	0.070***	(0.107)	16% (x)	–0.032***	(0.044)	7%
R-squared		0.99			0.99			0.99	
Adjusted *R*-squared		0.92			0.97			0.98	
Durbin-Watson stat		1.90			1.54			1.61	
F-statistic		42280.91			6819.52			61431.05	
Prob (*F*-statistic)		0.00			0.00			0.00	

***Statistical significance at 1%; **statistical significance at 5%; *statistical significance at 10%; without *, no statistical significance.
(x) denotes a province where the provincial contribution to national production is 10% or more.

of the National Department of Agriculture (NDA) in Pretoria, including agriculture surveys from 1971, 1973, 1975, 1978, 1981, 1983, 1988, 1993, 1995, and 2002. Interpolation was used to construct a complete time series for all the provincial shares for which no data exist. Most importantly, all nominal values were deflated using relevant price indices obtained from the NDA. Gross income in constant prices was plotted against the volume of production index revealing the same trend and slope—a clear indication that an appropriate deflator was used.

Results

The results from the SUR model for field crops, horticulture, and animal production are summarised in Table 3. The model does not allow for variation in the slope of the net income function among regions, but the variation in the intercept of the regions through the SUR model specification has been permitted. The Adjusted *R*-squared values of 0.92 and higher indicate that the SUR models represent a good fit of the data, supported by significant *F*-statistics of 42 281 (field crops), 6 820 (horticulture), and 61 431 (animal production), respectively. The coefficients of the interaction variables are almost all significant at the one per cent level ($P < 0.01$).

Based on the estimations obtained in Table 3, the net income function (Equation 1) can be specified for field crops, horticulture, and animal production for each province.

Field crops:

$$YFC_{it}^* = C_i - 0.26 input_{it} - 0.30 wages_{it} + 0.39 con_{it} + 0.21 \mathrm{P}rod - 0.05 temp_{it_i},$$

where $C_i = \alpha_i \mathrm{rain}_{it}\ (province)$

Horticulture:

$$YH_{it}^* = C_i - 0.45 input_{it} - 0.32 wages_{it} + 0.18 con_{it} + 0.12 \mathrm{P}rod - 0.01 temp_{it_i},$$

where $C_i = \alpha_i rain_{it}(province)$

Animal production:

$$YA_{it}^* = C_i - 0.21 input_{it} - 0.54 wages_{it} + 0.25 con_{it} + 0.27 \mathrm{P}rod - 0.06 temp_{it_i},$$

where $C_i = \alpha_i rain_{it}\ (province)$

Since these net income functions were estimated in log terms, the coefficients can be interpreted as percentage changes, implying, for example, that a 1% increase in expenditure on intermediate goods and services will lead to a decline in net income of 0.26% for field crops.

Discussion

Gross farm income (gross revenue or turnover) in real terms (constant 2000 prices) over the entire period has grown only marginally, with the exception of the Western Cape. Here the growth in viticulture contributed significantly to the growth in the sector over the initial few years of the study period. This steady growth has been offset by a rapid rise in production costs in all provinces leading to a declining net income (revenue minus cost), which is currently at worrisomely low levels. Within the context of this paper, this suggests that first, increases in gross income occurred despite increasingly adverse climatic conditions; and, second, that the decline in net income is predominantly the result of an increase in input cost. The evidence from Table 3 supports this conclusion. The size of the coefficients of the costs, productivity, and sector size for each of the three agriculture sectors is far bigger than that of either rainfall or temperature. Third, this suggests that the increase in gross production could only be attained through the relative increase in the use of financial capital to attain this growth in gross income, but at a significant financial cost. The use of capital, as indicated by the formation of fixed capital (or investment), has remained constant in real terms since 1970 at approximately R6 000 million,[17] but employment has declined from more than 1.6 million in 1970 to just over 600 000 in 2005—or about 36% of the 1970 level.[4,18] This trend runs counter to the steady growth in both population and unemployment, and therefore signals a clear shift towards more capital-intensive agriculture. Fourth, the increase in capital intensification, also illustrated by the size of the coefficient for input costs, coincides with an increase in irrigation as discussed above. This suggests that, if it were not for irrigation, the growth in gross income might have been much

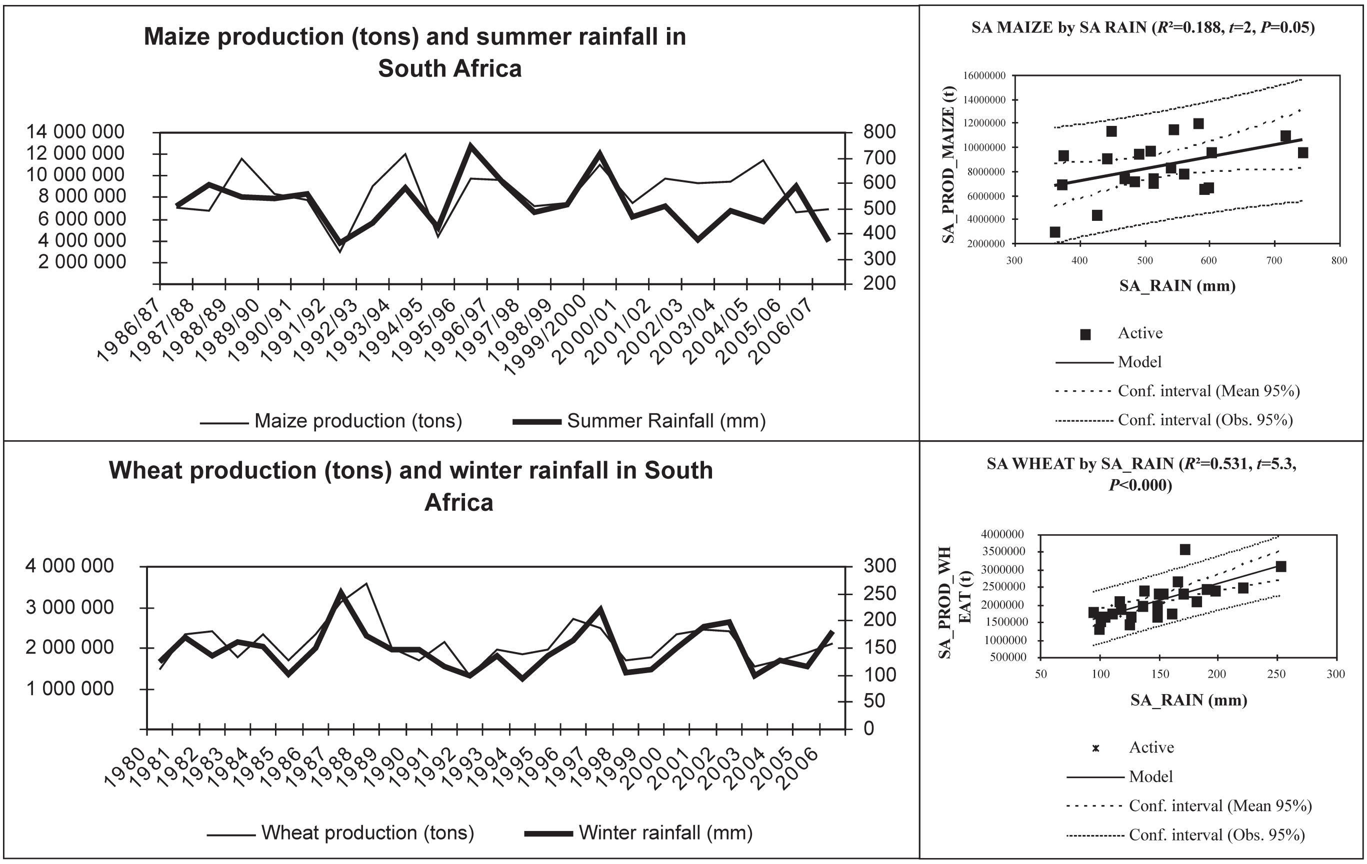

Fig. 2. Maize and wheat production (tons) with the annual total summer (Oct–March) and winter (April–Sept) rainfall (mm), respectively, in South Africa in the two left panels with their respective covariance indicated in the right panels (source: maize and wheat production: National Department of Agriculture; rainfall: South African Weather Bureau).

less, but that such expansion and intensification have important financial costs, which are rising much faster than the value of the product. Fifth, temperature is indeed negatively correlated with net farm income for the three sectors, but has a very small coefficient, and is not statistically significant for horticulture production. However, the results from Table 3, with regard to rainfall, reveal a positive correlation between rainfall and net income for field crops and horticulture, for each of the provinces that produce more than 10% of the national output—indicated with an 'x' in Table 3. These data are important from a food security perspective.

For animal production, the relationship is less clear. Animal production includes poultry farming—which is currently the single largest agricultural sector in the country—and cattle farming for beef. Beef production in South Africa today is largely feedlot-based, though most of the animals originate from cattle farmers. In other words, calves are free-ranging until they are about nine months old, when they are auctioned to feedlot owners. Cattle, however, are counted as part of animal production only after being slaughtered. Therefore, there is no direct link between rainfall and animal production, as both poultry and beef production use abstracted water. For beef production, this can lead to erroneous conclusions, as the productivity of free-range cattle husbandry is adversely affected by any reduction in rainfall. This degree of dependence is not reflected in the data used here, as livestock sales are not counted as animal production. In 2004, so-called subsistence farmers owned 5.6 million head of cattle, i.e. 41% of the national total of 13.8 million.[19] These individuals are extremely vulnerable to changes in climate and, given the small scale of their operations and the limited access they have to open markets, the value of their animal production is not captured adequately in a macro-economic data set, such as the one used here. This is also a group of farmers which has not yet been integrated into the formal agriculture sector, despite governmental pressure to do so. Adverse climatic conditions are likely to make this process more difficult to accomplish.

We have seen that rainfall is significant to the dominant horticulture production areas such as the Western Cape, where viticulture plays a major role. Horticulture, like animal production, makes extensive use of irrigation that temporarily offsets any sudden decline in rainfall. In contrast, dry-land agriculture, especially involving field crops, cannot make use of irrigation and is therefore much more vulnerable to changes in climatic conditions than horticulture and animal husbandry. Given both the importance of rainfall for field crop production, and that field crop production is likely to be most affected by any adverse changes—sudden or gradual—in climatic conditions, we conclude our analysis by considering the relationship between rainfall and field crop production in more detail.

Production of field crops and rainfall

There is a remarkable correlation between rainfall and crop production, whether summer (e.g. maize) or winter crop (e.g. wheat), as seen in Fig. 2, where we distinguish winter rainfall (April–September) from summer rainfall (October–March). We use maize and wheat as proxies for all seasonal field crops to demonstrate the link between rainfall and crop output.

To determine the specific relationships between rainfall and crop production for these respective crops, for each area, an elementary equation was used:

$$\% \text{ change in production}_{i,j} = \% \text{ change in rainfall}_i \,,$$

Table 4. The relationship between rainfall and gross income in field crops in the nine provinces of South Africa: 1970–2006.

	Coefficient	*t*-statistic	Adj. R^2	DW	Contribution to SA production in 2006
Western Cape: maize	n.a.*	n.a.	n.a.	n.a.	n.a.
Western Cape: wheat	0.37	2.86	0.22	2.02	35%
Eastern Cape: maize	–0.003	–0.012	–0.026	2.1	1%
Eastern Cape: wheat	0.30	2.1	0.13	1.47	0.5%
Northern Cape: maize	0.07	1.01	–0.17	1.93	8%
Northern Cape: wheat	–0.07	–0.89	–0.02	2.56	12%
Free State: maize	1.18	2.5	0.2	2.36	40%
Free State: wheat	0.53	4.26	0.37	2.79	37%
KwaZulu-Natal: maize	0.27	1.79	0.13	2.5	5%
KwaZulu-Natal: wheat	–0.03	–0.22	–0.12	1.98	1%
North West: maize	2.55	3.89	0.41	2.31	18%
North West: wheat	0.06	1.04	0.00005	1.95	7%
Gauteng: maize	1.12	3.55	0.38	2.22	4%
Gauteng: wheat	–0.53	–0.57	–0.03	1.95	0.5%
Mpumalanga: maize	0.68	3.2	0.33	2.75	21%
Mpumalanga: wheat	0.06	0.28	–0.5	2.76	4%
Limpopo: maize	0.17	0.7	–0.02	2.6	2%
Limpopo: wheat	0.5	1.67	0.05	2.35	4%
South Africa: maize	1.16	2.8	0.25	2.5	100%
South Africa: wheat	0.53	3.94	0.36	2.8	100%

*Not applicable, since the Western Cape is not a maize-producing area of any significance.

where *i* represents each province and *j* a given crop (Table 4). As the function was estimated as a percentage change, coefficients indicate that for every 1% change in rainfall, the expected change in gross production is '*x*'. For all the provinces contributing approximately 20% or more to national production for either maize or wheat—the Free State (40%), Mpumalanga (21%), and the North West (18%) for maize, and the Western Cape (35%) and the Free State (37%) for wheat—highly statistically-significant relationships ($P < 0.0001$) were found between crop production and rainfall. Maize production is generally more sensitive to changes in rainfall than wheat production, as indicated by the respective sizes of the coefficients. Alarmingly, a 1% change in rainfall should lead to more than a 1% change in maize production. This does not augur well for provinces such as the Free State, the North West, and the Western Cape, as these provinces were considerably warmer from 1997 to 2006 than in the three preceding decades (Table 2). Additionally, there is a strong negative relationship between temperature and rainfall, especially in the two former provinces. Should it become still warmer in the future and rainfall continue to decrease, then the three major maize and wheat production areas of the country will be susceptible to marked reductions in crop production.

Conclusion

South Africa, on average, has been hotter and drier during the last 10 years than during the 1970s. If this represents future climatic trends this has major implications for South African agriculture. Notably, there is very little scope for expansion of irrigation, given the limited supply of non-saline water and pressing socio-economic needs. This scenario implies that farmers are likely to rely increasingly on water-saving techniques that may drive up costs even further, in a sector that has a small net income margin and which is already facing rapid cost rises. This is likely to make it increasingly difficult for emerging farmers to enter the sector, despite the official national policy to help them. In addition, there likely will be significant impacts on food security, which is already under pressure.

Furthermore, there is a statistically-significant positive correlation between the production of field crops and horticulture in all the provinces that contribute more than 10% of the national supply. Given trends of declining rainfall and increasing average temperature, and the statistically-significant negative relationship between these two variables, this implies that both field crop production and horticulture are extremely vulnerable, especially rain-fed field crops. A 1% decline in rainfall is likely to lead to a decline in maize production of 1.16% and a decline in wheat production of 0.5%. Such a decline in rainfall is also likely to lead to a decline in net income in the most productive provinces.

As we have seen, only 1.4% of South Africa's water yield is currently available to address the demands of the poor, most of whom currently have no access to potable piped water. These 15 million people, who comprise 35% of the population,[20] are obliged to find and physically carry water to their homes and their livestock on a daily basis—clearly not a tenable situation.

Even under pre-industrial conditions, ecological systems, including agrosystems, were subject to influences from extreme events and global forcing factors, such as new markets or the collapse of old ones. In the context of recent massively accelerating anthropogenic climate changes, we need to adapt our ways of thinking, acting, farming, and managing vital resources, particularly water.

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Appendix 1. Annual rainfall (mm) for South Africa's nine provinces: 1970–2006.

	Western Cape	Eastern Cape	Northern Cape	Free State	KwaZulu-Natal	North West	Gauteng	Mpumalanga	Limpopo	South Africa
1970	455	621	203	466	774	405	569	609	421	502
1971	481	697	257	539	1010	631	893	912	639	673
1972	433	538	230	534	911	528	607	893	730	600
1973	416	561	290	502	946	591	686	966	655	624
1974	638	914	583	792	955	713	732	879	733	771
1975	528	635	364	675	1033	764	930	965	748	738
1976	683	904	481	806	1198	852	850	907	755	826
1977	751	684	329	573	977	623	716	862	829	705
1978	443	644	206	619	1108	591	800	890	777	675
1979	500	623	213	572	750	531	679	716	538	569
1980	530	470	217	484	759	520	731	866	762	593
1981	715	739	307	683	919	585	644	828	754	686
1982	524	517	213	498	721	470	568	556	395	496
1983	612	546	218	531	843	428	726	830	469	578
1984	565	519	179	466	1149	340	487	866	560	570
1985	676	816	283	521	1053	404	678	832	661	658
1986	603	647	184	585	836	519	713	742	540	597
1987	592	589	217	670	1334	477	830	945	622	697
1988	488	785	443	879	1121	714	627	809	678	727
1989	639	752	265	624	1024	630	786	866	602	687
1990	553	528	227	463	832	433	604	762	522	547
1991	583	662	373	687	1001	590	723	814	598	670
1992	613	451	123	380	550	337	507	566	429	440
1993	637	675	231	587	872	495	757	797	571	625
1994	533	597	208	446	763	387	691	585	396	512
1995	623	665	274	639	1042	612	876	832	647	690
1996	711	733	301	761	1103	647	959	1097	958	808
1997	510	665	232	636	1167	685	962	895	700	717
1998	563	697	215	638	878	594	719	848	631	643
1999	403	386	245	378	892	420	526	798	650	522
2000	498	763	289	671	1160	629	1006	1233	1274	836
2001	603	696	342	744	905	624	646	770	738	674
2002	608	663	251	566	794	431	569	620	367	541
2003	491	481	146	413	637	407	506	517	419	446
2004	537	689	205	516	865	534	690	828	731	622
2005	507	578	205	532	766	468	535	631	428	517
2006	624	879	351	771	1032	730	771	964	796	769
Average	**564**	**649**	**267**	**590**	**937**	**550**	**711**	**819**	**641**	**637**

Source: South African Weather Bureau.

Appendix 2. Average daily maximum temperature (°C) for South Africa's nine provinces: 1970–2006.

	Western Cape	Eastern Cape	Northern Cape	Free State	KwaZulu-Natal	North West	Gauteng	Mpumalanga	Limpopo	South Africa
1970	24.2	23.5	25.6	25.2	24.00	27.1	24.2	25.5	27.4	25.2
1971	24.1	23.0	25.5	24.6	23.37	25.7	23.0	24.2	26.2	24.4
1972	25.3	23.7	26.4	24.8	23.80	26.4	23.6	24.3	26.3	25.0
1973	25.2	24.0	26.0	24.7	23.43	26.3	23.4	24.6	26.2	24.9
1974	24.6	23.5	25.0	23.3	23.87	25.2	22.6	24.3	25.9	24.2
1975	25.0	23.5	25.4	24.1	23.46	25.6	22.9	24.3	26.0	24.5
1976	24.4	23.6	24.8	23.2	23.69	25.1	22.4	24.2	25.8	24.1
1977	24.7	24.0	25.5	24.7	24.42	26.5	23.8	25.0	26.6	25.0
1978	24.9	23.4	25.7	24.4	23.60	26.2	23.4	24.7	26.4	24.8
1979	25.0	23.5	26.0	24.7	23.66	26.6	23.9	24.6	26.3	24.9
1980	25.2	24.1	26.2	24.6	24.09	26.2	23.4	24.4	25.9	24.9
1981	24.7	23.4	25.2	23.4	23.55	25.6	23.0	24.0	25.6	24.3
1982	24.7	23.5	25.9	24.9	24.02	27.0	24.2	25.1	26.8	25.1
1983	24.8	24.2	25.9	25.6	24.30	27.6	24.6	25.4	27.4	25.5
1984	25.3	24.1	26.4	25.2	23.71	27.4	24.2	24.3	26.6	25.3
1985	25.2	24.4	26.2	25.2	24.66	27.3	24.4	25.0	26.5	25.4
1986	25.1	24.0	25.9	25.1	24.25	27.1	24.1	24.7	26.8	25.2
1987	24.9	24.0	25.9	25.1	23.94	27.4	24.2	24.9	27.0	25.3
1988	24.9	23.6	25.4	24.0	23.89	26.4	23.7	24.8	26.0	24.7
1989	24.7	23.3	25.1	24.1	23.79	26.3	23.5	24.7	26.5	24.7
1990	24.4	23.5	25.4	25.2	23.44	27.2	24.0	24.8	26.9	25.0
1991	24.6	24.0	25.4	24.5	24.08	26.5	24.0	25.1	26.9	25.0
1992	24.6	24.3	25.9	26.3	25.06	28.2	25.4	25.9	28.3	26.0
1993	25.4	24.3	26.1	24.8	24.58	27.0	24.3	24.9	27.3	25.4
1994	25.2	24.1	26.1	24.5	24.13	26.7	23.8	24.3	27.1	25.1
1995	24.5	23.6	25.6	24.8	23.67	26.7	24.2	24.1	27.3	25.0
1996	23.7	23.4	24.3	23.8	23.31	25.8	23.3	23.3	26.3	24.1
1997	24.8	23.5	25.7	24.7	23.23	26.2	23.5	23.8	26.8	24.7
1998	25.0	24.1	26.3	25.2	24.19	27.4	24.8	24.8	27.7	25.5
1999	25.7	25.0	26.3	25.7	25.08	27.3	24.5	24.2	27.3	25.7
2000	24.8	23.5	25.8	24.1	23.73	25.7	23.2	23.5	26.1	24.5
2001	24.6	24.1	25.6	24.2	24.31	26.2	24.2	24.0	26.8	24.9
2002	25.0	24.2	25.8	25.2	24.23	27.1	24.4	24.2	27.8	25.3
2003	25.0	24.5	25.9	25.9	24.33	27.6	25.1	24.3	28.2	25.6
2004	25.7	24.8	26.5	24.7	24.46	26.6	23.8	24.1	27.1	25.3
2005	25.1	24.5	26.0	25.4	24.46	27.3	25.1	24.3	28.3	25.6
2006	25.3	23.9	26.2	22.7	24.35	25.5	23.9	23.5	26.9	24.7
	24.9	**23.9**	**25.8**	**24.7**	**24.0**	**26.6**	**23.9**	**24.5**	**26.8**	**25.0**

Source: South African Weather Bureau.

Appendix 3. Explaining the SUR mode.

We employed the SUR model with a one-way error component, which allows cross-section heterogeneity in the error term; i.e. $u_{it} = \mu_i + \nu_{it}$. On the other hand, a two-way error component model allows cross-section heterogeneity, as well as time effects; i.e. $u_{it} = \mu_i + \lambda_t + \nu_{it}$. We adopt Avery's[21] approach, as presented in Baltagi,[16] to explain a SUR model in a panel context. The SUR model has a set of M equations:

$$y_j = Z_j\delta_j + \mu_j \text{ with } \mu_j = Z_\mu \mu_j + \nu_j \quad j = 1,...M\,, \tag{1}$$

where y_j is $NT \times 1$; Z_j is $NT \times k_j^{`}$ and the residuals from each equation with random vectors of $Z_u = (I_n \otimes l_T)$; $\mu_j' = (\mu_{1j},...\mu_{Nj})$ and $\nu_j' = (\nu_{11j},.....,\nu_{1Tj},....,\nu_{N1j},...,\nu_{NTj})$.

In addition, $\mu \sim (0, \Sigma_\mu \otimes I_N)$ and $\nu \sim (0, \Sigma_\nu \otimes I_{NT})$. From Equation 1, it follows that each different equation has the same standard variance-covariance matrix. However, within a panel SUR model, there are additional cross-equation variance components. Accordingly, Avery[21] defined a variance-covariance matrix that is not equation specific:

$$\Omega = E(\mu\mu`) = \Sigma_\mu \otimes (I_N \otimes J_T) + \Sigma_\nu \otimes (I_N \otimes I_T)\,, \tag{2}$$

where $\mu' = (\mu_1',....,\mu_M')$ is a $1 \times MTN$ vector of disturbances with μ_j and $\Sigma_u = [\sigma^2_{ujt}]$, as well as, $\Sigma_\nu = [\sigma^2_{\nu jt}]$ are both $M \times M$ matrices. Replacing J_T with $T\bar{J}_T$ and I_T by $E_T + \bar{J}_T$ provides the following:

$$\Omega = (T\Sigma_\mu + \Sigma_\nu) \otimes (I_N \otimes \bar{J}_T) + \Sigma_\nu \otimes [(I_{NT} - I_N \otimes \bar{J}_T)]\,. \tag{3}$$

It is then possible to estimate Equation 3 in a panel context, by replacing the matrix of disturbances for all M equations by OLS (Ordinary Least Squares) residuals[21] or within-type residuals.[16] To quantify the impact of rainfall's contribution to agriculture, we used an econometric model custom-made for this purpose. A net income function was estimated and fitted to the data with a cross-section SUR model for field crops, horticulture and animal production, respectively.

$$Y_i^* = f(input_i, wages_i, con_i, prod_i, temp_i, rain_i)\,, \tag{4}$$

where Y_i = net income for province i; Input$_i$ = expenditure on intermediary goods and services for province i; Wages$_i$ = wages, interest, and other sundry expenses for province i; Con$_i$ = proportional contribution to GDP for province i; Prod$_i$ = an index of gross income for province i; Temp$_i$ = temperature for province i; Rain$_i$ = rainfall for province i.

We compiled three separate models for each agricultural product, namely FC (field crops), H (horticulture), and AP (animal production), respectively, where each model contained the above independent variables per region/province and the dependent variable, i.e. the net income per province, for the respective agricultural product. After the initial round of estimating the net income function—for FC, H, or AP respectively—for each of the nine provinces, using the one-way error SUR model, two problems were encountered—heteroscedasticity and serial correlation—both of which had to be corrected, as we will now explain.

Heteroscedasticity

The standard SUR one-way error component model assumes that the regression disturbances are homoscedastic, when the same variance across time and individuals occurs. This may be a restrictive assumption for panels and agricultural type data, where the cross-sectional units may be varying in size and, as a result, may exhibit different variations.[22] Therefore, to correct for the potential problem of heteroscedasticity, White's cross-section heteroscedastic structure was specified in all the models, to ensure consistency and efficiency of the estimators.

Serial correlation

Another problem within the standard SUR one-way error component model is the assumption that the only correlation over time is due to the presence of the same individual effect across the panel.[22] This assumption ignores the effect of an unobserved shock that took place in the current period on the following periods, causing inefficient estimates of regression coefficients and biased standard errors. In an attempt to test for serial correlation, we employed the Durbin-Watson (DW) test and Lagrange Multiplier (LM) test. In particular, the LM-test is based on the test for random effects and serial correlation, where the null hypothesis is $H_0 = \sigma^2_\mu = 0; \lambda = 0$ or $H_0 = \sigma^2_\mu = 0; \rho = 0$. To construct the test, the following specification was used:

$$LM_1 = \frac{NT^2}{2(T-1)(T-2)}[A^2 - 4AB + 2TB^2] \overset{H_0}{\sim} \chi^2_2\,, \tag{5}$$

where $A = [\hat{u}'(I_N \otimes J_T)\hat{u}/(\hat{u}'\hat{u}) - 1]$ $(\sigma^2_\mu = 0)$; $B = A = (\hat{u}'\hat{u}_{-1}/(\hat{u}'\hat{u})$ $(\rho = 0)$ and $\hat{u}$ is OLS residuals.

The null hypothesis is rejected if the LM statistic exceeds the $\chi^2_2 (= 5.99)$ value. Moreover, Bhargava *et al.*[22] outlined the DW-test, with the null and alternative hypotheses as H_0: $\rho = 0$ and $H_A: |\rho| < 1$. These authors defined the test statistic as:

$$d_p = \sum_{i=1}^{N}\sum_{t=2}^{T}(\tilde{\nu}_{it} - \tilde{\nu}_{i,t-1})^2 / \sum_{i=1}^{N}\sum_{t=1}^{T}\tilde{\nu}^2_{it}\,, \tag{6}$$

with ν_{it} is the within residuals.

The critical values in Table II from Bhargava *et al.*[22] form the decision basis for this test. With the application of the DW and LM-tests, the results in Table A3.1 indicate that serial correlation was present.

Table A3.1. Results showing the presence of serial correlation.

Test	Field crops	Horticulture	Animal production
DW*	3.09	3.05	3.24
LM	69.35	50.27	50.73

*The DW-statistics show that negative serial correlation is present.

To correct for serial correlation, we estimate rho-values for each model and each province to account for the heterogeneity across the provinces. The rho-values reported in Table A3.2 confirm the presence of serial correlation in both models along with heterogeneity across the regions.

Table A3.2. Estimated rho-values as per region.

Province	Estimated rho-value		
	Field crops	Horticulture	Animal production
Western Cape	0.76	0.53	0.72
Eastern Cape	0.79	0.63	0.63
Northern Cape	0.78	0.89	0.79
Free State	0.67	0.81	0.78
Natal	0.79	0.93	0.69
North West	0.83	0.84	0.71
Mpumalanga	0.91	0.85	0.47
Gauteng	0.63	0.85	0.71
Limpopo	0.76	0.54	0.74

To correct for the serial correlation problem, the rho-values shown in Table A3.2 are used to transform the correlated errors into uncorrelated errors, based on a Prais-Winston transformation approach for each province. The DW- and LM-tests are performed again to determine whether serial correlation is still present in the models. Table A3.3 shows that the serial correlation problem has been addressed.

It is important to note that, with the correction for serial correlation, the sample size changed from the period 1971 to 2006, since observations have been lost through differentiation in the data transformation process. Given that the major data problems have been rectified, the final SUR models can now be presented. The results of each model are shown separately, first the field crops model, then the animal production model, and, last, the horticulture model.

Table A3.3. Results showing no serial correlation.

Test	Field crops	Horticulture	Animal production
DW*	2.21	2.16	2.26
LM**	5.69	5.54	5.59

*Constructing the critical value utilizing Table II from Bhargava *et al.*[22] with $T \approx 10$, $H \approx 250$ and $N \approx 9$. Following this approximation, the critical values yield 1.927 (D_{pL}) and 1.942 (D_{pU}).

When to stay, when to go: trade-offs for southern African arid-zone birds in times of drought

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Arid environments remind one of the punctuated equilibrium theory of evolution: they experience long periods of stasis and low productivity, interrupted with episodic rainfall which spurs reproduction and movement. Birds, as highly dispersive organisms, are among the most dramatic indicators of these fluctuations. Here we review birds' two main strategies, residency and nomadism, and the trade-offs faced by individuals in uncertain times. In general, wet years stimulate higher densities of nests (i.e. smaller territories), larger clutch sizes, unseasonal breeding, and at some times of year, higher breeding success. Rainfall above a certain threshold triggers breeding in resident species and an influx of nomadic species which breed and then move on. The environmental cues which trigger nomadism are sometimes poorly understood, but include distant thunderstorms for aquatic species, and perhaps for insectivores. Environmental cues that draw nomadic granivores to areas that have had recent rain are not known.

Key words: avian-nomadism, arid environments, Karoo-Namib Desert, Kalahari, breeding

Introduction

Prolonged spells of drought pose dilemmas for most organisms, even those adapted to hyper-aridity. For birds, reproduction, feeding, dispersal and moult are all activities which may need careful timing in relation to fluctuations in ecological productivity. In arid and semi-arid ecosystems, rainfall often triggers events in the life cycle which may be suppressed for months or even years during dry periods.[1,2,3,4] In times of very low productivity or harsh conditions, birds, like many other animals, can move to escape local conditions and improve their chances of feeding or reproduction.[5] However, some resident species may not move, but simply adjust their activities to 'ride out' difficult periods.

Semi-arid ecosystems are characterised by wet or dry states that are patchy in time and space. This patchiness is particularly true of southern Africa, where much of the region is semi-arid[6] and the environment experiences extremes in weather, from periods of intense and prolonged drought to exceptionally high rainfall events.[7] Rainfall in arid and semi-arid ecosystems in the southern hemisphere, including southern Africa, is greatly affected by El Niño Southern Oscillations (ENSO), leading to large variability in rainfall and prolonged droughts.[6] Similarly, extensive wet periods (La Niña events) have concomitant effects on ecosystem functioning.[8] The effects of El Niño and La Niña have been well studied in a few organisms, particularly birds, where changes in species richness and density[9] and reproduction[10] are correlated with the wet–dry cycles of ENSO years.

Birds, other animals and plants respond to increased rainfall in similar ways, and both birds and plants tend to increase reproductive effort with more rain.[11–14] The response by biota to extended dry periods in semi-arid environments, however, differs markedly between and within invertebrate and vertebrate phyla, and markedly between most animals and plants. Plants cope with droughts by dying after depositing dormant propagules (ephemerals) or becoming dormant and restricting their internal water use by discarding leaves or leaves and stems.[13,15] Although death and propagule dormancy are options taken by plants and some invertebrate taxa, *viz.* brine shrimp (*Artemia*), these options are not available to vertebrates, leaving escape and water conservation as the alternatives.[5,16]

Drought-induced dormancy in vegetation therefore has effects on animals. Animals in general, and birds in particular, cope with droughts and changes in vegetation by using behavioural and physiological tactics, including opportunistic movement away (in birds), shifts in habitat[5] and deferred hatching or dormancy in eggs (in locusts).[2,3,4] It is not known in detail whether birds make dietary shifts during extended droughts, but many species are opportunistic in their foraging and feeding in the Karoo[17] and it is very likely that such shifts do occur.

Our questions in this review are: (1) what is the influence of variability in rainfall on avian populations, including breeding and movements? and (2) how resilient are bird populations to extended dry periods? While we do not explicitly review climate change *per se,* our conclusions should be of value in predicting species-specific responses and levels of vulnerability to changing rainfall patterns in Africa.

The influence of rainfall on population dynamics

Exceptionally high rainfall may stimulate rare breeding events. For example, banded stilts (*Cladorhynchus leucocephalus*) in arid Australia arrive and breed in very large colonies following exceptionally high rainfall at ephemeral pans that may have been dry for decades.[1,18] Variability in rainfall has strong effects on clutch sizes and population dynamics in birds, as observed in unrelated species in different arid parts of the world, such as Galapagos ground finches on the Galápagos Islands,[10] galahs (*Cacatua roseicapilla*) in Australia[19] and larks,[20] thrushes and helmet-shrikes in arid southern Africa.[12,21] Droughts have different effects on bird populations, often stimulating movements into better-watered areas, but also, conversely and seemingly inexplicably, stimulating movements into dry areas.[22] Crowned hornbills (*Tockus alboterminatus*) wander from their forest habitat in the non-breeding season,[23] some years reaching far into the semi-arid Karoo.[24,25] These movements are thought to be related to unusual aridity or cold in their coastal habitats,[23] although these are probably always more mesic than the areas to which the birds disperse.

The movements of nomadic birds in arid and semi-arid ecosystems throughout the world have been reviewed by Dean.[5] We know that some birds have evolved to cope with stochastic weather events in their habitat. What is less clear, however, is what resident bird species do when faced with increasing aridity in their environment. For those species that move, the benefits must outweigh the costs.[26] Similarly, for those species that are resident, the benefits of being resident must outweigh the cost of

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Table 1. 'Equally Good Months' (EGMs) for selected southern African species. Data are from the Southern African Nest Record Card Scheme.

Species	Southwestern Cape	Karoo
Mountain wheatear (*Oenanthe monticola*)	2	4
Karoo scrub-robin (*Cercotrichas coryphoeus*)	2	4
Chestnut-vented tit-babbler (*Parisoma subcaeruleum*)	2	3
White-throated canary (*Crithagra albogularis*)	3	4

moving. For example, in partially-migratory rock kestrels (*Falco rupicolus*), individual males used one or the other of these two tactics.[27] Males departed for non-breeding areas later than did females, and returned to their territories earlier than did females. Not all males migrated, and those that remained successfully retained their territories and had a higher probability of breeding in the next breeding season. However, there was a cost: males that stayed on their territories during the winter faced increased competition for food. Males that migrated probably had higher survival, but risked losing their territories. Male rock kestrels in the Karoo thus faced a trade-off between increased chances of breeding and the risk of mortality.[27]

Trade-offs are necessary where rainfall is highly unpredictable. Unlike the short breeding season in the temperate northern hemisphere, the concept of extended 'equally good months' for breeding (EGMs)[28] often applies to bird populations in drier parts of the southern hemisphere, where weather patterns are less predictable and suitable or unsuitable conditions for breeding may arise at any time of the year. EGMs are calculated as the months in which there are breeding records equal to or above the average number of breeding records per month for the species. Africa and Australia both have a mean EGM 1.9 months a year longer than anywhere else,[29] presumably caused by out-of-season rainfall, or rainfall in areas that have been dry for a long period. Even within South Africa, areas with higher coefficients of variation in total annual rainfall,[30] such as the Karoo, have more EGMs than areas with more sharply seasonal, but more predictably timed, rainfall such as the southwestern Cape (Table 1).

The most frequently measured responses by birds in arid regions to above average rainfall or isolated rainfall events are breeding out of season, breeding in large numbers, and increases in clutch size or number of young produced. For example, 'heavy rains' following a five-year drought in the western Karoo stimulated bird breeding activity, with a number of species recorded with eggs and young, and all collected specimens in breeding condition[31]. Similarly, 170 mm of rain between January and March 1985, following a severe drought in the central Karoo, was believed to have stimulated breeding in 27 species of birds[32]. However, no studies of breeding activity in either case were made during the 'severe drought' broken by the rains, so the level of increase in breeding activity was difficult to evaluate.

Better data on the influence of rainfall on population dynamics

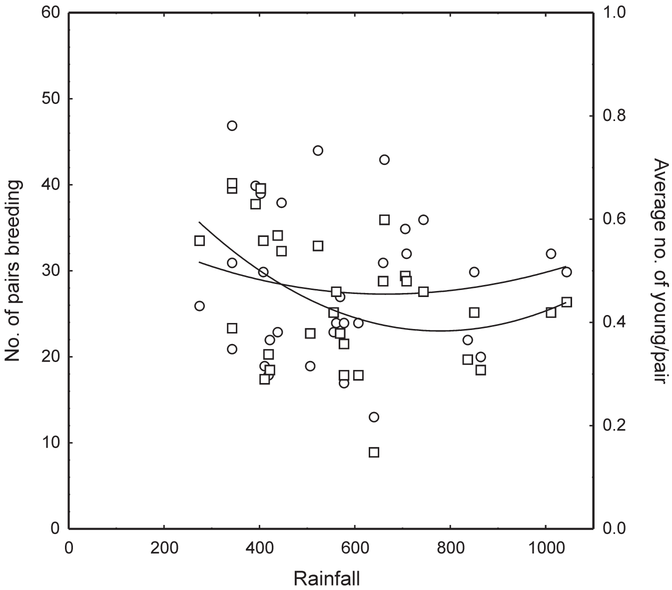

Fig. 1. The number of pairs of Verreaux's eagles, *Aquila verreauxii* (○, upper curve) observed breeding in the Matobo Hills, Zimbabwe and the average number of young/pair (□, lower curve) in relation to total annual rainfall. Data from Gargett *et al.*[33]

are provided by long-term studies. Verreaux's eagles (*Aquila verreauxii*) breeding in the Matobo Hills, Zimbabwe showed responses to variations in annual rainfall amounts. The number of resident pairs of Verreaux's eagles increased during the high rainfall years and correlated with increases in the number of hyraxes (*Procavia capensis* and *Heterohyrax brucei*)[33]. Both the number of pairs in the local population that bred and their production of young fit a negative exponential curve (Fig. 1), suggesting that the eagles benefit from both lower and higher rainfall years, but not from average rainfall years. Lower rainfall years have as many pairs breeding as higher rainfall years, with relatively higher breeding success. This suggests that breeding success is not only correlated with rainfall, but that other factors also influence the population dynamics of this species at this locality. Average rainfall years may increase competition for hyraxes, or higher rainfall years may lead to increased chick mortality.

In deciduous woodland habitats that come into leaf before the rains, there is some evidence that the level of breeding activity in birds is correlated with rainfall during the previous year. A study in the Miombo woodland in Zimbabwe[21] showed that rainfall during both the previous breeding season and current breeding season influences the number of nests and clutch sizes in Kurrichane thrushes (*Turdus libonyanus*) and white-crested helmet-shrikes (*Prionops plumatus*) (Tables 2 and 3). Both are resident species, generally maintaining territories all year round. The difference in breeding effort between years was not very marked in the Kurrichane thrush following the dry year of 1972, but breeding effort following the wettest year (1973)

Table 2. Breeding data for the Kurrichane thrush (*Turdus libonyanus*) at Great Zimbabwe, Zimbabwe (data from Vernon).[21,34] The start of the breeding season was defined as the date on which the first nest was found, and end of breeding season as the date when the last active nest was found.

Year	Rainfall (mm)	No. of breeding pairs	Start of breeding season	Duration of breeding season (days)	No. of nests	Nests/ha	Average clutch size	Total no. of eggs
1970	695							
1971	810	42	21 Sep	68	84	0.77	2.9	216
1972	392	49	16 Sep	80	71	0.73	2.8	194
1973	1316	49	27 Sep	68	77	0.72	2.9	216
1974		51	06 Sep	54	126	1.06	2.9	330

Table 3. Breeding data for the white-crested helmet-shrike (*Prionops plumatus*) at Great Zimbabwe, Zimbabwe (data from Vernon).[21,34] The start of the breeding season was defined as the date on which the first nest was found, and end of breeding season as the date when the last active nest was found.

Year	Rainfall (mm)	Breeding groups	Total no. of birds	Start of breeding season	Duration of breeding season (days)	No. of nests	Home range (ha)	Territory (ha)
1970	695							
1971	810	15	85	02 Sep	104	33	7.7	5.3
1972	392	17	85	15 Sep	78	28	5.3	4.5
1973	1316	13	68	22 Sep	79	20	9.4	6.7
1974		18	85	02 Sep	102	46	5.6	4.2

Table 4. Breeding data for grey-backed sparrowlarks (*Eremopterix verticalis*) in the Kgalagadi Transfrontier Park, Northern Cape, South Africa (data from Maclean).[35]

Period	Rainfall (mm)	No. of nests	Duration of season (days)
Dec 1964–Jan 1965	28.6	11	21
Apr–Nov 1965	139	99	210
Jan–Apr 1966	131.3	84	84

increased markedly, with an earlier start to breeding, increases in nest density per hectare (Table 2) and increases in the number of breeding attempts.[21,34] With lower rainfall in the previous season there were decreases in the number of breeding groups and total number of birds, and increases in home range and territory sizes in white-crested helmet-shrikes (Table 3).[21]

In a more arid environment, Maclean[35] showed that resident and nomadic larks (Alaudidae) and resident sociable weavers (*Philetarius socius*) in the Kgalagadi Transfrontier Park responded quickly to rain, and that the duration of the breeding 'season' varied according to the amount of rain. Table 4 gives data for one species, the grey-backed sparrowlark (*Erempoterix verticalis*) and Table 5 presents data for the sociable weaver. The average annual rainfall for this area is about 180 mm per year so the amount of rain that fell in April–November 1965 and January–April 1966 was more than 70% of the average annual rainfall. The relationship between rainfall, breeding season and breeding success, however, is not linear. Maclean[36] suggested that the duration of the breeding season is not directly governed by the amount of rain, but rather by the time of year in which rain falls.

This suggestion is supported by Lloyd[20] who noted that the timing and length of the breeding season in Bushmanland, Northern Cape Province depended on the integrated effect of rainfall and temperature on the growing season of the vegetation. Higher breeding success, measured as the percentage of young that left the nest, apparently depends on time of year and not the amount of rain *per se* (Table 5). The breeding success of sociable weavers was markedly lower during the hot summer months of January to April than the cooler, longer period from April to November[36] (Table 5).

Clutch size may vary with rainfall and aridity. In sociable weavers[35] there was some variation in mean clutch size per month, but specific rainfall data for those months were unavailable. However, a study of a bird community in Bushmanland, Northern Cape, showed that breeding activity of five species increased markedly after rainfall (Table 6), and more than half the species showed an increase in average clutch size compared to drier conditions.[20] Two species, black-eared sparrowlarks (*Eremopterix australis*) and grey-backed sparrowlarks, showed a rapid response to rain and began laying larger clutches within seven days of 78 mm of rain.[20]

The influence of drought on bird populations

Movements in birds may be in response to rain or in response to drought. In general, drought, or extended dry periods, has the effect of reducing bird diversity and reducing the number of individuals,[37] either through emigration[5] or lowered survival.[38] We do not know how resilient bird populations are to drought in southern Africa, because there are no intensive long-term studies of birds that have covered a full cycle of dry and wet years. There are, however, studies showing that resident birds may be quite resistant to drought. A long-term study at Tierberg, near Prince Albert in the Karoo, showed that the number of individuals of resident long-billed larks (*Certhilauda subcoronata*), spike-heeled larks (*Chersomanes albofasciata*), Karoo chats (*Cercomela schlegelii*) and rufous-eared warblers (*Malcorus pectoralis*) showed relatively small annual fluctuations regardless of rainfall[39] (Table 7). This data support the idea that in some cases the benefits of remaining in an area outweigh the costs of moving.

However, in the Kalahari, Botswana, resident species may show less resistance to drought, suggesting that resistance may depend to some extent on more subtle factors. For example, dry-season bird diversity, and number of individuals, were high following a higher rainfall wet season, and markedly lower following a poor rainfall season.[37] Of 39 resident and nomadic species, populations of three resident species were stable and nine resident and nomadic species increased in abundance during the wet year following a dry year. But 20 species, including some nomads, decreased in abundance during that year. In the dry year following a wet year, all species had decreased markedly in number, and 12 species were no longer locally present. All nomadic species showed large increases in number in the wet year. Only one of the nomads, Temminck's courser (*Cursorius temminckii*), was present during the second dry year. There was no general pattern apparent in the residents or nomads, except that bird numbers were generally lower in the wet season following a dry season than in the dry season following a wet season. Both groups of birds showed fluctuations in number that cannot be entirely explained by rainfall amount. Some residents (but not all) showed some initial resilience to the dry conditions. Such resilience, however, did not last over the entire period of the study.

Studies of birds under drought conditions show that responses

Table 5. Breeding data for sociable weavers (*Philetarius socius*) in the Kgalagadi Transfrontier Park, Northern Cape, South Africa (data from Maclean).[36]

Period	Rainfall (mm)	No. of nests	Total no. of eggs laid	Total no. of eggs hatched	No. that left the nest	% Success
Dec 1964–Jan 1965	28.6	79	371	140	19	5.1
Apr–Nov 1965	139	382	1841	874	328	17.8
Jan–Apr 1966	131.3	159	577	154	18	3.1

Table 6. The number of nests per kilometre found after episodic rainfall events in Bushmanland, Northern Cape, South Africa (data from Lloyd).[20]

	Rainfall (mm)		
Species	20	26	154
Double-banded courser	0.167	0.072	0.667
Spike-heeled lark	0.669	0.144	2.113
Tractrac chat	0.334	0.144	0.278
Rufous-eared warbler	0.084	–	0.612
Sclater's lark	1.756	0.722	0.723

Table 7. Estimated numbers of resident birds (birds km^{-1}) from counts on 1 km transects at Tierberg, near Prince Albert, South Africa (data from Dean and Milton).[39]

Year	1988	1989	1990	1991	1992	1993
Annual rainfall (mm)	297	272	192	164	224	231
Long-billed lark	8	12	12	14	16	7
Spike-heeled lark	25	27	30	24	30	30
Karoo chat	15	18	15	14	16	16
Rufous-eared warbler	16	17	17	16	19	17

to changes in environmental conditions may be species-specific. In Bushmanland, Sclater's lark (*Spizocorys sclateri*) showed some resistance to drought, nesting at a higher density during low rainfall than during a wetter spell (Table 6). During the dry period, the larks fed on, amongst others, the large seeds of a grass (*Enneapogon desvauxii*), a dependable resource in dry times because the seeds are held almost below ground at the base of the plant. Because of the difficulty of extracting the seeds, this resource is used only by Sclater's larks and Stark's larks (*S. starki*). Stark's larks are nomadic and absent during drier periods; Sclater's larks are thus able to use the resource without competition during droughts.

In species for which the costs of moving may be high, for example, dune larks (*Calendulauda erythrochlamys*) on sparsely vegetated 'islands' in the Namib Desert dune sea, some individuals nevertheless moved away during a drought, with the population on some islands reduced to about one half or one third of their former size.[40] There was also a reduction in foraging group size during the drought. Foraging group sizes in wetter periods were 2–6 individuals,[41] whereas during the drought no groups larger than two birds were seen.[40] No shifts in diet or changes in foraging methods and patterns between the wetter period and the drought were apparent, but there were seasonal differences in foraging patterns, and presumably diet, regardless of whether there was a drought or not.[40] Whether the larks remained on their patch or moved away was strongly dependent on plant composition and the state of the vegetation and invertebrate populations. Safriel[40] suggested that in patches where plant and invertebrate resources remained rich, foraging patterns (and presumably diet) would remain similar all year round. Dune larks can probably only be resident in the absence of any competition. The Namib Desert supports large numbers of nomadic granivores following rainfall.[42] Some nomadic species overlap temporarily in habitat with dune larks, but depart as the ecosystem dries out.

Dune larks are thus able to remain on their patches provided there is no potential competition.

Decision making: when to stay and when to go?

We have shown, in this brief review, that birds use two main strategies for coping with the environment getting wetter or drier. In general, 'wet' years stimulate higher densities of nests (i.e. smaller territories), larger clutch sizes, unseasonal breeding, and, depending on the time of year, higher breeding success. Rainfall over a certain amount[20,35,36,43] triggers breeding in resident species and an influx of nomadic species that breed and then move on. The amount of rainfall needed to trigger breeding varies between areas and seasons; 60 mm of rain in two days, followed by 22 mm eight days later in summer (January) stimulated breeding in the Kalahari,[35] but 41 mm in Bushmanland over several days in summer (February) without any follow-up rains did not trigger breeding.[20] It did, however, lead to an influx of nomadic granivores which did not breed at that time, whereas 54 mm of rain in winter (July) in the same area triggered breeding in all species.[20]

Nomads move in response to environmental cues, which are poorly understood for small terrestrial granivores,[5,44] but better understood for larger aquatic species.[45] Environmental cues for aquatic bird species may include distant thunderstorms, indicating heavy rain and thus the formation of temporary pans.[45] This scenario may also hold for small terrestrial insectivores, but for small avian granivores the lag between rainfall and the response by the plants may be a week or more. It has been suggested[5] that drifts of awns of grasses (used by nomadic larks and buntings for nest linings) may provide a strong visual cue that the area is suitable for nesting, but which other cues draw the birds initially to the area is not known.

Coping with an environment that is drying out may be easier for nomadic species. The environment dries out, particular food items become scarce, and provided that their young are large and able to fly, the nomads move on. What they must decide is where, and not when, to go. For resident species, however, whether to go or stay is a more difficult and apparently individual process. The examples we give suggest that in resident bird communities, there is a community-wide response to below-average rainfall, with fewer birds breeding in dry years and lower than usual production of young. But whether to breed or not, to stay or not, or to join a larger group remain individual decisions, possibly influenced by the decisions made by conspecifics.

If birds make the decision to remain in their area during a drought, they have several options to increase their chances of survival. They can increase territory size if neighbouring territories have become vacant or poorly-defended; they can shift their diet to eat a wider range of items; or they can abandon territories and join mixed-species foraging flocks. There is very little evidence of any of these tactics being particularly obvious in drought years. Furthermore, the benefits of all tactics have to be traded off against the losses. Territories that have increased in size might be too large to defend when good times arrive, territories that are abandoned need to be re-established when the drought is over, and shifts in diet may have consequences for the health or reproductive success of individual birds. But more importantly, resident species usually know their territory or home range very well.[46] They know good places to forage, to nest and to avoid predators. This knowledge will increase in quality over the years.[47] This fact is supported by Hanmer[38] who shows that adult birds survive droughts better than immature ones, and suggests that it is due to the adults' better knowledge of parts of the habitat that gives them an advantage. Resident bird species are thus more likely to be resistant to drought and to use available resources as best they can without giving up their patch.

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Drought, climate change and vegetation response in the succulent karoo, South Africa

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For the winter-rainfall region of South Africa, the frequency of drought is predicted to increase over the next 100 years, with dire consequences for the vegetation of this biodiversity hotspot. We analysed historical 20th century rainfall records for six rainfall stations within the succulent karoo biome to determine if the signal of increasing drought frequency is already apparent, and whether mean annual rainfall is decreasing. We found no evidence for a decrease either in mean annual rainfall or in the incidence of drought, as measured by the Standardised Precipitation Index (SPI) over the 20th century. Evidence points to a drying trend from 1900–1950 while no significant trend in rainfall and drought was found at most stations from 1951–2000. In a second analysis we synthesised the information concerning the response of adult succulent karoo biome plants and seedlings to extended drought conditions. General findings are that responses to drought differ between species, and that longevity is an important life history trait related to drought survival. Growth form is a poor predictor of drought response across the biome. There was a range of responses to drought among adult plants of various growth forms, and among non-succulent seedlings. Leaf-succulent seedlings, however, exhibited phenomenal drought resistance, the majority surviving drought long after all the experimentally comparative non-succulent seedlings had died. Our synthesis showed that previous studies on the impact of drought on succulent karoo biome plants differ greatly in terms of their location, sampling design, measured values and plant responses. A suite of coordinated long-term field observations, experiments and models are therefore needed to assess the response of succulent karoo biome species to key drought events as they occur over time and to integrate this information into conservation planning.

Key words: biodiversity hotspot, mortality, population dynamics, recruitment, Standardised Precipitation Index

Introduction

More than 90% of South Africa is either arid or semi-arid and drought is a characteristic feature of the climate.[1] Because drought has significant ecological[2] and socio-economic[3] impacts, investigations into its causes, consequences and mitigation have been regularly undertaken in South Africa over the last 100 years.[4] Recent climate change scenarios suggest that there will be an increase in the frequency of extreme events, including drought, particularly in the winter-rainfall region of southern Africa[5,6] as a result of the predicted pole-ward retreat of rain-bearing frontal systems.[7]

Such predictions raise two important questions. Firstly, is there evidence in the climate record that annual rainfall has already declined and the incidence of drought has increased over the last 100 years in the winter-rainfall region of South Africa? Previous analyses of the historical winter rainfall record found little evidence either for a decline in rainfall[8] or an increase in drought over the 20th century.[1] However, a more detailed analysis of Namaqualand's rainfall record described the pattern as spatially complex, with some areas exhibiting wetter and others drier conditions since 1950.[7] Unequivocal evidence for a recent increase in drier conditions, such as was recorded for the Sahel in the 1970s and 1980s,[9] will help motivate the region to prepare for the inevitable consequences of less rain and help offset some of the worst effects of drought. A detailed analysis of the historical rainfall record will also place any future drought in its proper context in terms of the intensity and duration.

The second question which arises from the climate change scenarios is concerned with the response of vegetation to drought. Both the fynbos and succulent karoo biomes, which characterise the winter-rainfall region of South Africa, are internationally recognised for their high levels of biodiversity and endemism.[10] Oscillating wet and dry climatic conditions in the succulent karoo and a moderate climatic history within the succulent karoo have both been suggested to be instrumental in the development of high levels of floral diversity.[11,12] The moderate climatic history argument has lead to the suggestion that the flora is vulnerable to the effects of climate change.[12] What will be the impact of less rain and a higher incidence of drought on the vegetation of these biomes? While several studies explored the impact of future climate change on fynbos[13] and succulent karoo biome vegetation[12] none has assessed the historical impact of drought on fynbos species and only four studies have been undertaken in the succulent karoo biome. All have focused on the response of leaf- and stem-succulent shrubs relative to non-succulent evergreen and deciduous shrubs and have returned contradictory results. Some studies have reported that leaf succulents were negatively affected by drought[14,15] while at other sites leaf succulents were either hardly affected at all[16] or were less affected[17] than non-succulent shrubs.

In the first part of this paper we examine the 20th century rainfall record at six stations across the succulent karoo biome to test whether annual rainfall has declined and whether or not the incidence of drought has increased since 1900. In the second part we review the results of previous studies to understand the impact of drought events on both adult plants and seedlings which occur within the region.

Methods

Rainfall and drought

Long-term trends in annual rainfall over the period 1900–2000 were investigated at six representative succulent karoo biome sites located at regular intervals along a north–south (Lekkersing, Springbok, Clanwilliam) and west–east (Worcester, Oudtshoorn, Steytlerville) gradient within the biome (Fig. 1). The choice of station was based on the availability of reliable long-term data, the absence of any local orographic influence and their location relative to the sites where the drought studies were undertaken. Annual rainfall values were extracted from

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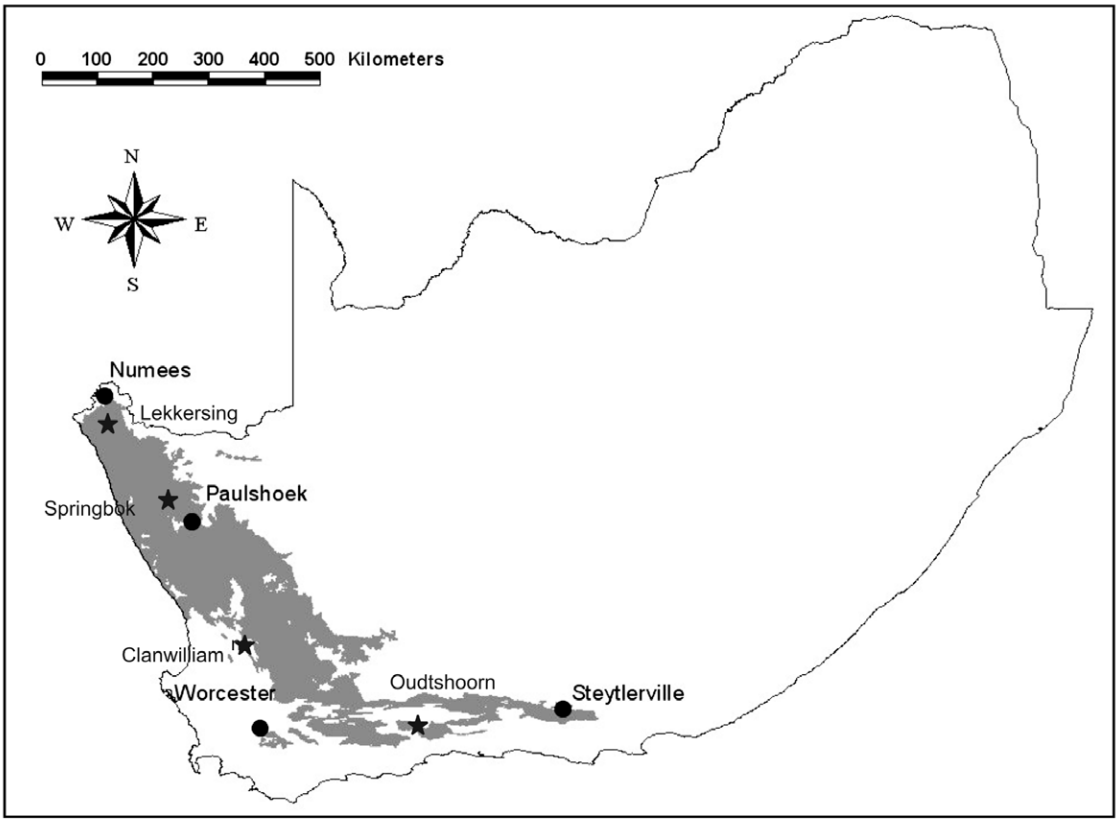

Fig. 1. Location of the four main drought studies (Numees, Paulshoek, Worcester, Steytlerville) in the succulent karoo biome and six weather stations (Lekkersing, Springbok, Clanwilliam, Worcester, Oudtshoorn, Steytlerville) used in the rainfall and drought analysis.

Lynch[18] and augmented by data from the South African Weather Service.[19] A Mann-Kendall analysis for trend[20] was used to test whether there had been a significant change in annual rainfall over the 20th century as well as for the periods 1900–1950 and 1951–2000 at each of the six rainfall stations. This non-parametric test for trend calculates an S statistic based on the sign comparisons of pairs of values and compares them to a standard Z frequency distribution.[21]

The same long-term rainfall record for the six stations mentioned above was used to investigate the incidence of drought over the 20th century in the succulent karoo biome. We used a Standardised Precipitation Index (SPI)[1,22] for a 12-month time scale and present the SPI value for the end of the winter rainfall season (i.e. August) each year for each of the six rainfall stations. A Mann-Kendall analysis for trend in the SPI values was used to test whether there was a significant increase or decrease in the incidence of drought over the 20th century as well as for the periods 1900–1950 and 1951–2000.

Vegetation response to drought

The effect of drought on adult succulent karoo biome plants was assessed using the four main studies that have been undertaken in the region[14–17] (Fig. 1). The experimental design of each study was described and the key findings summarised, with a particular focus on the effect of drought on the three dominant growth forms in the region, namely leaf succulent, stem succulent and non-succulent shrubs.

A synthesis of the three main studies[16,23,24] which have investigated the effect of drought on the survival of leaf succulent and non-succulent shrub seedlings was also undertaken. Details of the experimental design of each study and the response of leaf succulent and non-succulent seedlings to an extended drought treatment were analysed.

Results

Rainfall and drought

Annual rainfall

During the 20th century, total annual rainfall fluctuated considerably at the six succulent karoo biome climate stations analysed (Fig. 2). No stations showed either a significant increase or decrease in annual rainfall over the full 100-year record from 1900–2000. When divided into pre- and post-1950 periods, Springbok ($n = 50$, $Z = -1.66$, $P < 0.05$) and Worcester ($n = 50$, $Z = -3.61$, $P < 0.001$) showed a significant downward trend in annual rainfall for the period 1900–1950. There was no significant trend in annual rainfall for the post-1950 period for any of the climate stations, except for Lekkersing, that showed a significant increase in rainfall from 1965–2000 ($n = 36$, $Z = 2.48$, $P < 0.01$). These results were unaffected when a Bonferroni correction was applied ($P_{crit} = 0.017$), except the 1900–1950 Springbok trend, that became non-significant.

Standardised Precipitation Index

Throughout the 20th century, periods of meteorological drought, as measured by the Standardised Precipitation Index (SPI), have fluctuated with periods of high rainfall (Fig. 3). Major drought periods, which have been widespread in the winter-rainfall region, occurred during the periods 1924–1925, 1927–1929, 1949, 1969–1970, 1978–1979 (although Steytlerville was not affected at this time) and 1998–1999. Widespread wet periods occurred in 1917–1918, 1921–1922, 1925, 1954–1955, 1977 and 1996–1997.

There was no significant trend in the incidence of drought over the 20th century for the stations investigated, except for Springbok, that showed a significant increase in the incidence of drought from 1900–2000 ($n = 99$, $Z = -2.20$, $P < 0.01$). However,

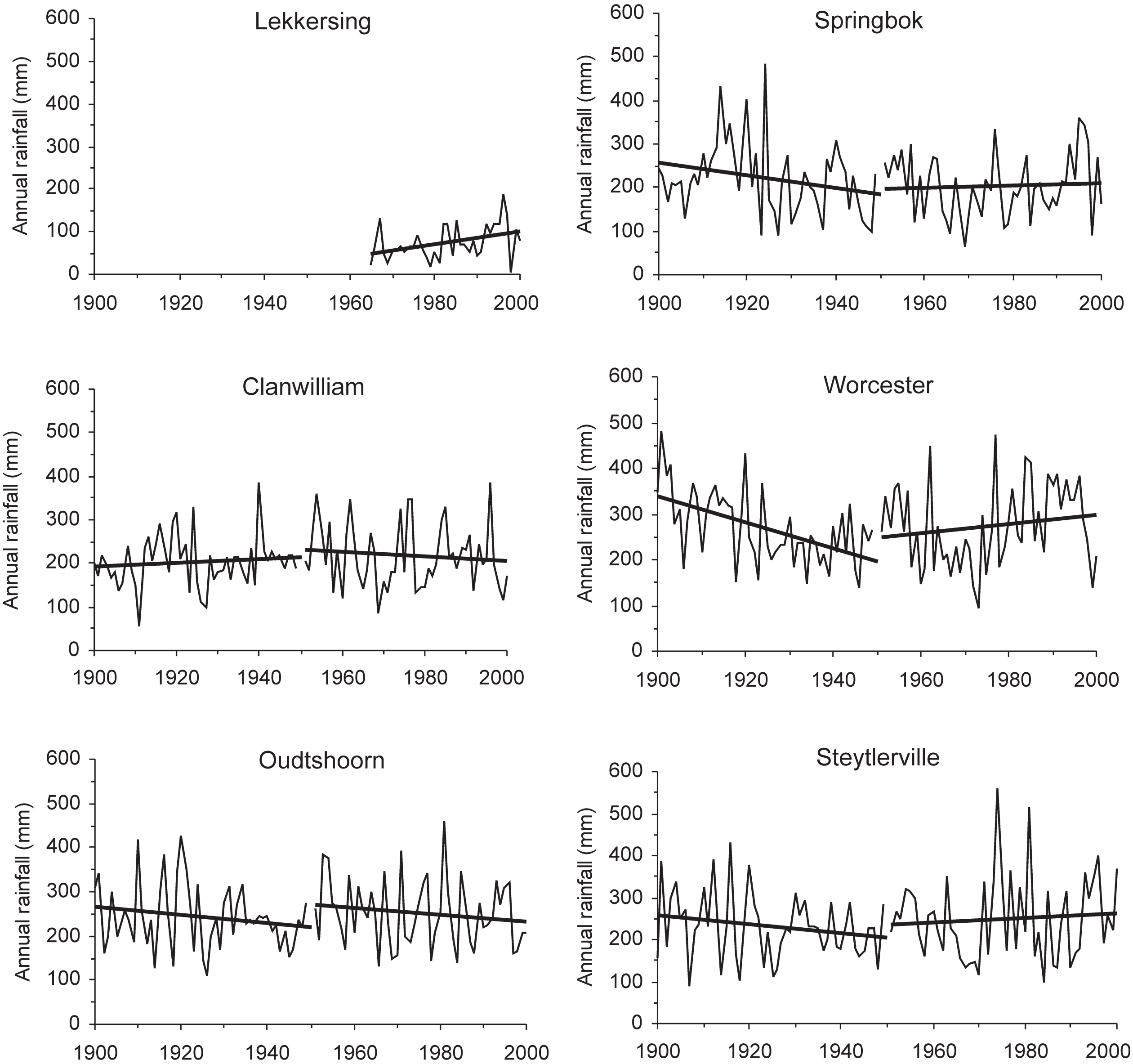

Fig. 2. Annual rainfall totals in the 20th century for six stations in the succulent karoo biome with linear trend lines shown for the periods 1901–1950 and 1951–2000 except for Lekkersing where the trend line is from 1965–2000.

for the period 1900–1950, Springbok (n = 49, Z = –2.66, P < 0.001), Worcester (n = 49, Z = –5.03, P < 0.001), Oudtshoorn (n = 49, Z = –2.31, P < 0.01) and Steytlerville (n = 49, Z = –2.26, P < 0.01) all showed a significant increase in the incidence of drought. In contrast, at none of the rainfall stations has the incidence of drought increased since 1951. At Lekkersing there has been a significant decrease in the incidence of drought from 1965–2000 (n = 36, Z = 2.22, P < 0.01).

Vegetation response to drought

Field studies on adult plant mortality

A summary of the four main drought studies carried out in the succulent karoo biome is shown in Table 1 and the key rainfall and drought characteristics at each of the sites are detailed in Table 2. Midgley and van der Heyden[15] used an experimental approach to investigate the impact of drought on adult plant responses while the other three studies were observations of plant mortality after the drought had been broken. The studies were widely scattered across the succulent karoo biome and differed significantly in terms of their sampling design, what was recorded, as well as their key findings.

In the southern Richtersveld at Numees (Fig. 1), the 1979/80 drought reduced both species richness and the number of individuals relative to the average values which were recorded over the next 17 years (Table 1). Jurgens *et al.*[14] showed that populations of the four leaf-succulent Aizoaceae species investigated in detail, exhibited a high degree of turnover. There were significant inter-specific differences in temporal pattern which were often unrelated to prevailing rainfall conditions (i.e. dry and wet spells). Both recruitment and mortality (measured as a percentage of the observed population) were continuous over the monitoring period and ranged between 62% and 89% and between 60% and 85%, respectively. The mean age of individuals of these four species ranged from 4.6 to 5.6 years.

Carrick[16] reported the mortality of the six most abundant species at Paulshoek in the eastern Kamiesberg (Fig. 1, Table 1). He found very low levels of drought-related deaths irrespective of their positions along a degradation gradient (differing largely in grazing intensity). Mortality in the two shallow-rooted leaf-succulent shrubs investigated, *Leipoldtia schultzei* and *Ruschia robusta,* was similar at 3.5% and 3.8%, respectively. For the stem-succulent shrub, *Euphorbia decussata,* mortality was

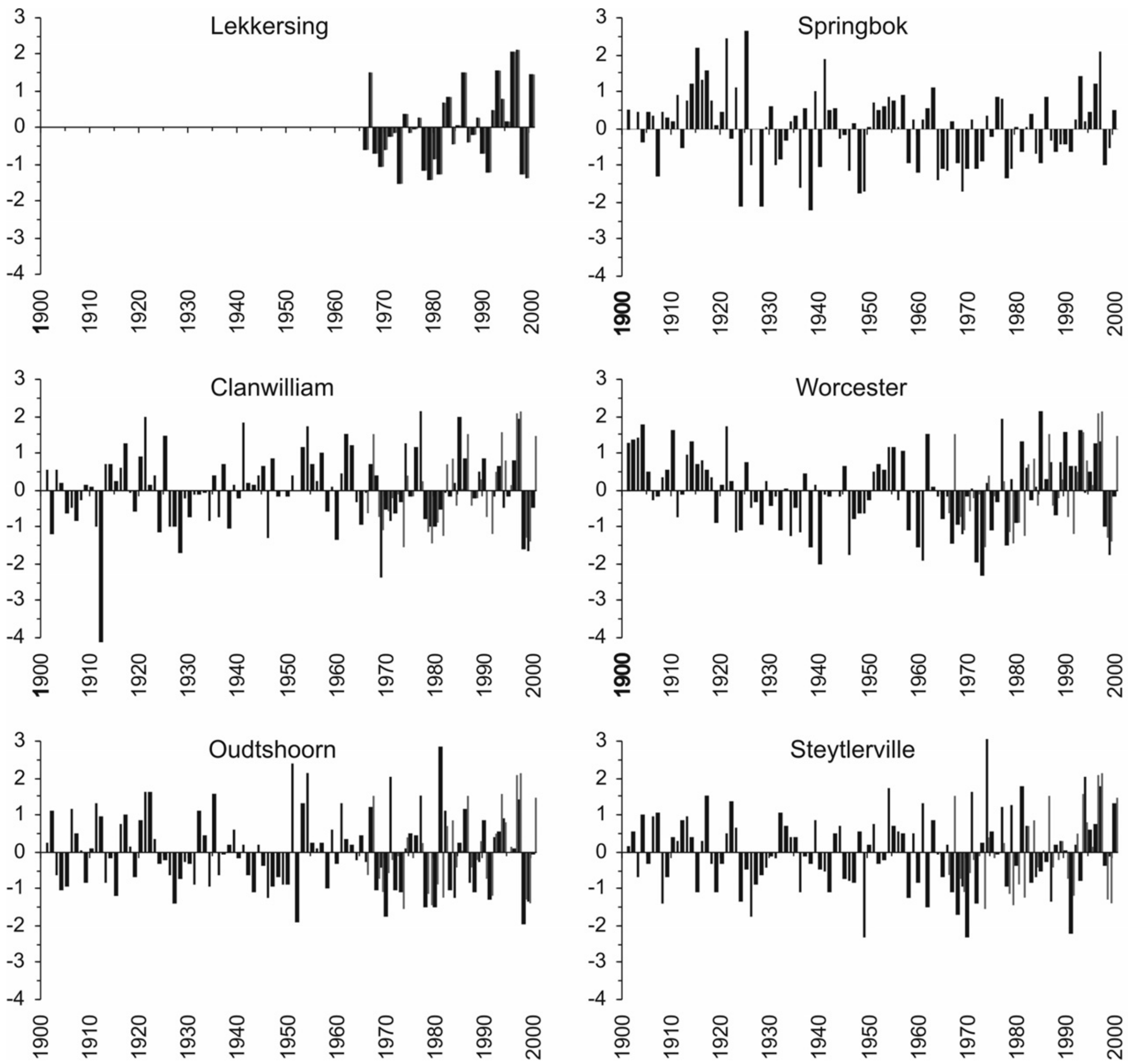

Fig. 3. Standardised Precipitation Index (SPI) values for six weather stations within the succulent karoo biome for the period 1900–2000 except Lekkersing which is from 1965–2000. SPI values are for a 12-month period from September to August (i.e. end of the rainy season) each year.

even lower at 2.0%. In the three non-succulent shrubs investigated, mortality was 0.3% and 1.8% for *Hirpicium alienatum* and *Tripteris sinuatum,* respectively, although for *Galenia africana* it was considerably higher at 5.4%. While the non-succulents are all relatively deep-rooted species, the first two mentioned above are late-successional species. *G. africana,* however, is usually the first shrub to colonise heavily grazed or highly disturbed, bare areas. Of the three, *G. africana* is relatively short-lived,[25] while *H. alienatum* is likely to have the highest longevity.

In their experimental manipulation of rainfall at the Worcester Veld Reserve (Fig. 1), Midgley and van der Heyden[15] reported higher levels of drought impact on leaf-succulent shrubs and less for stem-succulent and non-succulent species (Table 1). The LD_{50} value (i.e. the number of days of drought required to kill 50% of the shoots) for the leaf-succulent shrub, *Ruschia caroli,* was 259 days while for stem-succulent species, *Euphorbia mauritanica* and *E. burmannii,* the values were 343 and 595 days, respectively. For the non-succulent evergreen species, *Pteronia incana,* the LD_{50} value was 518 days. Another non-succulent, evergreen shrub, *P. paniculata* and a non-succulent, deciduous shrub, *Lycium cinereum,* showed minimal shoot die-back after 600 days of drought. Midgley and van der Heyden[15] showed that *L. cinereum* had access to ground water although this was not the case for *P. paniculata.*

Milton *et al.*[17] observed a shift in growth form dominance near Steytlerville following the 1990/1 drought (Fig. 1, Table 1). Overall perennial plant cover was more than halved by the drought with a greater impact on non-succulent than succulent shrubs. The two most common non-succulent shrubs, *Eriocephalus ericoides* and *Pentzia incana,* were particularly negatively impacted by the drought, losing 88% and 70% of their canopy cover values, respectively. Population recovery in the immediate post-drought period was also slow and for the first two years after 1991 the vegetation was co-dominated by perennial succulent shrubs and by a suite of post-drought pioneers, including the alien pauciennial, *Atriplex lindleyi.*

Of the three locations where observations of drought impacts were carried out, Numees near Lekkersing in the Richtersveld is clearly the most arid site with the highest variability in annual rainfall (Table 2). The 1979/80 drought was also the most extreme of all the sites for nearly all of the values computed from the daily rainfall record. The Paulshoek study site in the Kamiesberg and the one at Baroe near Steytlerville are more similar in terms of mean annual rainfall and most drought parameters. However,

Table 1. Summary of key drought studies undertaken in the succulent karoo biome.

Authors	Location and study site description	Sampling design and measurement	Main findings
Jürgens *et al.*[14]	Numees, southern Richtersveld. Very steep, south-facing slope on shallow, rocky quartzite.	One 10 × 10 m plot in which the number of individual perennial species was mapped over 17 years after the 1979/80 drought and included a detailed analysis of the population dynamics of four leaf-succulent shrubs.	Drought impact reduced species richness and the number of individuals to about 60% of the mean value recorded for the next 17 years. The four leaf-succulent shrubs exhibited species-specific patterns of continuous and high levels of recruitment and mortality. Mean age was 4.9 years.
Carrick[16]	Paulshoek, eastern Kamiesberg. Plains on relatively deep, gneiss-derived loamy sands.	Sixty 5 × 5 m plots located along a grazing intensity gradient in which individuals of six species were classified as either alive or as having died in the 1998/99 drought.	Drought-induced mortality was relatively low (leaf succulents = 3.7% of the individuals died in response to the drought, stem succulents = 2.0% and non-succulents = 2.5%).
Midgley and van der Heyden[15]	Worcester Veld Reserve. Steep, south-facing slope on shallow, shale-derived soils.	Two 6 × 6 m rain exclosures in which the LD_{50} (i.e. number of days to 50% shoot mortality) of select perennial shrubs was recorded.	Leaf-succulent shrubs appeared more drought sensitive than stem-succulent and non-succulent shrubs. Two of the four non-succulent species showed minimal dieback despite nearly 600 days without rain.
Milton *et al.*[17]	Baroe, near Steytlerville. Valleys, plains and slopes with a wide range of soil types, depths and degree of rockiness.	Seven 20 m line transects within valleys, plains and slopes along which the canopy cover of perennial shrubs was classified as either live, moribund or dead after the 1990/91 drought.	Pre-drought cover for non-succulents (23%) and succulents (20%) was similar. Drought reduced perennial cover from 45% to 21%. Mortality for non-succulents was higher (65%) than for succulents (42%), resulting in a succulent-dominated perennial flora following drought.

the drought at Steytlerville appears more severe largely because of the overall longer period of drought (nearly 50% longer than at Paulshoek) and the greater number of days without a rainfall event >5 mm. In addition, the conditions preceding the drought period itself differed considerably between the sites. The Steytlerville and Richtersveld droughts were preceded by average or below-average rainfall for five years (Fig. 3). In contrast, the Kamiesberg drought was preceded by five years of above-average rainfall.

Greenhouse studies on seedling mortality

Three experiments have tested the impact of drought on the survival of succulent and non-succulent shrub seedlings (see Table 3). All studies were carried out under greenhouse conditions using seedlings grown in pots. The experiments differ in terms of their sampling design, soil medium used, length of the experimental drought period and time taken to reach permanent wilting point. There are also no shared species, although in all experiments the leaf-succulent shrubs investigated were species within the genus *Ruschia* (Aizoaceae). Despite these differences, all investigations showed that the seedlings of leaf succulents were able to survive long periods without water even when soil water content dropped close to 0% of field capacity. For non-succulent shrubs, however, there was considerable variation in their ability to withstand drought. In some species (e.g. *Galenia africana*[16], and the two fynbos species used by Lechmere-Oertel and Cowling[24]) death occurred within a month of the start of the drought treatment. For *Pteronia pallens* and *Tripteris sinuatum*[23] however, survival of at least some individuals was nearly six times as long, with the last individuals dying 125 and 160 days, respectively, after watering had stopped.

Discussion

Rainfall and drought

Future climate change scenarios suggest that over the next 100 years the winter-rainfall region, including the succulent karoo biome, will experience hotter and drier conditions than those experienced in the 20th century[26] although there may be considerable spatial variation.[7] These changes may have dire consequences for the region's biodiversity.[12] Our review addressed two main questions: Is there evidence in the historical rainfall record

Table 2. Comparative information about the meteorological drought events at each of the three study sites where observations on the effects of natural drought on succulent karoo biome plants have been carried out . Meteorological drought was defined, using the Standardised Precipitation Index (SPI) for a 12-month time scale, as the period during which the SPI is continuously negative and reaches a value of –1.0 or less. Drought conditions start when the SPI first falls below zero and ends when the SPI is greater than zero following a value of –1.0 or less.[22]

	Study site location		
	Richtersveld	Kamiesberg	Steytlerville
Study site characterisation			
Author(s) of study	Jürgens *et al.*[14]	Carrick[16]	Milton *et al.*[17]
Closest weather station	Lekkersing	Springbok	Steytlerville
Distance to study site (km)	50	90	25
Period of rainfall record	1965–2000	1900–2000	1900–2000
Mean annual rainfall (mm)	75	213	240
Coefficient of variation (%)	52	37	37
Drought characterisation			
Period of meteorological drought	Apr 1978–May 1982	Jun 1998–Aug 1999	Oct 1990–Jul 1992
No. of months of drought	50	15	22
Longest period without rain (days)	149	64	74
Longest period without rain event >5 mm (days)	341	137	232

Table 3. Summary of three separate seedling experiments that measure the ability of succulent karoo and arid fynbos species to survive drought. All three experiments use field-collected seed, establish the seedlings in pots under greenhouse conditions and then measure the mortality of individual species following the cessation of all watering. In all three experiments the mortality of leaf-succulent species is compared with that of non-succulent species.

Authors	Experimental design	Soil medium	Main findings
Esler and Phillips[23]	Three species and 50–120 seedlings per species in pots sown at densities of 10, 6 or 1 seedling per pot depending on the species and not watered for 400 days. Soil water potential fell below permanent wilting point (1.5 MPa) after 35–140 days.	2 parts soil from Prince Albert, 4 parts pasteurised river sand and 1 part compost.	70% of the seedlings of the succulent shrub, Ruschia spinosa, survived the experiment while none of the two non-succulent shrubs, *Pteronia pallens* and *Tripteris sinuatum* survived. Seedlings of the latter two species were all dead within 125 and 160 days, respectively.
Lechmere-Oertel and Cowling[24]	Four species and 9–20 seedlings per species, each in their own pot and not watered for 77 days. Soil water potential was not measured.	Separate experiments on shale and sandstone soils collected from the Matjiesrivier Nature Reserve.	100% of the seedlings of the two succulent shrubs investigated, *Ruschia* spp., survived on sandstone soils and 80% survived on the shale soils. None of the non-succulent shrub seedlings, *Passerina vulgaris* and *Leudadendron pubescens*, survived the experiment on either of the soils. The mean survival period for these two species was 26 days on sandstone and 22 days on shale.
Carrick[16]	Two species and 35 seedlings per species, each in their own pot and not watered for 160 days. Soil water potential, in all pots, fell below permanent wilting point (1.5 MPa) after 6 days.	1 part soil from Paulshoek (eastern Kamiesberg) and 1 part acid-washed river sand.	86% of the seedlings of the succulent shrub, *Ruschia robusta*, survived the experiment while all of the seedlings of the non-succulent shrub, *Galenia africana*, were dead within 21 days.

that a drying trend has already started? How have plants within the succulent karoo biome responded to drought in the past?

Our analysis finds no evidence for a decreasing trend in annual rainfall from 1900–2000 for the six rainfall stations investigated, and except for Springbok, there was no increase in the incidence of drought over the 20th century. Our analysis is in agreement with Warburton and Schulze[8] who also report no decrease in annual rainfall for the winter-rainfall region in the latter part of 20th century. In fact, they suggest that relative to the period 1950–1969, the winter-rainfall region experienced an increase in rainfall from 1980–1999. MacKellar *et al.'s* analysis[7] of Namaqualand's historical rainfall record suggests a spatially variable pattern with annual rainfall totals at some stations (e.g. Springbok) showing a decrease in rainfall while locations to the north (e.g. Lekkersing) and south (e.g. Kamieskroon) have experienced the opposite trend. Springbok experienced exceptionally high rainfall during the period 1911–1925 with total annual rainfall nearly 50% higher for these 14 years relative to the mean value for the next 75 years. These 14 wet years are the main driver behind the pattern of a significantly increased incidence of drought at this location over the 20th century.

What emerges strongly from our study is that most stations in the succulent karoo biome showed a significantly higher incidence of drought between 1900 and 1950 relative to the second half of the 20th century. Coupled with the high stocking rates that built up steadily during the first half of the 20th century,[27] the impact of episodic, severe drought (e.g. in 1949) on the vegetation of the region must have been significant over this period, since drought and heavy grazing combine to reduce plant cover, especially of palatable species.[28,29]

Concern over drought in southern Africa is not new. There were severe droughts in southern Africa in 1821–23, 1845–7, and 1862–63, which triggered the emergence of a 'desiccationist' narrative, linking decreasing rainfall with human activities, especially the removal of vegetation and reflecting international concern over climate change and conservation at global, regional and local scales.[30]

Similarly, despite the lack of evidence of increasing drought from the rainfall records, a desiccationist narrative has emerged around the effects of climate change on the succulent karoo biome.[12] Concerns for the diversity and stability of natural resources in a drier, hotter succulent karoo are based on future scenarios derived from General Circulation Models (GCMs), rather than evidence of increasing drought from historical sources. When historical analyses have been conducted they show either little change in the long-term record,[31] a spatially complex trend in the data[7] or an increasing trend in rainfall in the latter part of the 20th century (ref. 8; this study). It might still be the case that rainfall in the succulent karoo biome will decline in the 21st century as suggested by most GCMs.[5,6] However, an analysis of the historical record has failed to support such a generalised desiccationist narrative for the 20th century in the winter-rainfall region.

Vegetation responses

Despite the succulent karoo biome's unique flora and ecology and relatively poor conservation status, to date, only four studies have examined the effects of drought in this region. These four studies were conducted at widely different locations within the biome, each with its own particular on-site land use and climate history, and drought characteristics, and using a wide diversity of approaches. Under such circumstances, finding coherent patterns of drought sensitivity amongst growth forms would be indicative of very strong selective pressures on those growth forms in response to drought. Perhaps unsurprisingly, no such pattern emerged from the four case studies, indicating instead, a heterogeneous system where the specific flora and drought conditions resulted in different patterns of mortality.

All four studies summarised in this analysis suggest that some succulent karoo biome species are more susceptible to the impact of drought than others but provide contradictory results concerning the impact of drought on different growth forms. Except for the short-lived, leaf-succulent species within the family Aizoaceae in the Richtersveld study[14] and *Pentzia incana, Eriocephalus ericoides* at Steytlerville[17] and to some extent *Galenia africana* at Paulshoek,[16] all the other species were remarkably resistant to drought, irrespective of growth form. *Lycium cinereum, Pteronia paniculata* and *Hirpicium alienatum* stand out as being particularly drought resistant.

Our analysis provided little evidence for the suggestion that adult succulent plants are more susceptible to drought than non-succulents.[15] While data from the Richtersveld[14] and Worcester[15] suggest that leaf succulents are susceptible to drought, the majority of species reported on in these two case studies are short-lived, relatively weedy leaf-succulent species colonising disturbed environments. In Steytlerville, leaf-succulent species survived the drought better than non-succulent shrubs[17] while in the Kamiesberg, there was little difference in survivorship between leaf-, stem- and most non-succulent shrubs.[16] A more definitive answer about the relative drought sensitivity of succulents and non-succulent growth forms awaits additional research which directly addresses this issue. Clearly, the growth form classes are too broad to accommodate the wide diversity of life history traits exhibited by the species that define them. A far narrower differentiation of growth forms based on traits such as longevity, size at maturity and population density is needed.[32] Carrick,[16] for example, suggests that the lifespan of a species is a far better predictor of its ability to survive a drought than its broad growth form definition.

Of particular interest was the variation in mortality between the different case studies. Most comparable in terms of climate are the Paulshoek[16] and Steytlerville[17] studies. Both of these locations have a similar mean annual rainfall and the drought characteristics appeared to be similar in length and severity (Table 2). However, the vegetation responses differed considerably. Carrick[16] recorded percentage mortality of less than 5%, whereas Milton *et al.*[17] report up to 65% mortality rates. What could account for this variation in mortality? It is possible that conditions prior to the onset of the drought affected drought susceptibility. In Steytlerville, total annual rainfall was well below the long-term average for half of the six years prior to the 1990 drought. In contrast, the Paulshoek drought was preceded by five years of very high rainfall. The causes of drought mortality in plants are remarkably poorly understood, but it is possible that the cumulative stress of several years of below-average rainfall may result in higher rates of mortality.[33]

While few generalisations can be made about the impact of drought on adult plants within the succulent karoo biome, the seedlings of leaf-succulent *Ruschia* spp. exhibited a remarkable ability to survive extreme drought conditions. The three seedling experiments suggest that there might be a coherent pattern of drought resistance among the Aizoaceae or possibly the leaf-succulent growth form, which would indicate a response to strong selective pressures. This phenomenon needs to be tested for other leaf-succulent genera not only within the Aizoaceae but also within other succulent families common in the region, such as Crassulaceae. The measurement of soil water potential is critical in experiments of this nature and field-based observations of the fate of individual seedlings over time[34] would also be helpful.

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Water resources in the Klein Karoo: the challenge of sustainable development in a water-scarce area

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The Klein Karoo is situated in the Western Cape, South Africa, and is characterised by low rainfall (100–450 mm yr^{-1}). The Klein Karoo is situated in the primary catchment of the Gouritz River. The mean annual runoff (MAR) for the three major tributaries of the Gouritz River arising in or feeding the Klein Karoo (Touws, Gamka, Olifants) is 540 Mm^3 yr^{-1}. Groundwater recharge in the three Klein Karoo catchments is ±257 Mm^3 yr^{-1}, but only a portion of this reaches the rivers. The very variable flows result in low 1:50 year yield of 161 Mm^3 (30% of MAR). The current demand for water in these catchments is 182 Mm^3 yr^{-1}, which exceeds the yield, and demand is projected to increase between 23% and 150% by 2025. Changes in the approach to water management are required, including improving the efficiency of irrigation and land restoration to improve water infiltration and reduce soil erosion. We believe that it is time to change to a water management approach that is designed to anticipate and manage the inherent variability in water resources in the Klein Karoo, thereby placing the region on a path to sustainable development.

Key words: water resource management, surface water, groundwater, variability, water demand, land management, sustainable development

Introduction

The Klein Karoo is an ecologically and economically diverse region of South Africa situated in a broad east–west oriented valley between the relatively well-watered Langeberg-Outeniqua Mountains in the south and the Witteberg-Swartberg Mountains in the north (Fig. 1). It lies within the Gouritz River system whose tributaries extend through the Swartberg Mountains into the Great Karoo. Three biomes meet in the Klein Karoo:[1,2] Fynbos, Succulent Karoo and Thicket. Both Fynbos and Succulent Karoo are recognised as global biodiversity hotspots[3] with a variety of plant species. The perennial reaches of the Gouritz River system are also important for the conservation of aquatic biodiversity, including a number of threatened fish species.[3,4] A history of poor management has left much of the Klein Karoo degraded by over-grazing and poor cultivation practices.[5] The riverine areas are the worst affected, with only 11% in a near natural state, almost all of which is in source areas which are too steep to cultivate and provide poor forage.[5] Extensive land degradation has already altered the hydrology and geohydrology of the Klein Karoo and its aquatic and groundwater-dependent ecosystems.[6,7] Vegetation loss and trampling by livestock have altered key processes such as water infiltration, increasing soil erosion and changing river flow regimes.

The Klein Karoo is a semi-arid to arid area and fresh water is a critical constraint to future economic development. Although water is widely recognised as a critical constraint, there is a dearth of information on the state of the water resources in the Klein Karoo. This paper reviews information on the water resources of the Klein Karoo, covering both groundwater and surface water, and highlights some of the key issues, knowledge gaps and future options. Recent overviews include the Water Situation Assessment[8] and internal strategic perspective prepared for the Gouritz Water Management Area (WMA),[9] which includes the catchments of some of the adjacent coastal river systems.

Study area

There are different definitions of the extent of the Klein Karoo, depending largely on whether the boundaries are defined geographically, biogeographically or hydrologically. This study uses hydrological boundaries based on the boundary of the catchment of the Gouritz River system,[10] which falls within or overlaps the geographical boundaries of the Klein Karoo used by Vlok *et al.*[1] Much of the water used in the Klein Karoo is sourced from catchments which are situated to the north of the Witteberg-Swartberg Mountain Ranges, including their northern slopes, so these catchments are included as well (Fig. 1). The exceptions are the catchments of the Kingna River (Montagu area) and the Tradouw River (Barrydale area), which are tribu-

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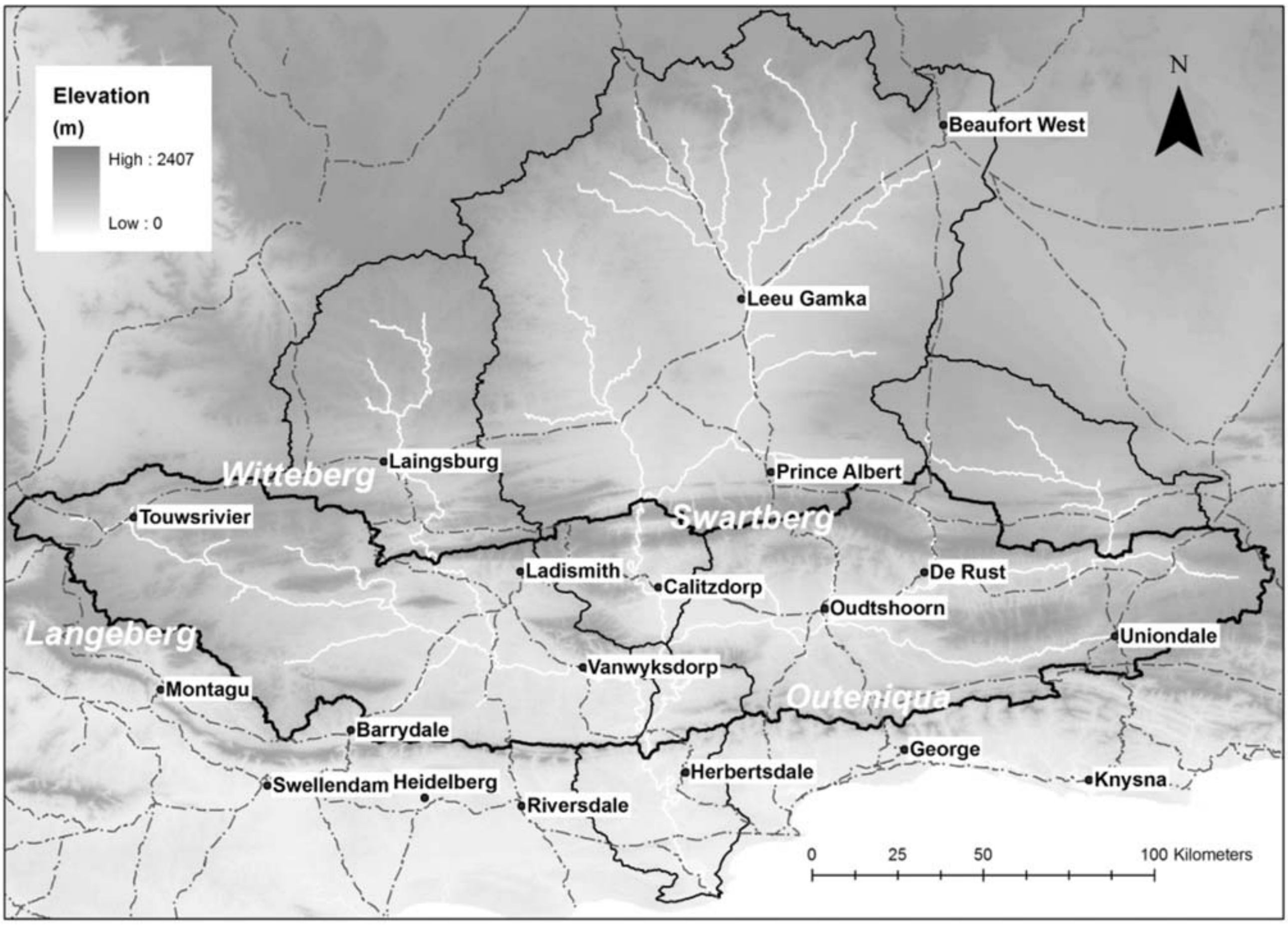

Fig. 1. The study area (thick black line) with the main towns, road (dashed lines) and mountain ranges. The main sub-catchments of the Gouritz River system are indicated by the thin black line.

taries of the Breede River system. Detailed data on water use and demand for these specific systems are lacking so they are not dealt with in this paper. The focus of this study is on the major sub-catchments of the Gouritz River system within or supplying the Klein Karoo (Fig. 2): the Touws, Buffels and Groot Rivers (secondary J1); Dwyka and Gamka (J2) and the Olifants and Kammanassie Rivers (J3). The final sub-catchment is the Gouritz River itself, which is the secondary catchment J4, called the lower Gouritz in this analysis to distinguish it from the whole Gouritz River system (J). The WMA also includes the catchments of the Duiwenhoks River (H8), Goukou (H9) and the coastal catchments from the Klein and Groot Brak Rivers (K1) to the Keurbooms River (K6).

Data sources and methods

The primary sources of climatic data were the climate atlas[11] and mean annual rainfall from Lynch.[12] Additional climatic data for specific localities were obtained from the South African Weather Bureau[13] and Wentzel.[14] Hydrological data for surface water per quaternary (4th order) catchment and naturalised flows at dams and weirs were taken from Midgley *et al.*[10] Data on river baseflows were taken from statistics calculated using the *SPATSIM* modelling framework software.[15]

Information on water use and demand was obtained from the South African Department of Water Affairs and Forestry overviews,[8,9] supplemented with information from the Water Authorisation Registration and Management System (WARMS) database. A total of 8 325 registered water use points were obtained[8,9] for the Klein Karoo, of which 93% fell within the study area and were used. The data have been provisionally reviewed, but because the information must still be verified, only comparative analyses are presented.

Data on groundwater recharge and contribution to baseflows were obtained from the Groundwater Resource Assessment (GRA).[16] Groundwater quality data for boreholes in the study area were extracted from the WARMS database. The database contains a number of zero values in the case where only minor ions were analysed. In order to compensate for this, the zero values were deleted prior to calculating any statistics. This resulted in a total of 3 141 data entries. Where there was a time-series for the borehole, the values were treated as individual data entries. The WARMS database provides latitude and longitude data for borehole localities, which were used to allocate them to quaternary catchments and to principal aquifer types based on a 1:1 million scale geological map.[17,18]

Groundwater recharge was calculated using the GRA[16] values of recharge per quaternary catchment and was spatially joined with the aquifer types to calculate the volume per polygon. The layer was then cropped to the Klein Karoo study area boundary, and the area values recalculated. A Microsoft® Excel 2003 pivot table was used to summarise the data. Average recharge (mm) per aquifer type was calculated by dividing the volume by the area of the aquifer.

Biophysical environment: climate and water resources

Climate

Rainfall

The Klein Karoo is characterised by marked orographic rainfall gradients and rain shadow effects. The upper slopes of the

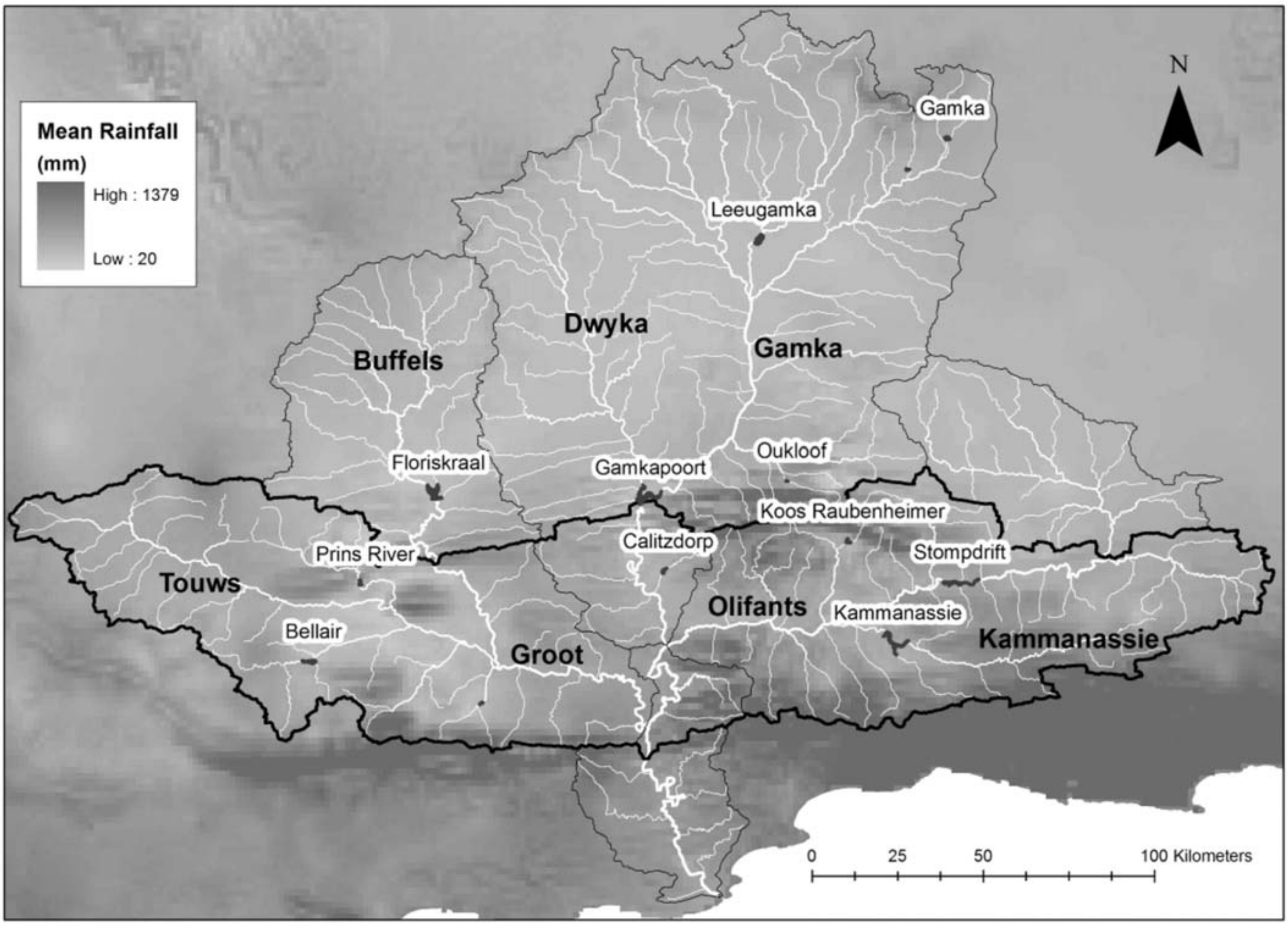

Fig. 2. Mean annual rainfall (mm) in the Gouritz River catchment and adjacent areas (data from Lynch[12]). The Klein Karoo study area is outlined in the thick black line and the sub-catchments in the thin black line. The names of the major dams are shown in white-outlined text. The main tributaries have been labelled and the width of the river reach corresponds to the Strahler order (1 = headwater).

Langeberg-Outeniqua Mountain Ranges receive up to 1 650 mm and the Witteberg-Swartberg more than 1 000 mm but most of the low-lying central valley receives 100–300 mm per year (Fig. 2). The driest areas are in the west where some parts get only 50–100 mm. The seasonal distribution of the rainfall varies from winter-dominant in the far west (Montagu, Fig. 3), to bimodal (Ladismith), to summer in the east (Willowmore). The winter rains are brought by cold fronts associated with low-pressure systems and westerly winds.[19,20] Summer rainfall is dominated by moisture from the east and convective systems which are less affected by orographic gradients. The rainfall regime is also characterised by extremely high rainfall events, associated with cut-off low pressure systems,[20] which can result in major floods: e.g. Laingsburg to Montagu in January 1981, Montagu in March 2003 and Zoar in 2004.

The variability in the rainfall increases as the rainfall decreases. In areas with <300 mm per year, the coefficient of variation is 36–40% compared with 15–20% in the high rainfall areas.[20] Areas receiving winter rainfall have more reliable rainfall than those receiving summer rainfall, and the difference increases as the mean annual rainfall increases.[20,21] The Klein Karoo has a quasi 10–12 year cycle: roughly five years with more and five years with less rainfall and a range of 10–30% either side of the long-term mean.[19,22]

Temperature and evaporation

The mean daily temperature in February is >30°C in the lowlands and in the upper 20s in the mountain areas and the coastal side of the Klein Karoo[11]. In August the corresponding temperatures are 20–22°C and 12–14°C. The corresponding mean daily minima for January are 14–16°C and 10–12°C and for August 4–8°C and –2–2°C.

The area receives more than 80% of the potential solar radiation throughout the year,[23] resulting in high evaporation rates. The potential evaporation (PEt, A-pan equivalents[11]) is more than 2 000 mm per year and exceeds 2 250 mm per year (>10 times the rainfall) in the dry central region. There is an east–west gradient in the seasonal distribution where the ratio of the January to June PEt ranges from more than five in the west to three in the east, emphasising the greater seasonality in the west.

Surface water resources

Mean annual runoff

The Gouritz River system (catchment J) was estimated to have a mean annual runoff (MAR) of about 674 Mm^3 (ref 10) although the most recent study[9] gives 562 Mm^3. Most of the surface runoff statistics were obtained from Midgley *et al.*[10] so we have used the data from their study unless otherwise indicated. The MAR is equivalent to 12.5 mm or about 5.7% of the mean annual rainfall, substantially lower than the mean for South Africa of about 9.0%,[10] but similar to arid parts of Australia.[24,25]

Spatial variation in surface runoff

The Gouritz River system has been divided into four main sub-catchments (Table 1). More than 90% of the Olifants and

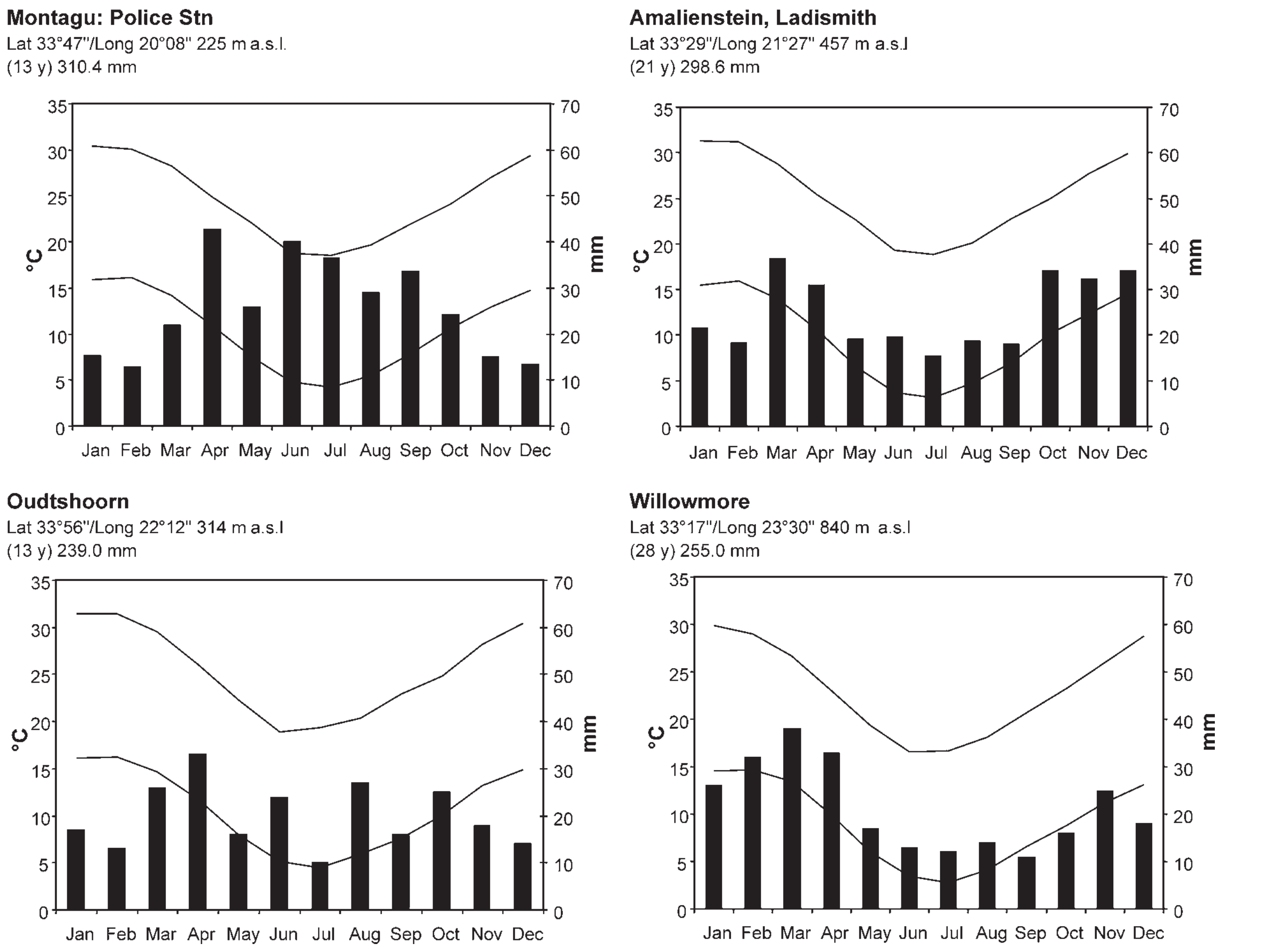

Fig. 3. Climate diagrams for selected stations ranging from the western to the eastern part of the study area. Data obtained from the Weather Bureau[13] and from the Department of Agriculture.[14] The upper lines show mean daily temperature maxima and lower lines minima for each month. Willowmore is about 50 km northwest of Uniondale (see Fig. 1).

Kammanassie sub-catchment (J3, Fig. 2) lies to the north of the Swartberg, within the Great Karoo, but the flows supply the Gamkapoort Dam which supports irrigation in the Klein Karoo. The sub-catchments of the Dwyka and Gamka (J2) and the Olifants (J3) fall mainly within the Karoo, but sub-catchment J4 (lower Gouritz) is situated mainly south of the Outeniqua Mountains (Fig. 2). Although catchments in the Klein Karoo comprise only 43% of the Gouritz River system, they produce most (56%) of the runoff (Fig. 4) and capture more than 70% of the estimated recharge (Table 1) because they include a large proportion of the TMG aquifer.

Surface water flow variability

The volumes of runoff are not only low, they are also very variable, with the coefficient of variation (CV) for streamflow being 2–5 times the CV of rainfall, as found in other arid areas.[24,25] Analyses of the naturalised runoff records in Midgley *et al.*[10] show that the quaternary MAR varies between 1.1 and 2.8 times the median annual runoff.[7] The CV ranges from 0.7–1.7 times the MAR and decreases as the amount of runoff increases. The drier catchments have a high percentage of zero flow months, some more than 25%. The high runoff in wet years or during floods is reflected in the maximum annual runoff being 2–12 times the MAR and the minimum 0–0.3 times.[7]

Multi-year trends in mean annual runoff

Analysis of the naturalised runoff and cumulative deviations from the mean volumes of naturalised runoff, measured at dams and weirs, highlight the spatial variability of the flows.[7] Each of the records that was analysed had unique features (Fig. 5). Most of the flows have extended periods of below-average runoff, e.g. the Prins River from 1922–1936 and Calitzdorp Dam from 1940–1974. The high runoff measured in the Prins River in 1920 plays a dominant role in the pattern of deviations, as does the

Table 1. The size, mean annual runoff (MAR) and estimated groundwater recharge for the whole Gouritz River catchment and the sub-catchments which comprise the Klein Karoo.

Secondary catchment	River systems	Area (km^2)	Klein Karoo (%)	MAR (Mm^3)	Klein Karoo (%)	Recharge ($Mm^3 yr^{-1}$)	Klein Karoo (%)
J1	Buffels, Touws, Groot	13 312	69.7	105	71.5	90	87.5
J2	Gamka, Dwyka	18 484	7.7	206	16.5	48	24.6
J3	Traka, Olifants, Kammanassie	11 017	72.2	229	96.5	118	97.9
J4	Gouritz	2 321	29.1	134	36.5	48	34.5
All	All	45 134	42.8	674	56.2	305	73.2

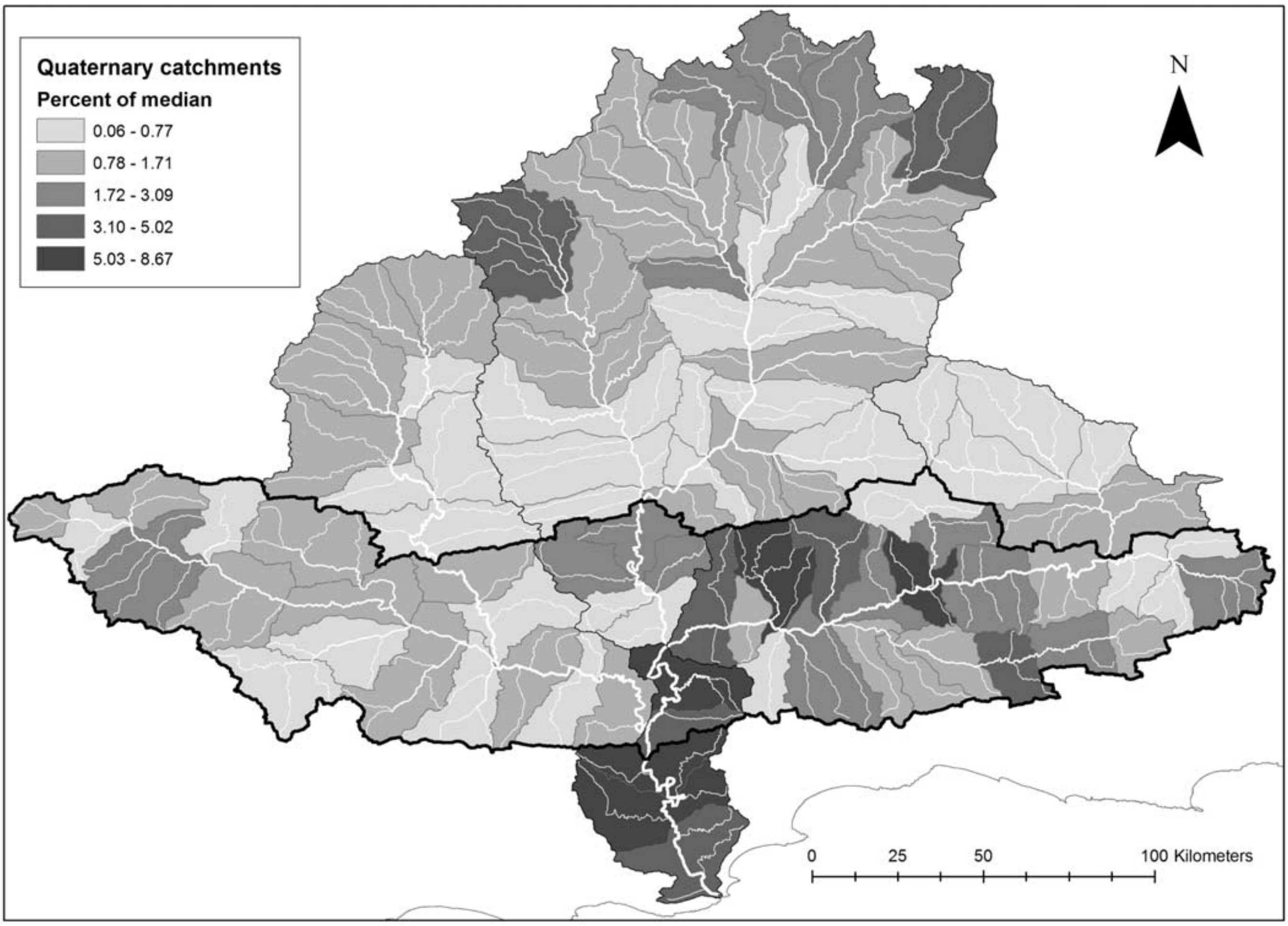

Fig. 4. The relative importance of each quaternary catchment's runoff in the Gouritz River catchment, where the importance is the percentage of the median total annual runoff based on data from the *SPATSIM* model.[15]

massive volume of runoff at Paardekloof (Olifants River) in 1980. If these exceptional values are replaced with the mean for those series, the cumulative deviations are negative for the Prins River until 1956; Paardekloof has a negative cumulative deviation until 1938 and then is positive until 1978, reasonably similar to the Kammanassie Dam.[7] The high variability of the flows and the long-term deviations result in low reservoir yields (based on a 1 in 50-year failure probability), even from a reservoir with a capacity equal to the MAR (Table 2).[25,26]

Surface water quality

Much of the groundwater in the Klein Karoo is saline because the geological formations which form most of the aquifers give rise to naturally saline groundwater (e.g. the Enon conglomerate near Oudtshoorn)[8] combined with high evaporation rates. This makes the water naturally poor quality for agricultural purposes. Natural salinity also affects the river systems draining the Great Karoo and has been increased by the return flows from the irrigated lands in the Touws, Buffels and Groot River catchments. The water quality is generally acceptable in the upper catchments, except for the Buffels River upstream of the Floriskraal Dam, and declines downstream–becoming unacceptable in the Groot River (J13).[8] The water quality is unacceptable in the lower reaches of the Olifants River, largely due to the return flows from irrigated areas. No data are available for the main stem of the lower Gouritz River (J4) but the quality reaching the

Table 2. Information on rainfall, runoff and reservoir yields in selected catchments in the Karoo.[26] The Leeu and Cordiers Rivers are situated in the Great Karoo on tributaries of the Gouritz River. MAP = mean annual rainfall, CVP = coefficient of variation of rainfall, MAR = mean annual runoff; CVR = coefficient of variation of runoff; Mm^3 = millions of cubic metres. The percentage yield is calculated for a hypothetical reservoir with a volume equal to the MAR and for a 1 in 50 year failure to sustain that level of supply.

River system	Location	Area (km^2)	MAP (mm)	CVP	MAR (Mm^3)	CVR	Reservoir yield (%)
Huis	Barrydale	28	599	0.25	3.9	0.72	46.8
Prins	Prinsrivier Dam	757	421	0.36	3.5	1.44	36.4
Brak	Bellair Dam	558	288	0.23	2.3	1.07	35.3
Nels	Calitzdorp Dam	170	383	0.31	6.7	0.67	67.4
Leeu	Leeugamka Dam	2 028	198	0.35	30.3	1.29	30.9
Cordiers	Oukloofdam	141	393	0.30	3.6	1.07	49.2
Kammanassie	Kammanassie Dam	1 505	837	0.23	38.7	1.10	46.0
Olifants	Kromlaagte	4 305	382	0.23	17.7	0.92	33.3

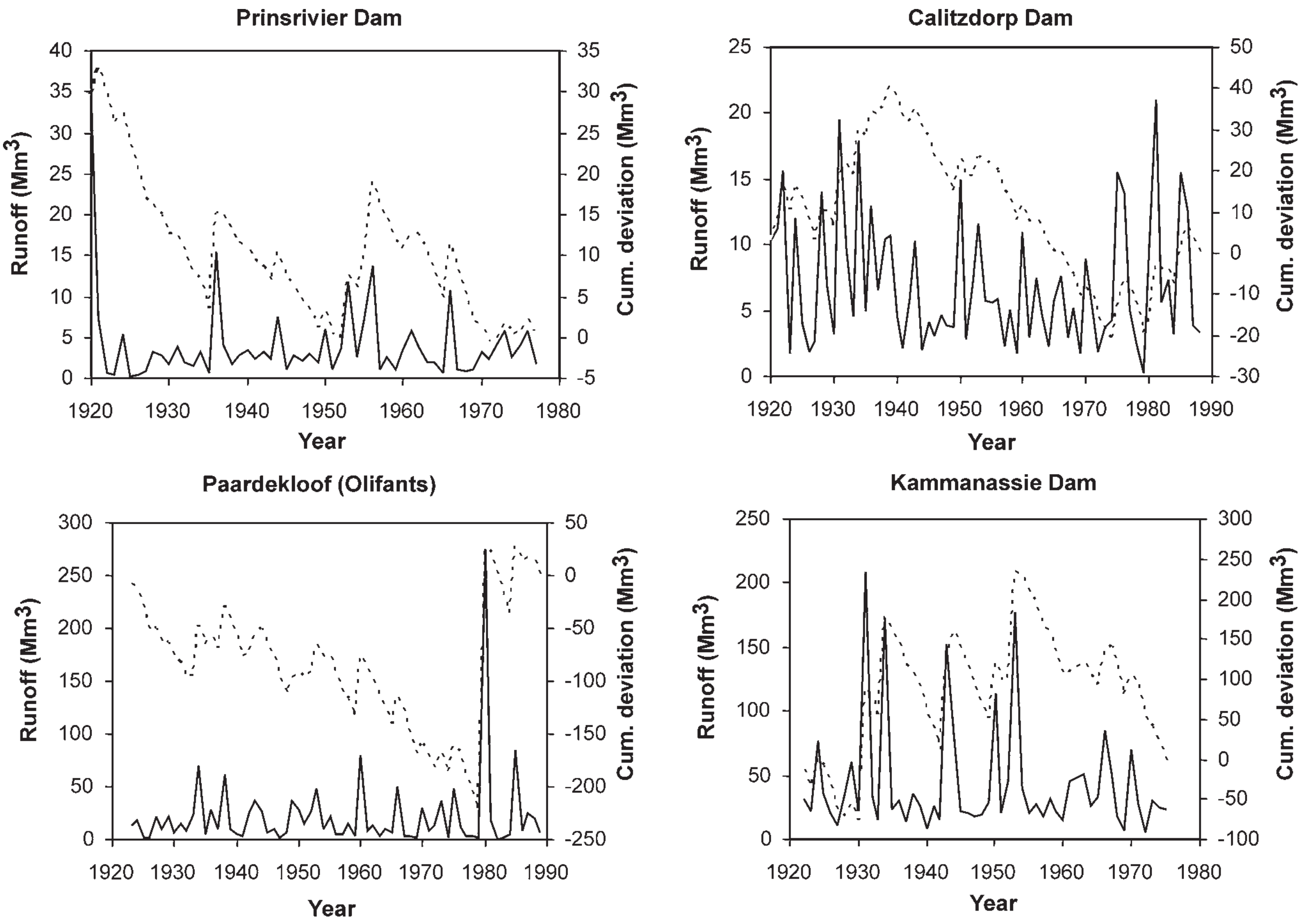

Fig. 5. Mean annual runoff (solid line) and cumulative deviations (dotted line) for different catchments in the study area. Data taken from the naturalised flow records for the catchments given in Midgley *et al.*[10]

estuary is likely to be poor despite dilution by the better-quality water from the sub-catchments on the southern slopes of the Outeniqua Mountains.

Groundwater resources

Aquifer types

Groundwater in the Klein Karoo is stored in three types of aquifers. Primary aquifers are formed from unconsolidated sediments which have been deposited primarily as alluvium in the floodplains of the major river systems; these aquifers typically occur in low-rainfall areas and are mainly recharged during high flows and floods during the wet season. Secondary karstic aquifers are very limited in extent as they are only found in the carbonates of the Kango formation; dissolution fissures can store large volumes of water which flows relatively rapidly through them and results in springs and boreholes with high yields. Secondary fractured aquifers are the most widespread and extensive type in the Klein Karoo, including the Table Mountain Group (TMG) quartzites, Witteberg sandstones and the Bokkeveld shales. The water is stored in and flows through the fractures and fault systems; open fractures can store relatively large volumes of water but they represent only a small fraction of the total rock volume.

Recharge

The quartzitic sandstones of the TMG and, to a lesser extent, Witteberg, form the bulk of the mountains and the relatively high rainfall they receive results in high recharge: about 10% or >50 mm per year. The estimated recharge derived for the GRA study[16] is 305 $Mm^3 \ yr^{-1}$ for the whole Gouritz River system and 257 $Mm^3 \ yr^{-1}$ for the three main tributaries. This is equivalent to about 48% of the MAR for the latter catchments and is highest for the Groot River system (J1). A large but unknown proportion of the recharge is lost through transpiration by vegetation in the discharge areas, particularly riparian zones and floodplains which may explain why the base-flow in these catchments is only 95 $Mm^3 \ yr^{-1}$.

The TMG receives more than 70% of the total groundwater recharge for the entire Klein Karoo. The extensive faulting and fracturing of the TMG results in relatively high deep-groundwater storage in discrete fault zones, and discharge from the TMG aquifers maintains the perennial flows in the main river systems. The groundwater flowpaths may extend for tens of kilometers and reach up to 3 km in depth as shown by the temperatures of the hot springs in the area, for example 50°C at the Calitzdorp hot spring.[27]

Groundwater yields

The Bokkeveld shales comprise much of the central area of the Klein Karoo and have low recharge (<6 mm per year). Boreholes typically have low yields (<1 $l \ s^{-1}$) although the Ceres sub-group has three formations with greater permeability and higher yields (>5 $l \ s^{-1}$).[27] Yields from boreholes sited on water-bearing structures in the TMG may be higher. The TMG formations continue beneath the Bokkeveld in the synclinal structure known as the Outeniqua basin in the Oudtshoorn area. Estimates of the volumes of groundwater that could be abstracted from this basin, which is at least 1 000 mm thick, range from 58 to 320 Mm^3.[ref 28] Ongoing exploration drilling should provide a better estimate of the sustainable yield of the deep aquifer.

Table 3. A summary of the estimated yield of the surface and groundwater resources of the Gouritz WMA based on a 1:50 year sustainable yield and the impacts of different factors on those yields.[8,9]

Catchment unit	Area (km^2)	Estimated 1:50 year yields ($Mm^3\ yr^{-1}$)								
		Natural resource		Usable return flows			Impact on yield		Total local yield	Grand total
		Surface	Ground	Irrigation	Urban	Industry	Desktop reserve for rivers	Invasive alien plants		
J1	13 313	21	23	0	0	0	2	0	42	42
J2	19 051	26	24	0	0	0	2	0	48	48
J3	11 017	53	15	3	5	0	1	4	71	71
J4, H8, H9	5 299	66	1	2	2	0	2	10	59	59
K1-K6	4 459	97	1	2	4	6	33	22	55	55
WMA (total)	53 139	263	64	7	11	6	40	36	275	275

Table 4. A summary of the water requirements for the year 2000 level of development and based on 1:50 year yield ($Mm^3\ a^{-1}$), i.e. a 98% assurance of supply.[8]

Catchment unit	Irrigation	Urban	Rural	Industry	Afforestation (yield impact)	Total	Transfers out	Grand total
J1	49	2	2	0	0	53	0	53
J2	49	5	1	0	0	55	0	55
J3	62	10	2	0	0	74	0	74
J4, H8, H9	51	3	3	0	1	58	1	59
K1-K6	43	32	3	6	14	98	0	98
WMA	254	52	11	6	15	338	1	339

Groundwater quality

Only the TMG yields high-quality groundwater for human consumption, with its median total dissolved solids of <260 mg l^{-1}.[(ref 29)] The groundwater from the Witteberg, Bokkeveld, and the Uitenhage Group, which includes the Kango formation and is found in the Oudtshoorn area, range from 261–600 mg l^{-1} (good) to 601–1 800 (marginal) to >1 800 (poor to unacceptable) depending on the inherent salinity of the rock formations. In the case of the Kango formation the poor quality is due to high concentrations of carbonates rather than sodium. The groundwater quality is marginal over at least 60% of the study area. The limited data that are available indicate that most of the alluvial aquifers also contain marginal quality groundwater.

Water availability and requirements

Availability

The most comprehensive summary of the current availability and use of water resources is the data compiled for the Water Resource Overview[8] and Internal Strategic Perspective.[9] Unfortunately these sources use a grouping of sub-catchments where the lower Gouritz sub-catchment (J4) is combined with the coastal catchments.

The 2000 assessment of water availability highlights the limited amounts of water available. The low volumes, combined with the highly variable flows, account for the 1:50 year yields of only 161 Mm^3 for the three main tributaries (Groot, Gamka, Olifants) (Table 3), which is only about 29.8% of the mean annual runoff. The impact of the environmental allocation (Ecological Reserve, National Water Act No. 36, 1998) on the availability of water is not seen as being a major issue except for the coastal catchments, where river and estuary requirements have been set at very high levels (Table 3). However, it is important to emphasise that full determinations of the ecological reserve are needed so that the required amounts can be determined with a reasonable degree of confidence.

Current water requirements

The best available information on the current demand is the recent overview[8] (Table 4). The current total requirement for the WMA is 339 $Mm^3\ yr^{-1}$, about 30% of which is in the coastal catchments where there is high usage by the irrigation, urban and forestry sectors. The demand in the sub-catchments of the three main tributaries (Groot, Gamka, Olifants) was 182 Mm^3 in 2000 at a 98% assurance, with 160 Mm^3 for irrigation.[8] The majority (73%) of registered water use is for river abstractions, 15% from schemes (including groundwater schemes such as the Klein Karoo Rural Water Supply Scheme), 8% from boreholes, 3% from springs and only 0.6% from dams. The currently available water resources, based on the estimates for 1:50 year yields (Table 3), are not sufficient to meet the requirements (Table 4). The result is that there is a net deficit of 64 $Mm^3\ yr^{-1}$ for the WMA, two-thirds of which is in the coastal catchments and the balance in the three main tributaries (Table 5). This means there is already a water deficit, at least in terms of the estimated demand and

Table 5. Summary of the annual water balance for the Gouritz WMA ($Mm^3\ yr^{-1}$) showing the estimated status in the year 2000 and the scenarios for 2050.[8,9]

Sub-catchment	Net outcome for 2000					Scenario 2025	
	Availability	Local requirements	Transfers out	Total	Deficit	Base	High
J1	42	53	0	53	–11	–9	–10
J2	48	55	0	55	–7	–7	–12
J3	71	74	0	74	–3	–4	–12
J4, H8, H9	59	58	1	59	0	1	–1
K1-K6	55	98	0	98	–43	–60	–123
WMA	275	338	1	339	–64	–79	–158

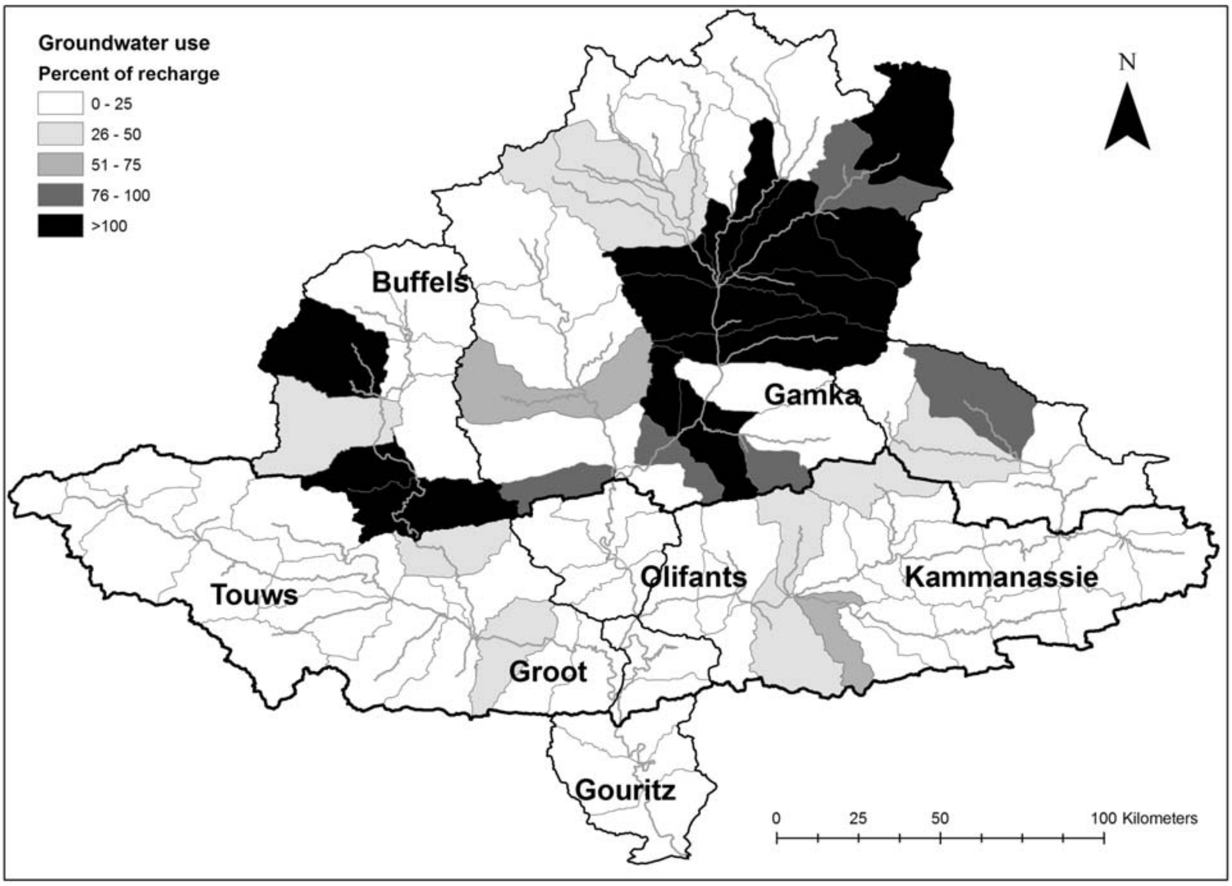

Fig. 6. Registered groundwater use as a percentage of the recharge in each sub-catchment based on data from the Groundwater Resource Assessment[16] and data collated from the Water Allocation and Resource Management System database.

desired assurance of supply. This is particularly acute in the Touws-Buffels-Groot catchment and can be expected to result in a decrease in the sustainable yield, or a reduction in the assurance of supply that needs to be addressed.

Irrigation

Irrigation currently accounts for 75% of all the water used in the Gouritz WMA and 84–92% of the water used in the three main tributaries. Although these figures must be interpreted with caution because the farmers generally operate with a low assurance of supply (because of the long periods in which there is below-average inflow into the dams), the pressure to retain all flood water in the dams does place a severe stress on the river systems and results in heavily modified flow regimes. In many cases the allocations exceed the available yields. For example, over-allocation within the Olifants River Government Water Scheme has resulted in the combined allocation from the Stompdrift and Kammanassie Dams being 87.7 $Mm^3\ yr^{-1}$, which is 266% of their combined 1:50 year yield.[8] The high levels of existing demand and use are important because of the drive to establish new irrigation schemes for formerly disadvantaged farmers and develop the resource base of rural communities. Irrigated farming is seen as the only form of agriculture that is currently economically viable and could be used for this purpose.[9]

Urban

Urban water use for municipalities and industries is generally low in the Klein Karoo catchments, except where there are reasonably large towns such as Calitzdorp (Gamka) and Ladismith (Touws-Groot).[8] Oudtshoorn accounts for almost all the 10 $Mm^3\ yr^{-1}$ taken from the Olifants River sub-catchment (J3) for urban use. Very limited population growth, or even a decline, is predicted for the Gamka and Touws-Groot catchments, but the population is expected to grow in the Olifants catchment.[8] The available data show somewhat different trends; the population of Kannaland (Ladismith) in the Touws catchment increased from 21 105 in 1996 to 23 971 in 2001 (14%) while Oudtshoorn grew from 78 846 to 84 692 (7%).[30] Migration of the rural populations to the local urban centres is expected to continue. Population densities are low, with 80% or more of the population residing in the towns.

Groundwater

The DWAF studies[8,9] used crude estimates of the amount of groundwater available. Since then, the GRA[16] study has provided estimates of the available resource based on recharge storage, but more detailed studies are required to determine sustainable yields. Data used in this study indicate that many of the Great Karoo sub-catchments and some of the sub-catchments close to Oudtshoorn are stressed, with more than 50% of recharge being registered for abstraction by users (Fig. 6). There is likely to be an overlap in total available water resources, where groundwater recharge contributes to surface water baseflow. This issue needs to be understood better to avoid over-allocation of groundwater resources in the future, and minimise the potential for significant adverse environmental impacts and clashes of interest between surface and groundwater users.

Impacts of invasive alien plants

The total flow reduction due to invasive alien plants is estimated at 121 $Mm^3\ yr^{-1}$ (ref 8) based on the data used for the Water Situation Assessment Model (which originally came from the study by Versfeld *et al.*[31]). The impacts on the 1:50 yields from the different sub-catchments are substantial (Table 3), especially in catchments which include the coastal mountain ranges where there are extensive invasions by *Hakea* species and by various *Acacia* species along the river systems.[31] Clearing of the invaders in the different catchments could help by substantially reducing the existing deficits in the Olifants River system and in the coastal catchments. The impact of alien invasive plants on the 1:50 year yield in the three main tributaries is estimated at 15 Mm^3.[(ref 9)] Large areas of the river bed and floodplain of the Olifants River, and to some extent the other rivers, have also been invaded by *Arundo donax* (Spaansriet), a species which probably has very high levels of water-use, but its impacts have not been quantified yet.

Impacts of climate change

The lack of information on the implications of climate change for the water resource situation in the Gouritz WMA was identified as an important issue.[8,9] Assessments of the implications of climate change for South Africa have been done at a national scale[32–34] but none have focused specifically on the Klein Karoo. A recent assessment for the Western Cape Province predicts the following general trends:[35] a reduction in winter rainfall; an increase in summer rainfall and rainfall intensity in the east; a monthly rainfall change of 10 mm or more; and an increase in air temperature, particularly the minimum temperature, by up to 2–3°C.

The decrease in winter rainfall will affect the western regions, the southern mountains and the Swartberg. The projected weakening of the cold fronts could be significant if this decreases the probability of them bringing substantial amounts of rain to the inland mountain ranges, which are important for surface water resources in the Klein Karoo (Fig. 2). The increase in air temperatures will substantially increase the evaporative demand, partially or potentially completely offsetting increases in summer rainfall and aggravating decreases in winter rainfall. The volumes of recharge to groundwater and runoff in catchments of the Klein Karoo are likely to decrease substantially, but montane areas may be less affected. The variability of river flows might increase with a tendency to more erratic flows and more frequent floods.

Water requirements in 2025

The projected water balance in 2025 was estimated using two different scenarios, one with limited increase in use and one with a high level of increase[9] (Table 5). Both show clearly that the projected trends will lead to increasing deficits. The baseline scenario results in a 23% increase and the high-level scenario nearly 150%. Protection of the ecological integrity of the system (termed the ecological reserve), could be met by the approximately 120 $Mm^3 yr^{-1}$ that would be released by complete clearing of invasive alien plants (see below), but the increases in yields will not be sufficient in most of the catchments and will not be of any use where their impacts are minimal (e.g. the Gamka catchment). About 22 $Mm^3 yr^{-1}$ of the total increase could be made available, at a 1:50 year assurance of supply. The greatest benefits will be in the Olifants River system, where the increase in the 1:50 year yield of 4 $Mm^3 yr^{-1}$ could help alleviate the problems caused by historical over-allocations, especially in the lower parts of the catchment.

Balancing supply and demand

As irrigation is the major water use, particularly in the inland catchments, it is clear that there will have to be a strategy aimed at improving water-use efficiency, which includes reducing the return flows of saline water that are affecting the river systems and downstream users.[8] Urban water requirements are not expected to increase substantially and most of the projected increase is expected to be in the coastal catchments rather than in the Klein Karoo. Overall, the increases in efficiency are unlikely to have a significant impact relative to those in the agricultural sector. Rural water requirements are not expected to increase substantially and may even decrease slightly with the trend of increasing movement of people to the urban areas.

The overview report[8] recommends that controlled burning of fynbos catchments to reduce the mean age of the fynbos and increase water yields could be investigated further. This intervention is unlikely to result in a substantial increase in water yields, as fynbos typically has a low biomass and relatively low water-use,[36,37] and frequent fires could have adverse impacts on the biodiversity functioning of these ecosystems.

Recommendations

The water resource situation in the Klein Karoo is approaching a crisis. The current levels of demand have passed the stage of sustainable use and balancing of human and ecological requirements envisaged by the National Water Act. Water demand is projected to increase significantly by between 23% and 150% by 2025, although there is no way of meeting this demand without even more severely compromising the functioning of the river systems. The impacts of climate change are uncertain, but are likely to result both in a reduction in the available water resources and even greater variability in flow regimes and recharge.

There are various options for mitigating this situation. First, the efficiency of irrigation could be improved by ensuring that the most efficient technologies are used in both water delivery and application to maximise crop yields while minimising the volume of return flows and, thus, the salinisation caused by irrigation. The possibility of changing to crops with a higher water-use efficiency and value should be assessed. Second, although water consumption by urban areas is a small proportion of the overall use, upgrading of urban water service infrastructure to minimise water losses (e.g. leaking water mains) could be beneficial at the local scale as well as reduce the volume of water that needs treatment. Third, making use of managed aquifer storage, including artificial recharge, could reduce water loss through evaporation compared with storage dams.

Even aquifers which have naturally high salinities may be used for the artificial storage of good quality water because mixing rates are quite low.[38] The Klein Karoo, with its very high rates of evapotranspiration, is well suited to subsurface storage of water in aquifers, particularly in alluvial aquifers, the TMG and the Kango carbonates.

Research is needed to get a better understanding of the dynamics of the groundwater resource, particularly recharge, and its sustainable yield in different parts of the Gouritz WMA.[8] This includes research into the potential use of groundwater from the TMG aquifer, particularly the deep groundwater. Research into the potential environmental consequences of large-scale abstraction needs to be given a high priority. Implementing alien vegetation control, particularly in the rivers on the northern slopes of the Outeniqua Mountains and foothills of the Swartberg, could further alleviate the situation. Lastly, effective land-care programmes could explore the synergies between improving water infiltration; reducing soil erosion and vegetation or crop productivity at small scales; and decreasing sediment loads and increasing sustainable yields at the scale of water supply schemes.

The mitigation measures outlined above are necessary and beneficial, but they are not sufficient. The current approach to water resource management has been designed to maximise human exploitation of the water resources of the Klein Karoo. Floods, droughts and water shortages have been seen as abnormal events rather than as normal and inherent in the system. The same inflexible approach to natural resource management has been applied to other land resources (e.g. natural grazing) and the net result has been severe land degradation. We believe that only a fundamental re-appraisal of land-use patterns could place the Klein Karoo on a path to sustainable development.[39,40] A partial solution could be the 'soft path' approach to water management,[41] which emphasises the need to move away from hard engineering technology to community-scale resource management wherever feasible; decentralised and open decision-making; equitable pricing; increasing efficiency of water-use (both in volumetric and economic terms); and implementing strong environmental protection measures. These changes may entail shifts in both social and economic systems which will affect everyone involved in the Klein Karoo in some way or other.

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Human response and adaptation to drought in the arid zone: lessons from southern Africa

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Human adaptation and response to drought is primarily through evasion or endurance. A review of historical agricultural practices in southern Africa demonstrates evidence of drought evasion response strategies in well-established transhumance routes, where herders move livestock on a seasonal basis in order to exploit resources subject to different climatic regimes. European settlers to the arid regions of South Africa quickly recognised the necessity of these evasion options to survive drought, and adopted the transhumance practices of indigenous farmers. Areas of geographically diverse resource bases became hotly contested by settlers and indigenous farmers. The success of evasion systems are shown to hinge on good social and institutional support structures. When movement is not an option, drought endurance is pursued by attempting to limit the damage to the natural resource base. This is through a number of means such as forage conservation, varying livestock types and numbers, water and soil conservation and taking up alternative livelihood options. State responses to drought over the last century reflect the general South African pattern of racially divided and unjust policies relating to resource access. Historically the state provided considerable support to white commercial farmers. This support was frequently contradictory in its aims and generally was inadequate to enable farmers to cope with drought. Since the advent of democracy in 1994, the state has intervened less, with some support extended to previously disadvantaged and poor communal farmers. Climate change predictions suggest an increase in drought, suggesting that the adoption of mitigating strategies should be a matter of urgency. To do this South Africa needs to build social and institutional capacity, strive for better economic and environmental sustainability, embed drought-coping mechanisms into land restitution policy to ensure the success of this programme, and acknowledge the diversity of the agricultural sector.

Key words: transhumance, drought-proofing, drought endurance, climate change, sustainable agriculture, social and institutional capacity

Introduction

'Everybody talks about the weather, but nobody does anything about it', said Mark Twain.[1] But this famous quote is decidedly inaccurate: people have long contemplated weather modification, and both adapt or adjust to weather conditions, and move towards or away from certain climatic regimes.[2] Southern Africa generally has a high coefficient of rainfall variation, making droughts a frequent occurrence.[3,4] The influence of this variable climate on agricultural activities cannot be over-emphasised.[5] A look at the history of humans in southern Africa confirms this view, and there is considerable evidence that people's lifestyles and livelihoods were and still are closely linked to climate. In arid and semi-arid regions the chief climatic regime requiring a response is drought. Vast areas of southern Africa are arid and provide limited options for intensive agricultural production and as a result most of this area is managed as rangeland for extensive livestock production.[6] Choosing appropriate livelihoods in these arid areas is the first of numerous human responses to climate.

While a lack of rainfall is the underlying cause of drought, diverse socio-economic, biological and agricultural factors determine the severity of its impact.[7] Drought takes variable definitions depending on the viewpoint of the individual experiencing it. This paper does not attempt to address the issue of defining drought *per se,* but aims rather to make the point that drought can be defined both biologically and socially. Drought can be variously defined as 'meteorological drought', 'agricultural drought', 'hydrological drought' and 'socio-economic drought', each with their own boundary conditions and thresholds (Box 1).[7] While drought is a climatic event with relatively predictable biophysical repercussions, social perceptions and responses to drought, at individual through community to state level, are highly varied and are the subject of this review.

Box 1. What is drought?[7]

Meteorological drought: a reduction in rainfall supply compared with a specified average condition, less than a certain amount (e.g. 70 per cent).

Agricultural drought: a reduction in water availability below the optimal level required by a crop during each different growth stage, resulting in impaired growth and reduced yields.

Hydrological drought: the impact of a reduction in precipitation on natural and artificial surface and sub-surface water resources.

Socio-economic drought: the impact of drought on human activities, including both indirect and direct impacts.

Responses and mechanisms

Drought has posed a challenge to livestock farmers for centuries,[8] to which they have adopted diverse responses. Across a temporal scale, responses to drought are variably defined. Coping is considered a short-term response to intermediate decline in access to food.[2,9] Adjustment is a response that requires more time where people might, for example, diversify their food sources or livestock types.[2] Adaptation to drought is described as a longer-term response that involves considerable change in lifestyles and livelihoods.[2,9,10]

Additionally, there is a spatial dimension relating to the mechanisms of response to drought. These mechanisms can be through endurance or evasion, and are sometimes coupled with drought prediction.[2] Drought response mechanisms are frequently determined by the type of farming practice, for example nomadic and transhumant pastoralists are able to evade drought, while ranchers, sedentary pastoralists and croppers must frequently adopt an endurance strategy.[8,11] How people respond to drought is a function of a variety of factors typically relating to the severity, frequency and duration of the drought.

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Evading drought – historical transhumance

Transhumance, or the seasonal migration of livestock, has long been recognised as an effective means of evading unfavourable climatic effects, such as drought, whereby moving domestic livestock across a landscape allows maximum forage use across a variety of climatic regimes and events.[12] Pastoral grazing strategies of this nature first emerged in northern and eastern Africa, and later moved with herders and livestock to southern Africa.[13] This climate-driven lifestyle was effectively used by the Khoikhoi in the southern and western Cape for over 2000 years and persists today, although constrained by land ownership patterns and influenced by social norms and current agricultural practices.[14–18] Transhumance is characterised by yearly movement cycles of livestock, following seasonal shifts in resource availability, coupled with variants in pattern associated with climatic events such as years of drought. A reduction in rainfall or even smaller scale shifts in the timing of rainfall, can result in ecosystem responses such as switches from grass to shrub-cover dominance or the failure of annual plant production.[19] Resource fluctuations are effectively evaded by following various well-established transhumance routes. The entrenched nature of the transhumance routes followed by the Khoikhoi, attests to a familiarity with resource variability and evasion during times of scarcity.[20]

European settlers to the southern and western regions of South Africa soon realised the significance of access to a diverse and temporally-variable grazing resource base, as well as the benefits of a transhumance lifestyle for effectively exploiting this resource base and evading drought.[20] Correspondingly, control of regions encompassing a diversity of climatic regimes was recognised as being highly strategic.[20] Control of climatically-diverse regions by European settlers was bitterly contested.[20] Conflict continued until these settlers had largely displaced the indigenous Khoikhoi pastoralists.[20] Settlers to these regions adopted lifestyle strategies similar to those of the recently displaced Khoikhoi, moving according to resource availability, tracking resources on a seasonal basis, or in response to drought. While the value of this strategy was self-evident for those relying on the rangeland for their livelihood, those in power, the Cape colonial government, did not have the same perspective. They viewed these new transhumant settlers as problematic, their lifestyle as demeaning, their farming strategy as weak, and did not like the freedom they assumed. They moved beyond the established frontiers in their attempts to sustain themselves through periods of scarcity, taking them beyond the reach of those governing.[21] This sentiment persisted and is reflected in the following quote by E.B. Watermeyer of Calvinia who saw degradation as a direct result of fires and overstocking: '…the great offender is the nomadic trekker, who makes his scherm in the veld and destroys all the surrounding bushes, and trees….'[21,22] Through imposition of regulations concerning fencing and subsidies for predator control and deep-drilled well points, colonial authorities transformed the transhumance lifestyle to one of settled ranching.[15,17,18,20,21,23] A clear example of how the transhumance cycle of Khoi pastoralists changed over time in the Namaqualand area, has been identified as changing from a wide range covering the area from the Orange to the Olifants rivers, followed by a restricted transhumance cycle confined to the broader Leliefontein communal area, and finally a constrained 'within-village' movement pattern for current herders.[24]

Evading drought – current practices

Despite considerable effort to contain pastoralists, reduce wide-ranging transhumance, and to formalise livestock production, vestiges of the movement patterns of climate-based resource exploitation and drought evasion remain today. Examples of this are found in both the communal and commercial livestock production systems in the arid regions of southern Africa. Some farmers on communal land still use herding strategies to manage environmental variability in conjunction with a variety of socio-economic goals.[25] Communal farmers in general have short-distance movement between key resource areas in normal years. In drought years movement is likely to be on a larger scale following general fodder shortage and in severe drought, large-scale transhumance would be practised.[13] In reality, however, extended movement to evade drought may be constrained by land availability, animal health and social issues, and large numbers of livestock starve to death.[26]

Movement strategies in association with climate and vegetation responses are also still evident in the commercial farming sector. Farmers move their livestock according to vegetation type in association with rainfall patterns, but strategies are constrained by land ownership, so they must adjust their strategy in accordance to their particular mix of available vegetation types.[16] Some commercial farmers in arid parts of the Karoo own two farms, one at high altitude which they graze in the summer and one at low altitude reserved for cooler weather. Livestock are moved between farms along public roads, either on foot or in trucks.

Landscapes are highly variable, both abiotically and biotically. Thus the drought response of a given plant species may differ with soil type, and different vegetation types respond variably to the timing and amount of rainfall.[13] These factors drive choices between pursuing cultivation or pastoralism, and more likely the degree of specialisation within each of these land-use strategies.[13,19] Superimposed on biological considerations are the mosaic of different land uses and the highly fragmented landscape of variable land tenure and access, all of which constrain current drought evasion strategies.

The long history of drought evasion in southern Africa, the rapid adoption of the system by European settlers, and its persistence in current agricultural landscapes clearly highlight the merit of this response strategy to variable climatic regimes and the avoidance of drought.[21] What facilitates and what constrains a drought-evasion strategy is discussed in more detail below.

Evading drought – facilitating factors

Drought evasion requires the movement of livestock and often entire families. Movement is difficult and requires considerable effort and adjustment. In order to move, farmers need networks and social linkages that extend into other ecological zones not created by drought.[13] These networks need to be strong, and are often affected through family connections, as securing tenure in distant places can be controversial. The strength of the institutions in place which regulate movement and access to resources is also significant in facilitating this movement.[13]

Drought-evading strategies of this nature have the benefit of cementing social relationships or maintaining social capital with potential reciprocation and interdependence.[21] In addition to considerations around access to land, the movement of belongings, people and livestock, often requires additional labour, with further social and financial costs: the availability of cash to hire labour or purchase feeds is related to herd survival.[13] In response to this constraint, people sometimes resort to resource pooling where groups of people come together to aid each other, for example, by joining livestock herds and reducing the number of herders needed or sharing transport and reducing these costs.[13]

A further recorded drought-evasion mechanism among both communal and commercial farmers is through loaning arrangements.[13] This is where livestock are sent to relatives to lower the stocking rate in the area experiencing drought. This response reduces the herd requirements, lightens the carrying capacity and spreads the risk of losing livestock to drought.[13] In some instances this may serve as a benefit to the recipients who may not have stock, typically benefiting from livestock products and the births of new animals.[13] This also has the benefit of cementing social relationships and interdependencies. Drought is immensely stressful and successful evasion is not always possible. Sometimes people have been reduced to illegally foraging on land that is not their own, or even to raiding other people's herds for livestock once theirs have succumbed to drought.[27,28]

Occasionally people will abandon their land entirely and move to a city. Alternatively, one or two members of the family will move to a city to seek an alternative livelihood depending on the length of and number of droughts experienced.[9,29]

Enduring drought

Endurance largely translates into the preservation of the ecosystem dynamics to aid recovery after drought.[8] This in essence means 'sitting it out' without damaging biological resources in the long-term. This strategy is mostly adopted by those who are more closely tied to the land through crop farming or ranching, for whom movement or evasion is not an option, and entails various farm management strategies aimed at compensating for the loss of the ability to evade a drought.[8]

The most obvious ecological aspects to be managed during drought are those systems that give rise to forage. This is particularly relevant to areas that have been overstocked and degraded. The variable response of natural vegetation to the late or early onset of rain, or reduced rainfall is demonstrated in the example where six million sheep died from poisoning in the widespread southern African drought of 1969, after grazing on the available toxic biomass.[30] Grazing strategies that rely on fenced paddocks and livestock rotation between these paddocks, are adjusted and managed very closely during droughts to ensure the most effective use of the forage resource, including those species susceptible to drought. Herds are also manipulated, typically reducing stock numbers to minimise the impact on vegetation.[10] This has been described as the best means of preserving ecosystem functioning and aiding recovery after drought.[8] Reducing stock numbers, through sales or slaughter, to meet drought-driven declines in grazing capacity has the same relative effect on grazing resources as increasing land area of a farm. However, the strategy of reducing stock numbers is unpopular because stock is expensive to replace and because banks regard livestock as collateral for determining increases in the magnitude of loans granted to farmers.[10] Drastic reductions in stock numbers place additional risks on farmers, for example, remaining livestock may be less genetically suitable to drought conditions compared with those sold off.

Other livestock management responses for enduring drought include improving the quality of livestock while reducing quantity, switching to hardier breeds, or changing ratios of animal types.[10] For example karakul, afrikaner, damara and dorper sheep are considered better drought adapted than angora goats and merino sheep.[8,10] Similarly goats are generally considered more drought-hardy than sheep and farmers adjust the composition of their herds as a means of reducing possible livestock losses.[8,11] While water requirements for sheep rise considerably with a rise in temperature, goats get most of their water requirements from forage.[11,31] Similarly, indigenous animals, such as springbok, eland and gemsbok, are often considered to be better adapted to local conditions and may fare better in drought than domesticated animals.[8,10]

The effective management and use of available water is critical to drought endurance. Water is acquired through water conservation and harvesting, river diversion, run-off farming and through the establishment of boreholes.[8,10] Improving water-use efficiency is also a key factor in making limited water go further and gains are mostly achieved through improved irrigation techniques. Water availability is described as the single most important health factor for livestock in drought and is seen as the primary limiting factor of herd size.[11] Sheep for example need 1.5 litres water for every 500 g of dry matter consumed, but at elevated temperatures, they may require up to 12 times more.[11,31]

Farmers respond to the shortage of grazing in times of drought by buying in or producing their own fodder, or renting additional pastures or grazing lands.[8,10,11] Sometimes money to buy additional fodder is made available through the sale of livestock or through state subsidy schemes. Fodder may be sourced in a variety of ways, for example by harvesting biomass from road verges and by chopping down branches or trees so animals can forage off these trees.[8] Planting drought-resistant crops or agroforestry are both known drought-endurance strategies. Species such as mesquites (*Prosopis* sp.), saltbush (*Atriplex nummularia*), agave (*Agave americana*), and spineless cactus (*Opuntia* sp.), have all been promoted as drought-tolerant fodder production species,[8,10] although all these species have a tendency to invade drainage lines where they may compete with indigenous trees and windmills for groundwater. In some cases, species such as saltbush are promoted as ruminant stimulants enabling animals to digest other less palatable species, as might be required when available forage is limited during drought. Moving towards more water-efficient feeds such as millet or sorghum in place of lucerne or maize is a further means of surviving drought.[8,27] The production of additional fodder on a farm or the purchase of supplementary fodder, as opposed to taking or moving livestock to available grazing, requires financial capital in contrast to the movement of animals.

Improving veld condition, through resting, pasture re-seeding and rehabilitation efforts aimed at preserving and enhancing ecosystem function, is a further drought-endurance strategy aimed at making the resource last, although views on the usefulness of this strategy are widely divergent.[10] In addition to preserving and enhancing grazing, protection and conservation of soil is seen as a key endurance strategy. Soil and water conservation techniques include contour furrowing, pitting, banking, terracing, benching,[8,10] retaining large amounts of crop residue on the soil surface and increasing the length of fallow periods.[32]

Farm-level diversification or the diversification of economic activities that a farmer engages in, is a well-established endurance mechanism.[10] This is typically evident in the diversification of on-farm animal breeds and crop types, as well as the establishment of alternative income-generation strategies such as commercial hunting, tourism or the sale of handcrafts, and off-farm work.[10,33,34] In the Little Karoo where more than 80% of farmers surveyed kept ostriches, only 17% were totally dependent upon ostrich farming for income, because they kept other types of livestock as well as engaging in tourism-related enterprises.[35] The success of such diversification is often linked to government policy and supported through incentives and appropriate legislation.[36] Regional trends and national and international fashions play a role too, but variety and diversification reduces risk.[36]

Financial endurance through drought periods is managed through reductions in resource consumption, self-sufficiency, as well as risk spreading, examples of these being reducing fuel usage, establishing woodlots, and the spreading of losses across a broader community.[10] Budgeting or planning for losses and accepting losses when they do come, expectedly or unexpectedly, are all noted.[10] Seeking external assistance through the acquisition of loans, either monetary or in the form of natural capital such as pasturage, or through communal efforts in resource pooling and labour sharing, are also evident.[10,34] Such approaches occur among the Tswana people; communal building and ploughing systems, and a system of sharing cattle and communal herding require a certain degree of community cohesion.[9] A further more common, cross-cultural request for external assistance is prayer for divine intervention.[9]

Predicting and anticipating

Mark Twain suggests there has never been a shortage of speculation and discussion around the weather and most communities have indicators and signs through which drought is predicted and anticipated. In southern Africa recorded indicators include variation in the timing and sounds of winds and rains, the use of livestock appearance such as the quality of their hair, the appearance of termites and their mounds, birds and their specific colour, the absence of mole hills or the presence of poisonous plants, the flowering of certain tree species, the appearance and size of stars, and higher-than-normal temperatures.[11,37] More obvious means of prediction are the measurement of lower than usual rainfall or through the use of climate forecast data.[38] A variety of meteorological and agricultural indices have been developed to predict and assess drought.[38,39,40] Perceptions on the accuracy of climate forecasts differ between communal and commercial farmers, with commercial farmers having a far greater trust in and reliance on these.[11]

It is also important to note that the timing and duration of droughts cannot always effectively be predicted, and while people are surprised by drought, the variety of social responses shows a deep understanding and belief that drought is always possible. Also significant to note is that while a drought may be predicted, the intensity and duration of a drought continues to be elusive, demanding considerable flexibility in adopting coping, adjustment and adaptation strategies and mechanisms.[40] Current efforts focus on modelling vegetation processes in response to rainfall and drought conditions.[41]

A history of response by the state in South Africa

The arrival of European settlers in South Africa, the ensuing period of colonialism, and the subsequent apartheid era, saw significant changes in both land tenure arrangements and social structures. The development of homeland policies, betterment schemes and forced removals saw indigenous people being dispossessed and removed from their land.[4] Generally this took place coincidentally with the development of considerable support to white farmers, who grew in economic strength in response to these interventions. Infrastructure was built, and strong support services established, including assistance from banks for land acquisition.[21] This saw substantial increases in output from white farmers. Farmers were protected from foreign competition as subsidies continued.[11]

Government policy over the past 100 years has acknowledged the significance of drought in South Africa. The Senate Select Committee report titled 'Droughts, Rainfall and Soil Erosion', released in 1914, was the first formal inquiry into drought as a driver in southern Africa.[22] This issue was tackled again in greater detail in the 1923 'Drought Investigation Commission', which documented and distilled understanding in this field from the previous 50 years.[42] This commission documented the need for a change in livestock management practices and change in natural resource use. Over the next sixty years there were eighty parliamentary acts rendering assistance to commercial farmers in response to drought and drought-related impacts.[11] These acts were far-ranging and a great deal of emphasis was placed on soil conservation.

State support for white commercial farmers was initiated in the 1930s and intensified during drought periods.[11,21] Contradictory government policy was evident from an early stage. Whilst the effects of heavy stocking were being noted by this commission, drought aid was being provided for restocking.[21] Colonisation of South Africa, followed by apartheid policy and legislation, affected animal movement, notably through veterinary restrictions and fencing acts. These had the effect of disrupting historical approaches to dealing with drought. In particular, evading strategies became those limited, recommended and sponsored by the government.[40] Subsidies for the mass railing of stock from drought-affected areas to non-affected areas, combined with special credit facilities and tax relief, were an example of this.[21] The agricultural credit board, established in the 1950s, gave loans to farmers, often following periods of drought, who were no longer found creditworthy by commercial institutions. The failure to incorporate climate variation and drought into commercial agricultural development and practice resulted in greater areas of marginal land being used for agriculture.[4] The livestock reduction scheme was a further policy tasked with improving rangeland condition, which would in turn facilitate drought recovery. This was a volunteer scheme, which ran from 1969–1978, where farmers in targeted areas were paid to reduce their stocking levels by one third of the Department of Agriculture recommended carrying capacity, thereby resting a third of their land. From the 1980s there was a shift towards more long-term drought assistance focussed on appropriate natural resource use.[11] This conservative approach encouraged the adoption of low-risk technology, correct carrying capacities and grazing strategies, with droughts being recognised as natural phenomena.[11]

The post-1994 stance of the first democratic government towards drought support reflected their greater agricultural support policies. This era, from the mid-1990s to the present, saw a more hands-off approach by government towards the agricultural sector, without the same degree of tax relief and easy finance extended to farmers. This was mirrored in their approach to drought, where farmers have largely been left to fend for themselves. This said, there has been some effort to aid previously disadvantaged, poor, and communal farmers, who have received some drought relief in the form of feed and government loans.

On reflection, state interventions cannot be viewed as having been highly successful. Interventions have largely been reactive, and not enough emphasis has been placed on developing capacity to cope with drought. No collective strategies to combat drought have been developed, and increasingly people respond in their individual capacity. There is historical distrust of the government and political fear of government or institutional response to collective measures. In the past there was greater local and regional alliance where people relied on institutions such as traditional leaders for support, as well as distant relatives. Now people tend to turn to national government for support. Drought remains a stressful and often crippling event for farmers across all sectors in South Africa today.

Coping and adapting into the future

Climate change predictions for the arid zones of southern

Africa include greater climate variability and potentially a greater increase in drought frequency.[43] Reflections on past strategies aimed at coping with drought suggest we need to review our approach to improve our ability to cope with drought. Our current inability to successfully manage drought, combined with climate change predictions, lends urgency to the need to effectively engage with drought and devise improved approaches.

History tells us that social capital, apparent in social interactions, labour and land loaning or sharing schemes are necessary in coping with drought.[33] Similarly, institutional capacity and structure in supporting larger community-wide efforts has also been shown to be necessary. Emerging research on adapting to climate change lends support to these historical lessons, and points to the need for the development and maintenance of supportive and informative networks and adaptive capacity of communities and individuals.[33]

Drought and climatic variability is reflected in our production systems with changing production levels and income variability. This variability needs to be managed, particularly with regard to drought where the economic repercussions can be devastating. For better financial stability, farming strategies need to take cognisance of the constraints imposed by climate and manage with the aim of having systems that are both economically and environmentally sustainable.

Financial stability will dictate responses. Wealthier farmers are better buffered against the impacts of drought.[33] By contrast poor farmers are at greater risk from the impacts of drought as they are more dependent on climatic conditions and have less ability to access other resources that would reduce its impact.[33] Paradoxically, while wealthier farmers are generally better able to endure droughts than poorer farmers, the latter are, in fact, better adapted to drought, often taking a proactive approach in adopting diverse income alternatives in anticipation of drought.[33]

Policies relating to land reform, land restitution and redistribution must include drought-coping mechanisms. Putting people on land without these identified drought-proofing strategies will result in a failure to meet restitution and redistribution ends, evidenced in bankruptcy, land sales and degradation.

History shows us there are a number of ways to respond to the spatial and temporal variability inherent in drought stress. Most future scenarios suggest that the South African agricultural landscape is going to become increasingly heterogeneous and variable. For example, gradients in vegetation responses to drought, coupled with grazing, have been found to be intensifying over the long-term in northern Botswana.[44] Agricultural response strategies to drought need to recognise the social diversity of these landscapes and be flexible enough to incorporate differing objectives, priorities of the farmers and opportunistic patterns of management.[13]

Conclusions

Drought has been around and responded to for as long as people have utilised the resources of southern Africa's arid landscapes. This is reflected in utilisation patterns of the past. Drought highlights social and biophysical connectivity, and coping with and adapting to drought requires acknowledgement and engagement with both these elements. A more recent analysis of drought response by the state reflects South Africa's history of racially-developed, unjust approaches. This era saw considerable reactive support to white farmers during times of drought. While this allowed the continuation of commercial agriculture, it did not encourage pro-active and adaptive developments in terms of enabling farmers to cope with drought. Future adaptation measures need to acknowledge the importance of social and institutional capacity and be sensitively integrated with current development pathways in order to be sustainable and relevant to local priorities.

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Coping with drought – do science and policy agree?

Colleen Seymour and Philip Desmet

Arid regions—which occupy about half the surface area of South Africa—experience highly variable rainfall and frequent droughts.[1] Natural ecosystems have adapted to this climatic variability, as have the human societies which inhabit arid zones, demonstrating intricate and diverse adaptation strategies to drought. Primarily, these communities respond to drought by evasion (seasonal migration) or endurance (e.g. through forage management, changing livestock types and numbers, water and soil conservation and finding alternative sources of income).[2] Our need to understand both natural and social responses to drought is made all the more important by the fact that the frequency and severity of droughts is expected to increase in response to anthropogenic climate change.[3]

Drought has been researched in South Africa since early last century, and drought losses have long been attributed to poor vegetation, soil and water management.[4] It has been argued that the impacts of drought have been exacerbated by the absence of a sufficiently complete management strategy.[4] But are our policy-makers making informed and sensible decisions, in light of the severity of water stress in South Africa? And how will climate change impact on our adaptation strategies?

Six papers in this issue, emanating from the Arid Zone Ecology Forum of 2007, discuss drought in arid areas, and particularly how its social and ecological effects are interlinked. Finding ways to reduce the impacts of drought on both ecosystems and society should be a major research focus. The ability of land users to deal with drought is becoming progressively dictated by the resilience of their agro-ecosystems; the diversity of livelihood options; and whether or not they have access to resources and good institutional support.[5] For the rural impoverished in South Africa, alternative sources of income, such as formal employment, pensions and state grants, have become increasingly important, with farming now primarily serving as a safety-net against unemployment. Yet there seems to be a mismatch between government policy and socio-economic realities on the ground: the South African Department of Agriculture is promoting full-time reliance on commercial livestock production, against a background of economic, climatic and political uncertainty.[5]

It also appears as if it is not just the Department of Agriculture for which drought management is not a policy priority. Despite South Africa's water-stressed status, half of the 12 proposed projects for the Accelerated and Shared Growth Initiative for South Africa are water-intensive and unlikely to be sustainable (J. Blignaut pers. comm.). These include a biofuels initiative that will include cultivation of crops in the Northern Cape and Free State, both provinces that have suffered severe droughts in recent years. By 2000, we had allocated almost 99% of that year's surface water yield and 41% of the annual usable potential groundwater to human use, primarily for irrigation.[6] Only 1.4% of South Africa's water yield is available to meet the needs of the poor, most of whom have no access to piped potable water.[6] Increased aridity will demand the adoption of water-saving technologies, with increased input costs, which will pose further challenges, particularly to emerging farmers.[6]

A search of the literature reveals that relatively few studies have been conducted on the ecological effects of drought. Hoffman *et al.*,[7] in reviewing the four published studies conducted on vegetation in the Succulent Karoo, found that they failed to reach consensus on how drought impacts plants in that biome, mainly because they employed various methods and measured different variables and responses. A review of the literature by Dean *et al.*[8] found that faunal responses to drought differ strongly both within and between vertebrate and invertebrate phyla. Again, investigations into the resilience of resident bird populations to droughts in southern Africa have revealed different responses, most likely because intensive long-term studies have not covered a full cycle of dry and wet years, and perhaps also because the subtler drivers of avian responses remain unexplored.[8]

Ecosystem responses are usually revealed only over time, and nowhere is this truer than in arid areas. Long-term research is therefore essential, and it is imperative that the South African research community and government agree to a suite of coordinated long-term field observations, experiments and models to inform agricultural policy and conservation planning. This may be an opportunity for the recently-established arid zone node of the South African Environmental Observation Network to develop and drive research and monitoring programmes that integrate ecological, social and economic impacts, ensuring that research contributes to our understanding of long-term variability and habitat change.

But research will have no impact on livelihoods unless there are mechanisms in place for translating findings into policies which address the needs of society in response to drought. The challenge here for institutions such as the South African National Biodiversity Institute and the Agricultural Research Council, is to convey information from researchers to government, as well as convince government that continued support for research will yield long-term dividends. The challenge to government—translating research recommendations into policy—is even more difficult, but no less crucial.


P.C. Desmet

Sheep in an arid Karoo landscape near Namies in the Northern Cape province of South Africa.

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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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