Observations on ENVIRONMENTAL Change in South Africa

SECTION 3





Editor | LARRY ZIETSMAN

Observations on Environmental Change in South Africa

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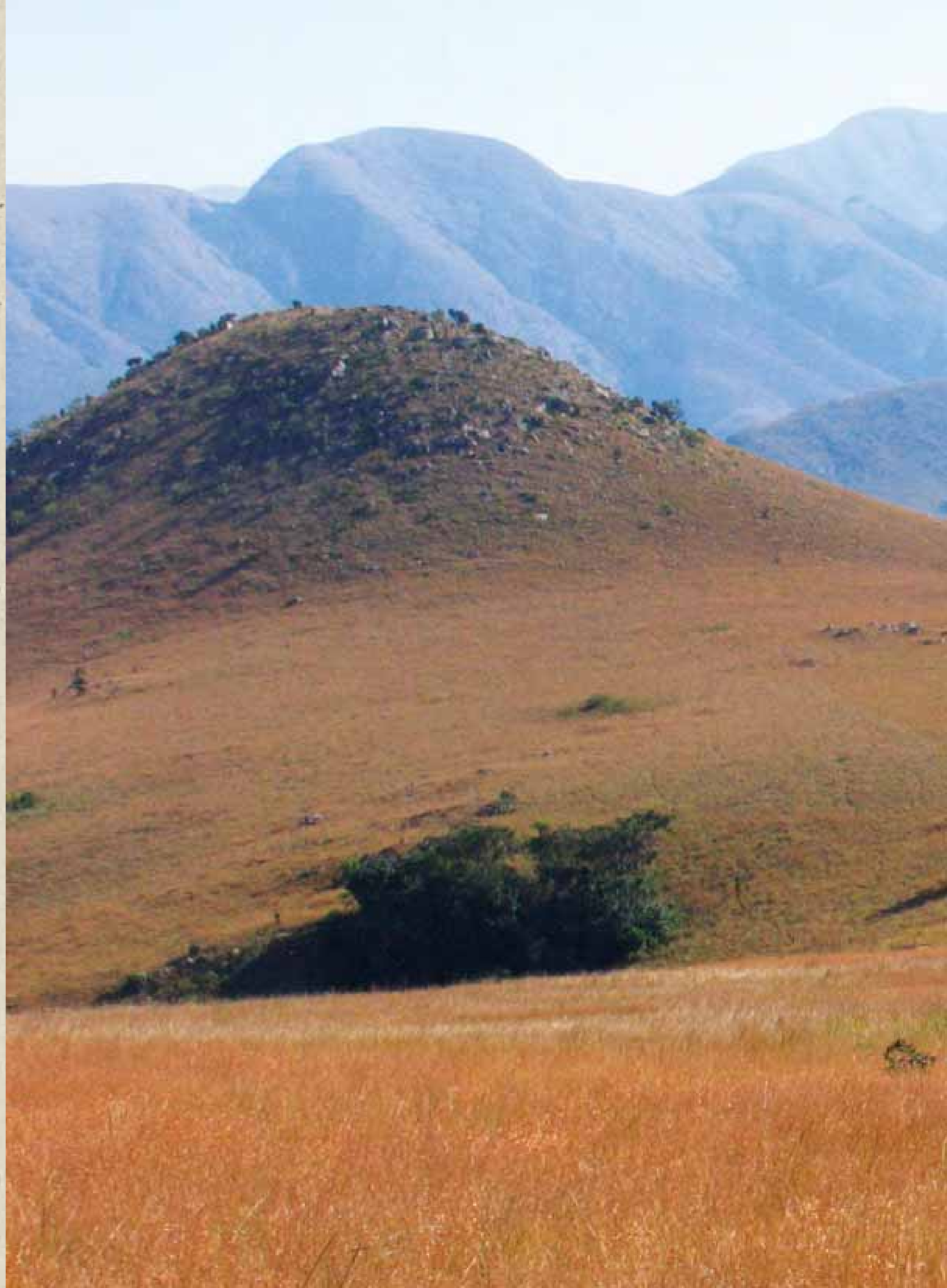
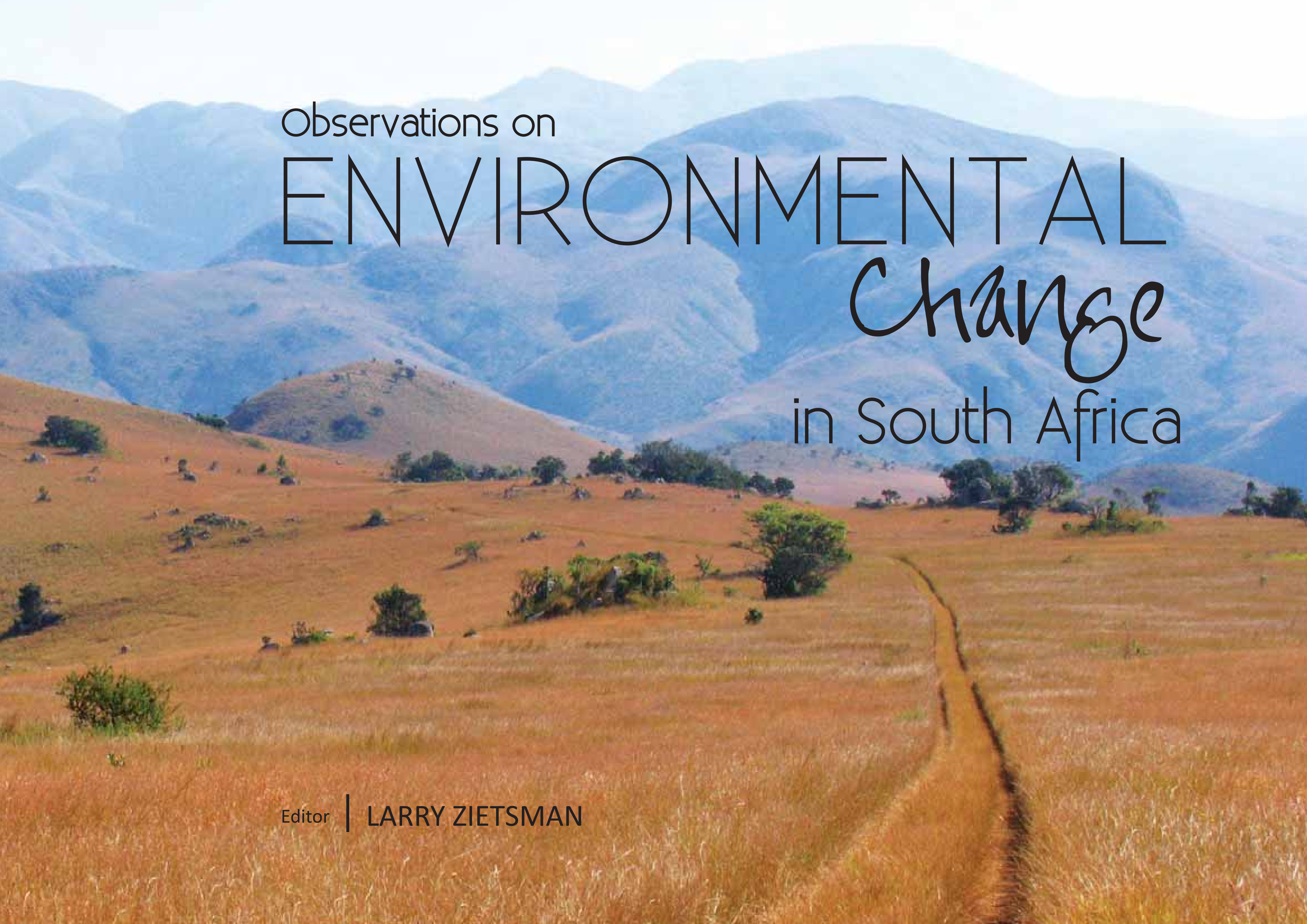
RIGHT Grasslands [Barend Erasmus]





Observations on ENVIRONMENTAL Change in South Africa

Editor | LARRY ZIETSMAN

Editorial Committee

RIGHT African Reed Frog [Barend Erasmus]

The mandate of the South African Environmental Observation Network (SAEON) is to establish and maintain state-of-the-art observation and monitoring sites and systems; drive and facilitate research on long-term change of South Africa's terrestrial biomes, coastal and marine ecosystems; develop and maintain collections of accurate, consistent and reliable long-term environmental databases; promote access to data for research and/or informed decision making; and contribute to capacity building and education in environmental sciences. Its vision is: A comprehensive, sustained, coordinated and responsive South African environmental observation network that delivers long-term reliable data for scientific research, and informs decision-making for a knowledge society and improved quality of life. SAEON's scientific design is adaptively refined to be responsive to emerging environmental issues and corresponds largely with the societal benefit areas of the intergovernmental Group on Earth Observations (GEO).

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The vision of the Department of Science and Technology (DST) is to create a prosperous society that derives enduring and equitable benefits from science and technology. Our mission is to develop, coordinate and manage a national system of innovation that will bring about maximum human capital, sustainable economic growth and improved quality of life.

We are guided by the corporate values of professionalism and competence. We will strive to deliver top-class, quality products and services, seek innovative ways to solve problems and enhance effectiveness and efficiency.

The DST strives toward introducing measures that put science and technology to work to make an impact on growth and development in a sustainable manner in areas that matter to all the people of South Africa.

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Acknowledgements

The idea for this book came from Albert van Jaarsveld. He discussed the possibility of a 'coffee table book' showing 'before and after' images of environmental changes in South Africa with Johan Pauw, who saw the relevance and necessity for such a book and its value for promoting the work of the South African Environmental Observation Network (SAEON), especially amongst politicians and decision makers, who by the nature of their work may not have much time to delve into the intricacies of scientific papers on environmental change, but need to advance sustainable policies for development. Together with Konrad Wessels, they developed the idea and approached me to act as project co-coordinator and to test the feasibility of the idea and set out a proposed table of content. Together we drafted a document listing broad topics or themes to be addressed and then went about listing potential contributors from the scientific and research community in South Africa. I then drafted a document formulating the goals that we would like to achieve and the approach to be followed by contributors to the proposed book. The potential authors were contacted and invited to participate in writing a book on 'Earth observation and environmental change in South Africa'. The scientific and research community responded positively to the idea and a set of guidelines were sent to those willing to contribute to this publication. These authors sent in proposed titles and abstracts of what they had in mind. Their submissions were evaluated and most were accepted for inclusion. The vast majority of these authors honoured their commitments and submitted their full texts within a reasonable timeframe. A tentative table of contents was drawn up and circulated. Valuable inputs, especially from Sue Milton, led to a revised, restructured and reordered table of content very similar to the final version. Barend Erasmus, Charles Griffiths, Lauri Laakso, Johann Lutjeharms, Matlala Moloko, Sue Milton, André Theron, Rudie van Aarde, Brian van Wilgen and Alan Whitfield generously supplied supplementary photographs.

The book that has materialised from this process is probably not quite what Albert van Jaarsveld had in mind. It took on a life of its own, in spite of my best efforts to keep it in line with out initial intentions! Although every effort was made to ensure that it would be '... an attractive, richly illustrated and easily readable book on the causes consequences and responses to environmental changes in South Africa', its scientific nature became much more prominent. We now have a publication '... conveying scientific evidence based on local case studies using examples to graphically illustrate these trends and impacts with a variety of satellite imagery, photo's, maps and other illustrative materials.'

The book gives a picture of environmental change and proposed responses on a range of themes and topics. It draws together work from as many scientific disciplines as possible, extracts the most pertinent information and presents it in a condensed format. As such this book should be very useful to inform the general public and senior political and public executive officials involved in policy formulation and decision making on environmental issues and implications of policies as initially intended. However, it will undoubtedly also be of value to lecturers and students at institutions of higher education.

I would like to acknowledge the time and efforts of all the authors and co-authors who graciously contributed their work without remuneration in the interests of science and our fragile environment. I also thank the editorial committee (Johan Pauw, Albert van Jaarsveld and Konrad Wessels) for their foresight, confidence and support in helping to bring this publication to fruition.

Hendrik L Zietsman
Editor
December, 2010

Foreword

Mrs G.N.M. Pandor, MP

South Africa has a rich history of scientific excellence and of undertaking pioneering work in the environmental sciences. This richly illustrated publication is yet another valuable contribution to that heritage. According to a report by Thomson Reuters, between 2004 and 2008 South Africa ranked above average in the scientific fields of Environment and Ecology, contributing 1,29% of world output, with a citation rate averaging above 5 per paper.

South Africa can also be proud of its strong tradition of exploiting scientific knowledge to support effective policy and practice in sustainable development. Supported by my department, the South African Environmental Observation Network (SAEON) emerged from that tradition to establish six strategic nodes that jointly cover South Africa and its adjacent oceans. These nodes function as observation systems and platforms that enable the environmental sciences community to perform longitudinal studies of environmental change, and ultimately to support sustainable development objectives. This work has made a valuable contribution to science-based initiatives such as the Southern African Millennium Ecosystem Assessment in identifying possibilities for improving human wellbeing, taking into account the capacity of ecosystem services to support these improvements.

South Africa continues to face crucial social and economic challenges. A set of 12 priority outcomes has been identified for focused attention over the next few years. Effective management of our natural environment and assets is not only a key outcome in its own right, but also has an important contribution to make in supporting outcomes such as a long and healthy life for all South Africans, food security for all, and sustainable human settlements.

The natural environment is a complex system with many interconnected strands. A range of human pressures combine with natural processes resulting in many and varied impacts and responses. Science investments are vital for the development of a knowledge base that can assist decision-makers to make sense of the complexity and to respond through policy measures and interventions. Science investments range from the development of long-term environmental observation capabilities, the effective integration of new and existing datasets and the initiation of longitudinal studies, to ensuring maximum exploitation of the data through appropriate knowledge products such as forecasts, early warning systems and impact maps.

Notwithstanding the strong foundation in environmental observation and research that already exists in South Africa, the Department of Science and Technology continues to prioritise this area for further development and investment within the context of its Innovation Plan. For example, we have committed to the development of satellites that will provide fine resolution and space-based data that we can exploit for areas ranging from environmental management to early warning systems for better disaster management.

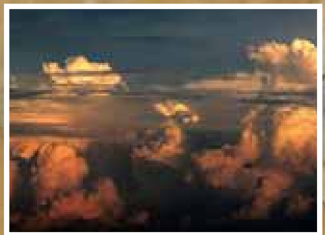
Over the next 10 years, through the Space Science Grand Challenge, we will be investing in satellites as well as supporting infrastructure that will constitute a stronger earth observation system. Coupled to these efforts are a range of other initiatives, under the umbrella of the Global Change Grand Challenge, which will support analysis and research on the basis of the available observation data sets as well as building a new generation of skilled scientists and practitioners.

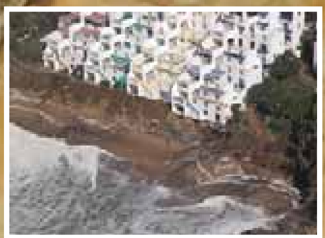
I would like to take this opportunity to congratulate the National Research Foundation, SAEON and the many scientists who contributed their time and expertise to this publication and to the work being done to maintain and strengthen our environmental science heritage.

More importantly, I would like to acknowledge the attempts being made to enhance the accessibility of complex and technical scientific material in ways that empower all sections of society.

Naledi Pandor

Mrs G.N.M. Pandor, MP
Minister of Science and Technology
December, 2010



Introduction

Johan C. Pauw
Hendrik L. Zietsman
Albert S. van Jaarsveld
Konrad J. Wessels

Environmental conditions on earth are changing rapidly. The degree to which these changes are human-induced could be debated, but the fact that changes are taking place is indisputable. As custodians of finite natural resources we do not have the luxury of being complacent. This highly illustrative book provides a glimpse into the environmental changes that have been observed. It is not a compendium of all changes, as that would require numerous volumes. The book highlights some pertinent aspects of environmental change and introduces ways in which satellite technologies and other observation systems are used to measure and monitor some of these changes. In many cases, the book describes the principle problems and discusses why these issues are considered problematic. The book also describes the main drivers of these changes, how the environment is responding, and how these problems can be solved. In addition, the book outlines the potential consequences of failing to act.

Why a book about environmental change in South Africa?

The key understanding that the reader will gain from reading this book is that scientific observation of environmental change is ubiquitous in South Africa and that these changes are progressively affecting the future of South Africans through their combined impacts on human livelihoods, security and prosperity. A conscious effort is made to distinguish 'environmental change' from 'natural environmental variability' in order to determine if the root causes of environmental change may be considered attributable to human activity. Natural environmental variability is normally of a periodic nature whereas environmental change can be experienced as a directional trend; either gradual or drastic, but with a high probability of being irreversible.

From the above, it follows that both the public and private sectors should rapidly mainstream environmental considerations and trends into their policy making, strategic planning, operations and market positioning. Consequently, the primary audiences for this book are decision makers and advisors at all levels of society, from government to civil society. The purpose is to provide them with a snapshot of pertinent scientific evidence to assist them in formulating intelligent and responsible policies and practices for the betterment of our society and to ensure the long-term futures of South Africans. Yet, the scope, breadth and depth of subject matter covered also renders this text useful reading for teaching and for further studies in related disciplines.

Making sense of environmental complexity

The natural environment is often illustrated as a spider's web consisting of interconnected strands. Although each strand is fragile on its own, the intricate and beautiful web structure provides it with resilience against external forces. Similarly, global-scale earth systems (i.e. biogeochemical cycles of the atmosphere, oceans and land) can be viewed as nested and multi-scaled ecosystems integrated through interactive processes. These systems are systemically afflicted by natural and human forces that act at multiple scales.

Amidst the obvious complexity of ecosystem studies, a standardised conceptual model of ecosystem function has emerged over time. This model was adopted by the United Nations Commission on Sustainable Development in 1995 and forms the basis of most state of environment reports, including those from South Africa [1]. The model is called the Driver-Pressure-State-Impact-Response (DPSIR) model (See Figure A) and it forms a golden thread that permeates the work presented in this book.

Batho Pele

Batho Pele – 'People First' – is the well-known slogan of the South African Government. It is therefore appropriate that the opening section of this book addresses issues of 'People and Environmental Change'. The subsequent chapters describe a variety of pertinent environmental issues grouped into broad large-scale ecosystem topics spanning the atmosphere to the oceans. The book ends with a concluding chapter.

South Africans, across the board, are dependent on these vital life-supporting systems and what is presented should serve as a reality check about the status of these systems. From our understanding of environmental change, people are collectively and rapidly transforming the environment for short-term economic and lifestyle gains, whether by choice or purely in order to survive. Yet, it should be clear that the longer-term impacts of irreversible environmental change will undermine the quality of human livelihoods and may compromise the essential life-support benefits derived from ecosystem services. In most instances, due to disparate access to resources, services, education and infrastructure, it must be anticipated that environmental justice and equality will suffer in the face of environmental change.

Environmental change is a global concern and requires ongoing observation, interpretation and responses from South African government and civil society. This book is therefore a bona fide 'science for society' contribution.

The GEO-4 CONCEPTUAL FRAMEWORK

The GEO-4 conceptual framework (Figure A) enhances our understanding of the relationships between the environment and development and how these affect human well-being and vulnerability. The main components of the framework are 'Drivers', 'Pressures', 'States', 'Impacts' and 'Responses'.

'Drivers' or driving forces are the fundamental processes in societies that motivate certain decisions and activities which lead to changes in the environment. Examples of drivers include demographic, economic, technological, institutional and political patterns and systems.

'Pressures' emanate from emissions, waste, inputs, modifications, extractions and other activities that lead to environmental change. Examples are pollutants, fertilisers, irrigation, resource extraction, deforestation and land-use changes.

'State' includes trends and pertains to natural conditions and induced changes in the environment. These changes are often linked in subtle ways, so that changes in one part of the system lead to changes in another part. Examples of natural processes are those that operate in the physical, chemical and biological systems. These are monitored by measuring levels, concentrations, compositions and movements such as solar radiation, temperature, moisture, gasses, chemicals, land use, species and services.

'Impacts' are the effects that these environmental changes have on human well-being, social and economic sectors or environmental services, whether negative or positive.

'Responses' refer to the policies, legislation, regulations, programmes and projects undertaken to reduce human or natural vulnerability, reduce or mitigate negative effects, or strengthen positive consequences to environmental change.

The conceptual framework also shows that these components are interrelated, scale and location dependant and operate differently at different scales (local, regional and global), in different geographical and social contexts.

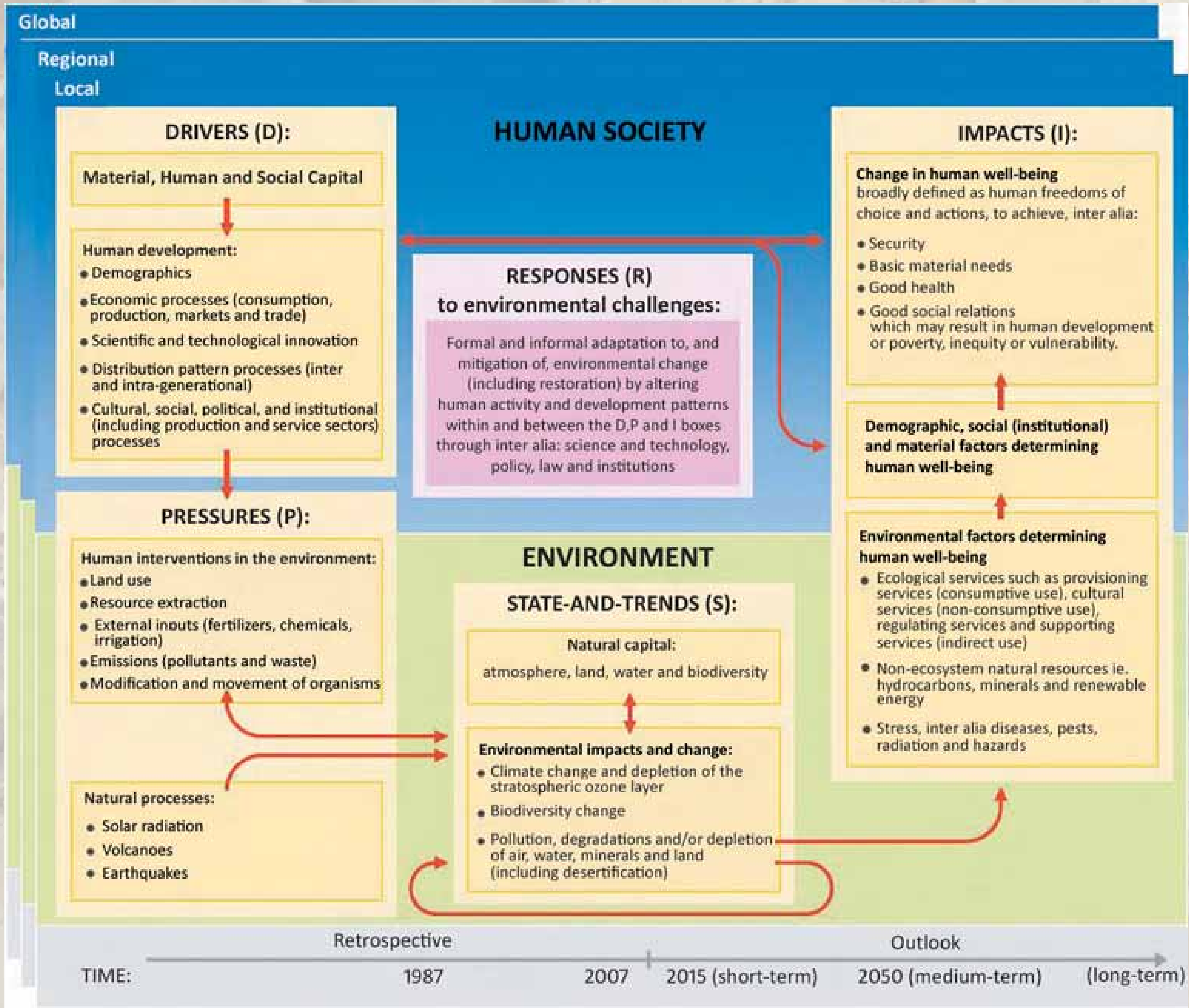


Figure A GEO-4 DPSIR conceptual framework. [Reproduced with permission from the United Nations Environment Programme. Global Environment Outlook – environment for development (GEO-4 Report, 2007). United Nations Environment Programme: New York]

Extensive non-sustainable low-density urban residential development in Maun, Botswana. [Barend Erasmus]

SECTION 3

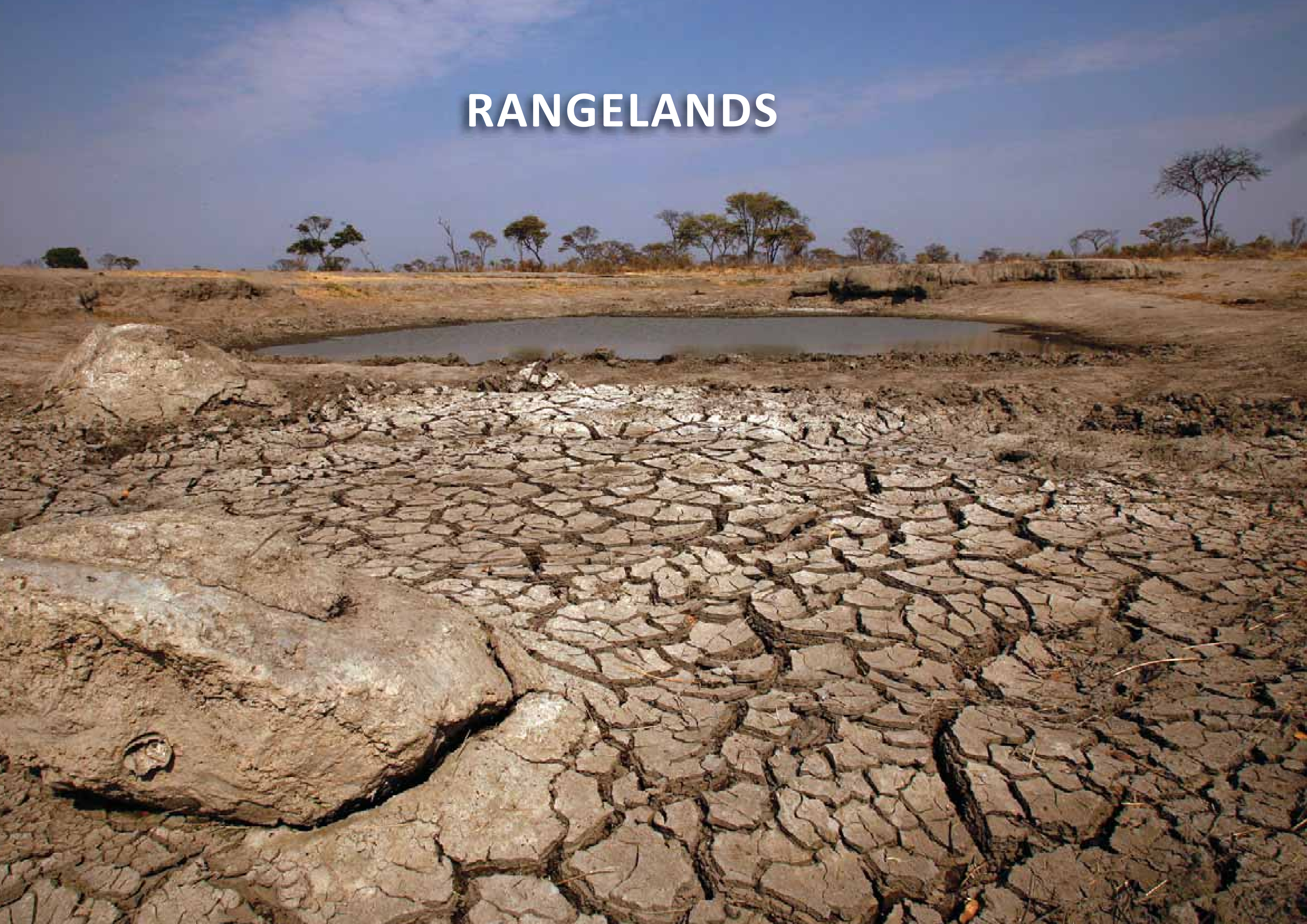
States and Trends in the Terrestrial Environment

RANGELANDS

INVASIVE ALIEN SPECIES

MINING

RANGELANDS



LEFT Trampling of rangeland and soil destruction around waterholes. [Rudi van Aarde]

RANGELANDS

Introduction

M. Timm Hoffman

South Africa's extensive rangelands support a complex set of biophysical processes and provide much of the food and water which sustains the nation. South Africans also draw cultural and spiritual inspiration from the country's rangelands and are proud of the unique biodiversity found in the region, which underpins a growing local and international tourism market. For centuries, however, there has been concern over the state of the region's rangelands. Numerous government-led investigations, such as the 1923 Drought Investigation Commission and the 1948 Desert Encroachment Committee, have warned of the dangers of long-term, unsustainable land-use practices. While the initial focus was on the impact of relatively large-scale commercial agriculture, more recently the shifting demographic patterns of South Africa's human population, as dictated by the ever-changing socio-political frameworks of the country, have emerged as the key drivers of rangeland degradation in the region. In particular, the forced removal of many South Africans and their subsequent confinement over the course of the 20th century to small, often ecologically-vulnerable regions in the eastern and northern parts of the country has transformed the rangelands of many of the former communally-managed, homeland areas. Many of these areas are considered degraded and are perceived as being less productive than their potential despite there being considerable variability between regions with similar histories. However, not all researchers and land users agree on this interpretation.

A range of land-use practices, such as cultivation, afforestation and livestock production, have been the most important pressures to have transformed South Africa's rangelands. Land-use practices, however, are dynamic and constantly change in both space and time in response to a wide range of influences. Shifts in land tenure and ownership, number of land users per unit area, changes in market prices and input costs, technological advances,

Karoo landscape – the nature of rangelands vary greatly across South Africa. [Peter Hardcastle] knowledge improvement and many other sometimes less tangible influences, such as an increase in conservation awareness, all act to change how rangelands are used and transformed over time. However, land use is not the only influence on rangelands and short- and long-term variations in climate and a changing fire regime also affect the composition and production of rangelands. A significant increase in CO_2 concentration and an increase in temperature in many parts of the country over the last 30 years have undoubtedly also played a role in what we see today.

While there is some understanding of how different pressures might affect ecosystems over time, a detailed national perspective of the state-and-trends of South Africa's rangelands has not emerged. One problem is that there is little agreement on the starting or benchmark conditions. This is because little is known about the cover and growth form composition of rangelands before they were transformed by large-scale human impacts. Palaeoecology and historical ecology have important roles to play in clarifying the state and composition of pre-colonial and early colonial rangeland environments. Another problem concerns questions of scale and national level perspectives of rangeland degradation that have rarely been achieved. Finally, uncoupling the impact of land use from short-term climatic variability is also difficult. It is, however, a necessary condition if trends in rangeland condition over time are to be determined accurately.

The full impact of land degradation on the range of services provided by South African rangelands has not been entirely appreciated or costed over space and time. In some cases, people who remain on degraded rangelands become increasingly vulnerable to the effects of severe drought and floods. Because of this vulnerability many rural dwellers have moved to urban centres across South Africa over the last 20 years in search of greater security and employment opportunities. Degraded land has many other key off-site effects. For example, increased erosion of rangeland soils increases sediment yield, which in turn increases the amount of silt deposited in downstream dams and lowers their capacity to store water.

Historically, South African responses to land degradation problems within South Africa's rangelands have been extensive. Excellent legislation currently exists within the agricultural and conservation sectors to safeguard the country's rangelands resources and several institutions, such as the South African National Biodiversity Institute (SANBI) and the National Department of Agriculture, have a targeted responsibility for the management of these resources. In recent years, however, the state agricultural sector has shifted its priorities from servicing large-scale commercial agricultural interests to seeing to the needs of the small-scale emerging farmer community. The transformation of the agricultural extension service has been one of the most influential changes in this sector since 1994 and together with the land redistribution programme will continue to affect the nation's rangeland resources for decades to come.

The chapters in this section address different aspects of the DPSIR framework. Sue Milton and Richard Dean outline the extent, causes and consequences of change in South Africa's rangelands and highlight several responses in order to sustain and improve rangeland natural capital. Timm Hoffman and Rick Rohde address the state of early 20th century rangelands and argue that repeat photography is a useful tool for determining the extent and rate of change over time. In three separate contributions, Konrad Wessels, Jan van Aardt and their colleagues show how imagery derived from satellites as well as more low-level platforms can be used to determine both the extent and the rate of land degradation. They adopt a comparative approach and assess the impact of different land-use practices, such as conservation, commercial agriculture and communal area subsistence agriculture, on South Africa's rangeland resources. Konrad Wessels and Patrick Dwyer document the effect of the El Niño Southern Oscillation on the vegetation of the Kruger National Park and demonstrate how pressures originating half-way across the world can influence South Africa's rangeland resources. David Ward addressed the issue of bush encroachment in South Africa's rangelands and explores several competing hypotheses to explain one of the most important trends in the region over the last half century. Finally, Dave Richardson and Timm Hoffman demonstrate the importance of models in the understanding of South Africa's rangelands resources. All contributions emphasise the importance of our rangelands for the continued well-being of the nation and highlight the central role that SAEON has to play in monitoring the extent and rate of modification under land use and climate change impacts.

Changes in rangeland capital

Trends, drivers and consequences

Suzanne J. Milton
W. Richard J. Dean

Rangeland, also known as natural veld, makes up 30% of the South African land surface, and ranching is the dominant land use in regions where rainfall is too low and unpredictable to support crops or commercial forestry, or where the ground is too rocky to plough. Poor management and changes in use of land and water, at farm, regional and even global scales, is decreasing the value of rangelands to people through losses of palatable plants, soil, firewood, and yield of clean water. Government support for extension services, land-use planning and restoration could help ensure sustainability of rangeland resources which are the basis of our rural economies.

What is rangeland natural capital and why are we losing it?

Rangeland 'natural capital' refers to all aspects of rangelands that people value, including forage plants, trees that provide shade and wood, thorny and poisonous plants that protect seedlings, medicinal plants, the soil that is the basis of rangeland productivity, insects that pollinate flowers, fungi that compost fallen leaves, lichens that stabilise soil surfaces, and wild animals whose daily activities (such as digging and dunging) improve water infiltration or move seeds about. The past 200 years of intensified land use have seen changes that are destroying the rangeland natural capital on which both rural and urban South Africans depend.

Rangeland use in South Africa is intensifying as a result of cultural changes, redistribution of people and an increase in human population density. Diverse wild herbivores and nomadic pastoralists who tracked rainfall have been replaced with a few kinds of domestic animals [1], settled pastoralism on fenced ranches supplied with groundwater [2], grazing regimes that allow insufficient time for vegetation recovery [3], and conversion of rangeland to planted pasture and cropland [4]. As a result of all these changes, rangelands throughout South Africa are suffering soil erosion, vegetation cover loss and undesirable changes in composition such as bush thickening or invasion by alien plants (Figure 3.1a). The most degraded rangelands, of particular concern for policy makers, were identified as steep slopes on the eastern escarpments of KwaZulu-Natal and the Eastern Cape, communal areas in the Limpopo, North West and Northern Cape provinces, and the Little Karoo (Figure 3.1b) [5].

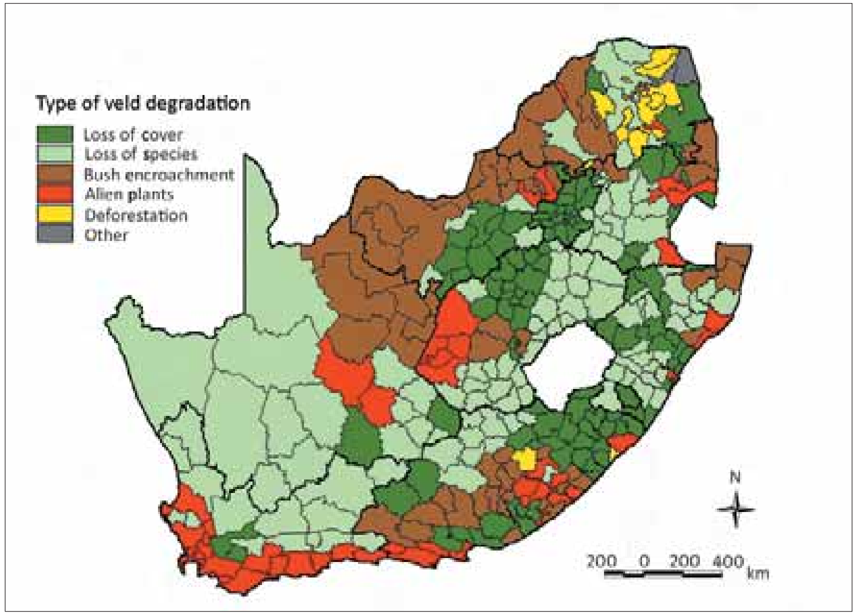


Figure 3.1 (a) Veld degradation type indicates the nature of remedial action needed in each magisterial district of South Africa. [Previously published: Hoffman, M.T. & Ashwell, A. 2001. *Nature Divided: Land Degradation in South Africa*. Cape Town: University of Cape Town Press.] [Reproduced with permission from University of Cape Town Press] [5]

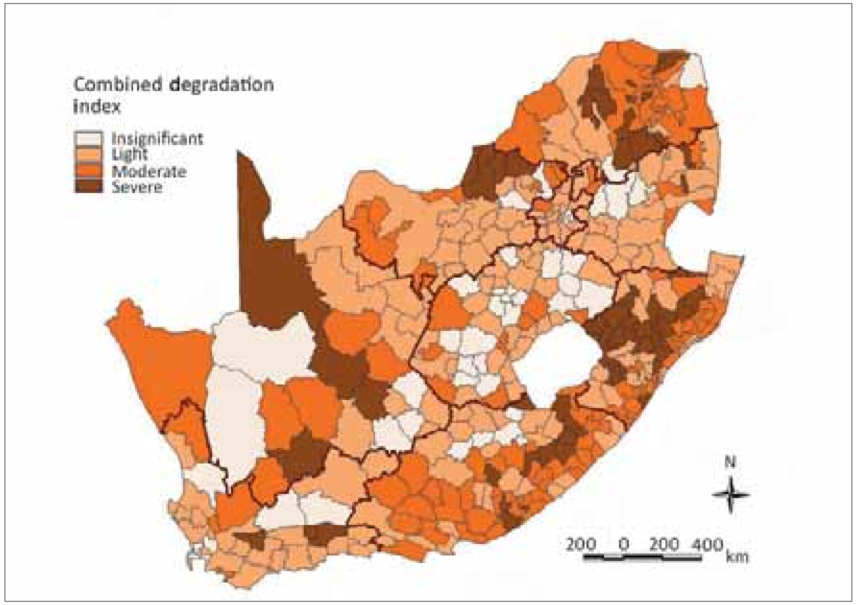


Figure 3.1 (b) The combined soil and rangeland degradation severity map indicates priority area management intervention. [Previously published: Hoffman, M.T. & Ashwell, A. 2001. *Nature Divided: Land Degradation in South Africa*. Cape Town: University of Cape Town Press.] [Reproduced with permission from University of Cape Town Press] [5]

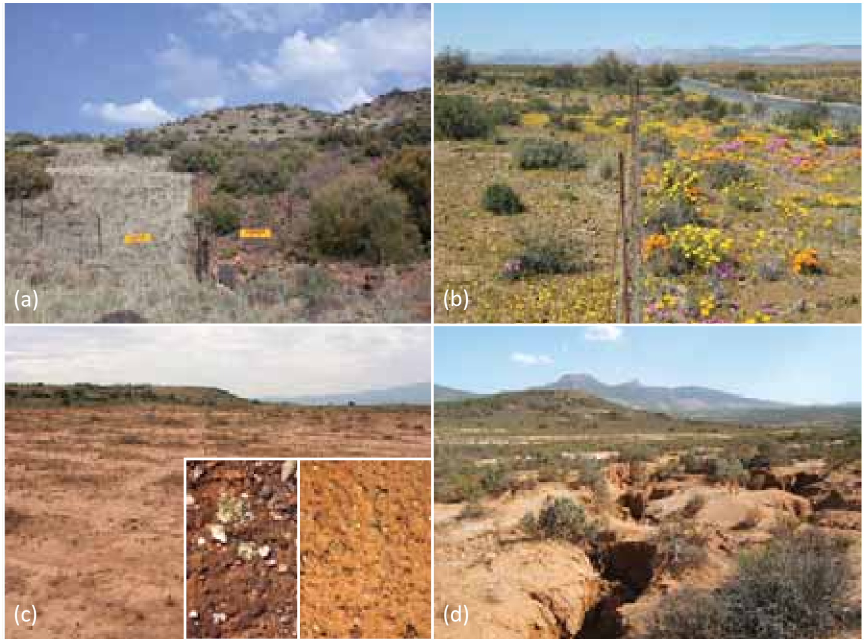


Figure 3.2 (a) Grazing season makes a difference to veld composition. At Middelburg, EC, long-term trials demonstrate that summer grazing eliminates grasses from the veld. [M.T. Hoffman, Oct 2002] (b) Fences keep the sheep in, and the flowers out of arid Nama Karoo veld near Prince Albert. [S.J. Milton, Sept 2006] (c-d) Trampling by ostrich has removed the lichen crust from the soil surface and led to sheet and gully erosion in the Succulent Karoo. [S.J. Milton, Feb 2003]

Fence line contrasts (Figures 3.2a and b) show how livestock management can change vegetation cover and the plant composition, even in arid areas where rainfall has a major influence. Repeated grazing during the growing season, such as summer grazing of grasses, prevents them reproducing and building root reserves, so that they eventually disappear from the rangeland (Figure 3.2.a). Their place is taken by plants that have less value for grazing, such as poisonous, thorny and bitter-tasting plants that have little forage value. Reduced vegetation cover, with trampling that breaks up the lichen crusts, cause accelerated runoff of rainfall (Figure 3.2c), and fast-flowing water cuts dongas that dry out the surrounding veld (Figure 3.2d) [6].

The need for subsistence crops on remote farms in the 1800s, and government subsidies for wheat production in the 1900s, led to the cultivation of alluvial soils along seasonal rivers and the ploughing of arable land even in regions that rarely receive sufficient rainfall to support crops. Later, from 1960 to 1990, high density resettlement of pastoral people caused overgrazing and over-exploitation of plants for building, fuel and medicinal use (Figure 3.3a). Diverse natural vegetation has been slow to colonise these damaged areas, especially as many are still heavily used by livestock. Many areas are now affected by bush thickening (Figure 3.3b) and unpalatable (Figure 3.3c) or alien plants (Figure 3.3d) that have little value for grazing, conservation, fuel or medicine.

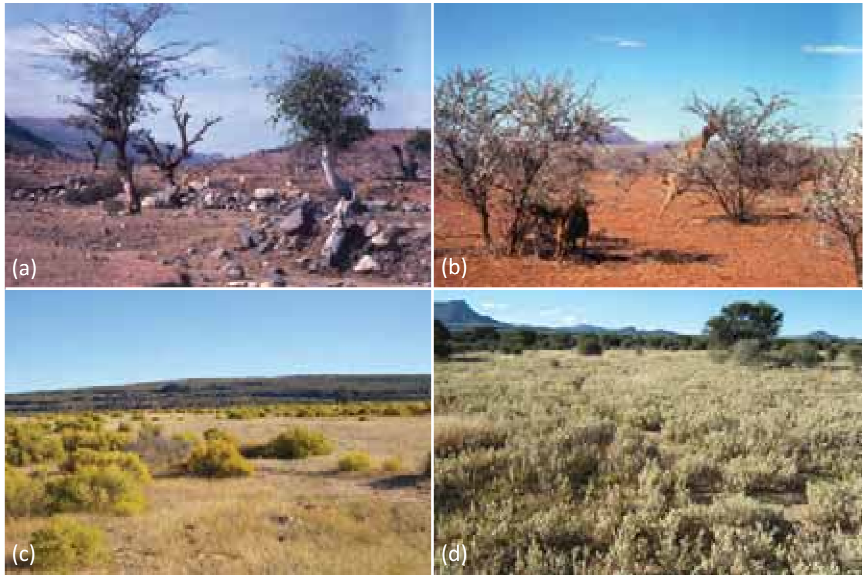


Figure 3.3 (a) Multiple overexploitation of grazing, firewood, building materials and medicine plants devastated valley bushveld in Mashunka, Msinga, KZN where rural people were resettled at high densities during the apartheid era. [S.J. Milton, June 1981] (b) Scrubby thorn bushes dominated veld and old fields in Msinga, KZN where cattle grazing has removed most of the grass. [S.J. Milton, June 1981] (c) Long-abandoned, old wheat fields in the Cedarberg. (d) In the Karoo National Park, Graaff-Reinet is dominated by unpalatable yellow kraalbos and small Australian saltbush. [S.J. Milton, Nov. 2006; May 2008]

The rapid growth of the human population in South Africa since the 1950s led to the expansion of towns and the development of industries such as mining (see the Section on Mining), which necessitated the pumping of ground water and the construction of dams, roads and power lines. All these disturbances to soil, vegetation and drainage make rangelands vulnerable to invasion by alien plants such as cactus or mesquite trees (Figure 3.4).

Figure 3.4 (a) Mesquite (Prosopis) clearing by Working for Water below the Smart Syndicate Dam, Britstown. (b) Livestock disperse mesquite seed into rangeland from roadside plantings. (c) Dense stands of mesquite provide little forage and shade out shrubs and grasses. (d-e) Few veld plants survive in the shade of mesquite so that cleared veld is bare and needs further restoration after clearing. [S.J. Milton, Oct 2003]

Trends in rangeland resources

There has long been concern about the deterioration of South African rangelands. In 1875, Shaw [7] was concerned that the Karoo was 'becoming a desert or a region of obnoxious and poisonous plants'. His concerns were reiterated by Acocks [8], who in 1953 produced the first South African rangeland degradation map, Talbot [9], who in 1961 wrote 'soil erosion has made the vegetation change irreversible', Dean and Macdonald [10], who linked decreases in stocking rates to declining natural capital (Figure 3.5a), and Hoffman and Ashwell [5], who in 2001 produced the first quantitative index of rangeland degradation for South Africa based on soil erosion, alien invasive plants, bush thickening and poor veld condition. The size of a commercial farm is related to economic viability, and as shown in Figure 3.5b, the average sizes of ranches in the Northern and Western Cape, Free State, KwaZulu-Natal and Limpopo provinces started to increase in the 1950s. This trend continued until the 1980s, suggesting a decline in the productivity of the land.

Transformation from rangelands to managed production systems, such as crops and pastures, greatly reduced species richness of plants and animals in both arid rangelands, such as those in Namaqualand [12], and in well-watered rangeland, such as the high altitude grasslands of the Drakensberg [4]. Rangelands on soils that have been chemically altered by fertilisers and eroded, or have lost most of their original plant species, do not recover spontaneously, even when rested from grazing by game or livestock. Saltbush or yellow kraalbos in abandoned wheat lands in protected areas in the Western Cape (Figures 3.3c and d) and missing spekboom on hillsides (Figure 3.7d on page 80) are evidence of this.

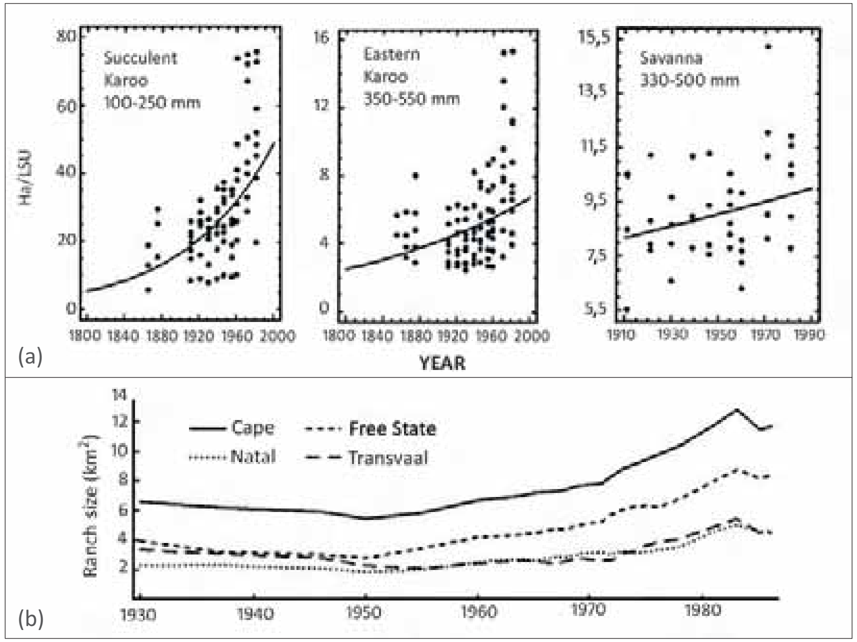


Figure 3.5 (a) Increasing areas of land needed to support livestock in various types of rangeland [11] seem to imply that rangeland condition started to decline rapidly in the early 1900s and continued to do so until the late 1900s when it may have stabilised and (b) increasing ranch sizes. [10]

Rangeland problems have been worsened by the global-scale human population growth and development that is driving climate and atmospheric changes. Increasing atmospheric carbon-dioxide promotes bush thickening (Chapter by David Ward), rising temperatures and more frequent extreme weather events such as floods and droughts (see Chapters by André Theron, Andrew Mather, Alan Smith *et al.* and Geoff Brundrit *et al.* in the Section on the Marine Inshore Environment). Where palatable plants have had no opportunity to set seed (Figure 3.6a), or rangeland is criss-crossed by animal paths and roads (Figure 3.6b), the droughts and floods associated with climate change worsen erosion. Range management can either increase or reduce the negative impacts of climate change on rangeland natural capital.

Figure 3.6 Rangeland management can exacerbate or ameliorate the impacts of climate change. (a) Poisonous 'geeltulp' became very abundant after drought killed Karoo bushes near Sutherland in 2006. This effect was far greater on rangeland in poor condition before the drought. [S.J. Milton, Sept 2006] (b) Paths and roads in rangeland near Calitzdorp (WC) are likely to lead to accelerated erosion and gully formation after heavy rain. [Image supplied by the Chief Directorate: National Geo-spatial Information (CDNGI) © CDNGI 2009]

What can be done to sustain rangeland capital?

There are five types of government intervention that could help to sustain and improve the rangeland natural capital, namely: (a) improved extension services, (b) incentives for increasing size of management units, (c) incentives for restoration of soil erosion and veld condition or disincentives for bad management of rangeland, (d) incentives for maintaining and increasing below-ground carbon stocks, and (e) incentives for removing invasive alien trees on ranches or along roadsides.

Government support for a better agricultural extension service would lead to more effective and sustainable ranching. Extension services, previously offered by government, are now being supplied by consultants who are unaffordable for most ranchers. Long-term grazing research trials maintained at Carnavon (NC), Dohne (EC), Elsenburg (WC), Phalaborwa (Mpl) and Middelburg (EC) (see for example Figure 3.1a) have been discontinued, but their crucial findings, including the damaging effects of early spring burns and repeated summer grazing in grassland and savanna [3], growing-season grazing in Karoo and Namaqualand [13], and the need for resting all kinds of veld to allow seed set, must be made known to ranchers.

Under some circumstances the intensification of agriculture reduces erosion. For example, a shift in ostrich management from keeping breeding birds in the veld to keeping them in small, intensively-managed paddocks, will greatly reduce area of natural veld damaged annually. But, intensive management of livestock and game is not always feasible for economic or practical reasons. An increase in the land management units could relieve pressure on the veld by allowing animals to move off overgrazed areas. Large management units can be achieved either by purchase or through agreements among neighbours.

Restoration of eroded, denuded, and transformed landscapes through construction of hollows or ridges that retain water and improve water infiltration (Figures 3.7a and b), especially when combined with reseeding, can hasten the recovery of rangeland productivity and diversity [14]. Restoration is costly and to be more widely applied needs incentives such as tax relief, or subsidised programmes such as 'Working for Woodlands'. This programme, which involves growing and establishing indigenous plants in degraded spekboom thicket in the Eastern Cape (Figures 3.7c and d), has shown that some original values of natural rangeland (water retention, wood and forage production) can be restored. The carbon credit scheme, which provides an incentive for maintaining and increasing below-ground carbon storage using indigenous plants [15], could contribute to maintaining biodiversity and productively in rangelands of all types.

Consequences of rangeland degradation for South Africans

Rangeland degradation, including soil erosion, weed invasion, decreased animal production stability, losses of plant and animal species and impaired beauty of the landscape, bring many hardships for rural people and increase costs to land owners, local and national government. Problems directly caused by rangeland degradation include siltation of dams, reduced options for land use, rising meat and wool prices, reduced tourism opportunities and depressed rural economies [16] that are characterised by unemployment and ghost towns with crumbling infrastructure and dysfunctional services [17].

Conversely, increased investment in rangeland extension and incentives for land restoration and good management in this important sector of the economy would do much to revitalise rural towns.

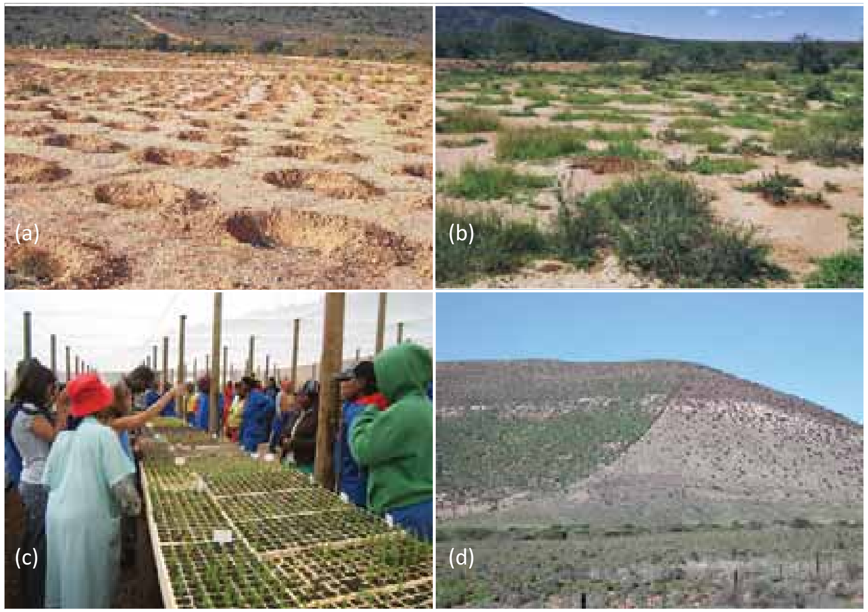


Figure 3.7 Restoration options for restoring overgrazed and eroded rangelands. (a-b) Pitting to trap seed, nutrients and water led to plant establishment in eroded Little Karoo. [Ken Coetzee] (c-d) The Working for Water nursery at Patensie (EC) has been established to grow skills and plants for repairing degraded spekboom thicket. [S.J. Milton, Jan 2009]

RANGELANDS

Long-term changes in the vegetation of southern Africa as revealed by repeat photography

'A picture is worth a thousand words'

M. Timm Hoffman
Rick Rohde

Natural landscapes are constantly changing in response to climate and human pressures. Repeat photography is a powerful tool for investigating the state-and-trend of local environments over time scales of decades and centuries. Four repeat photographs are used to illustrate the change in southern African landscapes across a rainfall gradient from the mesic eastern part of KwaZulu-Natal to the more arid parts of Namaqualand. Accurate interpretation of the state-and-trend requires a detailed environmental history of the local landscape and incorporates knowledge of both social and biological systems and how they have changed over time in response to key drivers and pressures.

Introduction

The world around us is always changing. From day-to-day and month-to-month nature responds to a multitude of direct and indirect drivers and pressures such as rainfall, atmospheric pollution and livestock grazing. Measuring the extent and rate of environmental change in response to these drivers and pressures is important because by knowing the past we will be better able to predict likely responses of the environment in the future. However, it is difficult to document these changes, particularly over relatively long time scales of decades and centuries. One approach we can use to do this more accurately is repeat photography. This involves the re-taking of an historical photograph from the same position as the earlier image. These changes are interpreted by looking closely at the ecology of the landscape as well as by talking to land owners who often provide invaluable insight into the patterns that are observed and measured.

The use of repeat photography in African environmental studies

Africa has a long history of using repeat photography as a tool to investigate environmental change. In one of the earliest examples showcasing the value of this approach, Shantz and Turner [1], two American plant physiologists, revisited a number of sites in 1956 that Shantz had first photographed in 1919 and produced a classic analysis of environmental change on the continent. Several recent studies have also highlighted the importance of this tool whether investigating erosion in Kenya [2], the impact of communal grazing on the arid grasslands of Namibia [3] or the influence of agricultural policy and resettlement in Ethiopia [4].

Although the use of repeat photography to understand environmental change in southern Africa has grown significantly over the last decade, there is a great deal more that can still be done. Fortunately we have thousands of excellent historical landscape photographs taken by some of the region's most notable botanists including Rudolf Marloth, IB Pole Evans, Margaret Levyns and John Acocks. Their photographs cover a large proportion of the country and more than 500 sites have been re-visited and re-photographed. In many cases the results reveal dramatic landscape changes, such as in the mesic savannas of KwaZulu-Natal near Weenen (Figure 3.8). In 1955, recent flooding in the region had cut deeply into the sparsely-vegetated river banks leaving steep-sided and crumbling walls of sand. The hills below uMkholome ncane mountain in the distance were also relatively unvegetated in 1955 and the occasional large tree in the landscape provided a parkland feel to this open savanna environment. In 1998, however, the sloping river bank supported a dense stand of trees including *Acacia karoo*, *Ziziphus mucronata* and *Celtis africana*. The distant hills also exhibited a dramatic increase in vegetation cover dominated mostly by *Acacia karoo*, *A. tortilis, Combretum erythrophyllum* and *Aloe barbarae* trees. Grasses were not present or were rare in the 1955 image, but in 1998, grasses such as *Cynodon dactylon* and *Hyperrhenia hirta* were present along the river bank in the right foreground. Several other photograph pairs from this region support the general finding that a number of Acacia species and many broad-leaved trees have increased significantly in the region since the 1950s [5].

Figure 3.8 The Mooi River near Weenen in KwaZulu-Natal photographed by Edwards in 1955 [Reproduced with permission from SANBI] (a) and by Hoffman and O'Connor in 1998 (b).

Understanding the reasons for these changes, however, is more difficult since changes in a number of biotic and abiotic drivers, either singly or in combination, could account for the increase in tree cover. For example, an increase in both temperature and atmospheric CO_2 levels would favour the rapid growth of Acacias over smaller shrubs and grasses while the impact of herbivory on the grass layer would also lead to a significant reduction in fire frequency in the region which in turn would promote the spread of Acacias. Other changes, such as a reduction in firewood harvesting over time, might also be important in explaining woody biomass increase in the region.

Repeat photographs are particularly useful in testing hypotheses about the rate and extent of environmental change. For example, in 1953 John Acocks warned that if overgrazing of the Free State grasslands continued as before then the more arid-adapted Karoo shrublands would expand and dominate the more palatable grasslands of the wetter areas to the north and east. Acocks produced several maps to support his views which dominated the South African desertification debate for decades. The 1962 image of Wepener (Figure 3.9) clearly shows the abundance of Karoo shrubs such as *Chrysocoma ciliata* at this site in support of Acocks' hypothesis. However, perhaps because of this warning, farmers and government institutions, such as the Department of Agriculture, became aware of the importance of conservation farming [6] and by 2009 the dominance of grasses including the palatable *Themeda triandra* at this site is clearly evident.

In some cases, repeat landscape photography is intimately linked to the political drama of southern Africa's history, such as in the two photographs taken of the Magersfontein battlefield, near Kimberley, more than 100 years apart (Figure 3.10). While the first image reflects a somewhat surreal view of the bloody Boer War battle which took place a few weeks earlier at this site and where many young men lost their lives, the somewhat pastoral image of the site, taken in 2003, masks the tragedy and extent of human suffering that was experienced here. *Acacia tortilis* together with a few *Acacia mellifera* trees dominated the plains in 2003 while the relatively barren early hill slopes were covered with *Rhus lancea* and particularly *Tarchonanthus camphoratus* which is widespread throughout the Kimberley area and beyond.

Figure 3.9 The town commonage just outside Wepener on the Free State/Lesotho border photographed by Roux in 1962 (a) [Reproduced with permission from Dr P. Roux] and Hoffman, Masubelele and Gambiza in 2009 (b).

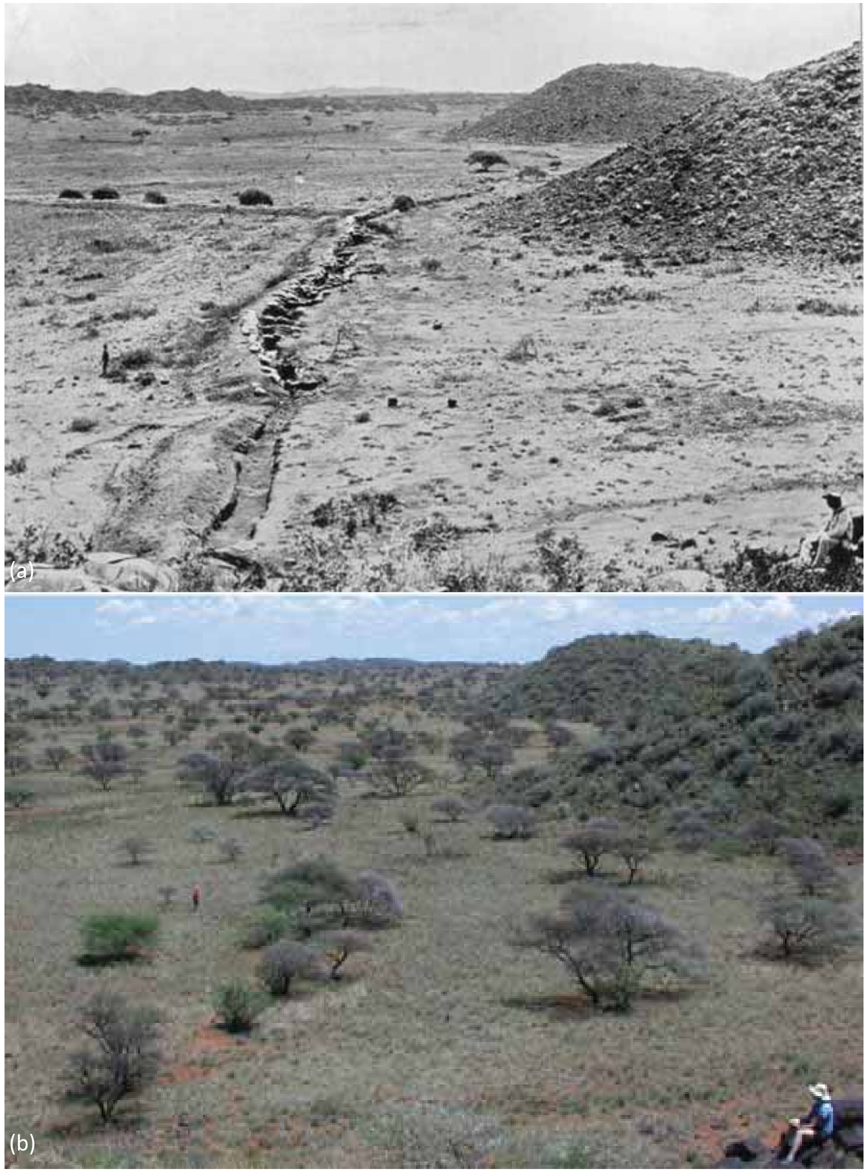


Figure 3.10 Boer War trenches photographed by H. Exton just after the battle of Magersfontein near Kimberley in 1899 (a) and by Hoffman and Ward in 2003 (b).

The final pair of matched photographs is from the Succulent Karoo (Figure 3.11) near Loeriesfontein and shows that natural landscapes can also remain largely unchanged over relatively long time periods. It is particularly important to have as many historical photographs from this biodiversity hotspot as possible as it is this biome which will purportedly be impacted the most from future climate change [6]. With an anticipated decrease in rainfall and an already measured increase in temperature, which is predicted to increase even more in the future, the Succulent Karoo Biome is one of the most threatened regions in southern Africa. To date, however, the evidence

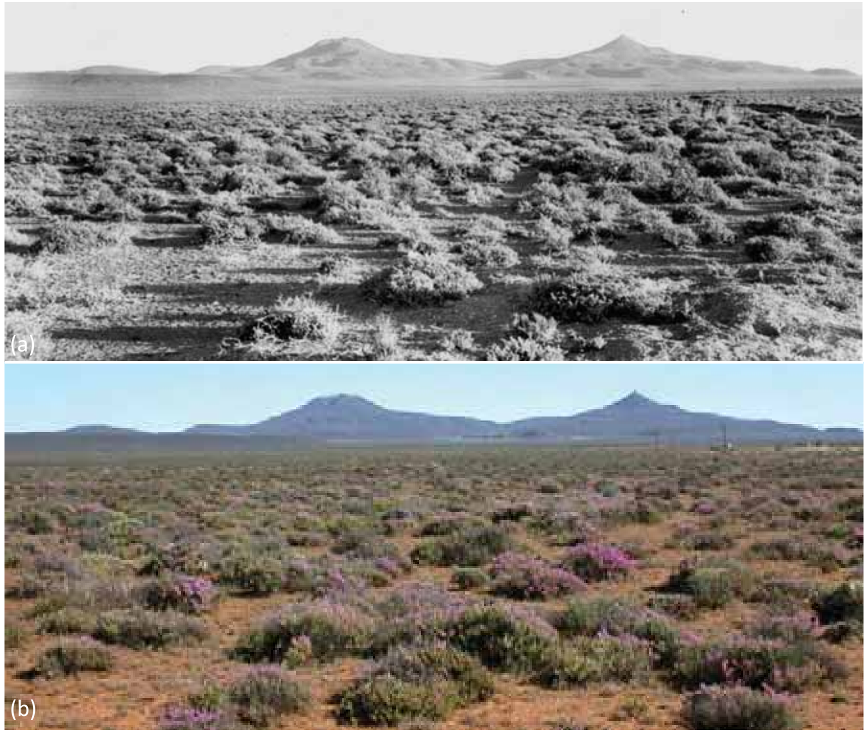


Figure 3.11 Succulent Karoo shrubland just north of Loeriesfontein in the Northern Cape province photographed by Pole Evans in 1920 [Reproduced with permission from SANBI] (a) and by Rohde and Hoffman in 2002 (b).

from more than 150 repeat photographs of the biome suggests that there has been very little change in cover and composition of plants over the course of the 20th century [7], even under severe grazing pressure such as is often found in the communal areas of Namaqualand [8].

Repeat photography requires interdisciplinarity

Repeat photography provides a powerful tool for understanding the past. Photographs can be understood and interpreted by a wide spectrum of people interested in the environment including researchers, farmers, politicians and the lay public. With the explosion of image analysis technology in recent decades, significant advances have been made in the quantification of information derived from photographs. Getting the best out of each image, however, requires a dedication to detail and a love for a range of disciplines including ecology, sociology and history. Working across disciplines is the brief of environmental historians and repeat photography has found a home within this emerging field. The most difficult aspect of this approach, however, lies in understanding the drivers of change. Usually one only has a pair of photographs; one from the past and one for the present. Interpreting the extent of change is a relatively simple matter compared to understanding why the change has occurred. Talking to land users is essential but not always possible. However, ecological insights about the nature of change, together with detailed land-use histories, provide a powerful combination for documenting the environmental history of a wide range of landscapes in southern Africa. Furthermore, if such sites are well-surveyed and the photographs properly archived, they will provide a rich source of material for future generations to continue a programme of long-term monitoring of environmental change in response to climate and landuse drivers.

Acknowledgements

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RANGELANDS

Bush encroachment in southern African savannas

David Ward

Bush encroachment affects the agricultural productivity and biodiversity of large parts of southern Africa. Many people believe that either heavy grazing by domestic livestock or fire is the sole cause of bush encroachment. However, bush encroachment is widespread in areas where grazing is infrequent and light. Bush encroachment also occurs in many arid regions where fuel loads are insufficient for fires to be an important causal factor. A number of small-scale and some large-scale factors may explain the causes of bush encroachment. Some of the most important factors may include increased CO_2 induced by global climate changes and rainfall, disturbance and soil nutrients.

Introduction

Savannas are areas with a discontinuous cover of trees or shrubs and a continuous grassy or herbaceous cover (Figure 3.12). Bush encroachment (also called shrub encroachment or woody plant encroachment) is the replacement of grasses by trees or shrubs (Figure 3.13). Many of these trees in South Africa are thorn trees or shrubs (for example, *Acacia mellifera*, *A. karroo*, *A. tortilis*, *A. sieberiana*, *A. nilotica*, *Dichrostachys cinerea* and *Rhigozum trichotomum*). This reduces their palatability to many game and livestock species. Furthermore, because many of these trees contain tannins, their digestibility is further reduced because tannins bind to proteins consumed by the animals. Bush encroachment is also considered to be a problem by many ranchers because it reduces the amount of grass available for domestic livestock. However, some communal ranchers (for example, in the Kuruman area [1]) do not consider this a problem, perhaps because they largely ranch with small stock (especially goats) and donkeys, which are mixed feeders eating grasses and some shrubs and trees. It is also considered a problem in some game reserves. For example, in arid Madikwe Game Reserve (North West province), a 30% increase in bush density was recorded between 1955 and 1998 [2]. A similar problem is experienced in several mesic/humid KwaZulu-Natal game reserves, such as Ithala and Hluhluwe-iMfolosi [3, 4]. It is considered that between 12-20 million ha of land in South Africa is affected by bush encroachment [5].

Figure 3.12 Open savanna north of Kimberley, South Africa. [David Ward]

Figure 3.13 Bush encroachment by *Acacia mellifera* north of Kimberley, South Africa. [David Ward]

Spatial and temporal variability of savannas

Savannas are inherently spatially variable, regardless of where they occur [6, 7, 8]). Savannas are also temporally variable [4, 9, 10]. For example, major increases in tree densities (and a concomitant decline in grass densities) were recorded in arid areas near Kimberley, South Africa (Figure 3.14) between 1967 and 1993 (Figure 3.15) in spite of a lack of change in grazing intensity [10]. Similarly, a 30% increase in density of the thorny shrub *Dichrostachys cinerea* in mesic Swaziland between 1940 and 1997 was recorded [9], while large increases in vegetation density in the mesic Hluhluwe-iMfolosi area were also recorded [4].

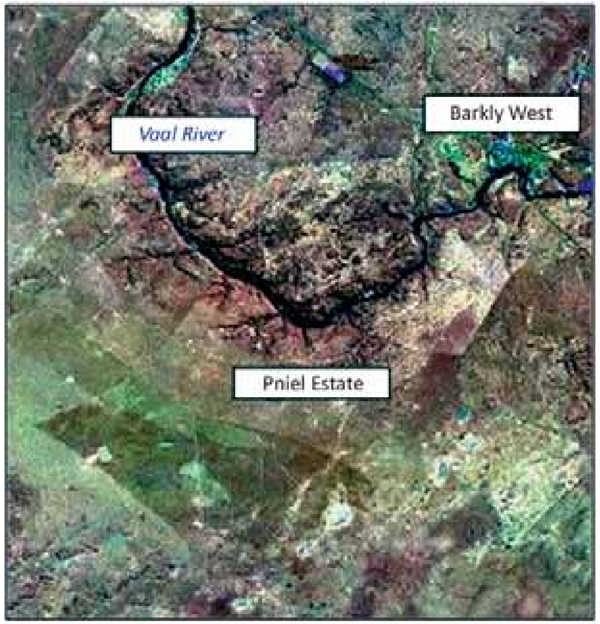


Figure 3.14 Satellite photograph of Pniel Estates in the Barkly West area, 35 km north of Kimberley, South Africa. The relatively bare area below the town of Barkly West is the communal area of Pniel Estates. The darkest green area is the area ranched for wild game species. The areas on both sides of the Vaal River (regardless of grazing strategy) are rocky and encroached by *Acacia mellifera*. [David Ward]

An interesting example of long-term changes comes from the Magersfontein battlefield from the Second Anglo-Boer War (1899-1902) where photographs were taken during the war and can be compared to current photographs (Figure 3.16). There are now many *Acacia tortilis* trees on the plains and the hills are encroached by *Tarchonanthus camphoratus*. See Figure 3.10 in the previous chapter.

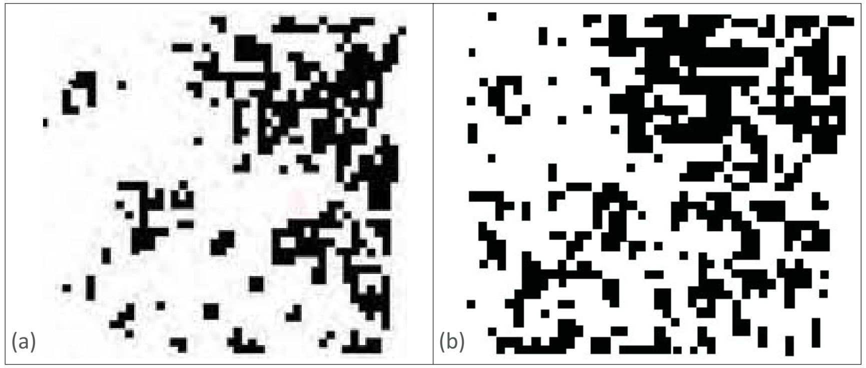


Figure 3.15 Aerial photographs of Pniel Estates. Black pixels are encroached areas. (a) 1967 aerial photograph. (b) 1993 aerial photograph of the same area. Note the large increase in encroached areas in the latter photograph (1993) relative to the 1967 photograph. [David Ward]

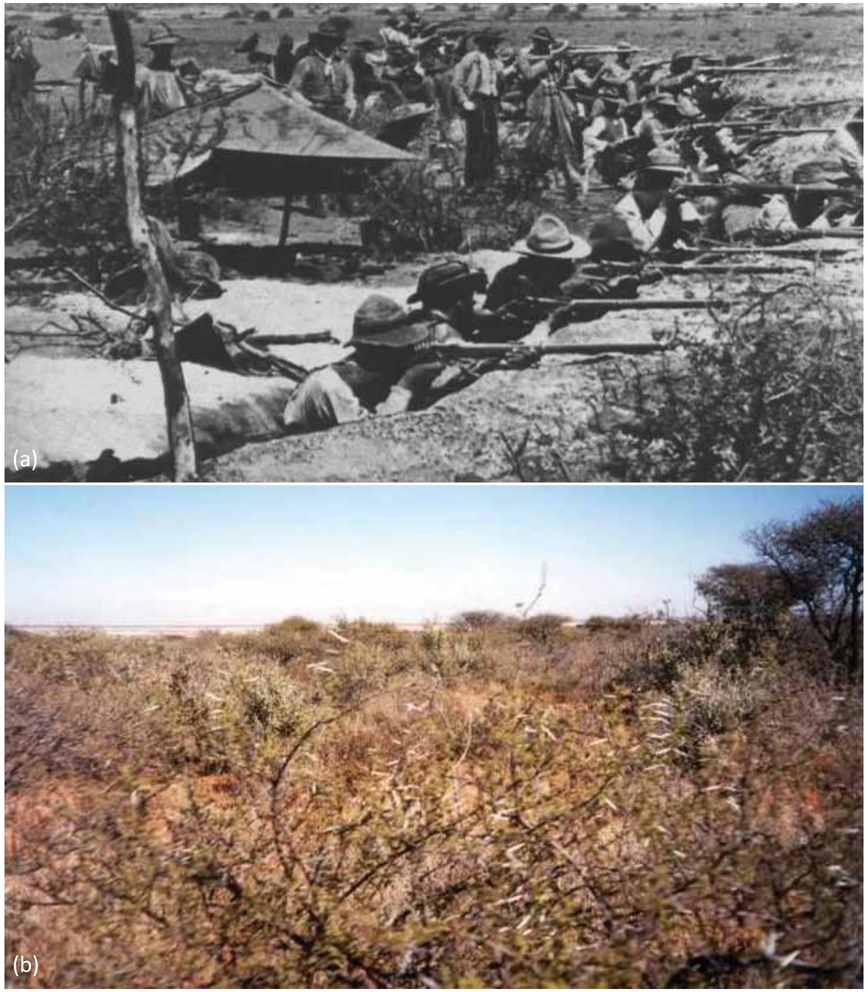


Figure 3.16 Magersfontein battlefield. (a) Taken just before the battle on 11 December 1899. (b) The same photograph as (a) taken in 2001, heavily encroached by *Acacia tortilis*. Note that the Boer soldiers would not have been able to annihilate the British soldiers of the elite Black Watch Regiment had there been trees present. [David Ward]

Small-scale features affecting bush encroachment

Small-scale features that affect bush encroachment include: (a) *Rainfall*: There is a negative correlation (in space and time) between mean annual rainfall and its coefficient of variation [8]. Water availability far outweighed the importance of grazing, fire and nutrient addition in a study near Kimberley, South Africa (mean annual rainfall = 360 mm) [11]. (b) *Geology and soil*: Changes in the cover and density of shrubs and trees in the Kruger National Park based on aerial photographs from 1940 until 1998 showed differences in woody cover that depended on geology [12], with a 12% increase on granite substrates and a 64% decrease on basalt substrates over the study period. Encroachment by *Acacia mellifera* was associated with andesite rocks but not with other habitats [10]. (c) *Fire*: This is considered a major determinant of spatial variation in savanna structure, particularly in mesic savannas [13]. Fires can result in increased space for trees to germinate *en masse* [14] or they can cause trees to die, resulting in a more open savanna [15, 16]. Because of the large variation in fuel loads caused by differences in rainfall and soil type, fire intensity and duration varies considerably, resulting in considerable variation in spatial structure [14]. (d) *Propagule pressure*: Seed densities may affect the likelihood that a site will become encroached but this may only occur in high rainfall years [15]. Introducing safe sites for seedling establishment by simulating the effects of various small-scale heterogeneities allowed coexistence of trees and shrubs [17]. (e) *Grazing*: This is widely purported to be the main factor affecting increases in tree density [15, 18]. This is largely ascribed to heavy stocking by domestic livestock, removing grass and making space for trees to germinate *en masse*. Piosphere formation (heavy grazing near water holes) [19]) and fence line effects (differential effects of herbivore densities on either side of a fence) [8, 20]) are also a major source of the spatial variation in savannas. At two savanna sites in the Kalahari Desert, piospheres were found to occur at the high rainfall site (385 mm), but at the low rainfall site (220 mm) piosphere development was influenced by rainfall only [21]. (f) *Physical disturbances*: These occur where soil is turned over, such as in mining and agricultural areas.

Large-scale features that affect bush encroachment

In some cases, vast areas of savannas may be affected by bush encroachment. For example, the Sahel, which covers ten countries immediately south of the Sahara, is subject to large changes due to a change from migratory livestock to fixed patterns of livestock control [22]. Migratory ungulates use nutritious but seasonal food and probably maintain larger populations as a consequence. Nomadic pastoralists were forced to settle with their livestock. This caused heavy grazing near water holes (leading to piosphere formation) [22] and has resulted in bush encroachment in many places [19]. Global climatic changes may also affect the abundance of trees in savannas, in particular changes in CO_2 [23]. Previously considered relatively unimportant, increased global CO_2 levels may be resulting in increased woody vegetation and higher bush densities due to a switch in the net photosynthetic efficiency of trees relative to grasses (these grasses are currently more efficient than trees) as global CO_2 levels increase from their current levels [8, 14, 24].

Relationships of models of bush encroachment to savanna functioning

Several models have attempted to explain the phenomenon of bush encroachment. Some models are *equilibrial* in that they assume that there is stable co-existence independent of rainfall variability and disturbance [18, 25]. The classical example is the two-layer model [18], which has some limited support [26]. Grasses are assumed to remove water from the upper soil layers, while trees remove water from the lower soil layers. However, trees still need to grow their roots through the upper layers and may even maintain their roots in the upper layers for the purposes of nutrient acquisition [27]. Other models that make no explicit assumption of equilibrium seem more appropriate (for example, [13, 28]), particularly *patch dynamic* models [7], which differ from non-equilibrium and disequilibrium models because they include intraspecific competition among trees as part of a cyclical process. According to patch dynamic models, at the scale of the whole landscape, savannas can be stable, persisting over millennia due to the fact that the landscape consists of many patches in different states of transition between a grassy and a woody dominance. However, there is currently no unified theory of how trees and grasses coexist in savannas.

Other effects of encroachment on ecosystems

Bush encroachment affects other aspects of ecosystems. For example, in an experiment where encroaching trees were removed at a 1 ha scale, different bird species occupied encroached and unencroached plots [29]. In a study in central Namibian rangelands, lizard species diversity varied according to encroachment [30]. *Mabuya varia* was absent from all encroached plots but was present in all other plots, while *Pedioplanis undata* and *Lygodactylus bradfieldi* were less abundant in the encroached plots. The fourth lizard species *Mabuya striata* (these four species made up 97,5% of all lizards) was more common on encroached than on open savanna plots.

Drivers, pressures, state, impacts and responses

Overall, the relationships between drivers, pressures, state, impacts and responses can be portrayed as in Figure 3.17. Probably the most effective means of controlling or responding to encroachment is to alter timing of fires to minimise further impacts and to reduce further grazing where possible [8], since both fire and heavy grazing create space in the landscape for encroachment to occur. This may not always be possible because of the need to maintain high livestock numbers in communal grazing areas [31]. Removal of encroached areas can be achieved by burning and by subsequent goat browsing of young seedlings because, as mentioned previously, burning alone seems to be relatively ineffective. Other effective means are chemical removal (which is expensive) and removal of small trees by physical means, such as cutting or taking the entire tree out or breaking of stems. When trees are large, breaking of stems has been most effective because resprouting of clean (sawn) breaks can occur. Clearly, limiting CO_2 as a result of global climate changes may be the most effective means of reducing or at least limiting woody plant densities [8, 14].

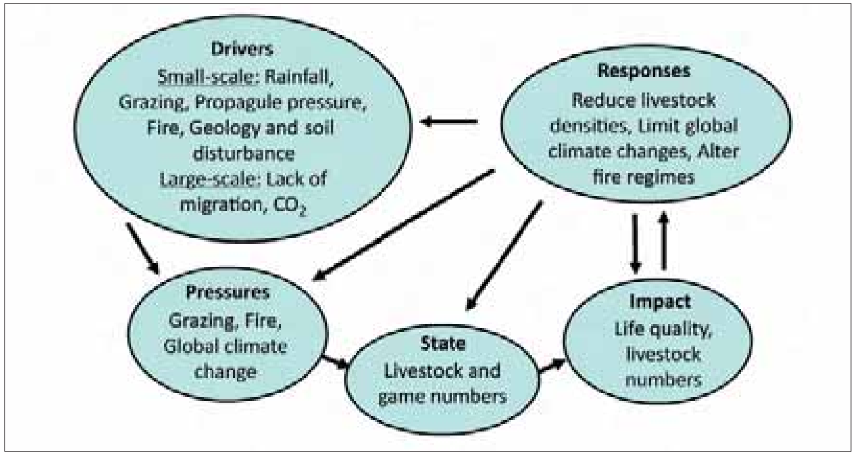


Figure 3.17 The causes and consequences of drivers, pressures, state, impacts and responses of bush encroachment.

Detecting inter-annual variability in the phenological characteristics of southern Africa's vegetation using satellite imagery

Konrad J. Wessels
Karen Steenkamp
Graham von Maltitz
Sally Archibald

Vegetation phenology refers to the timing of seasonal biological events (for example, bud burst, leaf unfolding, vegetation growth and leaf senescence) and biotic and abiotic forces that control these. Daily, coarse-resolution satellite imagery provides consistent measurements of vegetation greenness which captures phenological cycles and vegetation function. Understanding the inter-annual variability in phenology is imperative, as phenological changes will be one of the first signs of the impact of climate change on ecosystem dynamics. This chapter offers new insights into the spatial patterns of the phenometrics and their inter-annual variability that could not be mapped without long-term satellite time-series data. This technique helps to close the gap that existed between plot-level vegetation data and broad-scale climate data during traditional regional vegetation mapping.

Introduction

Vegetation phenology refers to the timing of seasonal biological events (for example, bud burst, leaf unfolding, vegetation growth and leaf senescence) and biotic and abiotic forces that control these [1]. The dynamic phenology of terrestrial ecosystems reflects response of the biosphere to climatic factors (for example, temperature and rainfall) and these climatic drivers are largely responsible for the geographic distribution of different vegetation zones.

Field data on leaf phenology are difficult to obtain. Data collection is labour intensive and the data can only give information at one point on the ground. Daily, coarse-resolution satellite imagery provides consistent measurements of vegetation greenness which captures phenological cycles and vegetation function. South Africa has the rare privilege of having received, archived and processed daily 1 km^2 AVHRR satellite data to calibrated ten-daily, near cloud-free composite images, since 1985.

Each 1 km^2 pixel thus has a time series of data from which vegetation phenology, such as the start, peak and length of the growing season, can be extracted using specific algorithms. These phenological cycles are very different between vegetation types (Figure 3.18). Insightful maps were produced for the entire southern Africa showing patterns in phenological metrics, such as the start of season (Figure 3.19), which otherwise would have been impossible to observe.

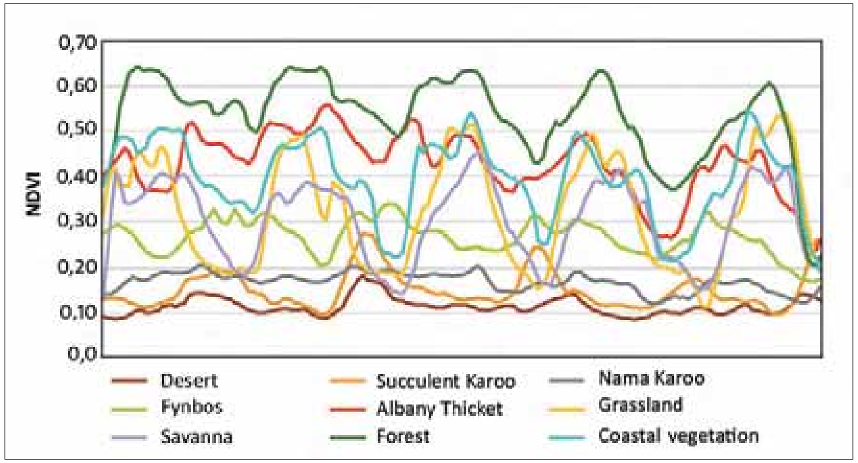


Figure 3.18 Time series of vegetation greenness for a typical pixel in each of the biomes of South Africa.

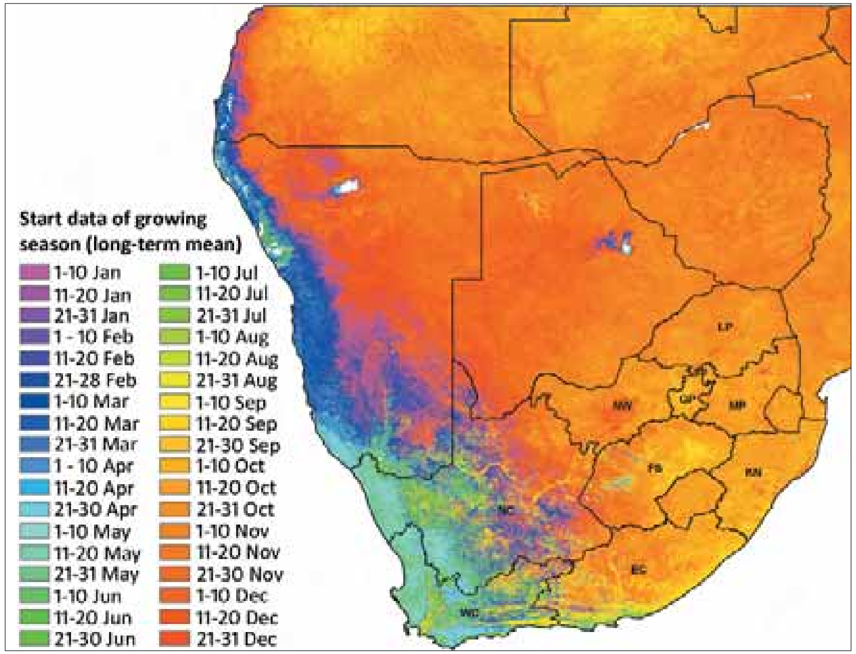


Figure 3.19 Mean start date of the growing season derived from 1 km^2 AVHRR satellite data, 1985-2000.

It is imperative to understand the inter-annual variability in phenology, as phenological changes will be one of the first signs of the impact of climate change on ecosystem dynamics. Studies based on phenology derived from satellite data have already indicated an earlier start and longer growing season in northern latitudes [2, 3]. Similar trends have not yet been detected in South Africa, however it is important to develop a base line understanding of our phenological patterns as climate change models predict significant changes in the near future [4]. The objective of this research was to describe patterns of satellite-derived vegetation phenology, including their inter-annual variability, across southern Africa.

Extracting vegetation phenology from satellite data

There were various computational problems that needed to be overcome in order to extract useful phenological information. Time series of satellite vegetation index data are notoriously noisy due to cloud and atmospheric contaminations and varying sun and sensor angles. Thus, robust models have to be developed to distinguish the seasonal vegetation signal from the noise and to reconstruct a clean time series for each image pixel (for example, Figure 3.18).

The seasonal cycles of vegetation greenness provide a time series of data for each image pixel from which the start, midposition, end and length of the growing season can be numerically extracted (Figure 3.20) [5]. The total amount of vegetation growth, referred to as net primary production (NPP), can be calculated from the area under the seasonal growth curve (the large integral) (Figure 3.20, point F).

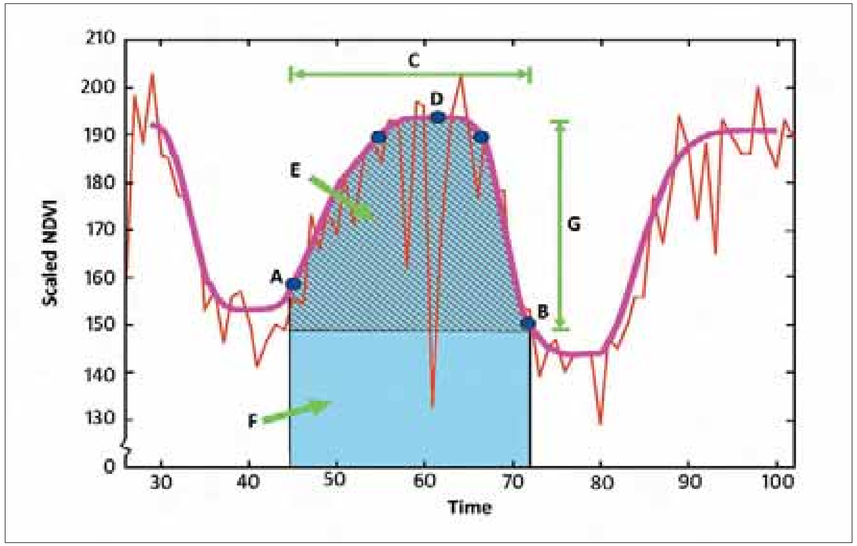


Figure 3.20 Phenology metrics extracted from the seasonal NDVI curve. A – start of season, B – end of season, C – length of season, D – maximum, E – small integral, F – large integral, G – amplitude.

The results show a very clearly defined spatial pattern in the start of growing season which is consistent with known plant phenological patterns and regional rainfall patterns (Figure 3.19). The winter rainfall of the southwestern and western coastal strip (start in beginning of May) is clearly distinguished from the summer rainfall regions in the remainder of the subcontinent (start in October to early November). The fynbos, though predominantly in a winter rainfall region, is known to span from winter in the west (start in beginning of May) to summer rainfall regions in the east (start in September) [6]. The areas in the western fynbos with later start dates (October) are mainly wheat fields where the pattern of planting and harvesting gives very uniform phenologies that are distinctly different from the surrounding vegetation (Figure 3.19).

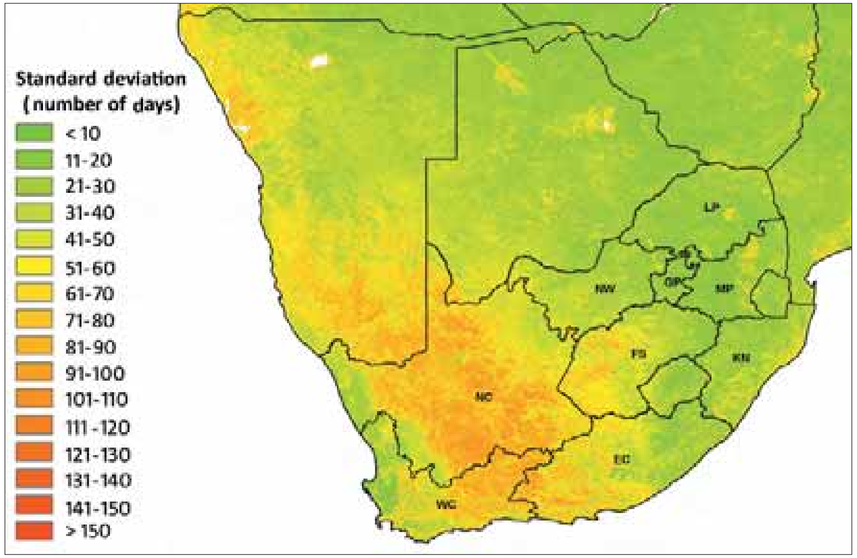


Figure 3.21 Inter-annual variability (standard deviation in days) in the start of growing season derived from 1 km^2 AVHRR satellite data, 1985-2000.

The standard deviation (in days) of the start of growing season is a measure of the inter-annual variability in this date (Figure 3.21). The greatest variability in the start of growing season dates is associated with arid regions, especially the Nama Karoo with its unpredictable rainfall. The grassland and savanna in the Northern and Mpumalanga provinces show the least variability in the start date, namely 20-30 days. The variability in start date in the cultivated areas of the Free State is very high, while it is very low in cultivated areas of the Western Cape (Figure 3.21), reflecting the difference in the inter-annual variability in first rainfall and planting dates.

The large integral indicating vegetation production shows a clear relationship with rainfall, from the very arid areas in the Northern Cape to the high rainfall of the forests and exotic plantations along the escarpment and the Indian Ocean coastal belt (Figure 3.22). Negative trends in the large integral through time can be used to identify areas experiencing land degradation [7] and/or potentially climate change, whilst taking account of the natural inter-annual variability.

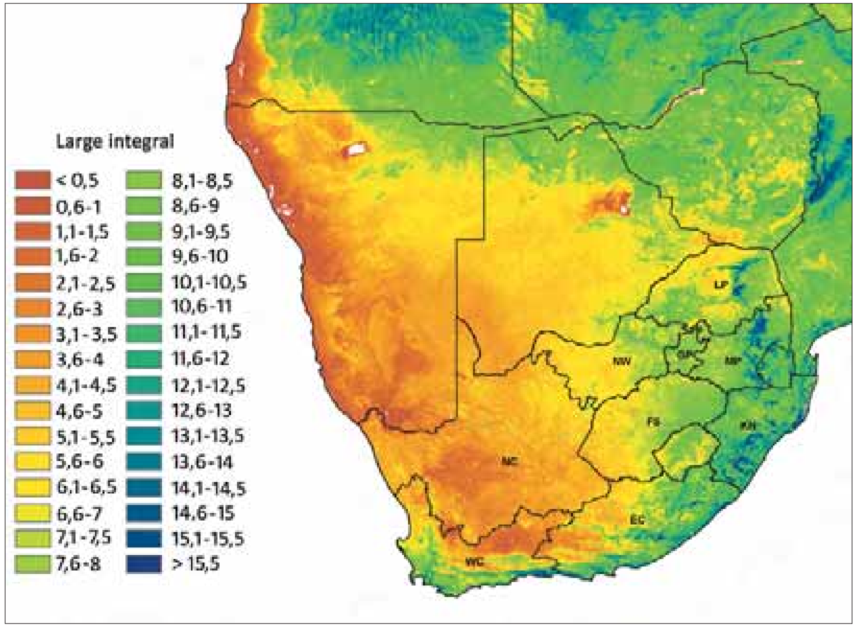


Figure 3.22 The mean large integral of the seasonal growth curve indicating total vegetation growth per season.

Phenology of the biomes of South Africa

The newly-defined biomes of SA include biomes such as Grassland, Savanna, Fynbos, Nama Karoo, Succulent Karoo, and Desert and were mapped based on the grouping of the more detailed vegetation types (based on plant species distribution data), as well as climate data (Figure 3.23) [8]. The phenology of these biomes (for example, Figure 3.18) were analysed to gain insight into their differences in terms of vegetation function and dynamics. It furthermore highlighted the phenological aspects which should be monitored to detect the impact of climate change and potential changes in the distribution of biomes. The satellite-based phenometrics clearly captured functional processes that were not readily predictable from the combination of floristic data and climate variables alone.

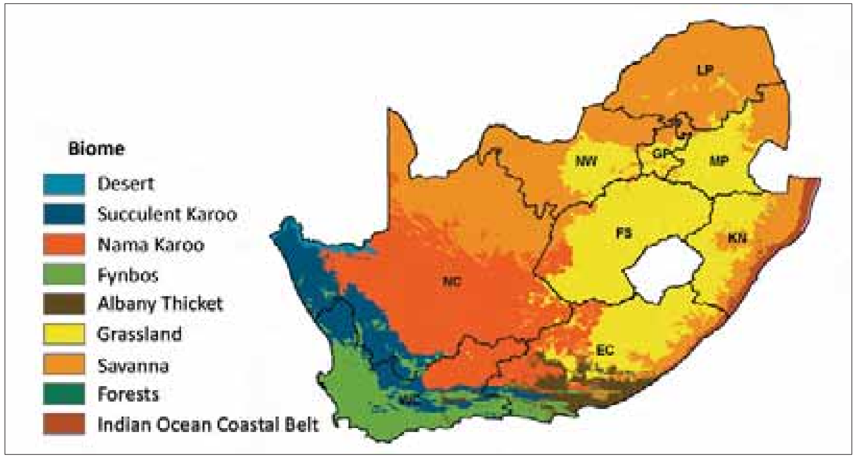


Figure 3.23 Biomes of South Africa. (After [8])

The biome map of South Africa could be reproduced from satellite-based phenology data with an overall accuracy of 75%. This is quite extraordinary considering that the biomes were mapped based on vegetation field data and climate data, while the satellite data recorded vegetation greenness. This technique helps to close the gap that existed between plot-level vegetation data and broad-scale climate data during traditional regional vegetation mapping. It can provide the opportunity to map vegetation functional types over vast areas of southern Africa where little floristic information may be available.

Ongoing research into phenology furthermore include: (a) quantifying the difference between the phenology of transformed land cover types, for example, cultivation and commercial forestry, and the natural vegetation, (b) relating phenological patterns to that of fire, (c) unmixing the phenological signal of grass versus woody components of vegetation, and (d) detecting potential change in phenological patterns through time.

Acknowledgements

The ARC-Institute for Soil, Climate and Water supplied and processed AVHRR and rainfall data. The research was funded by the CSIR Strategic Research Panel.

Impact of ENSO events on the Kruger National Park's vegetation

KONRAD J. WESSELS
PATRICK C. DWYER

The El Niño Southern Oscillation (ENSO) is a global coupled ocean-atmosphere phenomenon that is a primary driver of inter-annual variability in the rainfall and consequently the vegetation production of southern African rangelands. Evidence from the Kruger National Park shows the strong relationship between the ENSO episodes (droughts during El Niño and high rainfall during La Niña episodes), rainfall, grass production and satellite time-series data of vegetation activity. El Niño conditions have lead to the devastating droughts in 1991-92, 1997-98 and 2002-2003 while La Niña conditions lead to very high vegetation production (1995-96 and 1998-99), but also flooding (1999-2000). This chapter briefly discusses the management implication for the park and neighbouring communal areas.

Introduction

The El Niño Southern Oscillation (ENSO) is a global coupled ocean-atmosphere phenomenon that refers to temperature fluctuations in surface waters of the tropical Eastern Pacific Ocean. When sea surface temperature anomalies of greater than 0,5 °C persist for more than five months it is known as an El Niño (warm anomaly) or a La Niña (cold anomaly) episode. Droughts in South Africa are closely linked to warm ENSO (El Niño episodes) and the past twenty years have seen some of the strongest ENSO events in recorded history [1, 2]. ENSO is an important driver of inter-annual variability in the rainfall and consequently the vegetation production of southern African rangelands [2]. These droughts have caused huge livestock losses (especially in 1991-92) and thus pose significant challenges to communal and commercial livestock farmers, as well as wildlife managers. In addition, the 1999-2000 La Niña caused disastrous flooding in southern Africa.

Daily, coarse resolution satellite data (250 m to 1 km pixel size) are routinely used to estimate the photosynthetic activity of vegetation over vast areas. Vegetation indices, such as the Normalised Difference Vegetation Index (NDVI), use the contrast in the reflectance between the visible and infrared wavelengths to measure photosynthetic activity of vegetation. By tracking these vegetation indices throughout an entire growing season, the total amount of vegetation production can be estimated.

Time series of satellite vegetation index data allows us to monitor vegetation production and thus the impacts of droughts over multiple years. It is essential to quantify the impact of natural, inter-annual, climate variability (driven by ENSO events) on the ecosystem services, such as rangeland production, so that the impacts of human-induced land degradation and long-term climate change can be viewed against this background variability. This paper will demonstrate how the impacts of ENSO episodes on vegetation production in the Kruger National Park and surrounding areas can be monitored using long-term satellite time-series data and field measurements.

Satellite data

Daily Advanced Very High Resolution Radiometer (AVHRR) data have been recorded by the CSIR Satellite Application Centre since 1985 and is one of the most complete 1 km AVHRR data sets in the world. The data were consistently processed and calibrated by the Agricultural Research Council – Institute for Soil, Climate and Water (ARC-ISCW). The NDVI is calculated from the visible and infrared channels of the data and clouds are masked out. The impact of clouds and other atmospheric effects are removed from the data calculating ten-day maximum NDVI value composites. The NDVI values are summed over the growth season (October to April) to estimate total grass biomass production (Figure 3.24) [3].

The Moderate Resolution Image Spectroradiometer (MODIS) is a vast improvement on the AVHRR sensor and became available in 2000. The 16-day Enhanced Vegetation Index (EVI) (an improvement on the NDVI) composite data is available at 250 m resolution (pixel size) on the Internet. The growth season sum EVI was calculated after automatically detecting the start and end of the growth season as the 10% threshold of the individual annual amplitude (Figure 3.25). The growth season was therefore not fixed as in the case with the AVHRR data, but variable in timing and length.

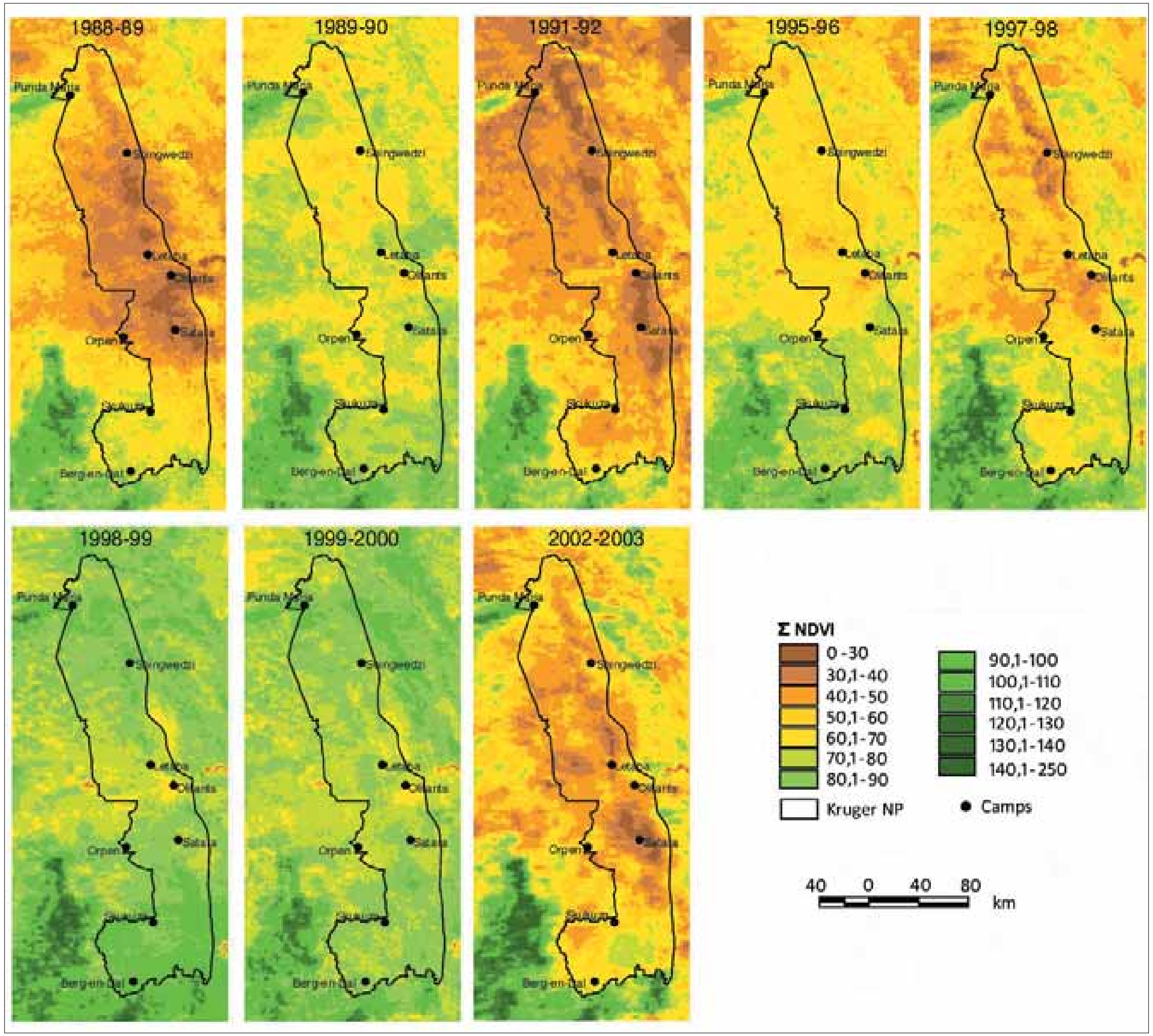


Figure 3.24 Growth season sum (October to April) of the NDVI of AVHRR satellite data illustrating the influence of the low rainfall El Niño (1991-92, 1997-98 and 2002-2003) and high rainfall La Niña (1996-96, 1998-99 and 1999-2000) episodes on vegetation production of the Kruger National Park and surrounding areas. [3]

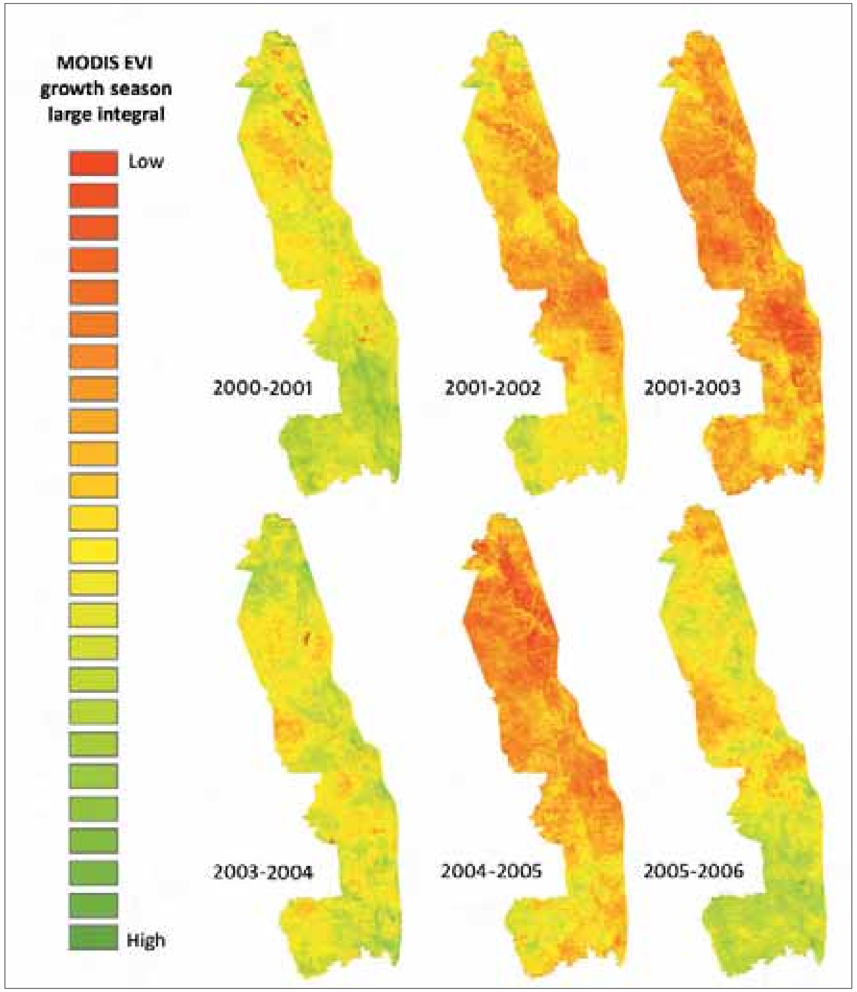


Figure 3.25 Growth season total (large integral of seasonal EVI curve varying between October to April) EVI of MODIS satellite data illustrating the influence of the low rainfall El Niño episodes (2002-2003 and 2004-2005) and above average rainfall (2000-2001) on vegetation production of the Kruger National Park.

Field measurements for 'ground truthing'

Satellite data are not of much use without field measurements of vegetation parameters, which are necessary for developing predictive models and testing the accuracy predictions of vegetation production. End-of-season standing grass biomass are recorded annually (since 1989) at more than 500 sites (called vegetation condition assessment or VCA sites) in the Kruger National Park. The remotely-sensed estimates of vegetation production (growth season sum NDVI and EVI) are strongly correlated with these field measurements (Figure 3.26) [3]. Although these VCA sites were not initially designed to be compared with coarse resolution satellite data, they turned out to be very useful. The VCA sites are only 50 × 60 m in size, which is significantly smaller than the 1 km AVHRR or 250 m MODIS pixels. Without these field data it would have been impossible to ground-truth the satellite data and demonstrate its value.

Figure 3.26 Annual grass biomass measurements taken with a disk pasture meter at one of 533 VCA sites in the Kruger National Park. [Konrad J. Wessels]

The impact of ENSO events on rainfall and vegetation production

The ENSO phenomenon is monitored from sea surface temperatures in the Eastern Pacific Ocean. The Oceanic Niño Index (ONI) is based on the three-monthly mean sea surface temperatures and expresses severity of the ENSO phenomenon on an ongoing basis [1, 2]. Figure 3.27 graphs the strong relationship between the ENSO (ONI index), rainfall, growth season sum NDVI (AVHRR) and grass biomass measured at Skukuza in the Kruger National Park. Given the diverse nature of the measurements involved (from sea surface temperatures in the Pacific, ONI to grass biomass in field plots) this strong relationship is truly remarkable.

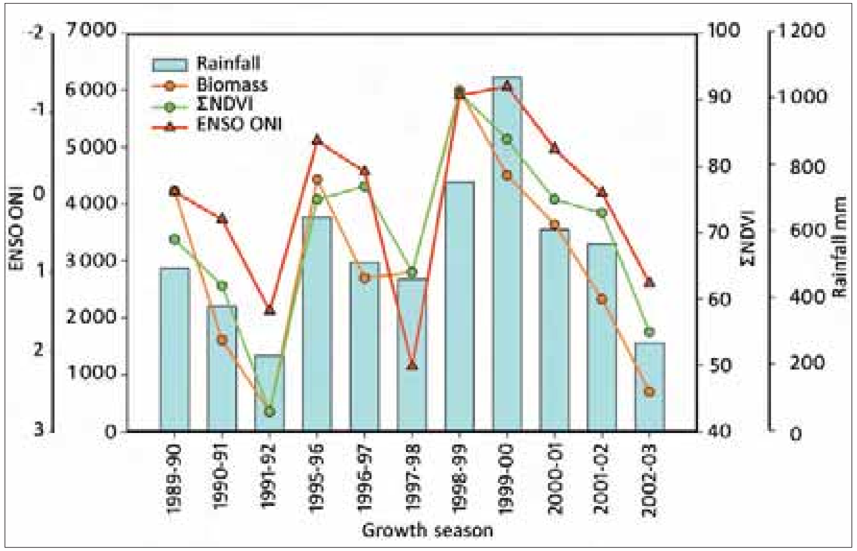


Figure 3.27 Graph showing the strong relationship between the Oceanic Niño Index (inverse scale, high + values indicate El Niño, high – values indicate La Niña episodes), rainfall, grass biomass and AVHRR satellite's growth season sum NDVI for Skukuza in the Kruger National Park.

During the 1991-92 El Niño, just over 200 mm rain fell in Skukuza with the result that less than 400 kg/ha grass was produced. In contrast, a very strong La Niña episode persisted over the 1998-99 and 1999-2000 seasons resulting in very high rainfall (750 and 1 050 mm respectively) and very high grass production, close to 6 000 kg/ha in 1998-99. All the rain that fell during the 1999-2000 flooding could clearly not be utilised by the vegetation (Figure 3.27). This illustrates the huge influence that ENSO has on rainfall and vegetation production.

The impact of the droughts caused by El Niño episodes on the vegetation production of the Kruger National Park is evident in the AVHRR satellite data for 1991-92 (one of the driest years on record), 1997-98 and 2002-2003 (Figure 3.24). The very high vegetation production as a result of the high rainfall during 1996-96, 1998-99 and 1999-2000 La Niña event is very clear in the AVHRR growth season sum NDVI (Figure 3.24).

The impacts of the 1999-2000 La Niña event was still evident in the high vegetation production in the 2000-2001 growth season, as indicated by the MODIS satellite data (Figure 3.25). This was followed by the droughts caused by the 2002-2003 and 2004-2005 El Niño episodes. The historical satellite time-series data can therefore provide essential spatial information on ecosystem variability and resilience in the context of ENSO episodes.

Responses to ENSO – management and adaptations

Drought driven by ENSO is a natural part of this highly variable ecosystem and SANParks policies and management do not attempt to override the impacts of this process [4]. In fact, droughts may be beneficial to the national park's conservation objective of maintaining natural patterns and processes in order to maximise the maintenance of biodiversity through time. For example, although herbivores may suffer during extreme and extended drought periods, other species such as predators (for example, wild dogs) may flourish. The reverse is true during extreme wet periods when the herbivores are widely distributed and generally in good condition. Although the provision of artificial water holes might appear to be a solution to the general public, research has shown that this merely exacerbates starvationinduced mortality of game [5] and may severely degrade the vegetation over large areas around the watering hole [6].

ENSO episodes also have a very large impact on fire in the Kruger National Park and fire is a major driver of vegetation structure, such as the balance between grass and trees in the savanna. In the winter season following an El Niño summer, only a very small portion of the park burns naturally (less than 5%) because there is very little grass to fuel the fire. Conversely, as much as 30-50% of the park can burn following a high rainfall La Niña summer season when grass fuel is abundant [7]. In order to avoid disastrous runaway fires following a high rainfall growth season (for example, 1996-97) the park applies prescribed burning early in the fire season (April to June) to reduce the amount of grass fuel and break up the landscape into a mosaic of burnt and unburned areas with low intensity fires. The park thus has to perform many prescribed burns in a La Niña year and very few, if any, in an El Niño year.

In contrast with the Kruger National Park, livestock and game farmers find themselves in a precarious position, where their livelihoods are often at the mercy of ENSO. The 1991-92 El Niño caused massive cattle deaths in the neighbouring communal areas when households lost more than half of their herds [8]. The cattle numbers are only now recovering to pre-1991 levels, although fewer households now hold any cattle. Interestingly, an adaptation to El Niño in the communal areas appears to be a switch from cattle to goats, which are cheaper, less vulnerable to drought and reproduce faster. The negative impact of drought on cattle ownership might force families to turn to new alternative livelihood activities not pursued before, such as the sale of fuel wood [8].

It is clear that ENSO has a very large impact on the rainfall, vegetation and fire in the Kruger National Park and surrounding areas. In fact, ENSO has a significant impact across southern and eastern Africa as well as the rest of the globe [2]. Long-term satellite data sets, climate data and field measurements are indispensable in monitoring these impacts, but need to be appropriately employed to reduce the vulnerability of rural livelihoods to ENSO episodes [9].

Acknowledgements

Philip Frost and Dawie van Zyl processed the AVHRR data. We thank SANParks for access to the VCA data.

RANGELANDS

Assessing degradation across a land-use gradient in the Kruger National Park area using advanced remote sensing modalities

Jan A.N. van Aardt
Renaud Mathieu
Moses Cho
Konrad J. Wessels
Barend F.N. Erasmus
Gregory P. Asner
Izak P.J. Smit

Land degradation is regarded as one of the most important environmental issues facing sub-Saharan Africa and is especially relevant in the former communal 'homeland' areas of South Africa. Although it has been a topic of intense research, efforts have reached a juncture at which regional modelling and monitoring are constrained by the relatively coarse scale and sensitivity of traditional remote sensing technology as compared to the fine scale at which many processes occur. However, two relatively novel remote sensing approaches, namely imaging spectroscopy (hyperspectral remote sensing) and light detection and ranging (lidar), have the potential to alleviate this constraint. Specifically, the Carnegie Airborne Observatory, a state-of-the-art integrated imaging spectrometer-lidar platform operated by the Carnegie Institution for Science, is being used by South African and international researchers to gain a better understanding of degradation and its impact on rural livelihoods and environmental protection in South Africa.

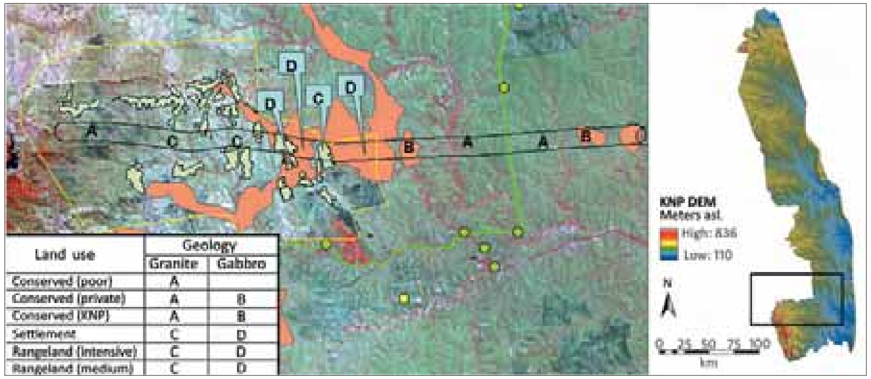
Introduction

Land degradation is defined as a persistent reduction in the capacity of the ecosystem to deliver ecosystem services to the broader community, for example, grazing, fuelwood, or habitat for wildlife. The process could involve a reduction in grass production, changes in plant species composition, and soil erosion as a result of overgrazing, as well as increases in tree cover (bush encroachment) or reductions in tree cover due to excessive wood removal. It is regarded as one of the most important environmental issues facing sub-Saharan Africa and is especially prevalent in the communal lands of the former 'homelands' [1]. It is therefore understandable that land degradation has been a topic of intense research [2, 3], but has approached a point at which regional modelling and monitoring are limited by the capabilities of traditional satellite remote-sensing technology. One of the limiting factors is the reliance on high revisit times, low to moderate spatial resolution (30-500 m pixels), multispectral (3-20 wavebands) remote-sensing data. Sensors, such as 1 km/pixel AVHRR, 500 m/pixel MODIS and 30 m/pixel Landsat TM sensors, serve best as regional or continental assessors of vegetation production. These spectrally and spatially coarse resolution data cannot unravel changes in the land surface (specifically reduced grass cover, increases in bare soil and reductions in tree biomass) at the scale at which the processes actually occur (a few meters), nor can they identify fine-scale vegetation composition and structure.

The need for fine-scale degradation assessment helped to define a new breed of sensors that (a) have a broader wavelength range, defined in narrower wavelength bins (imaging spectroscopy, also called 'hyperspectral' remote sensing) and (b) are capable of describing the three-dimensional vegetation structure, for example, lidar remote sensing. One such sensor platform is the Carnegie Airborne Observatory (CAO) operated by the Carnegie Institution for Science, shown in Figure 3.28.

Figure 3.28
The CAO system (a) in operation (Dr Greg Asner, the CAO principal investigator, left, and Ty Kennedy-Bowdoin, system engineer, right). The imaging spectrometer and lidar sensors (b-c) mounted in the aircraft for data collection.

More than two million people reside within 50 km of the western boundary of Kruger National Park, with the vast majority concentrated in the former homelands which are widely regarded as degraded. Previous work in these communal areas has raised the concern that excessive wood removal and transformation of woodlands by subsistence cultivation may be threatening the tree resources [4]. This provides the opportunity to investigate the impacts of contrasting land uses on ecosystems along a land-use gradient, from the Kruger National Park (conserved area) to private game reserves (managed for eco-tourism) and former homeland areas (subsistence livelihoods) in the Lowveld (Figure 3.29). Local and international researchers have collected hyperspectral and lidar data using the CAO during a six-week flight campaign in 2008. These data allow us to investigate how imaging spectroscopy and lidar can improve our understanding of local, fine-scale land degradation by looking for subtle changes in grass and tree species composition (spectral) and structure (lidar) along this land-use gradient. This will provide measures of ecosystem state variables that can be monitored to establish if the ecosystem can sustain ecosystem services and products such as fuelwood and grazing in the long term. Ultimately this work will support the development of operational, management solutions by helping researchers and managers to better understand how degradation manifests at such scales and to extract information from regional and space-based sensors for savanna degradation monitoring and management.



Land use	Geology	
	Granite	Gabbro
Conserved (poor)	A	
Conserved (private)	A	B
Conserved (KNP)	A	B
Settlement	C	D
Rangeland (intensive)	C	D
Rangeland (medium)	C	D

Figure 3.29 The study area in the Kruger National Park that shows the flight line spanning conservation, private game reserve, and communal lands, as well as a variety of geological strata.

The Carnegie Airborne Observatory (CAO)

A brief introduction to hyperspectral and lidar remote sensing modalities, onboard the CAO system, is warranted before looking at early results of this project.

- Imaging spectroscopy (hyperspectral data) provides a large number (>100) of narrow-band and contiguously sampled wavelengths for an area, usually in the range of 400-2 500 nm (blue to shortwave-infrared regions). Such a sensor is analogous to the human eye in the visible domain. Humans can see not only blue, green, and red, but subtle variations of these hues and combinations thereof – in other words, your eye is a hyperspectral sensor! This is in stark contrast to multi-spectral sensors. For example, the well-known Landsat satellite with six bands in the 400-2 500 nm range, which, in our analogy, can in fact only see blue, green and red (Figure 3.30). Hyperspectral data are typically useful for mapping vegetation stress, species composition, nutrient status, minerals, and such like. These are applications that require narrow spectral channels for extraction of very specific spectral features.
- Light detection and ranging (lidar), on the other hand, involves the emission of a laser pulse from an airborne sensor, the measurement of the laser pulse's return-travel time from sensor to target and the calculation of the distance travelled by the laser beam [5]. You can compare this to a high-tech range finder one buys at a local hardware store, except a lidar typically pulses more than 70 000 times per second and can accurately measure distances from as far as 4 km for large areas. A distinction can be made between 'discrete return' and 'waveform' lidar sensors. Discrete return sensors measure x,y,z (height) coordinates per laser pulse (Figure 3.31), while waveform systems capture the 'energy wave' of the laser as it interacts with a target, for example, a tree or building. The denser and more abundant materials make for a bigger wave and vice versa. Figure 3.32 shows an example of the hyperspectral imagery and lidar-based height data captured by the CAO.

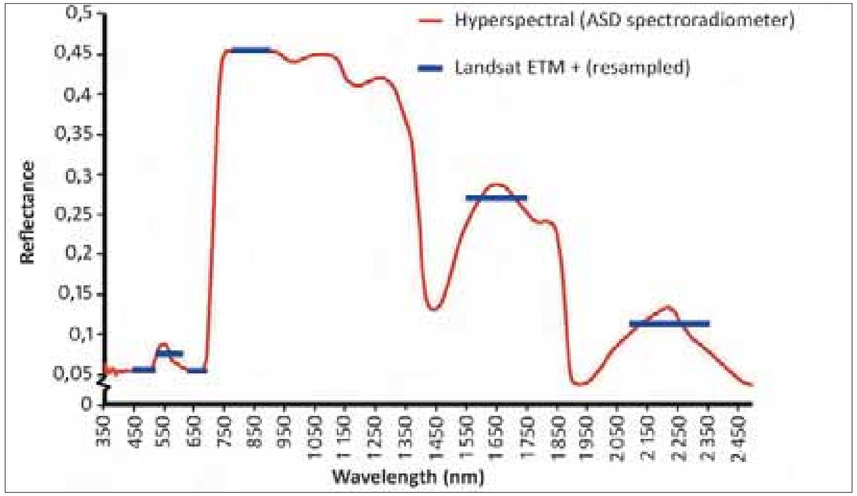


Figure 3.30 An example of hyperspectral data (ASD spectroradiometer) versus Landsat spectral sampling characteristics for a typical green vegetation spectrum.

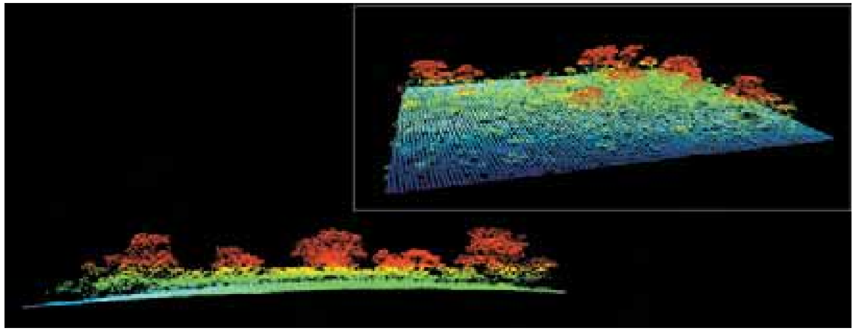


Figure 3.31 CAO discrete return lidar data that illustrate the concept of multiple lidar 'returns' or 'hits'. Each return has a defined x- and y-coordinate, as well as a z, or height value. We can use this information to better understand and improve characterisation of savanna vegetation structure.

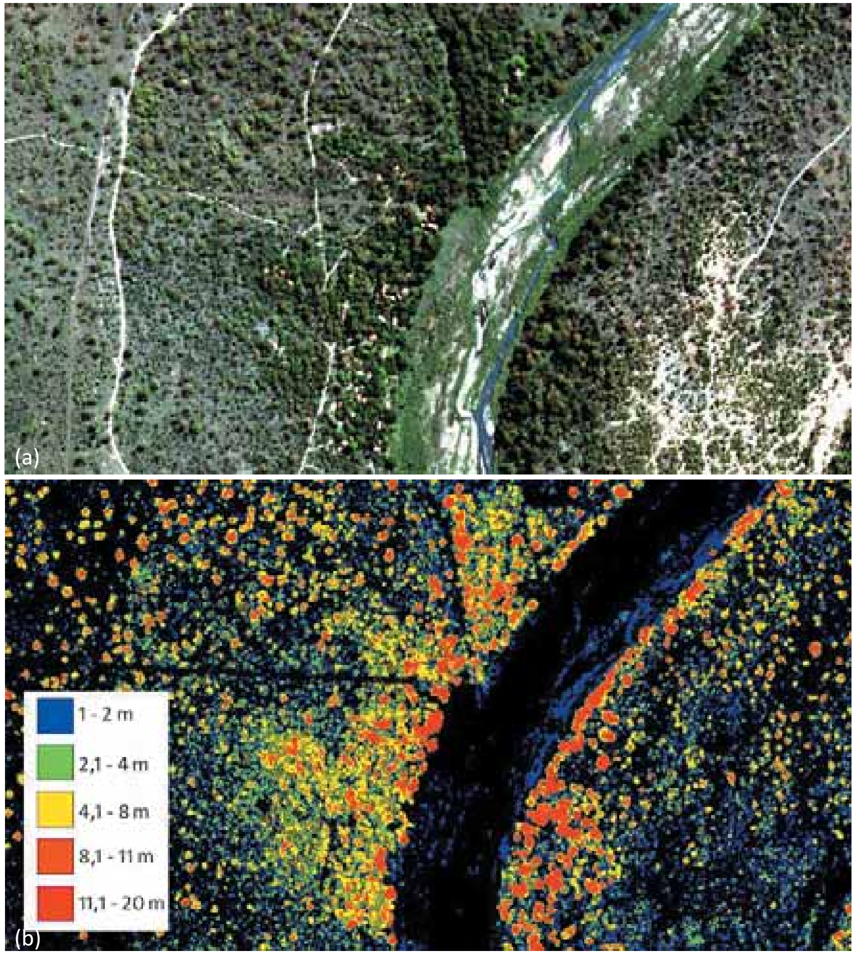


Figure 3.32 (a) Sample of hyperspectral true colour composite imagery and of Sabi River. (b) Lidar imagery of same area indicating tree canopy height (low-green to high-red). Both data sets were captured simultaneously by the Carnegie Airborne Observatory.

The CAO is an airborne platform that includes, over and above the hyperspectral and lidar sensors, the navigational and computational capacity to integrate them virtually in real time. The CAO is designed and operated by Dr Greg Asner (Carnegie Institution for Science) and is primarily a research instrument. This system makes use of the data properties of both hyperspectral and lidar technologies for describing any target (or natural system in our case) in spectral and structural domains. Such a novel approach presents significant benefits to ecosystem research, especially to the widespread and complex process of land degradation in South Africa.

Local research questions

A key set of research questions are being addressed collaboratively by the Council for Scientific and Industrial Research (CSIR) Ecosystems Earth Observation (Drs Renaud Mathieu and Moses Cho), Meraka Remote Sensing Research Unit (RSRU; Dr Konrad Wessels), and Ecosystems Processes and Dynamics (Dr Bob Scholes), along with the Wits Animal, Plant, and Environmental Science department (APES; Dr Barend Erasmus), Kruger National Park (KNP) Scientific Services (Dr Izak Smit), Rochester Institute of Technology (RIT; Dr Jan van Aardt), and the CAO team (Dr Greg Asner) groups (Figure 3.33).

Figure 3.33 The core team that heads up various aspects of the CAO research effort (from left-to-right): Drs Shaun Levick (CAO), Izak Smit (KNP), Jan van Aardt (RIT), Konrad Wessels (CSIR), Greg Asner (CAO) and Barend Erasmus (Wits). (Renaud Mathieu and Moses Cho (CSIR) are not pictured here.)

The main research questions and their impacts are:

- What differences in ecosystem state variables (for example, woody vertical structure, cover, and composition, grass biomass) can be observed across a KNP-rural settlement gradient? *Such information might address tree biomass changes due to wood removal and browsing and contribute to management policies in this region.*
- Can the quantitative measures of land degradation (for example, fractional area of bare ground versus grass cover; leaf area, leaf nitrogen and secondary chemicals) across such a gradient be improved using the spectral-structural interaction derived from the CAO? *Researchers will be able to gain a better understanding of land degradation processes and interactions by answering this question.*
- Which key spectral/structural indicators are necessary to address the questions posed above – how do we go from over-sampled spectral and structural data volumes to manageable solutions and quantitative measures of degradation, and how might future sensors be optimised? *This will allow managers to implement more operational versions of the expensive sensing modalities, especially once we know exactly what we need to effectively 'sense' remotely.*
- Can this package of information and integrated modelling be used to predict the annual production of ecosystem services, such as grazing and fuelwood, and therefore help to determine sustainable levels of utilisation? *Answers to these questions have distinct implications in terms of conservation and rural management policies.*

Recent project outcomes

The CAO mission to South Africa has presented an opportunity for research collaboration at the cutting edge of ecosystem state assessment. As noted previously, vegetation structure and composition, for example, tree density and size distributions, cannot be sufficiently measured and monitored with existing optical remote sensing; however, high spatial resolution lidar and hyperspectral technology provide a viable, reliable, and fine-scale alternative.

The project has thus far led to exciting preliminary results, many of which are truly novel, for example:

(a) Improved understanding of ecosystem degradation through the development of hyperspectral and lidar based metrics at the appropriate scales: A collaborative team has shown that bare soil, as well as woody and grass cover, can be mapped using the hyperspectral sensor onboard the CAO. This fractional representation of these different covers is a prime indicator of land degradation and is expected to differ across the Kruger National Park-game reserve-homeland land-use gradient. Figure 3.34 shows the difference between woody, grass and bare soil cover for (a) a rangeland site in the Kruger National Park and (b) a site of similar rainfall in the private game reserve. Note the change in especially woody versus grass cover due to different management regimes. The west-to-east rainfall gradient could also have had a marginal impact.

(b) Results that have management and policy applications: If we could better understand how the different management scenarios impact the natural systems, this should lead to improved management of conserved and highly altered ecosystems. Researchers have shown that structural differences in woody cover exist along the studied land-use gradient. There is evidence that not only woody cover but also the height distribution of the remaining trees in highly impacted communal areas are significantly different from those of comparable sites in the private reserves and Kruger National Park. Most notably, the total tree canopy cover is less than half in highly impacted communal areas, while in other communal areas the canopy cover is much higher due largely to increases in shrubs lower than 2 m (Figure 3.35).

(c) Finally, metrics of vegetation structure are being developed based on cutting-edge waveform lidar data to provide indicators of degraded ecosystems. Figure 3.36 on page 103 shows one such example, extracted by the team at RIT (Dr Jan van Aardt), of a typical lidar waveform visualisation showing the 3D vegetation structure and foliar biomass.

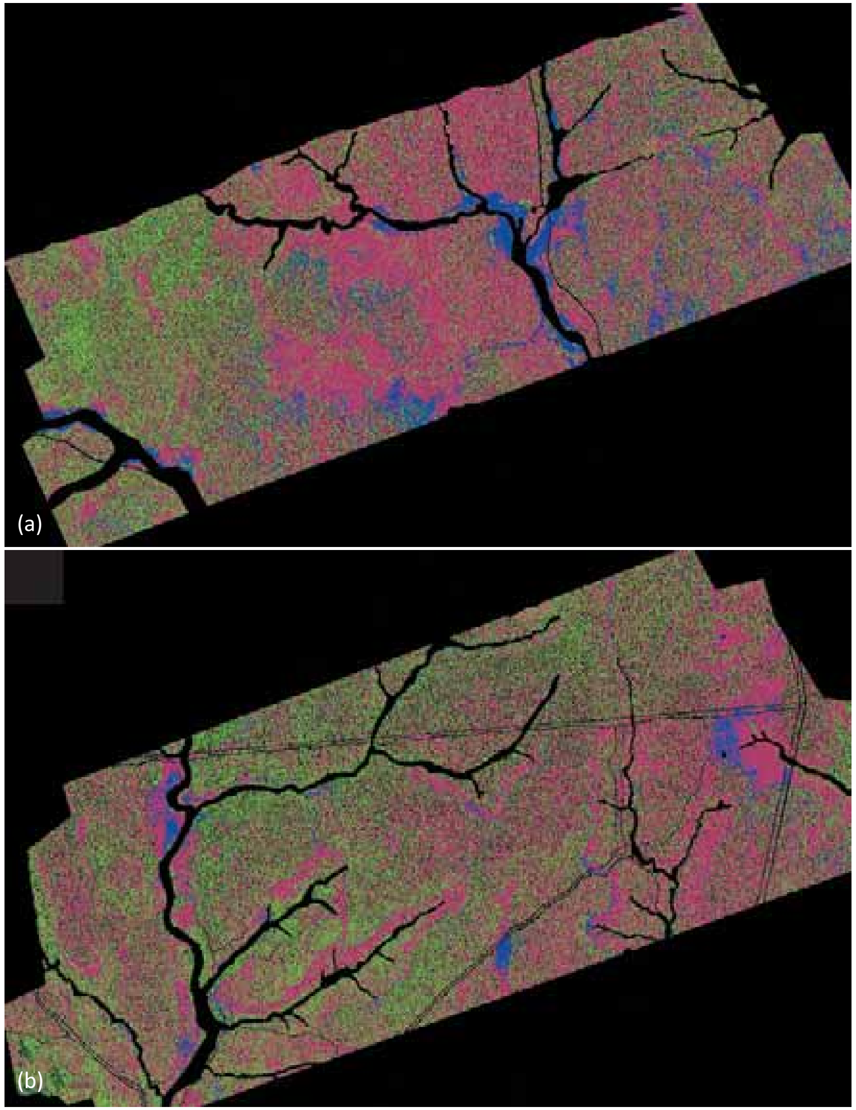


Figure 3.34 Thematic maps that show the woody (green), grass (red) and bare soil (blue) cover for (a) the Kruger National Park and (b) a private game reserve. These representations are for sites with a similar annual rainfall and show changes in cover, as driven by different management regimes.

Figure 3.35 (a) Very low tree cover (2%) in highly-impacted communal area on gabbro substrate as a result of long-term fuelwood removal. (b) Expected tree cover (11%) in conservation area on gabbro substrate near photo (a).

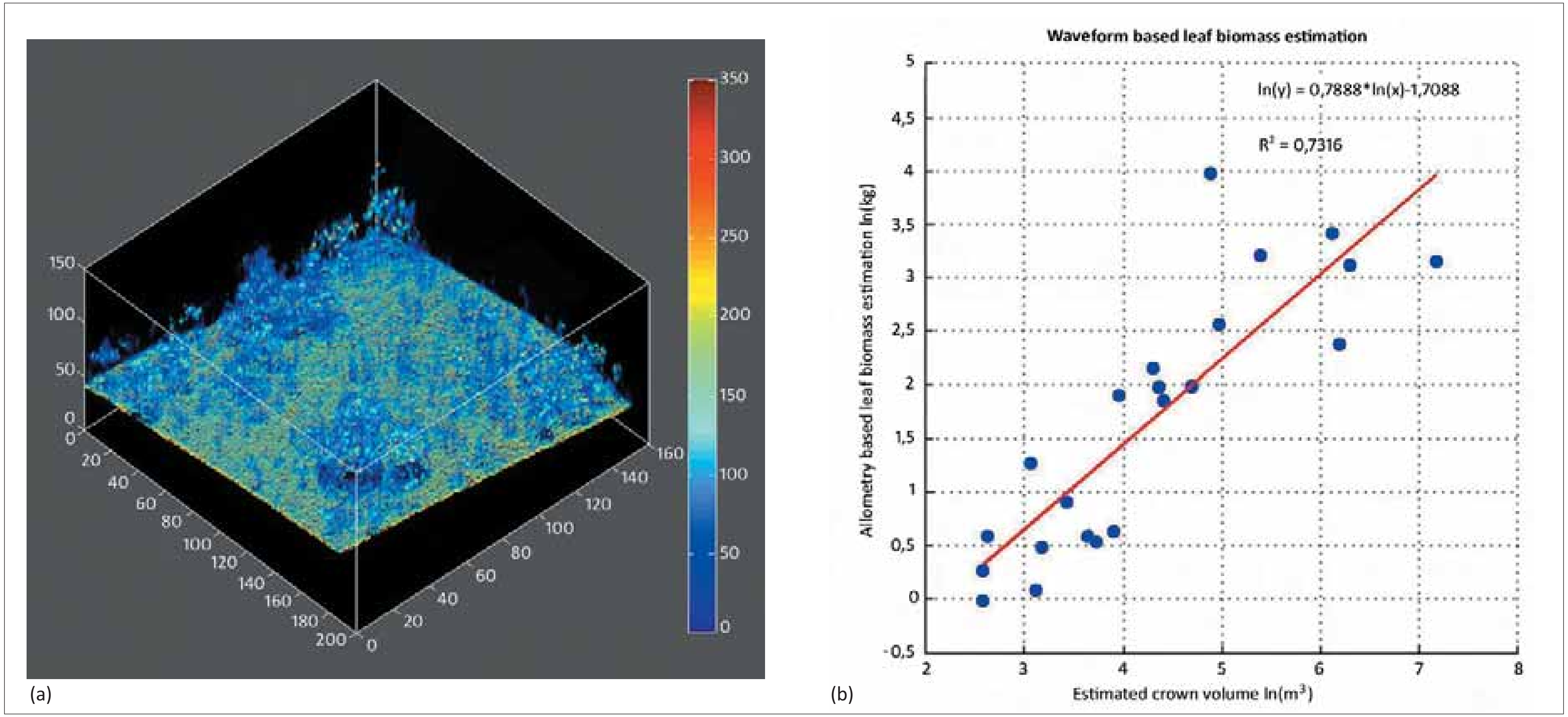


Figure 3.36 (a) A representation of the lidar intensity at a given x,y,z location (intensity refers to the bulk of matter that is returning a signal to the sensor; the legend shows the range of intensity values). (b) A plot of the relationship between modelled field leaf biomass and crown volume, derived from the waveform lidar data. Note that we are able to explain 73% of the variation (information) in foliar biomass using a single sensor.

Imaging spectroscopy (hyperspectral) and lidar (structural) research are in their infancy in South Africa. However, as we rapidly develop methods to extract valuable information from these data and this technology becomes more affordable, future monitoring systems can be based on lidar and hyperspectral imagery. In fact, lidar provides the only viable option for monitoring tree density, structure, and biomass across large areas. The work juxtapositions efforts by the CAO team and their focus on tropical forests; local research is designed to increase our understanding of animal and plant dynamics and interactions in a *savanna/rangeland environment*. Although certain principles are transferable across such diverse ecosystems, there are few substitutes for local knowledge and environment-specific data exploration. Such an approach and its associated outcomes are therefore especially critical, especially in terms of improved management and decision making of the natural resource base upon which many rural livelihoods depend.

RANGELANDS

Monitoring land degradation with long-term satellite data

KONRAD J. WESSELS

In South Africa, land degradation in rangelands has been regarded as a major environmental problem for many years. During the last ten years, attention focussed on the land degradation in the former homelands, now communal lands. There is an urgent need for a standardised, quantitative and spatially-explicit measures of ecosystem functions to map and monitor land degradation, especially in the light of land redistribution and restitution. We investigated the long-term vegetation production of these degraded areas with 18 years of satellite data which provided an objective and repeatable, regional monitoring tool.

Introduction

Desertification is defined by the United Nations Convention to Combat Desertification (UNCCD) as '*land degradation in arid, semi-arid and dry sub-humid areas (drylands) resulting from various factors, including climatic variations and human activities*' [1]. Land degradation includes diverse processes from changes in plant species composition to soil erosion that result in reduced biological or economic productivity of the land. We prefer to use the term 'land degradation' as it focuses attention on the human impacts on the land rather than confusing people with climate change processes.

In South Africa, land degradation in rangelands has been regarded as a major environmental problem for many years. During the first half of the 20th century, the topic was dominated by the 'expanding Karoo' theory, which described the alleged expansion of semi-arid Karoo northeastwards into the grasslands as a result of overgrazing by commercial sheep farmers [2]. During the 1990s, an extensive review could find no evidence to support this theory [3].

The SA National Review on Land Degradation (NRLD), subsequently directed attention to severe land degradation in the former homelands, now communal areas [4, 5]. The homelands, or self-governing territories, were established under the Natives Land Acts of 1913 and 1936 and during the apartheid-era, prior to majority rule in 1994, indigenous African people were involuntarily resettled and confined to these areas. Stable communities were uprooted and compelled to settle in areas where the unsustainable land use degraded the local resource base upon which their rural livelihoods depended. Today, communal areas are generally characterised by high human populations, overgrazing, soil erosion, excessive wood harvesting and increases in unpalatable plant species [4, 5] (Figure 3.37).

Figure 3.37 Soil erosion and overgrazing in communal areas. [K. Wessels]

Degradation continues to threaten the local resource base upon which rural communal livelihoods depend. The underlying cause of degradation is a combination of unemployment, poverty and an absence or failure of land-use regulation. The degradation observed in the communal lands is thus principally a consequence of high population densities aggravated by the oppressive apartheid system rather than the outcome of traditional communal pastoralism.

There is an urgent need for standardised, quantitative and spatially-explicit measures of ecosystem functions to map and monitor land degradation, especially in the light of land redistribution and restitution. Most maps of land degradation constitute subjective, expert opinions and cannot be used to systematically track degradation through time and space.

Mapping land degradation in South Africa

Over the past ten years in South Africa, significant efforts have been directed at this challenge, using diverse methods and data.

Firstly, the NRLD was based on a systematic survey of the perceptions of 453 agricultural extension workers and resource conservation technicians about the degradation status of 367 magisterial districts. From these surveys various indices of the severity, extent and rates of different types of degradation (such as reduced vegetation cover, plant species composition and bush encroachment) were estimated.

Secondly, a National Land Cover map (NLC) was prepared using single 1995-96 Landsat TM data, manual photo-interpretation and extensive fieldwork [6]. 4,8% (5,8 million ha) of the country was mapped as degraded. The 'degraded' classes in the NLC were defined as regions with lower vegetation cover and higher reflectance than surrounding areas [6]. These areas are degraded by both overgrazing and inappropriate land use, such as failed cultivation in marginal areas. Most of the large continuous areas of degradation mapped by the NLC occur within the communal areas.

Neither of these initial methods was sufficiently repeatable for regular land condition monitoring, although they do provide indispensable base-line information.

Monitoring land degradation with satellite data

Long-term, coarse resolution satellite data have been widely used to monitor vegetation dynamics and detect land degradation [7]. Vegetation production is routinely estimated with the normalised difference vegetation index (NDVI) derived from satellite data. NDVI captures the marked contrast between the strong absorption of solar radiation in the visible and strong reflectance in the near-infrared wavelengths that is characteristic of live, green vegetation and provides an estimate of the energy used by plants for photosynthesis. Remotely-sensed vegetation production may well be the single most useful indicator of land degradation at regional and decadal scales [7].

While repetitive, global remote sensing has been applied to mapping and monitoring degradation, however, interpretation of the results has not always been based on sound ecological principles. A critical aspect of a useful degradation mapping and monitoring system is the ability to distinguish the impacts of human activities from natural variability in climate and spatial variations in soils and land cover types.

These degraded rangelands have been subjectively mapped using single date Landsat TM images as part of the NLC. We investigated the long-term vegetation production of these degraded areas with 18 years of 1 km^2 resolution AVHRR NDVI data (1985-2003) and five years of MODIS satellite data (2000-2005), by comparing them to non-degraded adjacent areas with the same soils and climate. We found that the non-degraded areas had consistently higher vegetation production as indicated by the seasonal total of NDVI obtained from satellite observations despite a six-fold variation of annual rainfall (Figure 3.38). This indicates that the degraded areas produce less vegetation per unit rainfall and suggests that they may have changed to a different ecological state.

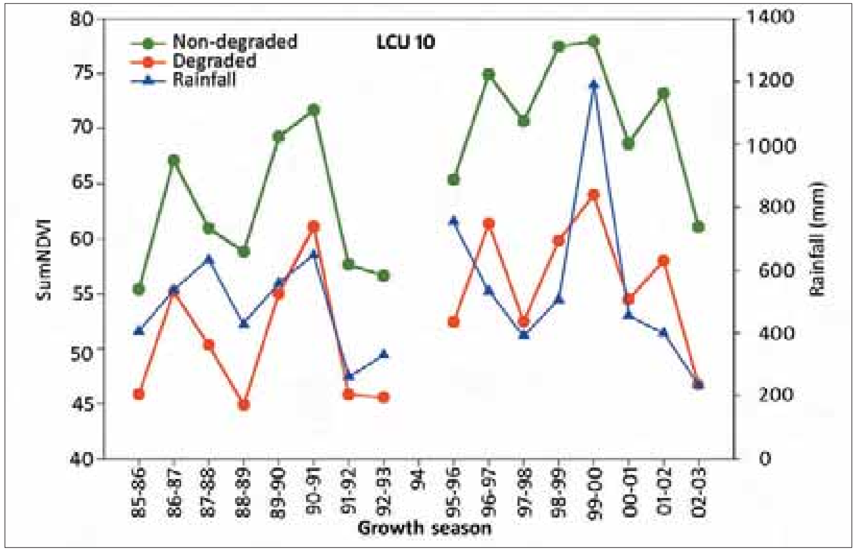


Figure 3.38 Annual productivity of non-degraded and degraded rangelands with the same climate and soils in Limpopo province, measured using the annual total of NDVI from AVHRR sensors on the NOAA series of meteorological satellites. The time series of NDVI indicates a consistent gap despite large variations in rainfall.

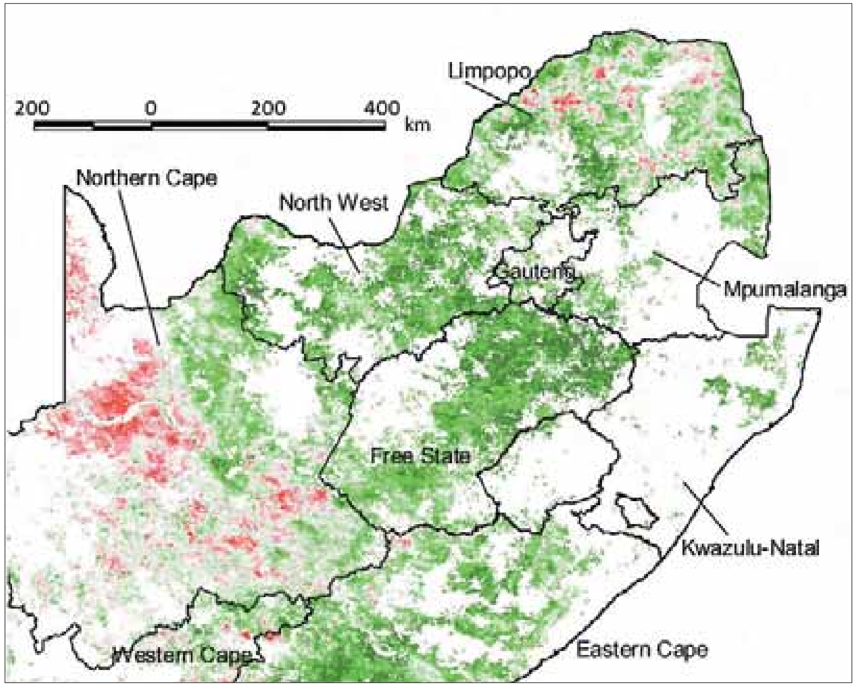
Although these degraded areas never reach the same vegetation productivity as the neighbouring non-degraded areas [8], they consistently support large numbers of livestock and results suggest that they are functionally stable and resilient. Therefore, there does not appear to be any danger of a catastrophic collapse as historically predicted [8-10]. Whether the difference in total rangeland production translates into economic loss remains to be determined, especially since communal use of livestock is completely different to the commercial cattle ranching. These results have made a significant contribution to understanding the ecological processes in degraded areas – research that would not have been possible without a long-term, regional satellite data archive.

Distinguishing human-induced degradation from drought

In arid and semi-arid regions vegetation production varies between years. This is caused primarily by inter-annual rainfall variability. Southern Africa suffers periodic droughts; some caused by the El Niño phase of the El Niño-Southern Oscillation (ENSO) cycle. Extreme variability in vegetation production between years makes it exceedingly difficult to distinguish long-term changes caused by human-induced land degradation from the effects of periodic droughts. One approach to monitoring land degradation is to use both long-term AVHRR NDVI data and rainfall surfaces to identify any negative trends in vegetation production per unit rainfall through time (1985-2003) [11]. In contrast to previous maps of land degradation in South Africa that were mainly based on expert opinions, the remote sensing approach is objective and repeatable and all indications are that it will furnish a valuable regional monitoring tool.

In the Limpopo province, negative trends were largely associated with the degraded communal lands, although some well-known degraded areas did not show continued negative trends during the study period (1985-2003) (Figure 3.39). It is important to note that remote-sensing based monitoring methods can only detect changes that occurred within the time series, and since the homelands were created as long ago as 1913 or 1936, much of the degradation could have occurred before the start of the satellite record in 1985 and may not have worsened since. This explains why all the degraded areas did not show continued negative trends.

Besides land degradation, other forms of land cover and land-use change (for example, expanding subsistence agriculture or informal settlements) as well as natural processes can also cause a reduction in production per unit rainfall. The present method should thus be used as a regional indicator to identify potential problem areas that can then be investigated in greater detail using high resolution remote sensing data and field data. It is unlikely that any method that depends exclusively on remote sensing from a single sensor will be able to unequivocally map the complex ecological process of degradation. Maps depicting the trends in vegetation production per unit rainfall, as shown in Figure 3.39, require extensive field verification before management and policy decisions can be based on them.



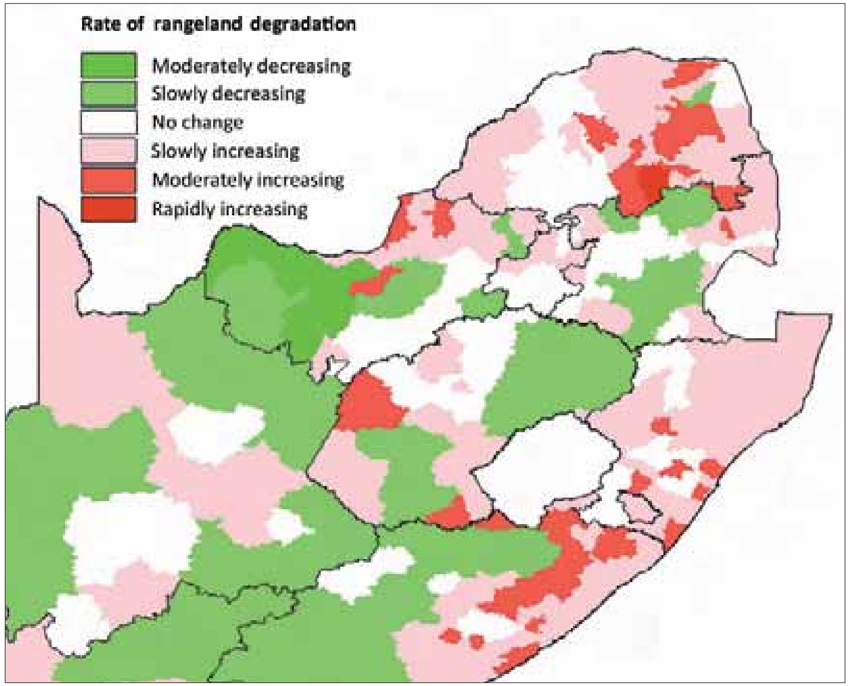


Figure 3.39 Temporal trends in vegetation production per unit rainfall in the summer rainfall region of South Africa (red: negative, green: positive) derived with NOAA AVHRR data from 1985 to 2003.

Validation satellite products – the long-term role of SAEON

The Department of Agriculture is actively involved in the verification process of the satellite-based land degradation maps by means of helicopter and field visits (Figure 3.40). These have provided positive results in some areas, but conflicting results in others. Changes through time can obviously not be properly validated without long-term field observations for comparison with satellite time-series data. This underpins the need for long-term field observations as endorsed by SAEON.

SAEON is designed according to the Global Terrestrial Observation System (GTOS), which follows a hierarchical site design for optimally sampling the environment at different scales. It strives to combine in-situ measurement with remote sensing data of various resolutions as well as models to approximate a comprehensive coverage in time and space from a sparse set of samples. However, this will require careful survey design to ensure that the field data can be scaled-up to be comparable to medium and coarse resolution satellite data. It is envisioned that these field data will be collected at SAEON's core sites on an ongoing basis. In addition, it is planned that South Africa's soon to be launched high-resolution satellite, called SumbandilaSat, will provide at least four images of each SAEON core site for validation and research purposes.

Acknowledgements

This work was partially funded by NASA Earth Systems Sciences Fellowship O2-0000-0130, SA Department of Agriculture (DoA, Land Use and Soil Management Directorate), and SA Department of Science and Technology (LEAD project funding). A special word of thanks to Dirk Pretorius of DoA for supporting this research. The ARC-Institute for Soil, Climate and Water supplied and processed AVHRR and rainfall data.

Figure 3.40 Dirk Pretorius (INSET) of the National Department of Agriculture in their helicopter, validating the AVHRR satellite product as an indicator of land degradation, using live GPS tracking visualised over the satellite data. Land degradation in the Limpopo province photographed from the Department of Agriculture's helicopter in 2008. [K. Wessels]

Using models to predict the probability of degradation of rangelands when subjected to different management strategies

F. David Richardson
M. Timm Hoffman

Models can link together our knowledge of factors influencing processes within rangeland production systems, including growth and survival of different plant species, diet selection by grazing and browsing animals, as well as growth, reproduction and mortality of livestock. Models have been specifically developed for Succulent Karoo and Savanna ecosystems. Model output predicts the effects of management strategy, rainfall and the numbers and kinds of animals on the probability of degradation of the vegetation and of decreased production of meat, milk and animal fibres.

Introduction

For many decades, concern has been expressed over the sustainability of livestock production from arid rangeland in Africa [1, 2]. Overgrazing has frequently been cited as the cause of declining productivity [2-4]. However, the expected long-term decline in livestock numbers on communal rangeland has not been observed in southern Zimbabwe [5], in the Herschel district of the Eastern Cape [6] or in Namaqualand [7], although numbers do vary substantially between years. On the other hand, Hoffman *et al.* [7] reported that a common trend in the lowlands of communal areas in Namaqualand has been to change a palatable perennial shrubland which comprises woody perennials (WP) and Mesembs (ME) to a mix of annual (AN) and unpalatable or poisonous plants such as *Galenia* (GA) (Figure 3.41). Furthermore,

Figure 3.41 Photographs of different Namaqualand Plant Guilds. (a) Woody Perennial (WP) *Tripteris sinuatum*. (b) Leaf Succulent Mesemb (ME) *Leipoldtia schulzei*. (c) *Galenia africana* (GA). (d) Annual (AN) *Lasiospermum brachyglossum*. [Timm Hoffman]

grass yields from savanna rangelands have been reduced as a result of an increase in the density of woody plants [8]. Explanations for these apparently inconsistent observations are required.

Modelling and monitoring rangelands

Management of rangeland to ensure its sustained productivity and to prevent degradation requires that we understand how the system works. Monitoring plant species, forage production and animal numbers, even for many years, may not enable us to predict future livestock production or the probability of degradation as it is impossible to distinguish between short-term changes in vegetation due to variation in rainfall and irreversible long-term degradation [9]. Moreover, monitoring merely records changes in observable parts of the system. Processes that are not easily measured, such as the loss of water by drainage or runoff and the amounts of plant material eaten by herbivores or lost by decomposition, determine the behaviour of the system. One objective of modelling is to increase the understanding of mechanisms within different rangelands that influence the effects of rainfall and the numbers and kinds of animals on changes in vegetation and on the output of milk, meat and animal fibres.

Semi-arid rangelands are complex systems which comprise soils, plants and animals. Their productivity and the probability of their degradation are influenced by many factors, including rainfall and its variation between and within years as well as the infiltration rates and water storage capacity of the soil. The standing biomass and species composition of the vegetation are important. The numbers and classes of herbivores, which in turn vary with the amount and nutritional value of the forage that they can eat, also influence the vegetation. Figure 3.42 shows the inter-relations between the parts of a rangeland system.

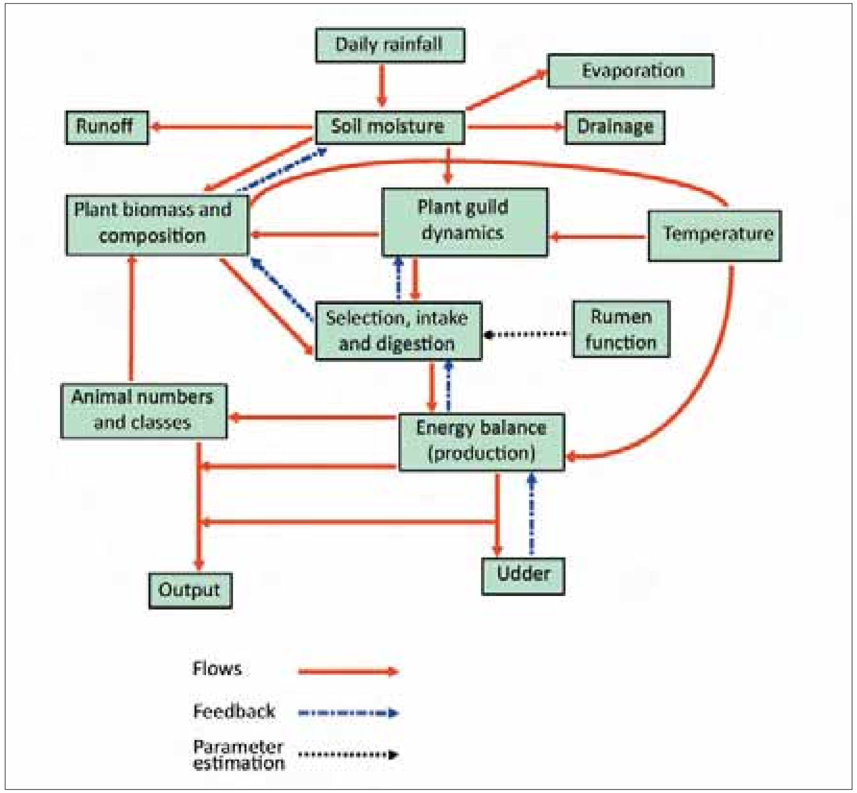


Figure 3.42 Components of rangeland systems and models showing that rainfall drives the system and how the different parts affect one another. (Adapted from Richardson and Hahn, 2007)

Monitoring the relative abundance of different guilds of plants, the yield of edible forage as well as the number and live weights of animals over time, only describes how the system is changing, but does not explain how variations in rainfall and the numbers of animals influence the vegetation. Biot [9] suggested that modelling the behaviour of rangeland is preferable to an approach based solely on monitoring for the prediction of long-term responses to management strategies. Mechanistic models enable us to integrate our knowledge of individual processes within the system. Experiments and the observations of farmers on rangelands rarely exceed 30 years [10]. Simulation models of specific rangelands allow for the responses of both vegetation and livestock to different management strategies to be studied for 100 years or more. Furthermore, model runs may be replicated many times to allow for variations in the distribution of rainfall over time. Mechanistic models comprise sets of equations and rules that describe the behaviour of a system over time.

Modelling scenarios

Short- and long-term models of two rangeland ecosystems (Namaqualand and Savanna) have been developed that link processes that range from the levels of tissue in, for example, the mammary gland, to milk yields, to the growth of the young, to reproductive and survival rates and to long-term changes in plant species populations at the ecosystem level [11, 12]. Variation in rainfall both between and within years is stochastic and changes in the livestock population and in plant species depend on coincidences between many factors. As a result, model runs must be replicated before the probability of such changes may be predicted. The models are run using recorded rainfall data for a specific area or simulated values having the same mean and variability as the recorded data.

Rainfall effects: Namaqualand

Two different sets of 200 year rainfall data for Namaqualand (45 and 49) (Figure 3.43) have been generated and are used in the simulations described.

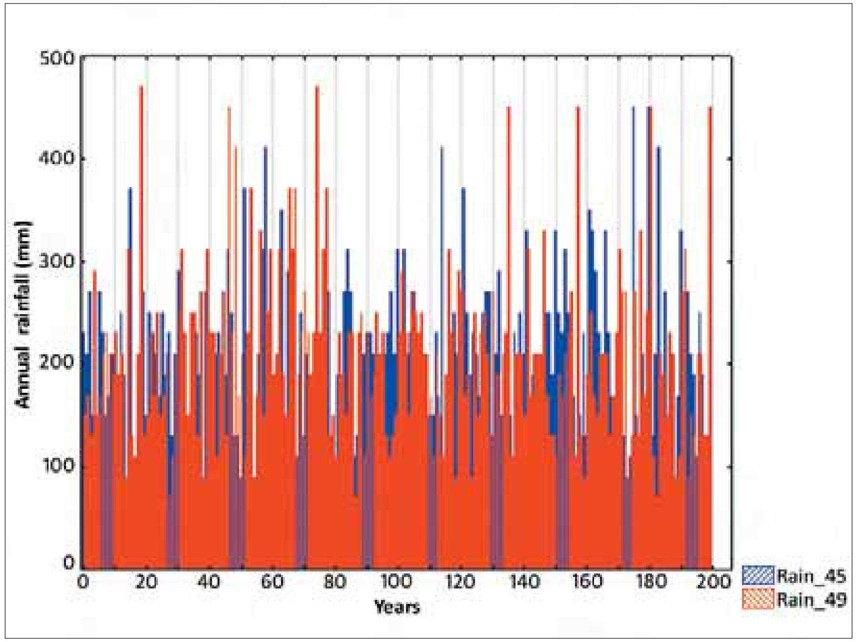


Figure 3.43 Two randomly generated 200 year sets of annual rainfall. Mean annual rainfall for sets 45 and 49 are 205,5 and 207,0 mm respectively.

The long-term model was run using these rainfall sets to simulate 20 000 ha in Namaqualand starting with 1 600 non-kids (adults + yearlings) and the initial percentage cover (a measure of relative abundance) for woody perennial shrubs (WP), leaf succulent shrubs within the family mesembryanthemaceae (ME) and *Galenia africana* (GA) set at 20%, 12% and 10% respectively. Two runs were performed for each rainfall set. First we investigated whether different rainfall sequences lead to different patterns in guild abundance and livestock numbers over time when stocking rates vary between years as a result of birth and death rates. During a drought when severe mortality occurs measures are taken to prevent animal numbers falling below 100 head. For both rainfall sets, goat numbers varied widely between years in response to rainfall (Figures 3.44a and 3.45a). When rainfall set 45 was used, the abundance of all guilds varied over time due to rainfall and animal density, but the palatable WP was the most plentiful guild throughout the 200 years (Figure 3.44a). A different rainfall sequence (set 49) leads to greater variation in animal numbers and in the abundance of all guilds, with GA being the most abundant guild from year 131 to 136 and from year 139 to 186 (Figure 3.45a).

Management effects: Namaqualand

The models were then used to study the consequences of two management strategies for the management of livestock numbers. First, for set 45, livestock purchases or supplementary feeding were used to prevent stock numbers declining below 1 000 head. This leads to a decline in range condition as there is a long-term decrease in WP during the first 100 years, thereafter GA increases substantially and is the most plentiful guild until year 200 (Figure 3.44b). On the other hand, imposing an upper limit of 1 500 non-kids results in an improvement in range condition for run 49. Animal numbers vary little over time and WP is now the most plentiful guild over the whole 200 year period (Figure 3.45b).

So far we have seen how two different rainfall patterns and three stocking rate strategies affect the abundance of different plant guilds. The probable state of the vegetation at the end of 100 years is an estimate of the probability of rangeland degradation. The condition of the Namaqualand range deteriorates as the total perennial cover decreases and the proportion of *Galenia* increases (Figure 3.46). As rainfall is so variable and interacts with the current state of the vegetation and animal numbers, the runs are repeated 1 000 times for each treatment so that the probability of a specific final state may be predicted. As the upper limit on animal numbers increases the probable final condition of the vegetation deteriorates (Figure 3.47).

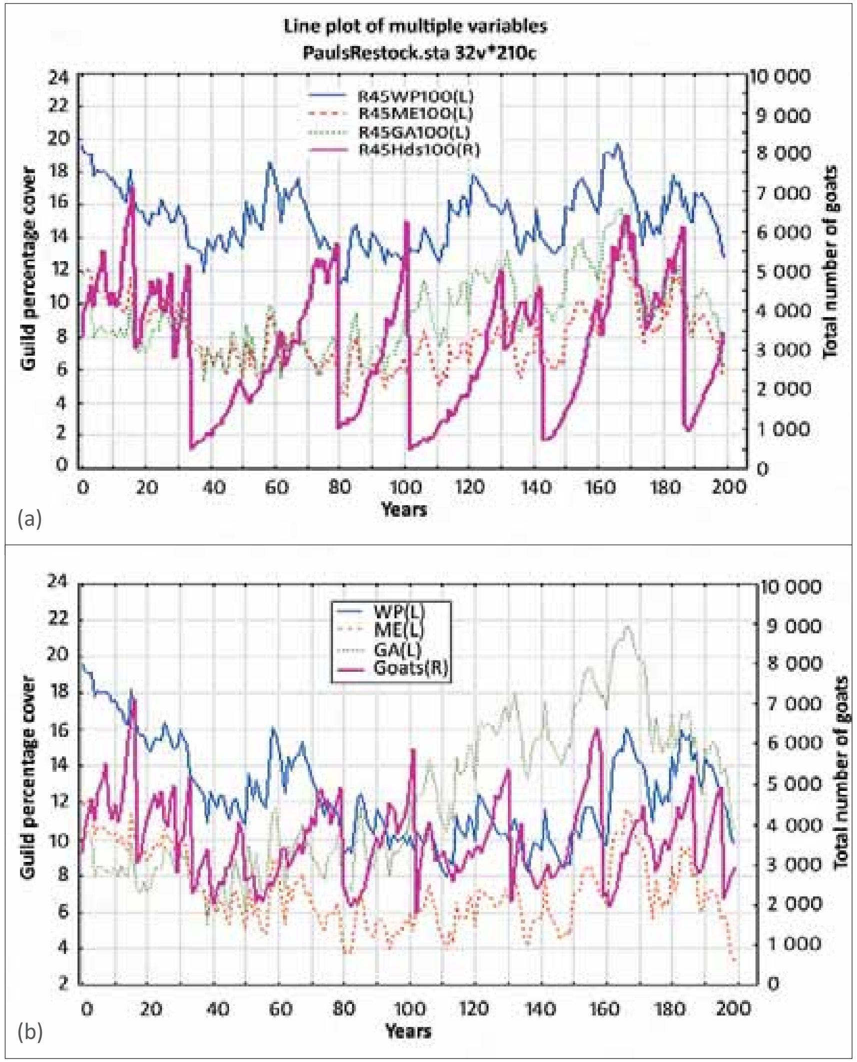
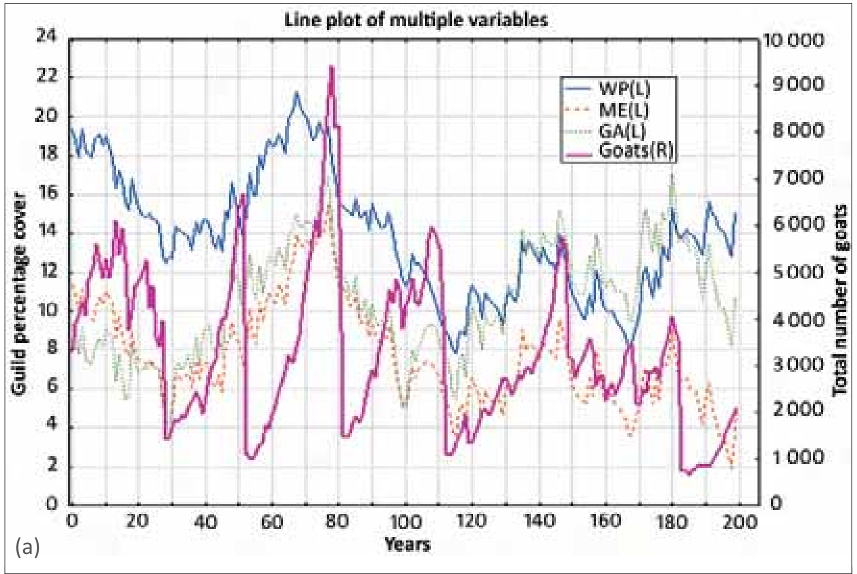


Figure 3.44 Variations in guild cover and goat numbers over 200 years using rainfall set 45. Animal numbers vary with birth and death rates. (a) Minimum stock number 100. (b) Minimum stock number 1 000.



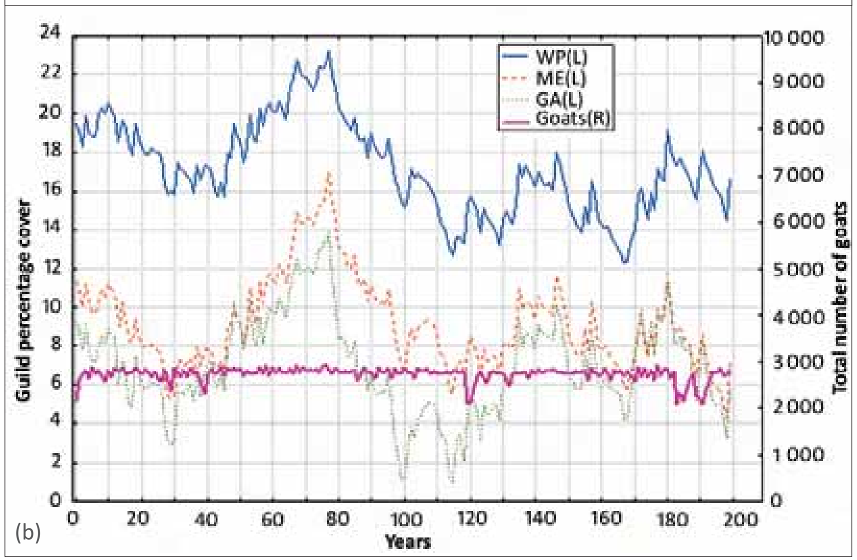


Figure 3.45 Variations in guild cover and goat numbers over 200 years using rainfall set 49. Minimum stock number 100 for both treatments. (a) Animal numbers vary with birth and death rates. (b) Adults + yearlings (non-kids) limited to 1 500.

Figure 3.46: Different states of the Paulshoek rangeland: (a) State 1 (good). (b) State 4 (severely degraded). [Simon Todd]

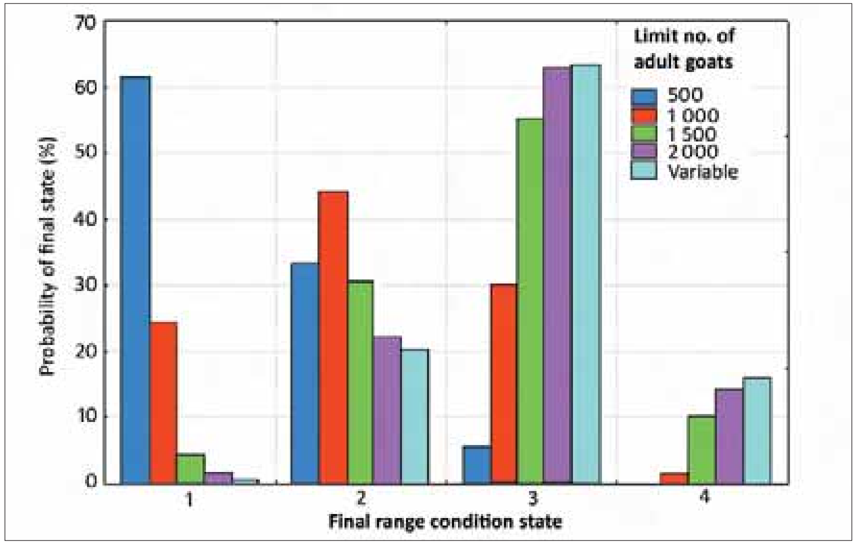


Figure 3.47 The effect of limiting adult goat numbers on the probability of final rangeland state after 100 years of grazing of a Namaqualand site. The states are defined by Richardson *et al.* [13] as good (1), light degradation (2), moderate degradation (3), severe degradation (4).

Management effects: Savanna

Savanna rangeland in good condition consists of a dense cover of palatable perennial grasses and scattered mature trees with few tree seedlings that supports a population of grazing and browsing animals. Degradation of savanna involves a decrease in grass cover and productivity and an increase in the density of woody plants. This may be a result of overstocking, too few browsing animals, elimination of fire and the effects of variable rainfall. The density of woody plants may increase until the range becomes thicket, where woody plants are so large and dense that cattle are unable to forage. Output from a model of a savanna ecosystem shows that the probability of the savanna used by domestic herbivores being degraded to thicket increases as the maximum number of goats (browsers) decreases. This probability is increased if the stocking rate is limited to 0,2 Livestock Units (LSU) per ha instead of allowing numbers to vary between years with birth and death rates (Table 3.1). The latter result is unexpected in the light of accepted good management practice. This is because stock numbers drop far lower under the variable strategy than when restricted thus increasing the probability of hot fires that reduce bush encroachment.

Table 3.1 The probability of a savanna ecosystem ending as thicket after 100 years for different management scenarios as reported by Hahn *et al.* [14]

Maximum goats	Cattle stocking rate strategy	
Goats ha-1	Variable	< 0,2 LSU ha-1
0	43	86
0,05	34	81
0,10	17	59
0,20	9	25
0,40	4	7
0,80	0	0

Conclusion

Model output shows that rangeland vegetation varies continually in response to rainfall variability and fluctuations in livestock numbers. Furthermore, the same management strategy and rainfall variability does not always lead to substantial changes in the abundance of palatable and unpalatable plants even over periods of more than 100 years (Figures 3.44a and 3.45a). Model output also indicates the possibility of unexpected results, such as accepted 'good management', leading to a greater probability of degradation. These two factors explain the contradictory results that have been observed and why we can only predict the probability of degradation for different management strategies.

RANGELANDS

Case studies in capital intensive crops towards system modelling of ecosystems using integrated hyperspectral remote sensing and in situ inputs

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Moses Cho
Russell Main
Renaud Mathieu
Ben Somers
Mark Norris-Rogers
Stephan Verreynne
Willem Verstraeten
Pol Coppin

Vegetation systems, which include both capital-intensive production systems and broader 'natural' ecosystems, are driven by a defined set of biotic and abiotic input factors in context of specific management regimes. Many of these inputs have been identified and incorporated in management, production, and early-warning models for such systems. However, the place that traditional in situ measurements and advanced hyperspectral remote sensing approaches occupy in management practices remains unspecified. We briefly discuss ongoing national activities in what is loosely termed 'integrated system modelling approaches' and highlight the importance that such activities have in the measurement, modelling and management of complex systems. Gone are the days where remote sensing promises to solve all sensing problems; we rather propose finding remote sensing's role in everyday management regimes.

Introduction

One of the broad research strategies of the international earth observation community, as encapsulated by the Group on Earth Observation (GEO), highlights the need in remote sensing research for an integrated sensing approach to monitoring our natural world. This implies that modelling of natural systems will increasingly be addressed by incorporating both in situ and remote sensing parameters in modelling efforts. An example could be a model developed to describe woody biomass trends in African savannas. This model may include variables measured in situ, for example, rainfall, temperature, soil moisture and humidity, as well as remotely sensed parameters, such as established or novel spectral indicators from airborne and space borne sensor platforms. Such an approach could potentially exploit the strengths of both sensing arenas, thereby including in-depth local knowledge and allowing extrapolation to larger scales through remote sensing applications. The research process in such modelling efforts can be subset into three broad phases:

(a) *Description of the vegetation system.* Any natural system needs to be understood at least at a broad level, even though it could be argued that fundamental understanding of many systems, for example, capital intensive crops and ecosystems of various types, is still lacking. However, in many instances we know enough about the drivers that will enable educated guesses to select the most essential input parameters, or those variables that determine system outputs, such as biodiversity, clean water or crop yields. An example is forest growth, where species (genetics), soil characteristics, meteorological inputs, and general site quality all dictate harvest volumes.

(b) *Combined remote sensing and in situ system description*. The key is to use either in situ or remote sensing to determine exactly which variables need to be measured. Many in situ type sensors already exist, for example, sap-flow gauges, soil moisture sensors and a variety of weather sensing instruments, all of which could be used to gather input data for a system model. We are, however, somewhat constrained by existing remote sensing sensors, which have been developed with a broad, and often large-scale application base in mind. Relatively novel hyperspectral sensors have recently enabled remote sensing scientists to gather spectral data across a broad, uninterrupted wavelength range at very fine spectral intervals, thereby allowing in-depth characterisation of how light interacts with any given surface, such as a patch of grass, a tree, or a conglomeration of trees. Such data are especially useful for detecting subtle changes in vegetation behaviour – changes which are often invisible to the naked eye and are generally related to water and nutrient stresses, diseases, and species-specific biochemical characteristics (Figure 3.48).

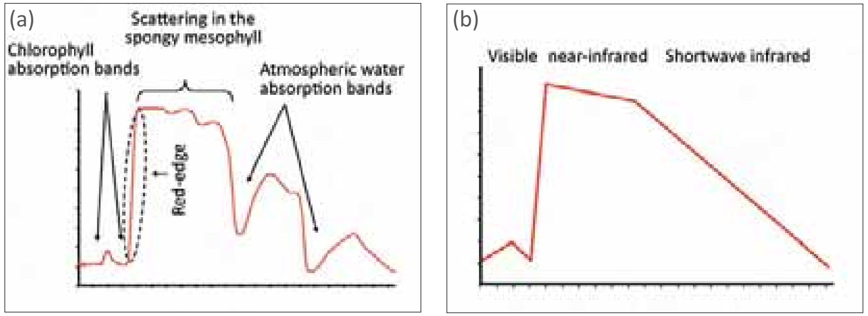

Figure 3.48 (a) Contiguous spectrum of healthy green vegetation measured using a handheld GER 3700 spectrometer (hyperspectral). (b) The same base data re-sampled to simulate the six Landsat TM bands (multispectral). [1]

Hyperspectral research and its incorporation into system models are in their infancy in South Africa and very much in an exploratory research phase worldwide. There is a need for these types of data to be further exploited and for applications to be developed towards integrated system modelling solutions. Initiatives such as the South African Earth Observation Strategy (SAEOS) and South African Environmental Observation Network (SAEON) highlight the need for integrating diverse sensing inputs. Hyperspectral data analysis techniques, furthermore, need to be developed and adapted for South African systems and conditions. The main objective with hyperspectral data often is not to apply the data 'as is' in an operational context, but rather to determine from such large spectral data sets which parameters are needed for a specific application. For example, researchers can develop an operational, affordable multi-spectral system by determining exactly which wavelengths (for example, 3-8 wavelengths) or indicators (for example, spectral curve slope and integrals) are needed to differentiate between various forestry species. Managers can then apply sensors that are cheaper and deliver data in manageable quantities, as opposed to scarce, expensive, and high data volume airborne hyperspectral scanners. The same principle holds true for a modelling approach. By using too much data, we can determine exactly which data we need to describe a natural system from a spectral perspective, along with in situ inputs.

(c) *Final integrated modelling with a specific system outcome in mind.* Knowledge of systems, expected outputs and drivers towards these outputs need to be combined with in situ and remote sensing indicators in order to develop truly integrated models. This will allow the user community to utilise the strengths of all sensing abilities to better understand and manage their vegetation systems.

All of these considerations have led to project efforts at the Council for Scientific and Industrial Research (CSIR) and the University of Stellenbosch and associated partners, Mondi Business Paper, Katholieke Universiteit Leuven (Belgium) and Rochester Institute of Technology (USA). We will briefly discuss these efforts to elucidate the research challenge.

Current case studies that are progressing our knowledge of integrated system modelling

Eucalyptus forest stands as homogeneous systems for integrated modelling development

The CSIR's Ecosystems Earth Observation and Forest and Forest Product Groups, along with Rochester Institute of Technology (USA) and Mondi Business Paper, have joined forces to study relatively 'simple' systems, namely mono-culture, homogeneous *Eucalyptus* forest stands. Their aim is to develop models that describe system productivity and health. Researchers evaluated 'system condition', as defined by foliar chemistry description, for example, chlorophyll *a* & *b*, Ca, Al, Mg, Mn, P, K, N, lignin, and cellulose content. Spectral and in situ data were collected in a Mondi Business Paper *Eucalyptus* plantation in the KwaZulu-Natal midlands (Figure 3.49) to assess our ability to link spectral indicators to foliar biochemistry and forest site quality. Site quality in this case was defined in context of soil available water, which in turn is a function of soil type, rooting depth, and water holding capacity. Forestry was chosen due to its relatively uniform environment and growth stock (for example, clonal material). It should be noted that this project is only the first step towards integration of remote sensing and in situ parameters for system state modelling. The final goal is likely to be achieved only after sustained research over a number of years.

To date researchers have found that:

(a) Water- and chlorophyll-related remote sensing metrics were significantly different between site qualities, suggesting that soil water could be limiting the growth of *E. grandis* [2].

(b) The discriminatory capabilities of leaf water, chlorophyll, and nutrient concentrations for *E. grandis* growing on different site qualities are seasonal by nature. For example, remote sensing-based leaf water and chlorophyll features were better indicators of site quality than foliar nutrient concentrations in winter, while the latter performed better in summer. This leads to the recommendation that remote sensing of *E. grandis* site qualities be conducted in winter rather than summer. Such results will define the sensing time frames for more complex modelling approaches, while integration of site information into growth models could further enhance the predictive capabilities of these models on a regional basis.

(c) Results for species-level classification of *Eucalyptus* and *Acacia* species were as high as 97% for between-species-within-age group (7-11 years) approaches, based on airborne CASI hyperspectral imagery. Such results underline the potential of remote sensing to be used in a *Eucalyptus* forest inventory context [3]. Figure 3.50 on the next page shows an example of the CASI hyperspectral imagery.

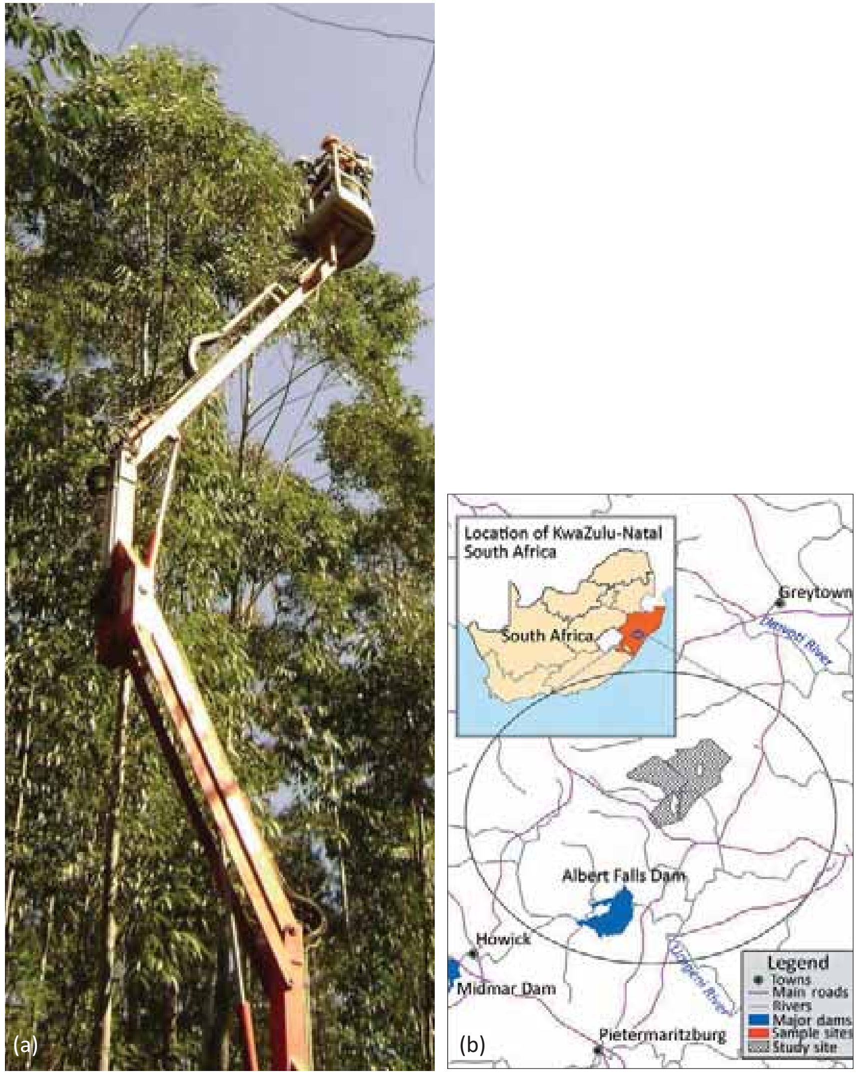

Figure 3.49 (a) Measuring canopy reflectance of *E. grandis* from a raised platform in (b) KwaZulu-Natal, South Africa.

Figure 3.50 An adapted CASI hyperspectral image used for classification of *Eucalyptus* and *Acacia* species in KwaZulu-Natal, South Africa. Forests show up in pink, agriculture/fallow land in blue, and bare soil/roads in green hues in this representation. This allows researchers to accurately delineate forest areas and species.

Integration of hyperspectral satellite imagery and in situ data to monitor, model and manage citrus production

The Katholieke Universiteit Leuven (Belgium) and the University of Stellenbosch are researching site-specific management in capital-intensive fruit crops. Precision agriculture is gaining importance in capital-intensive perennial cropping systems such as citrus, even though management practices (for example, harvesting and fertilisation) are typically implemented on the basis of management blocks. Farmers have, however, become increasingly aware that orchards are heterogeneous in terms of soil and environmental characteristics. Limitations in water availability, stricter land-use regulations and increasing consumer quality standards are also reducing profit margins and forcing farmers to take stock of environmental and quality issues. Researchers have therefore focused increasingly on site-specific management technologies in context of the citrus industry as an example of a capital-intensive crop system.

Work at the Geomatics Lab of the Katholieke Universiteit of Leuven, directed by Prof. Pol Coppin, have revealed potential for the early detection of pathogen threats in fruit orchards using satellite observations. Infrared wavelengths (700-2 500 nm), for example, have been used to detect early symptoms of apple scab infection, even before damage can be observed by the human eye [4]. Although this study was ground-based, extension of results to spaceborne platforms could enable proper and timely actions in reducing production losses caused by diseases and pests and may help to curb the excessive use of pesticides.

Another example is the challenge to monitor crop loads – remote sensing has shown potential to address this aspect as well. Somers *et al.* [5] corroborated this by comparing reflectance characteristics of trees after the systematic removal of oranges. Figure 3.51 shows significant changes in the infrared reflectance, which could be assigned to a drop in overall canopy moisture content when moisture-rich fruit is removed from the tree. The reflectance in the infrared could thus be used as an indicator for crop load monitoring, in turn leading to site-specific yield mapping. This site-specific yield information could provide insight in the short- to long-term spatial and temporal production variability and is therefore of extreme importance to evaluate the effectiveness of management practices [6]. Growers can properly plan harvest schedules, based on such yield forecasting schemes. Packers, shippers, and marketers can adapt production to logistics, budget and market requirements in order to streamline the flow of fruit.

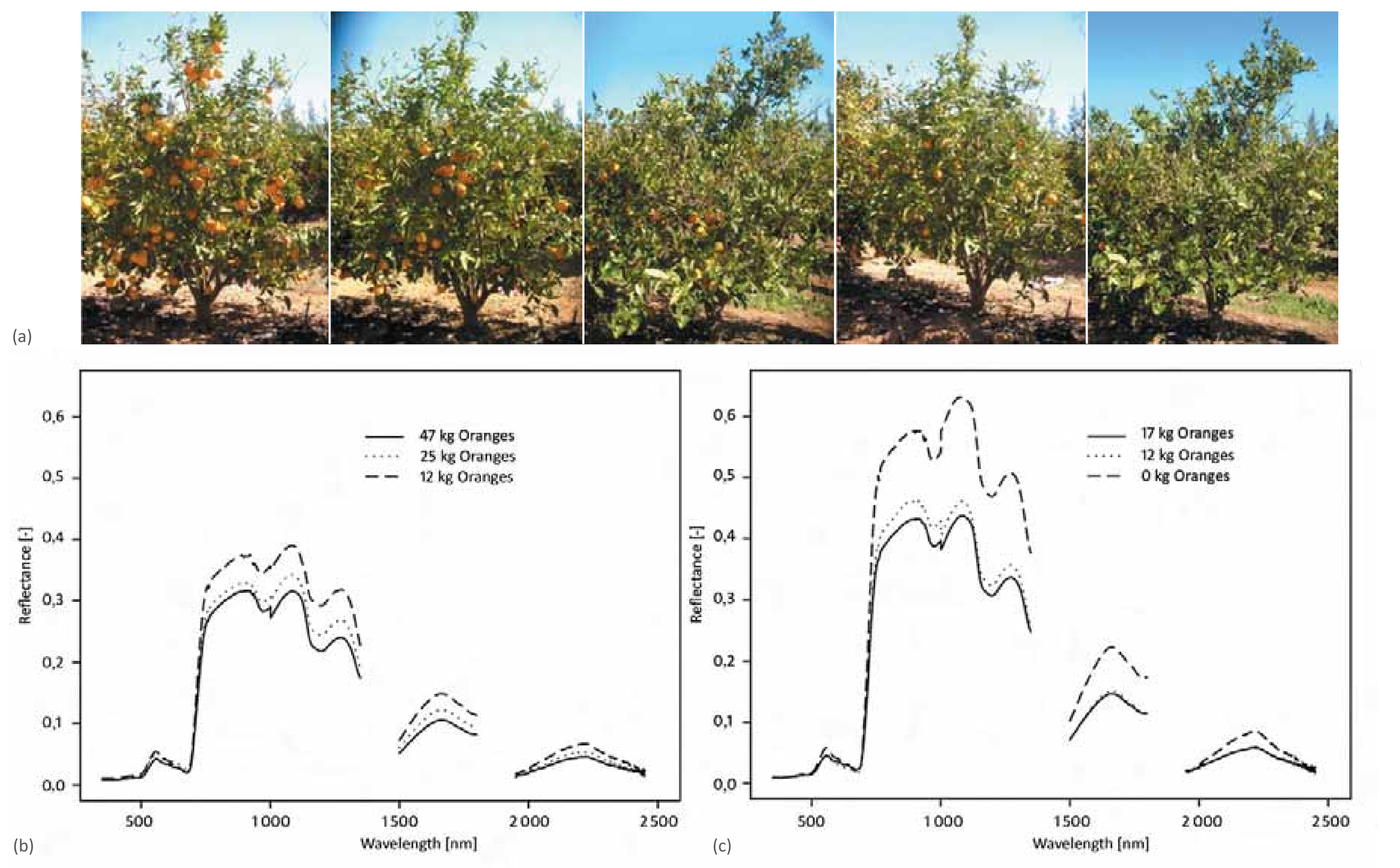

Figure 3.51 An illustration of changes in canopy reflectance caused by the progressive systematic removal of orange fruit, with photographic illustrations of the actual crop load scenarios. (a) Orange crop loads 47, 25, 17, 12, and 0 kg per tree, respectively. (b) Spectral differences among high crop loads. (c) Spectral differences among lower crop loads.

What are the potential benefits for inclusion of hyperspectral sensing in an integrated approach?

The commercial potential of such hyperspectral research is slowly coming to the fore. Ground-level hyperspectral sensors are more prevalent than air- and spaceborne sensors, although this is fast changing with sensors such as Hymap (www.hyvista.com/main.html), AISA (www.specim.fi), AVIRIS (aviris.jpl.nasa.gov), CASI (www.itres.com), CAO (cao.stanford.edu), and the current development of HysPIRI (cce.nasa.gov/pdfs/HYSPIRI.pdf) and EnMAP (www.enmap.org) space missions. It should be noted that, due to the nature of hyperspectral data (contiguous, high spectral resolution, broad spectral range), many context-specific commercial applications can be defined. General examples that illustrate the potential of hyperspectral sensing for integrated approaches to vegetation management include the following:

- *Detection of abiotic deviations (stress) from growth processes*: Research has shown that hyperspectral imagery can be used to detect nitrogen, lignin, chlorophyll, and water aberrations in crops and forests. Knowledge derived from hyperspectral data greatly increases the potential for precise (quantity/locality) allocation of management interventions.
- *Detection of biotic stress in vegetative systems*: Past and present hyperspectral research has proven that many biotic stresses (for example, diseases and pests) in vegetative systems can be detected at an early developmental stage, enhancing the potential for rapid response to limit or avoid crop losses.
- *Species and/or cover identification (mapping)*: The broad spectral range and contiguous nature of hyperspectral imagery allow for accurate identification of many land covers, including in a number of cases at species/community levels. This is essential in most large-scale land cover inventories.
- *Public health monitoring*: Hyperspectral imagery has the potential to aid in the monitoring of disease vectors, given the dependence of many such vectors on natural conditions. However, much research is still required in this field.
- *Water health monitoring*: The absorption and reflectance of specific wavelengths allow researchers to monitor turbidity, primary production (for example, phytoplankton and algae) and pollution in marine and inland water systems.

Extension of integrated modelling to complex ecosystems

Ecosystems research based on the Carnegie Airborne Observatory (CAO), an integrated light detection and ranging (LiDAR)-hyperspectral sensor flown in the Kruger National Park in April 2008, is a prime example of extension of modelling approaches to more complex systems. (A LiDAR sensor emits a laser pulse and measures the range between the senor and a target based on the return trip time between laser emission and detection at the sensor.) The CAO effort will serve to transfer outputs from the current national projects to the savanna ecosystem, which can be considered more complex than monoculture forest and orchard environments. This project's goal is to use multi-modal sensing (Figure 3.52) to investigate natural ecosystem variation, land degradation and fire ecology in the savanna ecosystem.

Finally, from a scientific point of view, the integration of inputs for system modelling across large scales is crucially important if we are to measure, model and monitor our natural resources effectively. This integration implies the use of both in situ and remote sensing data in order to evolve views on previous remote sensing research to the stage where we regard 'remote sensing as part of the solution, and not necessarily the only solution to large scale system assessment'. Issues related to ecosystem state, for example, land degradation, bush encroachment, species diversity, plant functional type qualification and quantification could be assessed more effectively towards sustained conservation and/or use of such systems.

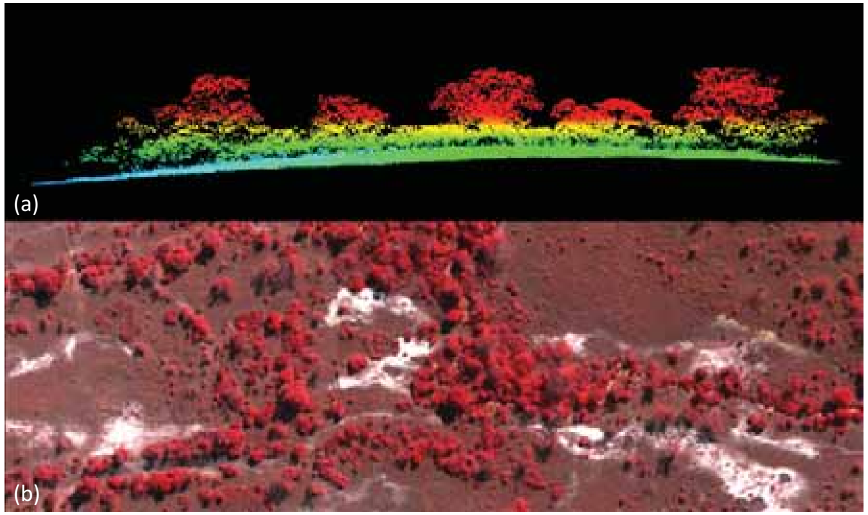

Figure 3.52 Multi-modal sensing platforms, such as the CAO which incorporates hyperspectral and light detection and ranging (lidar) sensors, might prove pivotal to integrated modelling of complex savanna ecosystems. (a) Lidar sensors provide 3-D or structural information. (b) Hyperspectral imagery provides insight into species composition and condition (red colours are indicative of healthy, dense vegetation).

RIGHT Hyperspectral remote sensing of vineyards in the Cape hold great promise for improving agricultural management practises. [Barend Erasmus]

INVASIVE ALIEN SPECIES

Introduction

Brian W. van Wilgen

Background

Invasion of ecosystems by alien species is an important and growing aspect of global change. Up until the late 19th century, mountains, large rivers, deserts and oceans provided formidable barriers to the movement and migration of species. As a result, ecosystems evolved in isolation. Early human migration saw the first intentional introductions of alien species as our ancestors attempted to satisfy physical and social needs. However, the magnitude and frequency of these introductions were minor compared to those associated with today's global agriculture and vast volumes of trade and passenger movements. The ongoing and increasing human re-distribution of species to support agriculture, forestry, mariculture, horticulture and recreation supplies a continuous pool of species from which invasive aliens are recruited. Invasive alien species are also a by-product of accidental introductions. The species concerned include plants that run riot over our landscapes, animals that compete with our native fauna, disease organisms that threaten crops, livestock and people, and insect pests. The problem is growing in severity and geographic extent as global trade and travel accelerate, and as human-mediated disturbance, and global changes in climate and biogeochemical cycling makes ecosystems more susceptible to invasion by alien species. As a result, human communities and natural ecosystems worldwide face a growing number of destructive invasive alien species. These species erode natural capital, compromise ecosystem stability and threaten economic productivity. This chapter provides some examples of the phenomenon and outlines the role of science in addressing the issue.

What are invasive alien species?

Alien species are those species that have been relocated outside of their normal distribution ranges. Some alien species become invasive – that is they display the ability to reproduce and spread in their new environment, often dominating vegetation and water bodies or displacing native species. It is important to recognise that not all alien species are invasive and that some are highly beneficial. Most of our food, fibre, and building materials are provided by alien species, as are many pets and garden plants. Many alien species that are not useful can also be benign, surviving without becoming a problem. It is the relatively small subset of alien species that become invasive that are a problem – although this 'relatively small' subset amounts to hundreds of species!

Why are invasive alien species a problem?

Invasive alien species can out-compete native species and they often eventually dominate the ecosystems that they invade. When this happens, native species can be driven to local extinction, and the whole way in which the ecosystem functions can be changed. Global reviews of the impacts of plant invasions, for example, suggest that the most damaging species transform ecosystems by using excessive amounts of resources (notably water, light and oxygen), by adding resources (notably nitrogen), by promoting or suppressing fire, by stabilising sand movement and/or promoting erosion or by producing dead plant material. Some invaders have been likened to 'ecosystem engineers' for some of the dramatic effects they can have on ecosystem dynamics. They can alter the flow, availability or quality of nutrients in the system; they change complex food webs on which many native species rely; and, in essence, change the very nature of the living space, making it uninhabitable for many native animals.

These impacts come at a significant cost to the economy. A recent overview for seven different countries estimates the global costs of control programmes plus the total costs of damage caused by invaders to be of the order of US$314 billion per year. Invaders also cost South Africans tens of billions of rand per year in lost agricultural productivity and resources spent on weed control. For example, a detailed assessment of the economic impact of black wattle gave an estimated net present cost of R8,4 billion, although the costs associated with invasion by black wattles are partially offset by the substantial social and economic benefits derived from the wattle industry. Many other invading species do not have any commercial value or use to offset their costs to society and their impacts on the environment.

The chapters that follow outline several aspects of invasions and their management. The first chapter looks at impacts of invasions on biodiversity. The second discusses how we can possibly assess the risk of any species we import becoming invasive, using reptiles and amphibians as examples. The third discusses Marion Island as a case study. The final chapter describes how remote sensing can assist in the detection and monitoring of species invasions.

Water hyacinths are treatening our precious and scarce fresh water resources and ecosystems. [Brian van Wilgen]

INVASIVE ALIEN SPECIES

Towards a predictive understanding of invasion success

Donald M. Iponga

According to Williamson's 'tens rule', only 10% of introduced plant species will become naturalised while another 10% of naturalised species can have a high probability of becoming invasive. Integration of information on environment type, disturbances and plant attributes is needed for understanding of the ecology of plant invasion. There are alien plants that clearly attain higher population sizes in the introduced than in the native range. Understanding the demographic forces that lead to this difference is a necessary step towards understanding the mechanisms by which some species become invasive.

Introduction

According to Williamson's 'tens rule', [1] only 10% of introduced plant species will become naturalised while another 10% of naturalised species can have a high probability of becoming invasive. Many authors consider that an integration of information on environment type, disturbances and plant attributes is needed for understanding of the ecology of plant invasion [2]. An understanding of the demographic forces that lead to some alien plants clearly attaining higher population sizes in the introduced than in the native range is a necessary step towards understanding the mechanisms by which some species become invasive. This chapter addresses some of the attribute that may lead an alien species to become invasive.

Species attributes

Regardless of extensive research, invasion ecologists have struggled to identify particular traits that are consistently associated with the tendency of plant species to be invasive. However, knowing the history of past invasion of the species may help to speculate on the invasiveness [3]. For example, the success of species abundance in their native habitats may point to their superior ability to find a suitable habitat when introduced [4]. Species that occur more widely and produce more propagules should have a better chance of being collected and transported and it seems that abundant species make better invaders, while scarce species are less likely to invade new habitats, although exceptions to this rule have been reported [5].

Certain life-history traits may be associated with invasiveness, for example, small seeds, short juvenile periods and short intervals between large seed crops. These traits seem important for allowing the species to disperse passively over long distances and win in competition against other plants, such as the genus *Pinus*, and indeed all woody plants. [5]. Invasive species are also the fastest-growing species and some of those species are used for commercial forestry [6].

Population size

Populations with a small range are more likely to go extinct than larger ones as consequences of environmental stochasticity [7]. Persistence and the opportunity for range expansion for an alien plant population in a new habitat are dependent on the maintenance of at least a minimum population size [8]. The more plants in a population that are distributed across the habitats, the more likely some will survive combinations of stochastic events, such as frost, drought, predation and weather. This is simply as a result of growing in effective sites. For example, a metapopulation of alien plants would be more likely to persist under environmental uncertainty than a single population because its members are collectively sampling a potentially large array of microsites across a large spatial scale [9].

Propagule pressure

Propagule pressure – the composite measure of the number of individuals released into a region to which they are not native [10] – is also a crucial determinant of the rate of geographical spread of alien plant populations [11]. Propagule pressure incorporates estimates of the absolute number of individuals involved in any one release event (event size) and the number of discrete release events (event frequency). As the number of releases and/or the

(a) Seed production *S. molle* tree.

(b) *S. molle* seed.

(c) *S. molle* plant dispersed under pole.

(d) *S. molle* growing in association with indigenous *Acacia tortilis.*

(e) Naturalised *S. molle* in old mine dump.

(f) Naturalised *S. molle* in old mine dump.

(g) Naturalised *S. molle* along river bank.

Figure 3.53 Examples of some of the aspects that may influence invasion success – the case of *Schinus molle* in South Africa. [S.J. Milton (c and g), E. Hermann (e)] number of individuals released increases, propagule pressure increases [12]. Some evidence suggests that propagule pressure is the cause of many invasions by non-native species in their new habitat [13]. The number of seeds produced by a plant is the biological propagule pressure that is independent from the effect of multiple introductions by people. For example, in the case of *Schinus molle*, which produces masses of seeds, this biological character may well be more important in terms of possible invasiveness of the species, than its distribution by people [14].

Residence time

Residence time – the period since introduction of an alien species – is an important factor in determining the invasion potential of an alien plant species [15]. Populations of introduced species often remain small and localised for long periods before they exhibit very rapid expansion. Until now little evidence has been available to support hypothetical explanations for these observed time lags or lag phases. The reasons for these time lags could be genotypic adaptations, cyclical disturbance, allee effects, or a combination of environmental conditions [2]. Because the duration of the phase between the introduction of a species and its spread is so variable, it is not possible to be certain that a species, although present for several decades, is 'safe' (which means it will not spread). For any particular region it is essential to understand the long-term disturbance regime as well as the specific ecology (including reproductive biology and regeneration requirements) of introduced species before any predictions can be made. Otherwise, close monitoring of natural and semi/natural vegetation, particularly after exceptional disturbance events, is necessary for the early detection of new invasions.

Habitat attributes

Several hypotheses have been postulated to explain differences in invasibility between habitats by alien plants. Those hypotheses include evolutionary history of the habitats, community structure, propagule pressure and disturbance. Interaction among these factors is likely to be important in determining habitat invasibility [6]. One aspect of evolutionary history thought to affect the invasibility of habitats is past intensities of competition and of human disturbance. In some habitats having intense competition over evolutionary time, invasibility might be low because natives have been well adapted for high competitive ability thereby preventing establishment of potential invasives [16].

Alternatively, the theory of fluctuating resource availability argues that the susceptibility to invasion of a community increases whenever the amount of unused resources, such as light, water, and soil nutrients, in that community are enhanced through disturbance [17]. High resource availability benefits fast-growing native or alien species [17]. Elton [18] first proposed that community resistance to invasions increases in proportion to the number of species in the community – its species richness. This followed his hypothesis that communities are more 'stable' if they are species-rich. This idea has been supported by theoretical arguments that less diverse communities have weaker interspecific interactions and more 'empty niches' [19]. The idea behind the empty niche is that a community with many species is unlikely to have any vacant niches and that the community can probably successfully 'defend' itself themselves from invasion by alien plants [20].

Positive and negative interactions in new environment

One of the most widely cited hypothesis attributes success of plant invasion to the fact that many alien plants, when introduced, are liberated from their specialist herbivores and pathogens [18]. Some alien plants are thought to obtain advantage when introduced to a new habitat because their populations are no longer suppressed by their specialist natural enemies. They consequently gain competitive advantage over native plants that may suffer from native predators [16]. The fundamental assumption is that release from strong suppression by native enemies in their native range enables plants to attain greater reproductive output [21] and survival [22] and thus higher densities in their introduced range [23].

Positive interactions may also facilitate the spread of alien plants in their new habitat. These include soil mycorrhizae, pollinators and dispersal agents [24]. Arbuscular mycorrhizal fungi can aid or disrupt the establishment of a new species by ameliorating or intensifying the abiotic stresses encountered in the new range. Mycorrhizal fungi can alter interactions among plants through direct effects, for example, by providing more resources to one species than to another [25], and potentially through indirect effects, such as by the transfer of resources and fixed carbon between individuals [26].

Another positive facilitation effect is the interaction between the introduced *S. molle* and native trees observed in semi-arid savanna of South Africa [27], where the establishment of the fleshy-fruited *S. molle* occurs predominantly under tree canopies, resulting in the formation of clumps around a single indigenous tree. This probably because by perching and nesting in trees, fruivorous birds direct seeds of *S. molle* to subcanopy sites [27, 28]. Some studies have demonstrated that subcanopy microsites conditions are favourable for seed germination and seedling establishment [29]. This process is known as nucleation [30] whereby the clumps tend to grow around a single founder tree.

Conclusion

There is clear evidence that biological invasions are one of most damaging phenomena that humans have ever generated on ecosystems. Despite intensive research into causes and consequences of biological invasion, we are still far from understanding the full complexity of the phenomenon. This is partly because so many different aspects need to be considered when trying to develop a general theory. This chapter has shown that no single trait can predict invasion success; those that seem to be correlated with invasiveness are to a large extent habitat specific. The chapter has highlighted that successful invasion appears to depend on number of factors that facilitate the surmounting of invasion barriers. Those factors include habitat features, recent disturbances and distance from putative source populations, life history traits and seed biology that may interact to facilitate invasions. It is also important to understand the links between traits of alien plants and features of the environment in mediating invasiveness.

Acknowledgement

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INVASIVE ALIEN SPECIES

Are invasive aliens a real threat to biodiversity in South Africa?

Brian W. van Wilgen
N. Dean Impson

South Africa has abundant biodiversity, but also has many invasive alien species, especially plants and fish, that can transform ecosystems. Invading alien trees and shrubs impact on fynbos and threaten up to a quarter of the nation's plant species. Freshwater ecosystems are often dominated by alien fish, while invasive alien plants invade the catchments of major rivers, riparian zones and open water surfaces. Invasive alien pathogens and diseases, such as the rinderpest that decimated wildlife and livestock at the end of the 19th century, pose a constant potential threat to biodiversity. Uncertainties in monitoring and predicting trends, and rehabilitating priority conservation areas are important challenges.

Introduction

Biodiversity is a term that encompasses the full range of variation in life on Earth. It is more than just a count of species, because it refers to the variety of ways those species co-exist in communities at different scales [1]. With its savanna, grassland, thicket, karoo, desert, forest and fynbos vegetation, South Africa is endowed with more than its fair share of the world's biodiversity. Each vegetation type has its own distinctive fauna, flora and ecological functioning and some have remarkably high concentrations of species. The country also has two internationally recognised biodiversity hotspots: the Cape Floral Kingdom and the Succulent Karoo (the only arid land hotspot in the world). With its extraordinary levels of biodiversity, South Africa is considered one of the 'megadiversity' countries in the world [2]. South Africa also has an abundance of invasive alien species, particularly alien plants and alien freshwater fish, and these pose significant threats to the continued survival of our remarkable biodiversity [3].

How invasive species affect biodiversity

Invading alien organisms are widely regarded as the second-largest threat to biodiversity, after direct habitat destruction. Invasive alien species simply out-compete many of our indigenous species and they come to dominate many areas if left to spread unchecked. Often, their ability to do this is because of the phenomenon of 'ecological release' – a term coined to describe the behaviour of introduced plants and animals when they are 'released' from the hosts of diseases, parasites and predators that keep them in check in their native ranges. They can transform the structure of vegetation, thus making it unsuitable as habitat for birds, insects and mammals, change the nature of veldfires, use excessive amounts of water and change the nature of nutrient cycles.

How has South Africa's biodiversity been affected?

Not all of our ecosystems have been equally affected by invasions. In the Western and Eastern Cape provinces, the fynbos shrublands have been literally over-run with alien plants, possibly because they have been settled for much longer than other areas. Freshwater ecosystems, too, are highly invaded, as alien plants and fish can rapidly spread along rivers once they are introduced. That is not to say that other ecosystems will not become invaded, given enough time. In the sections that follow, we have outlined three examples – the fynbos, freshwater ecosystems, and an introduced cattle disease – that illustrate the kinds of impacts that invasive species have had on our biodiversity.

Example 1: Invasive alien plants and the fynbos

The impacts of invasive alien species (especially invasive plants) on biodiversity are currently most keenly felt in the Cape Floral Kingdom (CFK), which covers 90 000 km^2 of southwestern South Africa. This area, barely 4% of the land surface of southern Africa, contains 45% of the subcontinent's plant species. There are almost 8 600 species of flowering plants and ferns, of which almost 70% (5 850 species) are endemic (that is, they are found nowhere else) [4]. The CFK is also the smallest of six such Kingdoms into which the world's vegetation is subdivided, and is the only one which is found entirely within the borders of a single country. Almost one-third of the Kingdom has already been lost to urbanisation, agriculture and forestry, and the remaining areas (mainly in the mountains) are under severe threat from invading alien plants.

There are few detailed studies on the extent of the problem, but where these have been done they confirm what can generally be observed. For example, a study in 1996 [5] showed that almost 40% of the Cape Peninsula has been transformed by agriculture and urbanisation. Of the remaining area, 10,7% was under dense stands of alien plants and another 32,9% was lightly invaded. The prognosis for the future of the Kingdom under a scenario of limited or no funding for the control of invading alien plants is grim [6]. Alien plants spread as a result of regular fires, as well as increasing levels of agriculture, road building, forestry and development. While spread rates are not fully understood, there are plenty of examples that illustrate the extent to which areas have become invaded. Indications are that southern Africa could lose almost a quarter of its plant species from this region alone due to invading alien plants.

Figure 3.54 Pines trees invading fynbos vegetation in the Eastern Cape. A forestry plantation (right centre) provides the initial source of seeds, from where the trees invade pastures (foreground) and upper catchment areas, displacing native species and reducing streamflow from the catchments. [B.W. van Wilgen]

Example 2: Invasive aliens and freshwater ecosystems

Freshwater ecosystems face significant threats from nutrient enrichment, chemical pollution, drainage and water extraction, erosion and dams. Invasion by alien species exacerbates these problems significantly [7]. Internationally, alien fish species top the list of threats to indigenous fish populations [8], and this is certainly true for the unique indigenous freshwater fishes of the CFK [9]. Most of our river systems now contain alien fishes that were introduced for angling and fish farming purposes in the 1900s. These species originate from both outside South Africa (mainly USA and Europe), as well as South African species stocked outside their natural distribution range (for example, Mozambique tilapia and sharptooth catfish). Alien fish species dominate CFK rivers, both in area occupied and numbers, with 16 species recorded to date [10]. Once common and widely distributed, indigenous fish species, such as the Berg-Breede whitefish and Clanwilliam sawfin, are now restricted to mountain streams and a few large dams where predatory alien fishes are absent or uncommon. The worst invaders are rainbow trout in the upper reaches of rivers and smallmouth bass, carp, Mozambique tilapia and sharptooth catfish in the middle and lower reaches of rivers of the CFK.

The predatory and competitive impacts of invasive alien fishes on South African fishes have been severe. There are 45 IUCN (International Union for the Conservation of Nature) red-listed fish species in South Africa, of which 24 are endemic or near-endemic to the CFK [9]. Invasive alien fish species (mainly predatory species like smallmouth bass) are listed as the primary threat for 23 of the 24 indigenous fish species in the CFK. Predation on fish is not the only impact alien fish have on indigenous biota; they impact on aquatic plants and invertebrates, removing the source of food for native fishes and affecting the ability of rivers to absorb and decompose organic material. Carp are internationally renowned for causing water quality problems through their bottom-feeding habits and destruction of freshwater plants [11].

Figure 3.55 Smallmouth bass. This alien fish of North American origin is now established in many South African rivers, especially those of the Cape Floral Kingdom, where it is responsible for sharp declines in the numbers of native fish species. [Dean Impson]

The catchments and banks of many rivers are invaded by alien trees (gums, pines, wattles, willows and others), which use excessive amounts of water and reduce the flow of rivers. Invasive alien trees along riparian habitats have led to the elimination of shade-intolerant dragonflies and damselflies; this is of especial concern where the species are endemic. Invasive alien plants, especially Australian *Acacia* trees along water-courses, are by far the most important threat to these dragonflies and damselflies in South Africa. Removal of the invasive alien trees has led to the recovery of several species that had previously been thought to be extinct [12].

Figure 3.56 Invasive alien black wattle trees along the Rondegat River, in the Cederberg, Western Cape. These trees dominate the riparian zone, completely replacing native trees, and make the habitat unsuitable for other organisms such as dragonflies. [Dean Impson]

In addition to alien fish, other introductions include invasive alien snails, mussels and freshwater crayfish, although their impacts are not yet clearly understood. Freshwater snails will almost certainly compete with native species for both food and physical space. They may also act as intermediate hosts for liver flukes that infect livestock (as they do where they are invasive in other parts of the world).

Floating aquatic weeds also take their toll. One study [13] was able to show that the red water fern formed dense mats (5-20 cm thick), on dams of up to 10 ha and on slow-moving water bodies in South Africa. The weed seriously affected the biodiversity of freshwater ecosystems and had severe implications for all aspects of water utilisation. These effects were considered to be most severe in the agricultural sector, where the weed increased siltation of dams and rivers, reduced the quality of water for agricultural and domestic use, clogged irrigation canals and pumps and caused drowning of livestock that were unable to differentiate between pasture land and a weed-covered dam.

Example 3: Rinderpest and large mammals

Diseases represent a potentially devastating aspect of invasive organisms, as modern scares such as avian flu have amply demonstrated. One such devastating invasion has already occurred in Africa in the form of the rinderpest epidemic that took place at the end of the 19th century [14]. Early in February, 1896, large numbers of cattle and wildlife were reported to be dying from an obscure disease on both sides of the Zambezi River. By March it had reached Bulawayo, where a diagnosis of rinderpest was made. From there the plague was rapidly conveyed southwards by means of transport oxen and migrating wildlife. As it spread southwards it caused ruin and devastation, killing the majority of domestic animals in the region, as well as countless thousands of wild ungulates. Serious attempts were made to stop the disease at the Orange River by erecting a 1 000-mile long fence, but this, too, proved ineffective. By 1897, an effective inoculation was developed, and before the end of 1898 more than two million head of cattle had been successfully inoculated. By the end of 1898 rinderpest was under control and temporarily disappeared from South Africa. Although rinderpest's stay in the region was relatively short, its effects on large grazing and browsing ungulates was immense and their numbers were so reduced that it took decades for them to recover.

Figure 3.57 The rinderpest epidemic at the end of the 19th century caused enormous losses of both domestic stock and wildlife. [15]

What does the future hold?

Invasive alien species are a large and growing problem of the environment. Attempts have been made to predict the future impact of these species, but predictions are difficult as both the rate at which these species spread and the extents to which they will come to dominate ecosystems are critical unknowns. However, if we simply project what is known about invasive species and their ability to colonise and dominate areas, the consequences could be staggering [6]. Whether or not the predicted levels of invasion are possible is a matter of conjecture, but there are indicators that we can use to assess the seriousness of the threat. Many of South Africa's remaining natural ecosystems are relatively free of significant infestations of invasive alien plants at present (with the notable exception of the Fynbos Biome, where infestations of invasive plants are at much higher levels). The fact that many invasive plant species already occur in many areas at low densities, and are known to be able to develop into dense closed stands over time, suggests that an ongoing escalation in the level of infestations can be expected. The situation can also be expected to worsen as new invasive species become established. New invasive species will continue to arrive, and many potential invasive species are probably already here – but not yet invading. Many serious invasions have exhibited a 'lag period' in which the introduced species may occur at very low population levels for several decades before becoming invasive, sometimes suddenly. This could be the result of exponential population growth, a period of selection of genotypes suited to the newly invaded environment, or the occurrence of a change in environmental conditions that constrain invasions. With the rapid growth in the rate of introduction of new species, most introductions of alien species have occurred recently. It is therefore likely that a large number of invaders are currently in their 'lag period' and the rate of new invasive species problems will increase dramatically in future. Global changes, such as changes in climate and in the rates and magnitudes of biogeochemical cycles, may further worsen the situation by bringing about conditions that would make some benign alien species suddenly become invasive.

Science has an important role to play in mitigating the effects of invasive alien species. Awareness needs to be raised about the problem and regular and effective monitoring will be required to detect new introductions or spread of alien species. Effective means of control also need to be developed and successfully implemented, preferably with the support and assistance of landowners and other key stakeholder groups. Regulations for alien plant and animal species that are currently being developed under the National Environmental Management: Biodiversity Act (NEMBA) will hopefully lead to more effective management of alien species.

Defining appropriate responses for addressing the increasing trade in alien species

The case of reptiles

Nicola J. van Wilgen
David M. Richardson

Biological invasions are not a new phenomenon in South Africa. Indeed, multi-facetted management operations have been in place to combat the problem of invasive alien species, especially plants, for many decades. Yet very little information is available for many other groups, including the majority of vertebrate animals. Invasive alien reptiles are not yet a problem in South Africa. However, escalating problems with invasive reptiles elsewhere in the world, and changing circumstances in South Africa (especially growing trade), suggest an increasing risk of problems in the future. This chapter provides a framework for actions necessary to improve South Africa's biosecurity strategy to prevent problems from the nearly 300 alien reptile species already present in the country and to prevent the introduction of high-risk species in the future.

Introduction

Alien reptiles may not seem like a major threat or a driver of global change, but some alien species in this group have had significant impacts in several parts of the world, and the problem is set to get worse. The brown tree snake on the island of Guam and the Burmese python in the Florida everglades are probably the best-known examples of invasive reptiles. These species have caused considerable damage to the environment and the tree snake especially has caused damage with serious economic consequences. One of the biggest threats associated with reptile invaders is that the drivers of their introduction are becoming more prominent. Among these drivers are the pet trade (deliberate introductions) and the nursery trade which results in the accidental introduction of species [1], though this is more of a problem with amphibians. Although there are not as many well-known invaders in this group as in some other animal groups (for example, mammals), the increasing rates of introductions and establishment are cause for concern [1].

Status quo in South Africa

Reptiles are rapidly increasing in popularity as pets in South Africa. For example, trends in the import of a subset of trade-endangered species (those listed by CITES, the Convention on International Trade in Endangered Species) show that there has been a linear increase in the number of countries exporting species to South Africa and in the number of species introduced over the last 30 years [2]. The actual number of individuals of these species imported has increased exponentially. However, the trade in South Africa remains much smaller than in other parts of the world [3], and despite these increases, few if any reptile invaders have been recorded in South Africa. During this same period many new invasive species have been recorded in other groups, for example, plants, fish, mammals and birds. This may seem surprising as nearly 300 species of alien reptiles have already been imported to South Africa [4]. There are a number of plausible explanations for the lack of reptile invasions to date. The time that these species have had to establish may simply be too short to have resulted in invasions. Reptiles have only recently become trendy pets, and there may not have been enough time for species to establish viable populations. Pets are also not usually kept at the densities that may be needed to start viable populations. Incidences in other parts of the world (for example, Florida) where pet species have established, have usually been associated with pet store owners who have started feral breeding populations on their grounds or where large numbers of individuals of the same species have been accidentally released simultaneously (for example, following hurricanes) [5]. There are also a number of other factors relating to climate, biotic interactions, habitat and food preferences which may play a role, but it is likely that there are some species currently kept in

South Africa that are well adapted to local conditions and which have an excellent chance of establishing feral populations if released from captivity. It is therefore important to look at drivers of trade and patterns of introduction in these species to highlight areas of potential concern and to develop a strategy to prevent invasions before they emerge.

Characteristics of popular pet species

One of the first things that must be understood is the reason for the imports. Without such an understanding, one cannot effectively communicate with all stakeholders (for example, pet stores owners, breeders, reptile parks and animal display facilities) (Figure 3.58). Recent research on the patterns and trends in reptile imports revealed that there are distinct characteristics which increase species popularity in the pet trade [2]. Pet stores tend to stock charismatic species with bright colours and interesting features to attract customers (Figure 3.58). Indeed, species which are colourful, large, have patterns or intriguing features (such as beards, spines, dewlaps), or those that are easy to handle or easy to keep are more abundant in the trade than species that lack these features (Figure 3.59). This does not explain the boom in reptile pets themselves (which can be explained in part due to availability and peer influence), but helps us to understand which species we might expect to see being imported into the country. Knowing this can help in formulating a strategy to prevent the introduction of potentially harmful species.

Legislation and implementation

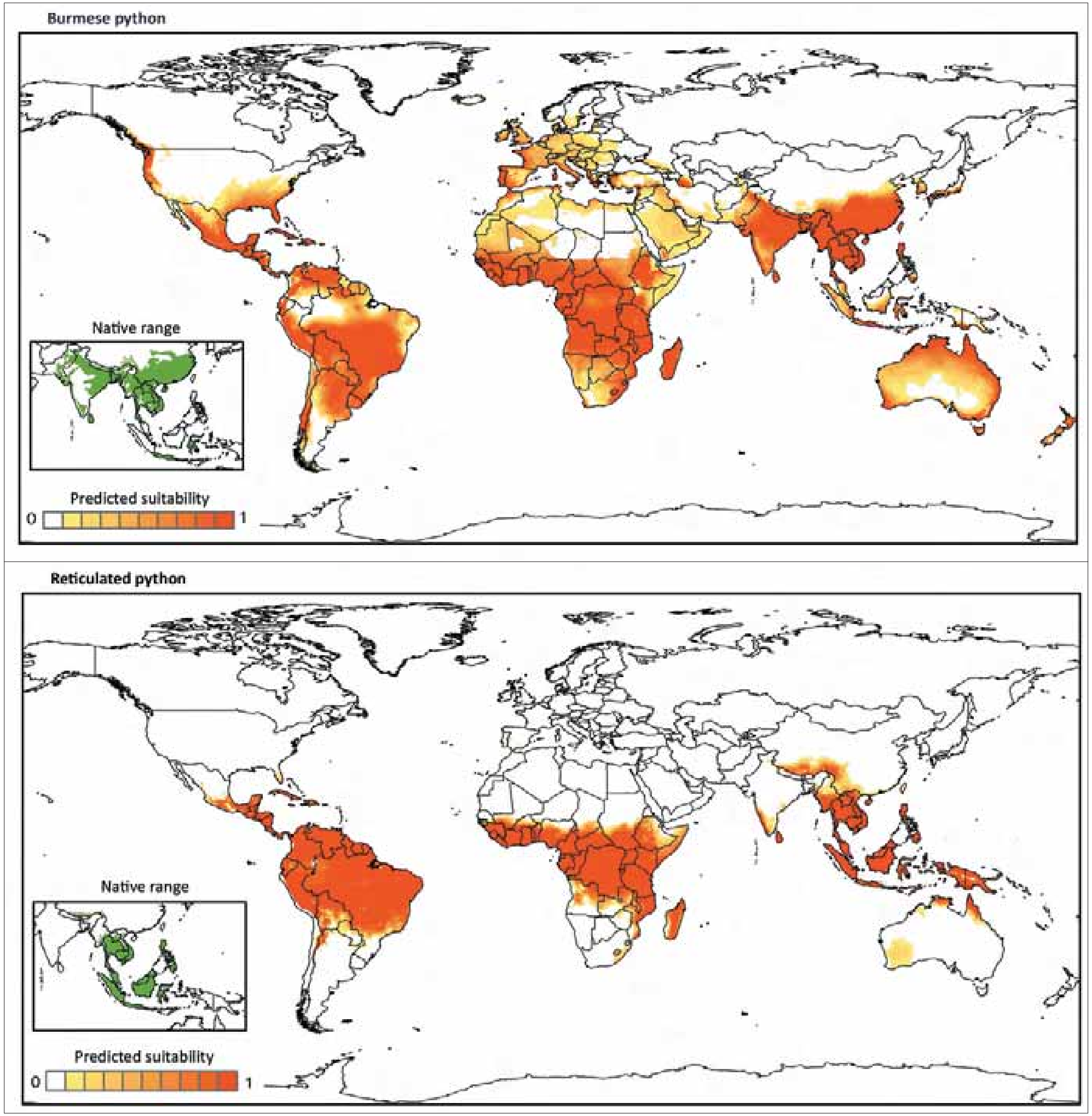
One of the problems here is that there are a number of species and shipments which arrive illegally in the country (some of which have received extensive media coverage) [6]. This may be to disguise the origin of the species (i.e. species that were caught in the wild, rather than the preferable captive bred variety) or because the species in the shipment themselves are not legally permitted in the country. Ways in which such incidences can be detected and protocols for follow-up need to be put into place at all potential ports of entry. The relevant legislation governing alien species and their movement, breeding and captive keeping is detailed in The National Environmental Management: Biodiversity Act, 2004 (Act No. 10 of 2004) (NEMBA).

Figure 3.58 In trying to deal with the problem of trade in reptiles, there are several aspects which need to be considered. Firstly there are the needs of the stakeholders and it helps to engage with them directly (a). Though some species do arrive in legal shipments (d), many species are imported illegally (for various reasons) and monitoring of ports of entry needs to be more effective. An understanding of what makes species popular and attractive is also important (e.g. colourful and attractive species b, c, e). Many pet stores attract customers with posters of colourful and charismatic species (f). [Photographs: (a) Mia van Wyk, (b, e, f) Nicola van Wilgen, (c) Reda Potts, (d) Jacques du Toit]

Figure 3.59 Popularity of species is influenced by the size of species: (a) a giant Aldabra tortoise at Tygerberg zoo; the ease with which the species can be handled and kept (b-c) (a snake rests in its water-bowl in a Johannesburg pet store); and (d) the presence of patterns (Gaboon viper, Johannesburg zoo); (e) bright colours (Kingsnake, National Zoological Gardens); and (f) interesting features (for example, the dewlap and spines of this iguana) [2]. [Photographs: (a, f) David Richardson, (b, c, e) Reda Potts, (d) Nicola van Wilgen]

NEMBA seeks amongst other things to reduce the impact and spread of alien and invasive alien species through a permitting system which controls the activities involving species which do not occur naturally in South Africa. There are three basic groups of alien species covered by the act: (a) alien species which are not thought to be problematic; such species are exempted from permitting requirements after approval by the Minister; (b) alien species which are prohibited and for which no permits may be issued; and (c) all remaining species, for which one requires a permit to carry out any activities.

To receive a permit for an alien species, the Act requires that an 'assessment of risks and potential impacts on biodiversity is carried out'. Thus, the way forward is to assess which of the species currently being kept and traded in South Africa pose a potential biodiversity threat. Such species should be noted for inclusion on lists of prohibited species. Further, a protocol for assessing the risks associated with species which have not yet been imported needs to be compiled in order to determine whether such species should be permitted for trading in the country. Research has shown that climate plays a particularly important role in a species' ability to establish [7, 8]. Using bioclimatic envelope modelling, we can predict whether the climate in South Africa is suitable for the species traded in the region (Figure 3.60). Species that come from areas with environments similar to South Africa may pose a greater threat of invasion than those that come from less similar areas. As South Africa has very diverse climatic conditions, it is unlikely that even species from similar areas should be able to prosper throughout the country.



(a)

(b)

Figure 3.60
Global climatic suitability for (a) the Burmese python (*Python molurus*) and (b) the reticulated python (*Python reticulatus*) predicted using six environmental variables, including rainfall and temperature minima and maxima [8]. The images show that the tropical and subtropical regions of South Africa may be suitable for the survival of the Burmese python, but that the more tropical reticulated python is unlikely to experience suitable condition in the country.

Climate alone, however, cannot tell us whether or not a species will be able to thrive in a new environment. Species-specific traits, such as clutch size, number of reproductive events per year and habitat use, play an important role in the initial phases of establishment as well as the subsequent survival of populations. The relatedness to taxa in the new environment is also thought to influence the chances of an alien species colonising successfully. Closely-related species may act as competitors, restricting the food or space available to the alien species [9]. However, the presence of closely-related natives may also indicate that there is a niche available for the new species, should it be able to out-compete native species or live alongside these. We are only beginning to understand the multitude of factors which influence species invasive success. It is therefore important to consider as many factors as possible when formulating an objective risk assessment protocol. Because of the dramatic impacts caused by some alien species, including reptiles, it is appropriate to adopt a precautionary approach in the absence of information. We should be particularly wary of species that possess both qualities likely to make them popular pets, and have invasive traits.

Reducing the risk of biological invasions demands a multi-facetted and pragmatic approach. The NEMBA legislation provides a sound foundation for the implementation of effective strategies, but much more information is needed on many aspects to devise, implement and enforce sustainable programmes.

INVASIVE ALIEN SPECIES

South Africa's southern sentinel

Terrestrial environmental change at sub-Antarctic Marion Island

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The Prince Edward Islands have experienced substantial environmental change over the past half century. Major pressures include rapid climate change, the impacts of invasive plant and animal species and interactions among them. Here, we focus especially on pressures, trends and responses in the terrestrial system. Indigenous and alien species have responded to climate change, with indigenous plants showing rapid increases in upper elevational margin and invasive alien springtail species benefitting more from warming and drying than their indigenous counterparts. Complex interactions among marine and terrestrial ecosystems make the islands ideal for observing and understanding land-sea interactions during times of change.

Introduction

The Southern and Northern hemispheres are very different. Viewed from an oblique angle somewhere above the 30th parallel, the contrast is stark. Between 30 and 60 degrees of latitude, the Northern Hemisphere is 15 parts land to one part water. By contrast, water dominates the southern high latitudes such that the ratio is 1:1. One consequence of the extensive areas of ocean in the mid- to high southern latitudes is the difference in importance that each of the major environmental change drivers assume by comparison with other areas of the planet. With the exception of parts of South America and the antipodes, islands form most of the land in the high latitudes of the Southern Hemisphere. They stretch from Gough Island in the north, to the much less hospitable Bouvet and South Shetland islands in the south, with the majority straddling the Antarctic Polar Frontal Zone.

Owing to their remote nature, most of these Southern Ocean islands were colonised very late on in the history of the globe, with many lacking any form of human presence. Some only have scientific stations, and just a few (such as the Falklands and Tristan da Cunha) house a small permanent human population. Consequently, the terrestrial systems are typically not affected by pollution, habitat destruction and overexploitation. Rather, climate change and the introduction of non-indigenous species (several of which have become invaders), which have transformed whole ecosystems, are the most significant drivers of change [1]. Likewise, in the marine systems surrounding the islands, pollution and habitat destruction are not as significant as climate change and substantial overexploitation of mostly fish resources.

The reduced set of environmental drivers mean that the detection of their impacts and the impacts of interactions among them is often more straightforward than elsewhere. Moreover, several of these Southern Ocean islands show rates of climate change that exceed many other systems globally. Thus, the islands form ideal sentinels for the kinds of change that can be expected elsewhere, and how interactions among change drivers might play out. Given the widespread political recognition that the mitigation of and adaptation to environmental change must be explored and further developed, such scientific sentinels are valuable and their worth has been recognised by a range of countries.

South Africa is the only African nation to have a presence in the Southern Ocean and on the Antarctic continent. South Africa has a long history of research in the natural sciences in the region, most particularly at sub-Antarctic Marion Island (Figure 3.61) [2]. This has enabled South Africa to contribute meaningfully to understanding and forecasting change in the region, and has ensured that the country has retained and grown its status as a major contributor to knowledge and policy that underpins regulation of the Southern Ocean and the Antarctic. Moreover, a window on environmental change in the region now exits that is almost unparalleled in its scope and significance. Here we provide a view through that window, illustrating how dramatic the changes at Marion Island have been in half a century and illuminating the lessons they provide to society more generally.

Figure 3.61 A view of the polar desert region of Marion Island from Ned's Kop down to Long Ridge on the left, with Prince Edward Island in the distance.

Pressures on the southern sentinel

Climate change

Although Marion Island and its neighbour Prince Edward can best be described as cold, wet and windy islands, their climates are changing rapidly. Over the past 50 years, the mean annual temperature recorded at the Marion Island scientific station (or base) has increased by 1,4 °C (about twice the global rate). Over the same period, the island has become less cloudy and rainfall has declined massively. Not only does it rain less frequently than it used to, but the rainfall events are becoming smaller. Thus, total annual precipitation is now less than 2 000 mm per year, when in the 1950s to 1960s it was more than 2 600 mm per year. A decline of 600 mm in total annual precipitation is equivalent to the annual rainfall received by the city of Pretoria. Thus, climate change is a major pressure on Marion Island.

Terrestrial biological invasions

In the terrestrial system, another pressure of considerable significance is invasive alien species. The deliberate or accidental introduction of species that are not indigenous to an area is a pervasive feature of human colonisation. Species are often introduced for food or commercial purposes (like farming), or they are commensals (for example, pets and pests) that become feral, or are simply accidental passengers that find the new environment suitable. The history of Marion Island can be thought of as a history of such introductions. House mice were accidentally introduced in the 1800s by sealers who sought out seals for their fur and/or blubber. Mice have since spread across the island, but are absent on nearby Prince Edward. Following annexation and establishment of the South African base in 1947, several species, including chickens, sheep, pigs and trout, were introduced for food. These species have all subsequently died out or were eradicated. However, a variety of other species were accidentally introduced either at the same time, presumably with feedstock for the animals, or over a period of years as unnoticed passengers travelling with building or food supplies. These plants and invertebrates have gone on to change the terrestrial system substantially. So, too, did cats, which were introduced in 1949 to control mice around the station, but which became feral, increased in population size and wreaked havoc with the seabird population, causing the local extinction of several species. While the cats were eventually eradicated by a targeted pest control programme, many other introduced species are substantially transforming the local system.

Introductions such as those described above are not unique to Marion Island and are often a major concern in many other parts of the world. Indeed, South Africa spends billions of rand annually dealing with the effects of species that have been accidentally or purposefully introduced, and has one of the most successful social investment programmes, ever, to do so (the Working for Water Programme). The difference between the continental situation and Marion Island is the extraordinary opportunity the latter provides for understanding several features of the invasion process and its management. These include what pathways non-indigenous species use to arrive in an area, why alien species often spread as quickly as they do and what limits this spread, and how climate change influences and might continue to influence the impacts of alien species. Most significantly, this research provides information on how to manage effectively the problem of invasive alien species.

For example, the distribution of the introduced slug, *Deroceras panormitanum*, which substantially alters soil ecosystem functioning, is not only well known across the entire 293 km^2 island (Figure 3.62), but the reasons for variation in abundance, and for limits to its distribution, are now also comprehensively understood.

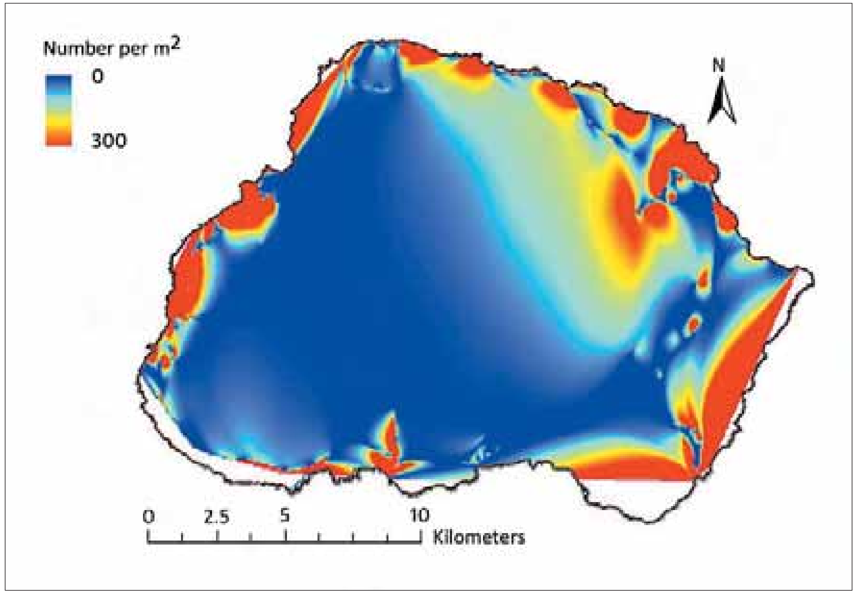

Figure 3.62 Densities (numbers/m^2) of the invasive slug, *Deroceras panormitanum*, across Marion Island as shown by nearest neighbour interpolation of 1 109 sampled quadrats from around the island. [3]

Local abundance varies with habitat because slugs are sensitive to dry conditions. However, they cannot survive where temperatures decline below -4 °C or where the soil has more than 3 000 mg/kg[1] of sodium. Thus, individuals of this slug species will be able to occupy higher altitudes as climates change, but the species' abundance will decline more generally as habitats dry out. In consequence, a simple prediction of overall benefit, as is so frequently made for invasive species under future climate change scenarios, is unrealistic. Rather, the outcome is more subtle: an important lesson for invasion biology and for climate change biology.

Trends over 40 years

Over the past four decades, substantial changes have taken place in the terrestrial system as a consequence of climate change, biological invasions and their interactions. A regular visitor to the islands might not notice the subtle changes in plant distributions that have accompanied warming and drying. However, comparisons of plant distributions along altitudinal gradients immediately reveal the change, as does repeat photography of specific sites.

Climate change signals in the indigenous flora

During the first biological expedition to Marion Island in 1965-66, the upper altitudinal limits of indigenous ferns and flowering plants were determined over several altitudinal transects. Some forty years later, these transects were investigated again and the change in upper elevational limits of the plants was examined. If climate change has affected the plants, a noticeable increase in altitudinal limits should be noticeable, because, as climates become warmer, plants can grow in places previously inaccessible to them. Exactly such a change has been found on Marion Island. On average, the plant species examined increased in their upper limit by 70 m, representing an ascent of 1,8 m per year. While considerable variation exists among species, only a few actually have descended in their upper limits, one has remained static, and the large majority have ascended the gradient (Figure 3.63).

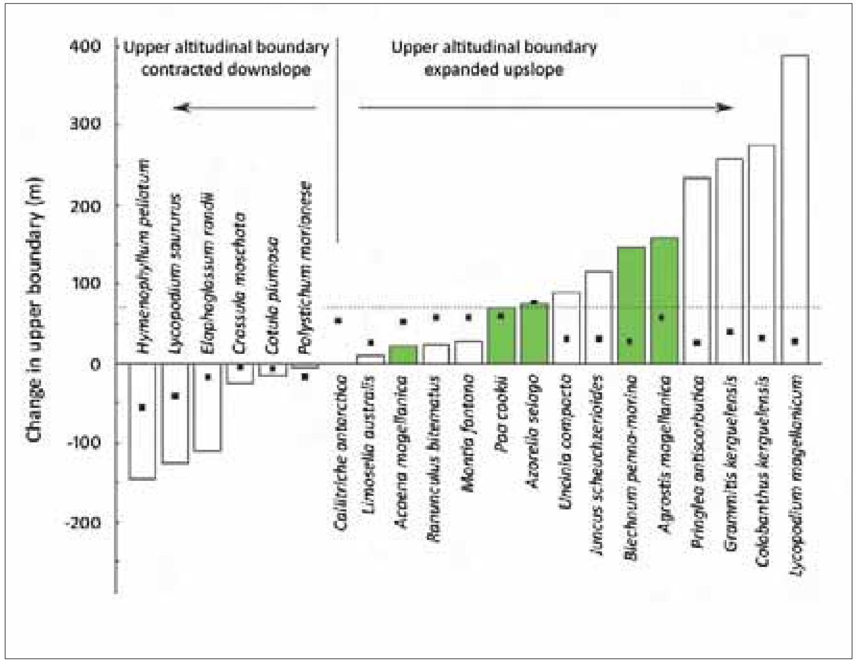

Figure 3.63 Changes in the upper altitudinal boundaries of the indigenous vascular flora of Marion Island over 40 years (1966-2006). The points represent the size of a range boundary change equivalent to 10% of the species altitudinal range in 1966. For example, *Uncinia compacta* has expanded upslope by 89 m, a change far exceeding 10% (38 m) of its 1966 altitudinal range. The dotted line indicates the average change in the upper altitudinal boundary for the flora. Shaded bars are those species that dominate vascular plant biomass. [4]

Climate change has meant a substantial increase in the altitudinal limits of many vascular plants on Marion Island. One of the species that is doing especially well in this regard is the indigenous grass *Agrostis magellanica*. It has increased its elevational range by more than 150 m over the past 40 years. This increase has not only been revealed by surveys, but also by repeat photography in 2009 of sites visited in 1966 (Figure 3.64).

Figure 3.64 *Agrostis magellanica* climbs the island – Repeat photography reveals the trend. In the first image (a), taken in 2009, the area surrounding the bare grey lava, covered in glacial striations, is clearly well covered by *A. magellanica* that is growing on the cushion plant *Azorella selago*. However, forty-three years earlier (b) it is clear that very little *A. magellanica* is present at this elevation of 160 m. Thus, changes in environmental conditions over the past 40 years have favoured the grass at this site. The image (c), of the pond behind Hendrik Fister Kop in 2009, shows the area almost completely covered by the autumnally yellow *A. magellanica*. By contrast, in 1966 (d), the area was largely dominated by the cushion plant *Azorella selago* with only a little *A. magellanica*, and larger, more open areas.

The process of invasion

Repeat photography and systematic surveys have also revealed substantial change in the non-indigenous vascular plant species. Most of these species were accidentally introduced to the immediate surroundings of the scientific station. Dividing the island into 500 × 500 m grid squares, all of the alien species initially occupied 1-2 squares. These were the squares where they were first introduced and became established. By 2007, many had spread around almost the entire island, with the exception of the harsh highland areas. For example, *Cerastium fontanum* and *Sagina procumbens* (Figure 3.65) are now widely distributed and occupy a total of 168 and 151 of the 724 grids below 400 m altitude, respectively, with the latter species transforming the landscape, especially along rivers.

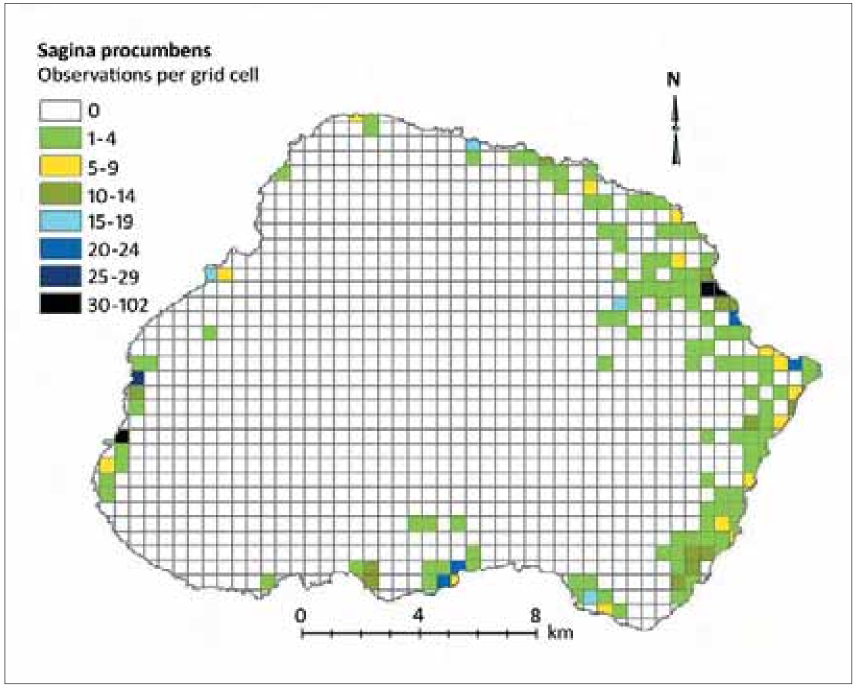

Figure 3.65 Map of the current distributions of *Sagina procumbens* on Marion Island, which spread, over nearly 45 years, from a local, accidental introduction at the research station on the east coast.

The small, relatively innocuous-looking forb, *Sagina procumbens*, or the procumbent pearlwort, was first seen in 1965 on Marion Island in a few small patches around the station. It has since spread to nearly all lowland areas on the island (see text Figure 3.65) and in many areas is dominant. This is especially true of some river bank areas (Figure 3.66).

Interactions between climate change and invasion

Research on the Marion Island terrestrial system has also revealed that climate change has significantly influenced the course of invasions and the interactions between invasive and indigenous species. In many ways this work has led the field, as the following two case studies clearly demonstrate.

By historical accident, invasive house mice occur on Marion Island, whilst the neighbouring Prince Edward Island is mouse free. Over the past several decades mouse densities appear to have been increasing, partly as a consequence of warmer temperatures improving mouse survival. The increasing numbers of mice have led to a decline in the population densities of their preferred prey – indigenous flightless moth caterpillars and weevils. Indeed, caterpillar density is now an order of magnitude lower than it was 30 years ago and is very much lower than on mouse-free Prince Edward Island. Likewise, weevil densities are also declining on Marion Island, as are their body sizes, because mice prefer to prey on larger weevils. Again, these changes are largely absent from Prince Edward Island. The caterpillars are exceptionally important for nutrient cycling, and indeed it appears that nutrient cycling and litter accumulation processes are changing between the two islands. Insects and other invertebrates that mice prey on also typically support indigenous Black-faced Sheathbills over the winter months, when they tend not to forage in penguin colonies and along the coast. Indeed, it appears that sheathbills have declined in abundance on Marion Island as a direct consequence of mouse predation on their preferred prey, while no declines have been documented on Prince Edward (Figure 3.67). Moreover, burrowing by mice also has a negative impact on the keystone cushion plan *Azorella selago*. This means double trouble for the plant, which is also sensitive to drying. These examples clearly show that climate change and invasive species are interacting synergistically to alter ecosystem structure and functioning on Marion Island.

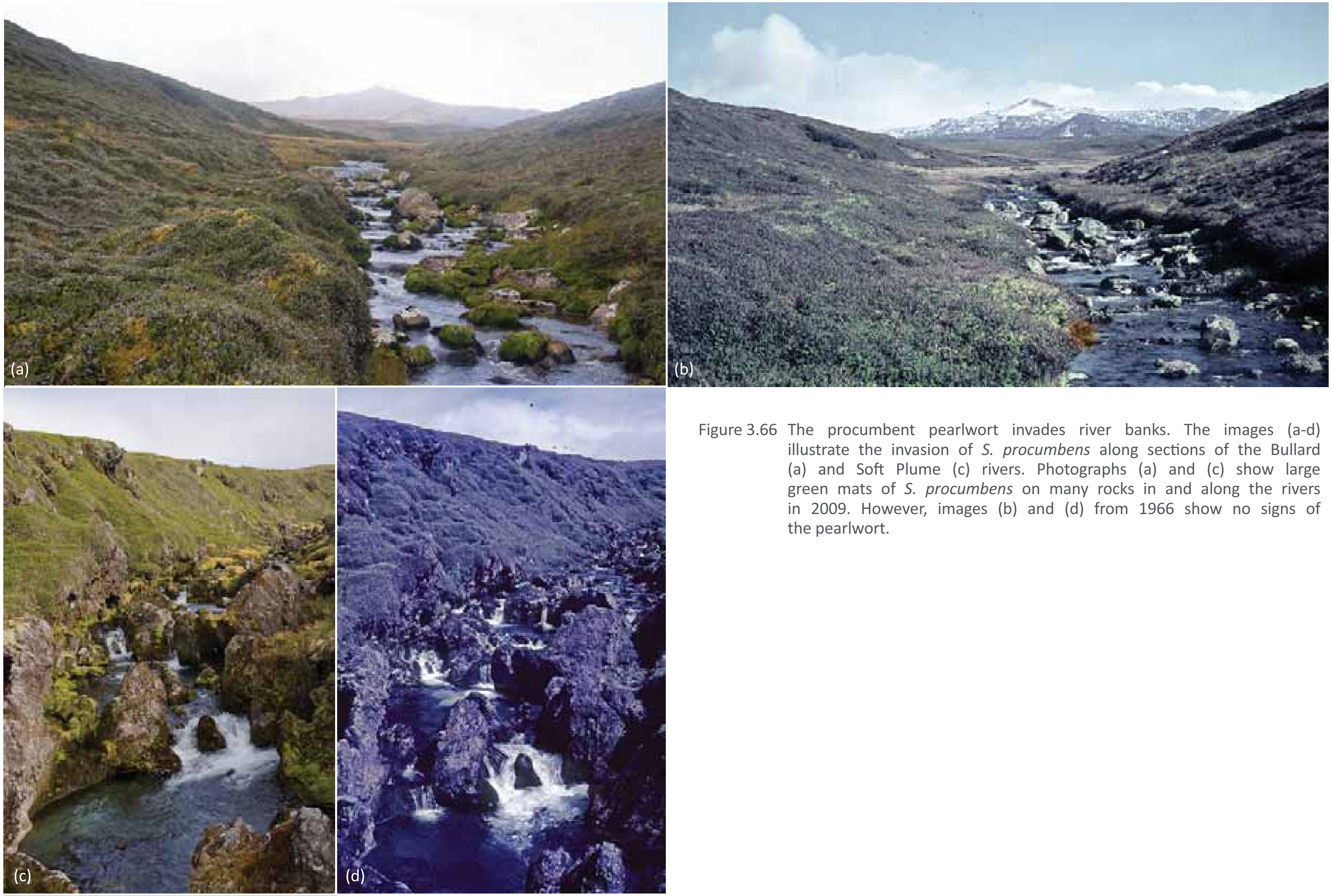

Figure 3.66 The procumbent pearlwort invades river banks. The images (a-d) illustrate the invasion of *S. procumbens* along sections of the Bullard (a) and Soft Plume (c) rivers. Photographs (a) and (c) show large green mats of *S. procumbens* on many rocks in and along the rivers in 2009. However, images (b) and (d) from 1966 show no signs of the pearlwort.

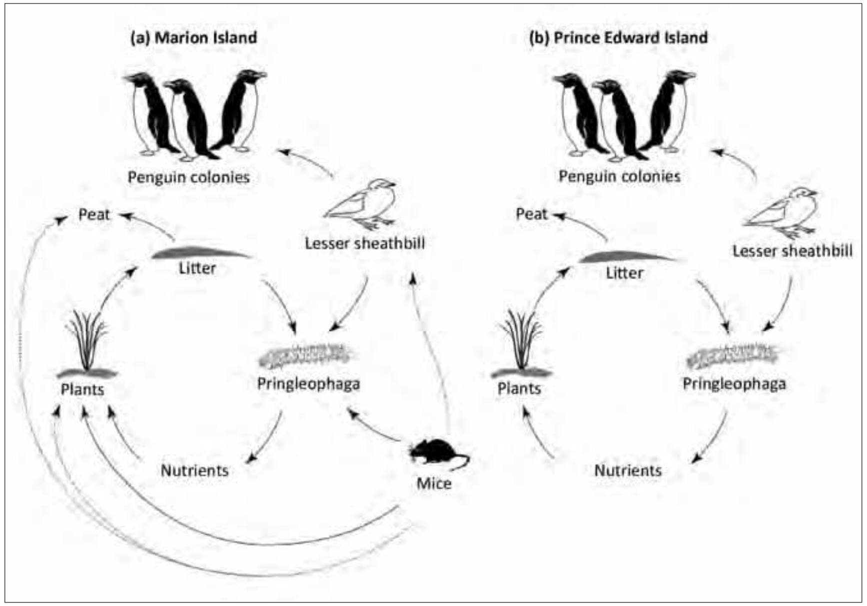

Figure 3.67 Schematic diagram showing interactions between plants, insects (notably caterpillars of the flightless moth, *Pringleophaga marioni*), mice and sheathbills on (a) Marion and (b) Prince Edward Islands. House mice are present on Marion Island. By feeding on invertebrates and plant seeds they are not only directly affecting these species (solid arrows), but are also indirectly affecting (broken arrows) nutrient cycling, peat accumulation and indigenous predators, such as the endemic Black-faced Sheathbill subspecies (*Chionis minor marionensis*). Prince Edward Island, by contrast, is mouse free. [5]

The introduction of small invasive species has also changed the system dramatically and seems set to continue to do so under a climate of change. Springtails, which are important contributors to soil ecosystem functioning, had naturally colonised Marion Island over its 500 000-year history, leaving ten indigenous species. However, with the arrival of humans, a further six species were accidentally added to the fauna. These species are typically 'weedy', having fast growth rates and strong responses to increasing temperature. Laboratory experiments have shown that under warmer conditions these invasive species are more resistant to drought than under cooler conditions, but that the very opposite is true of their indigenous counterparts. Thus, because of faster growth rates and greater tolerance to dry conditions, the invasive species should outcompete the indigenous ones as the climate on the island warms and dries. Field experiments that artificially warmed and dried a preferred habitat for these species demonstrated just such an effect. The indigenous species all declined in abundance, whereas the invasive species was largely unaffected.

These major changes in assemblage structure and food webs, which are a consequence of changing climates and interactions among indigenous and invasive species, demonstrate what might be expected in other systems. The impacts of global change-type drought are of particular significance for the South African system, and Marion Island provides an early warning of the kinds of surprises that might be expected elsewhere.

State and responses

Despite the variety of negative influences on Marion Island, and to a lesser degree, Prince Edward Island, wrought by anthropogenic environmental change, these areas remain among some of the most pristine on the planet. Indeed, in a recent analysis of the relative conservation value of all of the Southern Ocean islands, the Prince Edward Islands emerged as among the best conserved.

The high conservation value of the islands is a consequence of effective management informed by excellent and often long-term science. The Special Nature Reserve status of these islands means strict access control and particular attention is given to preventing the introduction of alien species and minimising waste generation. In the former case, new research has even identified those items of clothing, personal bags, and logistics containers that pose most risk of bringing seeds ashore, and appropriate management interventions have already been implemented.

Long-term research at the islands has resulted in effective conservation of an important and unique part of South Africa's natural heritage. It has also provided a remarkable range of lessons about what can be expected from climate change, invasive species, and their synergistic interactions. Synthesis of this research has shown that change is taking place rapidly, that it has substantial effects on ecosystems, and that the synergistic effects can lead to especially complex and surprising outcomes. These are valuable lessons for society, which is wholly dependent on natural systems for its future.

Acknowledgement

We thank the South African National Antarctic Programme for its support of our research over many years.

Species-level classification using imaging spectroscopy for the detection of invasive alien species

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Classification of vegetation at the species level using remote sensing approaches has long presented a challenge. The challenge is mainly due to soil- or phenology (seasonal)-driven natural variation in vegetation reflectance that often blurs spectral differences among species, or in other cases, by remote sensing platforms that lack the spatial and spectral resolution to detect subtle spectral differences among species. Accurate classification of species remains, however, a goal of many natural resource managers, often for inventory purposes or for programmes aimed at eradication of invasive plant species. This chapter provides a brief overview of remote sensing efforts towards species classification, with the intent to extrapolate findings to synoptic, accurate, and precise assessment of invasive species extent.

Introduction

Classification of land cover is typically viewed in terms of broad classes, for example, forest, urban and crop. Such classification schemes, although challenging due to the large area that needs to be covered, often do not present challenges in terms of spectral class differentiation. Consequently, land cover maps are generally produced from multispectral imagery featuring between three to ten bands. One can usually mitigate instances where spectral challenges do occur, typically due to large, mixed pixels that span multiple land cover classes, by either increasing spatial resolution (using smaller pixels) or by using multi-temporal imagery that captures seasonal changes in land cover reflectance. However, such approaches generally do not perform well while attempting to map vegetation at the species level, or even at plant community level. One type of sensor, called an imaging spectrometer or hyperspectral sensor, is however more adept at addressing the species classification challenge. We will review groundbreaking efforts in the United States, in general, and South Africa, specifically, which were based on the use of this advanced remote sensing technology for classification of vegetation at the species level.

Species-level classifications have many applications and resultant impacts on management and policy decisions. Examples include rare or protected species identification, weed detection and precision agriculture, mapping bush encroaching species, inventory of species, for example, volume-by-species assessment in forestry, and location of invasive species, for example, in the case of South Africa's 'Working for Water' Programme. Deciduous versus coniferous discrimination is easily attainable, even with coarse spectral resolution or multispectral sensors. This is because of the typical higher near-infrared reflectance of deciduous trees, due to different leaf cellular structures, when compared to coniferous trees. However, many species also exhibit differences in the visible region of the electromagnetic (light) spectrum, while longer infrared wavelength are instrumental in quantifying the bio-chemical make up which characterise each species (for example, nitrogen fixer versus non-nitrogen fixer). The key to this challenge is the use of sensors that are able to partition the electromagnetic spectrum in very narrow, contiguous wavelengths, as do imaging spectrometers or hyperspectral sensors. You can imagine a hyperspectral sensor as being similar to your eye – humans can differentiate many subtle changes in colors and are able to see many variations other than *only* blue, green and red.

Such sensors allow researchers and eventual practitioners to determine exactly which regions are amenable to differentiation among specific species. Classification examples of specific invasive species are generally hard to come by, with capital intensive crops, for example forests, often being the focus of studies. As a result we will look at (a) an innovative approach used by the South African Agricultural Research Council to map invasive species extent in lieu of the availability of operational remote sensing approaches, and (b) use of remote sensing to classify vegetation at the species level in the USA and South Africa. Arguably though, one could conclude that all roads lead to eventual implementation of refined remote sensing approaches, especially as sensor technology becomes cheaper and classification algorithms are refined.

Agricultural Research Council: An extensive invasive alien plant mapping effort

The problems and threats associated with invasive alien plant (IAP) species in South Africa have been widely recognised for many years and in-depth local knowledge and understanding of the subject exists (Figures 3.68 and 3.69). However, a study by Versfeld *et al.* [1] was the first assessment of the full extent of local invasions. The study was to determine the range and abundance of IAP species at 1:250 000 scale and was primarily based on local knowledge of resource experts across South Africa.

Figure 3.68 Many of the invasions are limited to riparian zones in South Africa, in this case mostly *Acacia mearnsii* and *Eucalyptus* spp. in fynbos in the Western Cape.

Figure 3.69 Landscape invasions are common on the coastal plains of South Africa and can be significant as in this case mostly *Acacia saligna*, *Acacia cyclops* and *Eycalyptus* spp. on the Cape West Coast.

A project was initiated by the South African Department of Water Affairs and Forestry's Working for Water Programme to reassess the range and abundance of major IAP species at a national level, namely the National Invasive Alien Plant Survey. The objective was to develop a cost-effective, objective, statistically-sound, and therefore repeatable monitoring system of woody IAP species at quaternary catchment level. The project thus extended past a mere update of the Versfeld *et al.* [1] map to the establishment of the Woody Alien Invasive Monitoring System. A multispectral remote sensing approach was considered to be inappropriate for this study for the following reasons:

(a) Alien invasive species can occur at different canopy levels. This would result in a species that occurs below a full canopy cover to go entirely undetected (Figure 3.70).

(b) The physiological structure of a species (for example, height, size and shape of branches and leaves) can be a crucial aid in the identification of a species (Figure 3.71).

(c) The extensive study area (South Africa, Lesotho and Swaziland) of 126,7 million hectares would be challenging, from a logistical and computing resource perspective, in terms of the quantity and high spatial resolution of remote sensing images required. Additionally, a detailed field survey or complete inventory for a study area of this size is not economically viable.

(d) The wealth of biodiversity, the total range and abundance of invasive alien plants, and the generally heterogeneous landscape would make classification techniques challenging, if not impossible.

The chosen approach therefore was a form of partial measurement or sampling using oblique aerial observations. A careful measurement of a small percentage of the units in a population frequently gives more reliable information than rough estimates obtained from the entire population and therefore allows for better inferences about that population of interest. The oblique aerial angle allows for more accurate identification of species as the structure of the plant is visible and various layers of plant growth can be identified (Figure 3.72).

The relationships between environmental variables (climate, soil and terrain) and species distribution and abundance (SAPIA database) were determined [2] and used to subset environmental variables into different classes. The study area was stratified according to these environmental classes and different sampling options were evaluated with the objective to determine the actual proportion of IAPs per quaternary catchment. The project is currently in a phase of data interpretation, following the allocation and stratified-random sampling of 74 156 sample points over a 12-month period.

Figure 3.70 Structural differences between vegetation such as the above savanna vegetation and the invading sub-canopy *Chromolaena ordorata* (light green) is a further challenge for remote sensing, not only in terms of spectral and spatial resolution, but often also temporal resolution when considering plant phenology.

Figure 3.71 A mixture of different IAP species (*Acacia Cyclops, Eucalyptus* spp.*, Acacia saligna, Acacia pycnantha, Pinus* spp.*, Leptospermum laevigatum*) of different densities, crown structures and size classes.

Figure 3.72 An oblique view of *Acacia cyclops* (darker green) in Fynbos (light green are mostly *Leucadendron* spp.) makes identification of such IAP species more accurate compared to a nadir view angle that will only result in the observer seeing vegetation canopy. Note the dead stems of *Acacia cyclops* trees from a previous fire.

Ultimately, the results of this study could be combined with existing multitemporal and multispectral sensor data by using different remote sensing tools to correlate and refine the actual proportion of IAP species within catchments. This approach could also provide the opportunity to investigate, for instance, hyperspectral options within selected areas to determine the possibility of using this technology to develop a cost-effective, objective, statistically-sound, and therefore repeatable monitoring system of major IAP species at quaternary catchment level.

Remote sensing: Classification of forest tree species

Past efforts at forest type classifications typically have relied on multispectral data (for example, [3]), while hyperspectral data have selectively been used to investigate species-level classification for mainly deciduous forest species in the USA (for example, [4]). Other researchers have evaluated the use of leaf-level [5] and canopy-level [6] hyperspectral data for classifying species within the *Pinus*, *Abies*, *Pseudotsuga*, *Sequoiadendron*, *Quercus*, *Melaleuca* and *Firmiana* genera. It is interesting to note that many of these genera are also considered 'alien' in a South African context. Classification accuracies ranged from 56-91%, but lacked application at airborne, or *operational* levels. However, Van Aardt and Wynne [7] were among researchers to extend results to operational levels by using airborne hyperspectral imagery data to classify *Pinus taeda*, *Pinus virginiana*, and *Pinus echinata*. Not only was it encouraging to note accuracies as high as 85% for species that are spectrally very similar, but it is also worthwhile considering that these species are representative of one of the primary exotic genera that we encounter in South Africa, namely Pines.

Figure 3.73 An adapted CASI hyperspectral image used for classification of *Eucalyptus* and *Acacia* species in KwaZulu-Natal, South Africa. Forests show up in purple and agriculture/fallow land in green hues in this representation.

Classification of another forest genus, namely *Eucalyptus*, has not been explored extensively. A *Eucalyptus*-specific study [8] evaluated high spatial resolution (0,8 m) CASI (Compact Airborne Spectral Imager) hyperspectral imagery for *Eucalyptus* classification (for example, *Eucalyptus acmenoides*, *Eucalyptus pilularis*, *Eucalyptus saligna* and *Eucalyptus sideroxylon*) in Australia and failed to accurately separate the *Eucalyptus* species. Researchers from the Council for Scientific and Industrial Research (CSIR) Ecosystems Earth Observation Group used 36-band (426-952 nm) CASI hyperspectral data (Figure 3.73) to classify *Eucalyptus dunnii*, *E. grandis*, *E. grandis* x *nitens* and *Acacia mearnsii* in the KwaZulu-Natal province, South Africa. They were able to show that near-infrared wavelengths, red-edge characteristics (Figure 3.74), and even one blue-region wavelength were useful for classification at species level, citing accuracies of 85% and 97% for between species and between-species-within-age group (7-11 years) classifications, respectively.

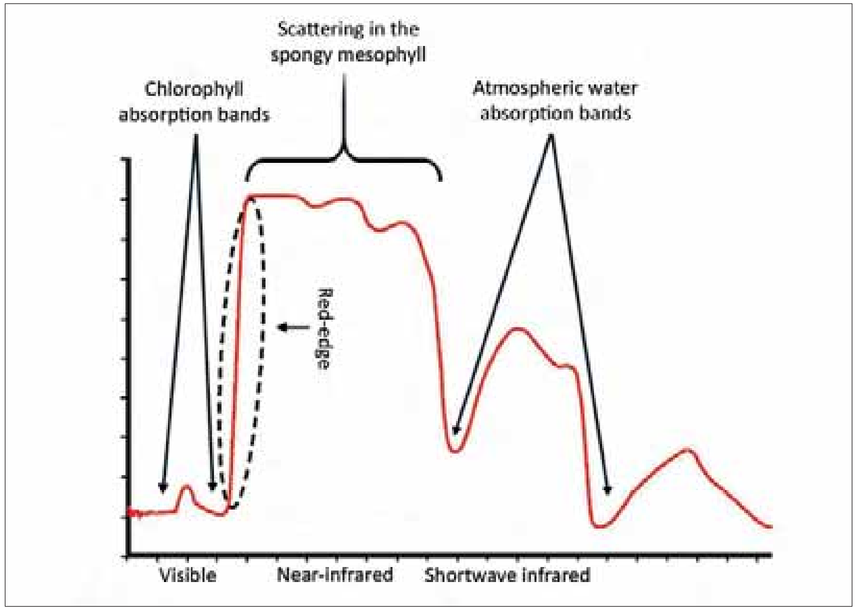


Figure 3.74 This graphic shows typical spectral reflectance features of vegetation: Blue and red absorption due to chlorophyll, the green reflectance peak (which explains why we perceive foliage as green), the red-edge 'ramp' to high near-infrared (NIR) reflectance. These red-edge and NIR regions are particularly useful for vegetation studies.

Extension to large scale invasive species mapping

Efforts such as those by the ARC and CSIR show that identification and mapping of invasive species for large aerial extents remain a priority and challenge in South Africa. However, it is evident that if we are to perform temporal analysis of these species while delivering extensive coverage for the country, we will need to revert to synoptic or space-based remote sensing approaches. Such techniques lend themselves to repetition and large area application, but arguably might lack the accuracy of extensive, but expensive, field campaigns. This drawback is being circumvented by the use of advanced remote sensing technologies, for example, hyperspectral remote sensing, and we are seeing proof of increasing accuracies for species that can be regarded as spectral very similar. To date, the only operational space borne hyperspectral instrument is Hyperion (NASA, USA), but an increasing number of missions are planned in the near future, for example, EnMAP (DLR, Germay), PRISMA (ASI, Italy), and MSMISat (SunSpace, South Africa), with spatial resolutions ranging from 15-30 meters. Much work remains, however, in defining exactly what an ideal 'species detecting sensor' should look like. It should be effective (accurate), operational (cover large areas) and cheap (have a limited number of spectral channels, for example, an airborne multi-spectral system). While one could argue that most of the species classification research has focused on forest or tree species, the extension to other plant species with exposed crowns is also undeniable, for example, savanna plants species in the case of the hyperspectral-lidar Kruger National Park campaign discussed elsewhere in this publication. It is, however, evident that we will be able to map most plant (invasive) species, given enough resources in terms of manpower and technological back-up. To this end, government programmes that sustain eradication and brute-force invasive species mapping must be run coincident to research and development efforts that are focused on finding elegant solutions to this problem.

RIGHT Pines invading Fynbos in the Southern Cape. [Brian van Wilgen]

MINING

Opencast diamond mining along the West Coast in a fragile environment.

MINING

Introduction

Theo D. Wassenaar

South Africa holds 80% of the world's reserves of manganese, 88% of its platinum group metals, 73% of its chromium and 45% of its gold. This exceptional mineral wealth is a consequence of a long and complex geological history that can be traced back for over 3,7 billion years. But the statistics also neatly paraphrase the extent to which the country's economy has been and still is dependent on the extraction of minerals from the earth. Minerals have been dug from the South African soil since long before the advent of the modern economy – as Richard Dean and Sue Milton point out in this section, the earliest diggings at Phalaborwa and other places date back to the Iron Age. But these early miners were mostly looking for copper-based minerals in the relatively shallow oxidised zone, and their mines were small and widely scattered across the subcontinent [1].

It was not until the start of European mining that the water table and the un-weathered rock was penetrated on any significant scale. What followed was remarkable. The 'diamond rush' and subsequent 'gold rush' were the catalysts for arguably South Africa's first major socio-economic upheaval, meshing intricately with the wider political environment [2]. Almost overnight, the economic focus shifted from coastal agriculture to the inland extractive industries. And despite some spectacular economic volatility in the industry from early on (a phenomenon that continues to this day), mining has proved to be a remarkably robust part of the South African economy. Which is good, of course, but it has a downside.

Perhaps because all ores are finite, the mining industry is almost hard-wired for exploitative practices. Not surprisingly, as Dean and Milton explain, mining has had a chequered environmental and social record. From early modern mining's labour practices to current problems with environmental pollution, the huge array of potential and real impacts has proven to be difficult to manage. Several of these impacts are directly or indirectly ecological in nature and their extent varies with mining type and size. Partly as a result of external pressure on the industry to improve standards and partly as a result of better techniques being developed in the last few decades, ecological restoration has emerged as an important strategy to counter impacts on biodiversity. Dean and Milton point out that best practice in restoration revolves around the retention of a range of biological resources, ecosystem functions and biodiversity itself. Careful management of ecological processes could make the difference between success and failure. By no means all restoration projects are successful, but Rudi van Aarde and colleagues describe one that apparently is. Coastal dunes north of Richards Bay are strip-mined for ilmenite. In this process the dune forests are entirely destroyed, but the mining company's 30-year old rehabilitation programme, relying on a natural process of succession, seems to be successfully replacing the forest species. As they point out, however, it is impossible to separate the mine from its regional context. The destruction of other forests in the region through changing trends in land use means a loss of source areas and thus a shortage of colonising forest species. An external factor, outside the control of the mine, may thus prove to be the biggest threat to the restoration programme's success.

Another good example of this inter-dependent nature of environmental management in a modern mine is the chemical and radiological pollution of water. In the coal mines on the Highveld, chemical reactions caused by the exposure of pyrite in rock to oxygenated water results in acidification of ground and surface water with consequent disastrous effects on downstream ecology. As McCarthy and Pretorius explain, this problem is old, insidious and huge. Large parts of the Olifants River have been affected, as have both Middelburg and Witbank dams. What makes these impacts especially perverse though, is that most of the mines that caused the problem have been closed for some time. Options for mitigation are therefore severely limited, and, perhaps more importantly, in this case the past points to a much more problematic future over a much larger area. Current large opencast mines are likely to lead to larger volumes of more acidic water when they begin decanting in the future. This is potentially a serious problem; one that might endanger the drinking water of a third of the country's population. The only option may be a drastic one: a moratorium on all new applications for mining licences until the cumulative impacts and mitigation options are better understood.

On a smaller scale, the problem of polluted water may be managed surprisingly successfully by using it to irrigate crops, as John Annandale and colleagues explain. Depending on conditions, water decanting from coal mines can be alkaline or acidic and is usually saline. Trials have shown, however, that water with high levels of calcium and magnesium sulphate may be used for irrigation with minimal effects on crop health or the environment in the short term. Irrigation is certainly among the cheaper of many mitigation options, and unlike in many agricultural settings, chemical quality can be selected (if not controlled) and leaching as well as impacts on groundwater can be controlled.

Clearly, all such mitigation options have to be investigated, but it is quite possible that some problems may yet prove to be intractable, if only because of their sheer scale. As much as it may be possible to mitigate ecological impacts, chemical and radiological pollution will probably be with us for centuries. Fortunately there are encouraging signs that the industry is beginning to understand the profound century-old impact that it has had and still has, but in many cases there is a glaring gap between intent and practice. For instance, many mining companies, aware that the government's capacity to enforce the generally adequate environmental legislation is poor, still seem to regard their primary responsibility as seeing how far they can stretch the definition of compliance. On the other hand, government appears to want to milk the mining cow for all its worth as a generator of economic growth, but seems to be unreasonably slow in developing sound policy and regulations to manage environmental impact. In view of such glaring potential disasters as described by McCarthy and Pretorius, this is unsettling to say the least. The ball is definitely now in the court of both industry and government. The chapters in this section show that our knowledge of both the nature of environmental impacts and how they can be prevented or mitigated is growing. However, unless industry and government take their environmental responsibility seriously, South Africa will lose more as a result of mining than what it stands to gain.

Overview of mining types, spatial distribution, costs and benefits

W. Richard J. Dean
Suzanne J. Milton

The social and environmental impacts of mining are similar, in that mining brings short-term gains and long-term problems ranging from sinkholes and cancers to ghost towns and unemployment. This overview chapter deals with broad spatial distribution patterns of minerals in South Africa, temporal trends in exploitation of mineral resources, and the need for minimising and mitigating the impacts of mining on natural ecosystems, human heath and local economies.

Introduction

This chapter on mining as a driver of socio-economic and environmental change in South Africa first discusses the spatial distribution of minerals in South Africa. The chapter then describes temporal trends in mining of various mineral resources, before dealing with ecological and social impacts of mining and the need for mitigation and restoration of natural capital. South Africa is an arid land with diminishing resources and a rapidly-growing human population and the critical message of this chapter is that both ecological restoration and social development are necessary following mine closure.

Spatial patterns in mining

Mining in South Africa has a long history that goes back more than a 1 000 years [1]. In those times, mining concentrated in the north and northeastern parts of South Africa and covered quite a large area [1, 2]. Ancient mining was chiefly for metal ores, such as copper, iron and tin, with a small amount of gold, but impacts were not very marked. Many of the old mine shafts and tunnels have filled in and few shafts remain open. Nevertheless, some ancient mine workings can be clearly identified and indicate that such major disturbances cannot be restored or the area rehabilitated without intervention.

Recent mining in South Africa includes copper, gold, iron and tin plus an array of other metals and minerals including building stone, dimension stones, gravels for road building, aggregates and sands for making concrete, clays, and silica sands for glass. Although economically viable deposits of minerals are found throughout South Africa, most mining activity occurs in the northwestern, northern and eastern, and north-central areas. Recent demands for zirconium and titanium has led to sand mining along the coasts. The dwindling oil supplies and the rising price of radioactive materials may soon lead to mining of the uranium-rich sedimentary rock of the central Karoo.

Temporal trends in mining

Recent mining in South Africa began in the late 1800s when diamonds were discovered in the area now known as the Northern Cape. The finding of a large diamond in 1865 and the discovery of the larger Hope diamond at Hopetown precipitated the 'diamond rush', and diggings followed the diamond bearing gravels north to where Kimberley was established.

Although there were numerous small gold mines during the 1800s, the development of the gold mining industry in Gauteng really began in 1886 when nine farms were proclaimed as public gold diggings [3]. Both diamonds and gold stimulated massive immigration of diggers and led to the rapid establishment of cities and secondary industries centred on the mines. Some 57 different minerals were mined in South Africa in 1995. This involved 816 mines and quarries, with mined products being used domestically and exported to 81 countries [4].

Early colonial mining activity in South Africa was controlled by a few men, who wielded both political and economic power [5]. Until recently, the mining sector in South Africa did not operate in a free market system [6], and even now, the production and price of diamonds is tightly controlled and prices have risen steadily over the last four decades [7]. The gold price, however, fluctuates, and low prices and rising labour costs have brought about a decline in production – a trend that may continue for another decade [3]. South African gold reserves are large and an estimated 45% of the world's gold remains in the Witwatersrand Complex [3].

Figure 3.75 Early colonial mining. [De Beers Consolidated Mines Ltd]

Recent developments in the electronics industries, growing interest in nuclear power and developments in medical science have increased demands for several other metals and minerals, including zirconium, hafnium, uranium and cobalt. There is also an increased demand for aggregates for making concrete [8], and the mining industry, as a whole, appears to be growing.

Ecological impacts

Mining impacts start before the mining process begins and may continue beyond closure. Prospecting generally involves test drilling or linear excavations and results in informal roads, camp sites, boreholes and damage to vegetation and soil caused by vehicles (Figure 3.76).

Figure 3.76 Uranium prospecting's impacts on a rural environment. (a and b) Soil contamination with radioactive ore samples. (c and d) Widening and compaction of farm tracks and damage to vegetation.

Ecological impacts of mining are diverse and may be direct or indirect. The main impacts are changes to the water table, natural ecosystems at the mine and the surrounding area, and alteration of scenery through the construction of mine dumps, slimes dams and open pits. The extent, intensity and duration of the impacts vary with the type of mining and the size of the ore body.

Opencast and open pit mining is used when the ore body is near the surface (Figure 3.77). Whereas topsoil may be saved and replaced following opencast mining in sediments (for example, mineral sand mining), pit mining for extraction of coal or marble leaves a large hole and has a severe and permanent local impact [9]. The open pits can be used for other purposes, such as waste disposal sites or reservoirs for water [10].

Sub-surface mining at various depths involves human labour or mechanisation underground. Shallow underground mining, with the exception coal mines, generally have had very little impact on the environment, but leave clear footprints [10]. The impact of coal mining on the environment is severe, and includes water pollution, disruption of land forms and disturbances to local plant and animal communities [10]. The above-ground environmental impacts of deep underground mining are restricted to the above-ground infrastructure, slimes dams and dumps, but wider impacts may include pollution of local ground water and changes to water tables through dewatering of the mine and local seismic disturbances [10]. Dumps are often colonised by alien plants and thus become centres from which seeds are dispersed to surrounding areas (Figure 3.78).

Solution mining (for example, for uranium) involves the insertion of a strong acid or alkaline liquid into an underground ore body followed by withdrawal of the liquid that then contains the dissolved mineral. The process uses large quantities of water that may be recycled. The benefits are that people and machines do not have to go into the ore body. However, if the ore body is not in a watertight compartment, there is a risk of groundwater contamination by leachate.

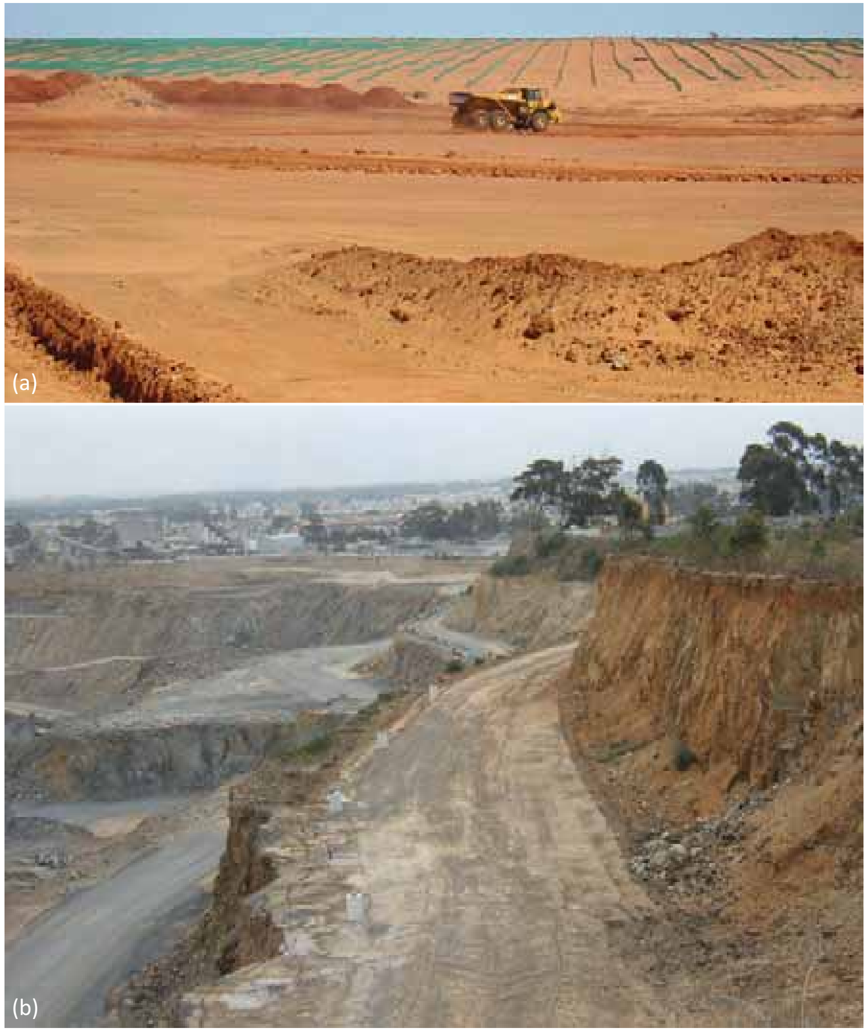


Figure 3.77 (a) Opencast mining of mineral sands on the Namaqualand coast near Brand se Baai. (b) Open pit gravel mine near Stellenbosch.

Figure 3.78 Kimberley diamond mine dumps colonised by alien invasive Fountain grass (*Pennisetum setaceum)* and Peruvian pepper tree (*Schinus molle*).

Practically all types of mining, whether opencast or underground, produce some waste products that need storage in slimes dams. Depending on the processing used to extract the mineral, the slimes (fine particles mixed with water and chemicals) may be innocuous or highly toxic and could contaminate ground waters if poorly managed [10]. Discarded mining products, such as asbestos and uranium tailings, pose a health hazard for many decades after mining has ceased. Many minerals are partially processed on or off the mine by the use of heat with or without chemicals, and processing plants frequently include a smelter that has potential to pollute the air with acids and particulate matter, and to produce liquid effluent.

Indirect effects of mining are related to the provision of water and energy for the mine, and housing and other resources for mine employees. Essential services to mines and mine villages include road and rail links, power lines and water pipes. These fragmented natural landscapes give people access to harvesting plant or animal populations that were formerly protected by their remoteness or inaccessibility and create disturbances vulnerable to invasion by alien plants. Supply lines and transport routes also make indelible scars across landscapes, particularly in arid areas [11]. Housing development for mine personnel has a direct impact on the environment. Fuel and food needs of mine personnel may be obtained from the vicinity of the mines, but when depleted, are sourced more widely. For example, firewood was imported to the diamond diggings from Botswana, so the woodlands there were almost totally destroyed [12].

Social impacts and local economic impacts

There are two major groups of ill health associated with the mining industry, namely ill health caused by the physical environment and ill health caused by the social environment. Risks in the physical environment are caused by the high probability of accidents through rock falls, exposure to radiation, dust, chemicals and explosives and the use of heavy machinery. Rigorous training and safety procedures help to minimise these risks.

Diseases and illnesses associated with the social environment are related to a combination of stress, boredom and isolation from normal cultural links and family ties. They include depression, substance abuse, sexually transmitted diseases (such as HIV) and domestic violence. An additional risk is that mine workers from outside South Africa may bring different strains of diseases. For example, the HIV-1 strain came into South Africa through migrant workers from Malawi and the HIV-2 was brought into the country from Mozambique [6].

Local economic impacts of mining are initially positive with the creation of new communities and wealth, skilled employment and training for local populations and improved infrastructure including roads, schools and health care [13]. Later, following closure, there is usually a period of emigration and unemployment. Many mining companies mitigate post-closure depression as part of their skills development and severance planning programmes.

Restoration, rehabilitation or reallocation

The National Environmental Management Act of 1998 requires pre-mining assessment of social and environmental impacts and implementation of environmental management plans throughout the life of the mining operation. This is aimed at minimising environmental risk and repairing damage. The closure of a mine is dependent upon achievement of specified environmental targets for the return of biodiversity, ecosystem function, land use options, aesthetics and environmental health.

Best practice restoration should focus on retaining resources, ecosystem function and biodiversity [14, 15]. Retaining resources is best achieved by salvaging and returning topsoil, mulch, seeds and plants [11], by contouring the soil surface to retain water and by controlling wind scour through use of nets and mulch [14, 15]. The restoration process can run concomitantly with the mining process on strip mines. Mined dune sands at Richards Bay, KwaZulu-Natal [16, 17] and sands in Namaqualand [15] are being successfully rehabilitated using this approach. As much of the original biodiversity as possible should be returned to a mine site because diverse plant communities enable a wider range of land use options, particularly in arid areas. A demand for ecological restoration provides opportunities for small businesses that collect and sow seeds, grow and translocate plants and erect erosion control structures [18]. Mine closure implies the termination of such services on a mine, but other sectors, such as agriculture, can make good use of these skills.

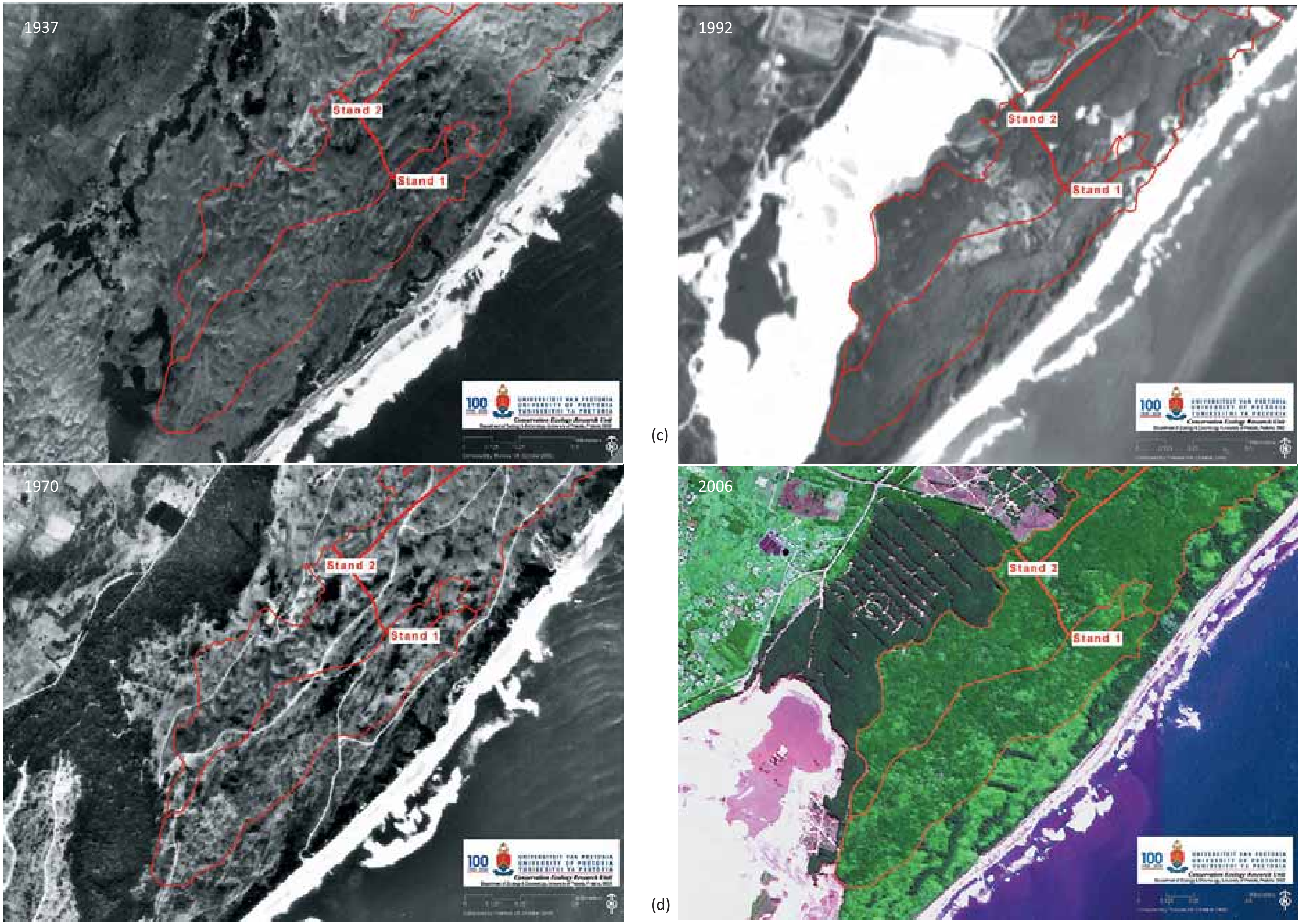
Restoring the mined coastal sand dunes of KwaZulu-Natal

Rudi J. van Aarde
Theo D. Wassenaar
Robert A.R. Guldemond

Strip mining, by its very nature, destroys biological diversity. Lessening this impact is a unique challenge, particularly in coastal dune forests that are also fragmented and threatened by human activities other than mining. For some 30 years, Richards Bay Minerals has been mining the mineral rich sand dunes of northern KwaZulu-Natal for various minerals. The mining company's concurrent post-mining rehabilitation of dune forest aims to restore the typical biological diversity and relies on ecological processes to regain and ensure the persistence of such diversity. Our 18-year old research programme suggests that dune forests can be successfully restored, but that success may be hindered by a variety of regional forces driven by the activities of people. This may call for the refinement of an adaptive management programme to enhance ecological restoration.

Introduction

Native forests are shrinking throughout the world. Human settlement, clearing for forestry and agriculture, mining and tourism development all contribute to the loss and degradation of forests. Consequently, biological diversity may be lost. At the same time, ecosystem services, such as water retention and carbon capturing and storage, are increasingly degraded. Forest restoration provides a way to either halt or reverse these losses and prevent further degradation. Our study on the ecological consequences of a post-mining forest restoration programme along the coastline of northern KwaZulu-Natal allows us to assess if forest restoration is feasible and if biodiversity and ecological services can be gained through restoration [1].



(a) (b) (c) (d)

Figure 3.79 Aerial photographs from 1937 and 1970 (a-b) show that prior to mining, large tracts of the coastal dunes were covered by a mosaic of grasslands, plantations and discontinuous patches of dune forests. Stand 1 and 2 delineated here, are two sections in the southern end of the lease area where rehabilitation started in 1977 and 1980, respectively. By 1992 these stands were dominated by canopies of Sweet thorn trees (c) and by 2006 natural die-offs of many of these trees resulted in visible gaps (d). [Chief Directorate of Surveys and Mapping, Mowbray, Cape Town, South Africa and the Richards Bay Minerals Mining Office]

In South Africa, dune forests are limited to the first few longitudinal dunes that run parallel along 240 km of the KwaZulu-Natal coastline. Here relatively steep dunes (they are in some places up to 150 m high) separate the high-energy shoreline from inland areas and therefore protect the landscapes and people of the hinterland from storms typical for the region. The dune forests, also known as the Indian Ocean coastal belt forests or the coastal subtropical Indian Ocean forests, are probably less than 8 000 years old and stretch from Mtunzini (28º57'13"S, 31º46'33"E) in the south to the Machangulo Peninsula (26º04'52"S, 32º57'09"E) in Mozambique in the north. This type of forest (ecoregion) covers some 223 km^2 (less than 1%) of the total area of Maputaland, which is internationally recognised as a Centre of Endemism [2]. The dune forest ecoregion therefore is a relatively small biome of high conservation importance. Some 65% of the dune forests are formally protected but much of the forest beyond these areas has a long history of degradation through human activities. At present nearly 20% of areas where dune forest may occur fall in mining lease areas where mining may continue for another 20 years. When mining started north of Richards Bay in 1976 only about one-third of all the lease area consisted of forests, some of which were relatively intact, but others that were degraded (Figure 3.79). The rest of the lease was covered in poorly maintained plantations that were invaded by exotic herbs and shrubs.

These aerial photographs suggest that much of today's coastal dunes were covered by grasslands as recently as 70 years ago. However, anecdotal records suggest that the region must have been completely forested before Iron Age people used these forests some 1 500 to 2 000 years ago. The increase in woodland cover since 1937 also shows that forests are dynamic and may regenerate after disturbances brought about by people and natural forces. Such disturbances come in various forms. For instance, excessive winds, rain, fire, tree felling by man, natural die offs, mining and slash and burning rural agriculture that remove trees leave gaps in the forest canopy. Consequently, a variety of species, other than those that died, can settle in these gaps. This adds to the variability in the presence of species with time and across the forests. Some argue that forests need natural disturbances to maintain their diverse nature, but this clearly depends on the scale, intensity and frequency of such disturbances.

Kick-starting the restoration of dune forests

Strip mining of sand dunes (Figure 3.80) can be considered a form of disturbance that destroys all vegetation and that occurs at a scale much larger than natural disturbances such as storms and tree fells. The recovery of dune forests following mining therefore needs intensive management to nurture ecological processes that can give rise to the development of indigenous forests.

Figure 3.80 Strip mining of the sand dunes in northern KwaZulu-Natal.

Since 1977, Richards Bay Minerals has committed itself to assist in the regeneration of coastal dune forests by 'kick-starting' ecological processes on a third of the mined area. In practice, this kick-starting begins with the collection of topsoil prior to mining. Soon after mining, the topsoil is spread over the mined sand dunes that have been mechanically restructured to resemble their pre-mining shape. A team of workers then erect fences of shade-cloth to prevent the topsoil from blowing away. To stabilise the soil further, the seeds of annual plants, such as sunflower and hemp, are sown. These annuals soon establish themselves, and from this point onwards, the process of natural development takes over. The images in Figure 3.81 illustrate the kick-starting process.

Figure 3.81 This sequence of images shows some of the activities associated with the kick-starting the rehabilitation process through the spreading of topsoil on mechanically shaped dunes, the erection of shields to protect the dunes and seedlings from excessive wind, and the sowing of seeds of annual plants.

The development of dune forest vegetation starts with the germination of the seeds of pioneer species, such as Sweet thorn trees, that are present in the topsoil or carried in by animals and wind. These Sweet thorn trees quickly form dense thickets, but after six to eight years gaps begin to appear when some of these trees succumb to storms and competition. This process of natural thinning reduces the density of trees from 20 000 per hectare at the onset of the process to less than 500 per hectare 15 years later. Then, forest species, such as the Coastal red-milkwood, White stinkwood, Natal karee, and Common turkey-berry, mostly spread by birds and mammals, settle in the gaps where pioneer trees have given way (Figure 3.82). With time, more forest plant species settle in under conditions now favourable for them. These are soon followed by an array of insects, birds and mammals typical of the region.

Figure 3.82 A sequence of images to illustrate the age-related development of an ecological sere of succession on areas that have been mined and are now regenerating in response to a forest restoration programme that is being maintained by the mining company.

Our ongoing research in this outdoor laboratory has been continuing for some 18 years [3]. Here we study the response of forest plants and animals to the restoration initiative (Figure 3.83).

Our information shows that forest development on mined dunes is similar to that on dunes that were not mined but were disturbed by people in the past. On all of these dunes the regeneration of forests may be dictated by ecological succession because species are continually added while some are replaced by others. Over time, the formerly mined dunes thus become increasingly similar to unmined and intact forests typical of the region and we have recorded these patterns for a variety of taxa [4, 5]. In Figure 3.84 we show that about 50% to 70% of forest birds (surveys done in 2006, 2007 and 2008), sub-canopy and canopy trees (surveys done in 2001 and 2005) and millipedes (surveys done in 2006, 2007 and 2008) have colonised the rehabilitating stands within a period of 30 years since regeneration was kick-started. Some of the soil processes that accumulate carbon, nitrogen, sodium, calcium and phosphorous and improve soil fertility are also intact and contribute to the ecological restoration of the biological diversity of dune forests and to the ecological services that they provide [6].

Figure 3.83 Some of our research activities include surveying birds and millipedes and measuring tree stem diameter of the Sweet thorn trees in the rehabilitating stands.

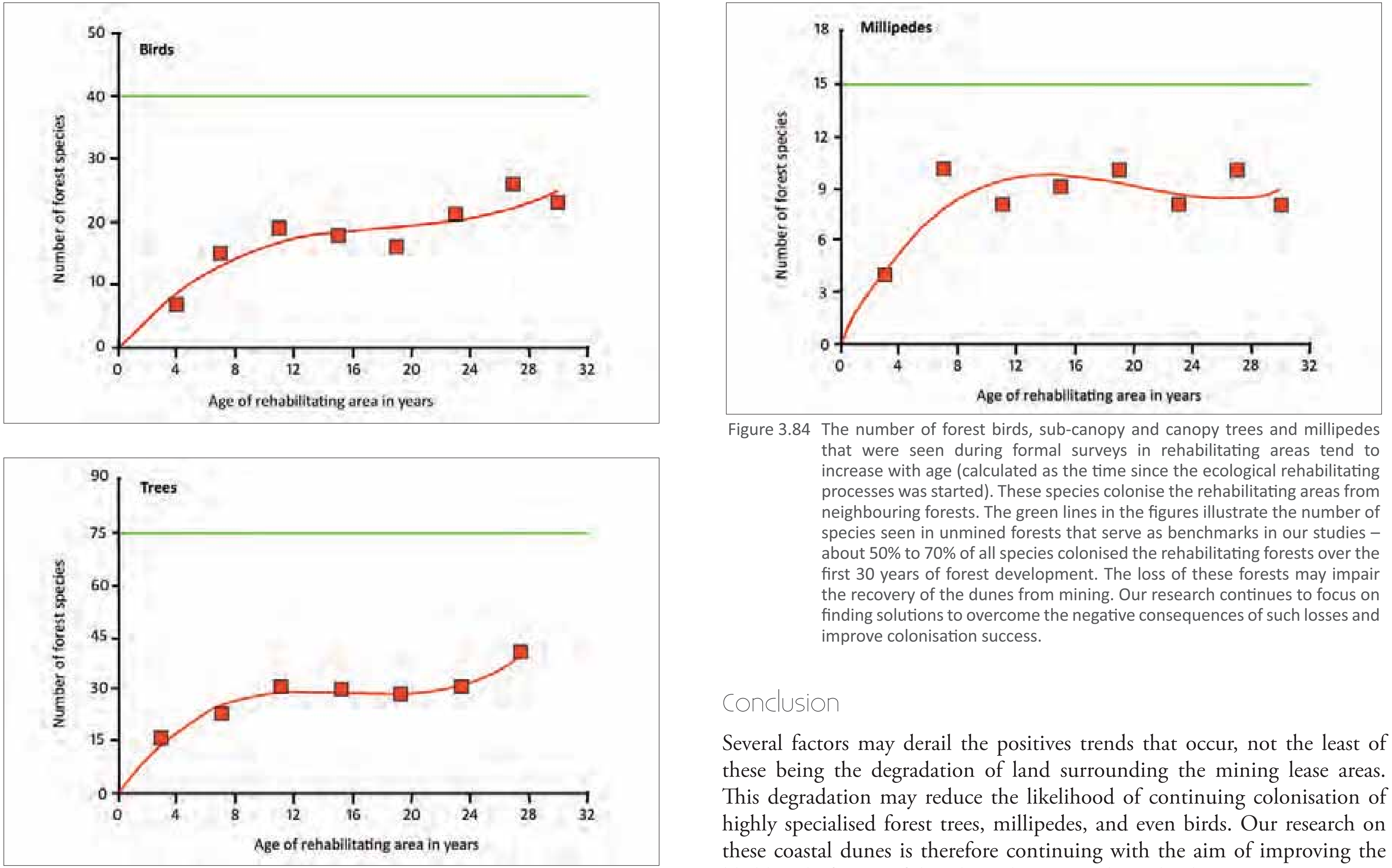


Figure 3.84 The number of forest birds, sub-canopy and canopy trees and millipedes that were seen during formal surveys in rehabilitating areas tend to increase with age (calculated as the time since the ecological rehabilitating processes was started). These species colonise the rehabilitating areas from neighbouring forests. The green lines in the figures illustrate the number of species seen in unmined forests that serve as benchmarks in our studies – about 50% to 70% of all species colonised the rehabilitating forests over the first 30 years of forest development. The loss of these forests may impair the recovery of the dunes from mining. Our research continues to focus on finding solutions to overcome the negative consequences of such losses and improve colonisation success.

Conclusion

Several factors may derail the positives trends that occur, not the least of these being the degradation of land surrounding the mining lease areas. This degradation may reduce the likelihood of continuing colonisation of highly specialised forest trees, millipedes, and even birds. Our research on these coastal dunes is therefore continuing with the aim of improving the likelihood of successful ecological recovery through adaptive management.

MINING

Coal mining on the Highveld and its implications for future water quality in the Vaal River system

TERENCE S. MCCARTHY
J.P. PRETORIUS

Coal mining commenced in the Witbank area in 1894 and continues to the present day. This region thus provides insight into the longer term environmental impacts of coal mining. The most serious impact is on water quality, and the Olifants River in particular has been severely affected, with total dissolved solids having increased ten-fold since mining commenced, and they are still rising. Mitigation efforts have thus far failed to reduce the impact. There is currently an upsurge in new applications for mining permits, especially in the upper Vaal River basin. If these are approved, mining could result in severe pollution of the Vaal River, which supplies the water needs of about a third of South Africa's nation population.

Introduction

The history of coal mining in South Africa is closely linked with the economic development of the country. Commercial coal mining commenced in the eastern Cape near Molteno in 1864. The discovery of diamonds in the late 1870s led to expansion of the mines in order to meet the growing demand for coal. Commercial coal mining in KwaZulu-Natal and on the Witwatersrand commenced in the late 1880s following the discovery of gold on the Witwatersrand in 1886. In 1879, coal mining commenced in the Vereeniging area and in 1895 in the Witbank area to supply the Kimberly mines and those on the Witwatersrand.

Given the long history of coal mining, some deposits have been worked out and mines closed. Numerous environmental problems emerged with the closure of mines. Extensive research has been done on the causes and extent of the problem, notably under the auspices of the Water Research Commission. In this chapter, we draw on the experiences from the Witbank area and particularly the impact mining has had on the quality of water in the Olifants River in order to assess future scenarios in other Highveld river catchments, and especially the Vaal River.

Environmental problems

A number of environmental problems have emerged as a result of coal mining. These are best exemplified by the Witbank field, which has experienced a long history of mining.

Underground fires, collapsing ground

Early mines in the Witbank field were shallow and were mined by the bord-and-pillar method. The coal seams came to outcrop although the actual coal seam outcrop was generally covered by soil. The No. 2 seam was a particularly important horizon and is between 5 and 6 m thick. Only the lower 2 to 3 m was mined as the rest was considered of too low quality. Thus, some 60% of the seam was left in the ground. After closure, the remaining coal in many of the mines caught fire, and as the fires burned, the roof rocks collapsed, creating dangerous ground conditions and making the surface unusable (Figure 3.85).

Figure 3.85 A collapsed, burning coal mine.

Acid mine drainage

The most serious environmental problem arising from coal mining is the generation of sulphuric acid as a result of a chemical reaction between an iron sulphide mineral (pyrite) present in the coal and its host rocks and oxygen-bearing water (infiltrated rain water). Mining breaks up the rock mass allowing free access of water and the acid-producing chemical reactions proceed faster than the acid can be neutralised. Consequently, the water becomes acidic and toxic to animal and most plant life. The acid water dissolves aluminium and heavy metals (iron, manganese and others) and increases its toxicity (Figures 3.86 to 3.88).

Figure 3.86 Acidic, iron-rich water filling a collapsed coal mine.

Figure 3.87 Barren soil caused by seepage of acidic water from a flooded coal mine.

Figure 3.88 The Wilge River during a coal mine-related pollution event in June 2007. The blue colour is believed to be due to the precipitation of aluminium compounds.

The mining method used has a significant impact on the acid generated. In bord-and-pillar mining, only the pillars come into contact with water, and hence acid generation is limited. Collapse of the roof increases the contact area and also facilitates the ingress of rain water, thus increasing acid generation. Consequently, longwall mining results in more acid generation than bord-and-pillar mining. In opencast mining, the rock mass is completely fragmented, maximising the contact between water and rock. This is, therefore, the most acid producing mining method.

Acid water produced in the mines may seep out at surface, where further reactions with oxygen occur, precipitating iron and generating yet more acid. This water sterilises the soil with which it comes into contact (Figure 3.87). The water enters rivers which become acidified, reducing biodiversity to a few particularly hardy species. Neutralisation reactions occur as a result of mixing with other neutral water sources and may result in the precipitation of aluminium (Figure 3.88), which is toxic to fish and possibly other aquatic animals. Ultimately, the acidity is neutralised, but the water remains sulphate-rich and typically contains 2 000 to 3 000 ppm (parts per million) sulphate. (The recommended limit for water for human consumption is 200 ppm.)

Destruction of groundwater reservoirs

The rolling hills of the Highveld are characterised by abundant seasonal wetlands, perennial and seasonal streams and many fresh to mildly saline pans. This diversity arises because of the unique nature of the groundwater aquifers. Three different groundwater aquifers are found in the Highveld: the first is formed by fractures in the bedrock; the second by the deeper regolith; and the third by the zone above the plinthite layer (perched aquifer). Water quality differs in the different aquifers, being highest in the perched aquifer (<20 ppm dissolved solids) and lowest in the fractured rock aquifer, where the dissolved solid concentration is in the order of hundreds of parts per million.

Mining disturbs the aquifer structure. Bord-and-pillar creates additional voids in the fractured rock aquifer, but the regolith aquifers remain intact provided there is no collapse of the workings. However, water filling the mine void is of extremely low quality and is detrimental to the environment should it leak out. At the other extreme, opencast mining completely destroys the groundwater aquifers and creates a single massive aquifer in the mine void. After mine closure, water fills this aquifer to the lowest elevation of the bedrock rim and additional water entering the void decants over the rim. This water is of extremely low quality. Longwall mining fractures the bedrock, creating additional void spaces and increases both inflow into the void and seepage. The water is also of low quality. Once an area has been mined, borehole water from that site will generally no longer be usable for agricultural or domestic use.

Disposal of excess water during mining

The coal mines are not particularly water-rich, and mining activities do consume some water. However, from time to time, operating mines find themselves with an excess of water, often as a result of heavy rains. The water is usually heavily contaminated, and releasing it into streams can have severe environmental consequences, often resulting in large-scale deaths of fish (due to aluminium poisoning) and other aquatic animals.

Consequences of mining on water quality in the Witbank area

Coal has been mined in the Witbank area for more than a century and the area is replete with examples of the negative aspects of mining that have been discussed. Many mines are still in production (Figure 3.89). Routine analysis of water samples in the Olifants River system, which drains the coalfield, began long after mining commenced in the area, so there is no record of the quality of river water prior to mining. However, the upper Olifants tributaries that lie outside the mining areas have total dissolved solid (TDS) concentrations in the order of 50 ppm, and probably reflect the pre-mining condition. The water quality in Witbank and Middelburg dams over the last three decades is shown in Figures 3.90 and 3.91 respectively. Both show a steady increase in TDS and sulphate concentrations over the past 30 years. Bearing in mind that prior to mining the rivers concerned probably contained about 50 parts per million TDS, mining has resulted in a ten-fold increase. Of greater concern is that the sulphate concentration in the Middelburg Dam now exceeds the maximum recommended concentration for water for human consumption, and is still rising.

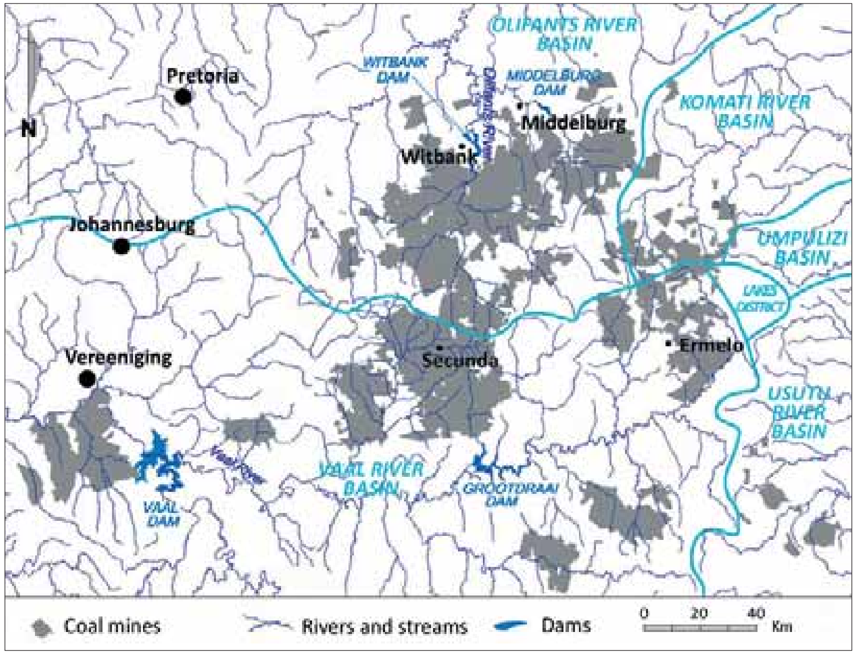


Figure 3.89 The distribution of coal mines in the Highveld region in relation to river catchments.

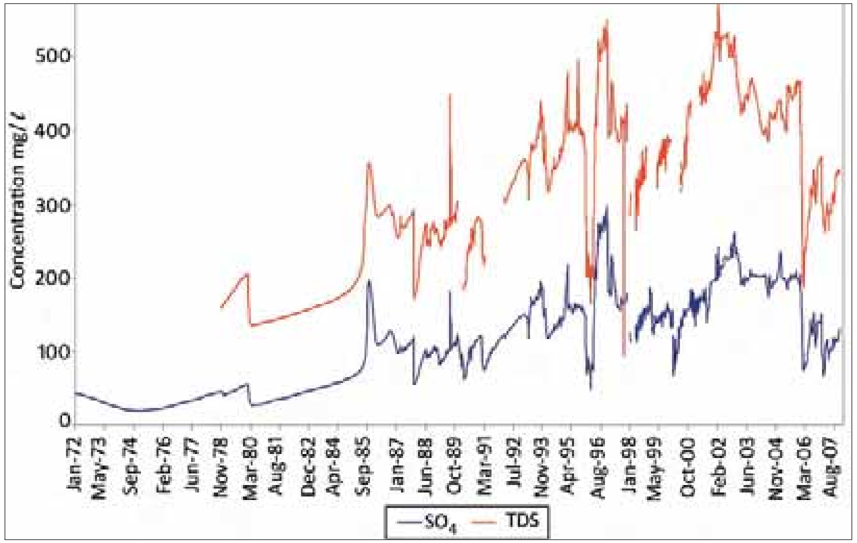


Figure 3.90 Total dissolved solid (TDS) and sulphate concentrations in Witbank Dam between 1972 and 2007.

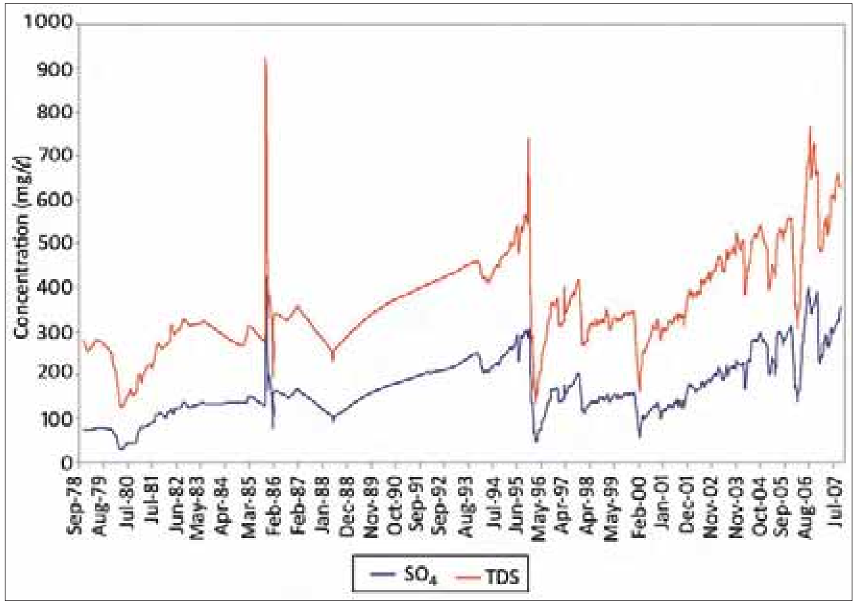


Figure 3.91 Total dissolved solid (TDS) and sulphate concentrations in Middelburg Dam between 1978 and 2007.

Water quality in the dams partly obscures the extent of the quality problem because dams tend to improve water quality compared to their inflow. This is because short duration flood events are stored and dilute the dam water, and possibly also because of biological remediation processes operating in dams, such as sulphate fixation by anaerobic bacteria in dam sediment. The dilution effect is reflected in the rather jagged appearance of the graphs in Figures 3.90 and 3.91. Nevertheless, water quality in both dams shows a trend of deterioration over the data period.

Mitigation

Various measures have and are being implemented to try to mitigate the deteriorating water quality in the Olifants River. In considering the various mitigation options, it is necessary to distinguish between those that are used whilst mines are still operating, and those that will be used after closure. In the latter instance, it is important to bear in mind that the effects of mining, and especially the production of acid mine drainage, are likely to persist for centuries after closure.

Seven methods of mitigation are currently employed to alleviate the problem, but with varying success, namely, evaporation dams, using contaminated water for irrigation, limiting oxygen ingress into closed mine workings, acid neutralisation, water purification, controlled release of polluted water and soil protection by adding calcium carbonate to the lower part of the replaced soil layer in opencast mines to neutralise the acidity.

There are many closed and abandoned mines in the Olifants River catchment that have been polluting the river for decades. The records spanning the last 30 years indicate that the pollution level is still rising. The full effects of mining are yet to come, when the current generation of large opencast mines fills with water and begin to decant. Of the mitigation strategies mentioned, only water purification is capable of producing water of a quality equivalent to that which existed prior to mining. The cost of treatment is high, however. It is estimated that water from current mining operations entering the Witbank and Middelburg Dams amounts to 30 million cubic metres per annum and this will rise to 44 million cubic metres by 2030. To treat this water to pre-mining standards would cost R300 million per annum currently, rising to R440 million per annum in 2030 (at present rand value).

The Vaal River catchment

Although mining takes place in the Vaal River catchment (Figure 3.89), much of the coal is deep. Many of the mines are still in production and water management is good so pollution levels from coal mining in the catchment generally are low.

The total dissolved solid concentration in the Vaal River rises progressively downstream (Figure 3.92). The Klip River, which is heavily polluted by mining and industrial activity on the Witwatersrand, adds significantly to the pollution load. For the reasons mentioned, dams along the river (Grootdraai, Vaal and Bloemhof) have a moderating effect on the salinity levels, but insufficient to prevent the downstream increase in TDS. Water quality in the lower Vaal is relatively poor and has caused soil salinity problems in the Vaal-Harts irrigation scheme.

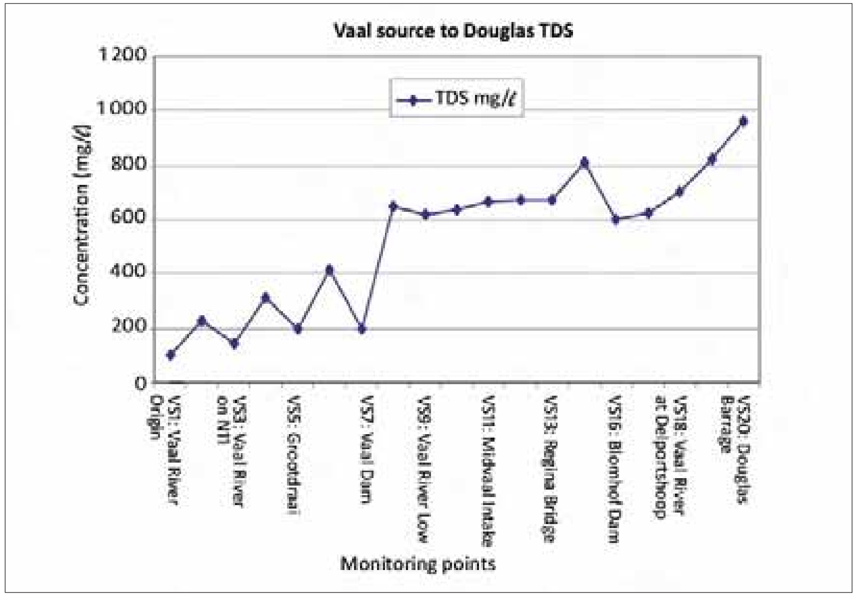


Figure 3.92 Diagram showing the changing total dissolved solid concentration in the Vaal River.

A disturbing development is the large number of applications that have been made to open new coal mines in the Vaal River catchment. If all of the coal resources of the upper Vaal River basin are exploited, it will result in the undermining of the entire basin from the headwaters to a position downstream of the Vaal dam. In the future, once these mines are closed and commence decanting, it is likely that the water quality in the upper Vaal River will suffer the same problems as the Olifants River system. It can be expected that water quality in the Grootdraai and Vaal Dams will come to resemble that in the Witbank and Middelburg Dams (Figures 3.90 and 3.91), and the water could ultimately become unfit for human consumption. The effects on downstream users of Vaal River water will be even more serious as TDS in the lower Vaal River is already very high, even though it rises from a presently low initial base. Pollution in the upper regions will result in extremely high TDS levels in the lower reaches of the river.

Other catchments

Currently, the Mpuluzi and Lakes District catchments are free of mining (Figure 3.89) and the aquatic systems are pristine. Only a few mining permits have been granted in the Usutu Basin, and water quality in this catchment is generally good. However, a large number of applications have been submitted in these areas (Figure 3.93). Should these be granted, these presently pristine river systems will suffer the same fate as the Olifants River catchment.

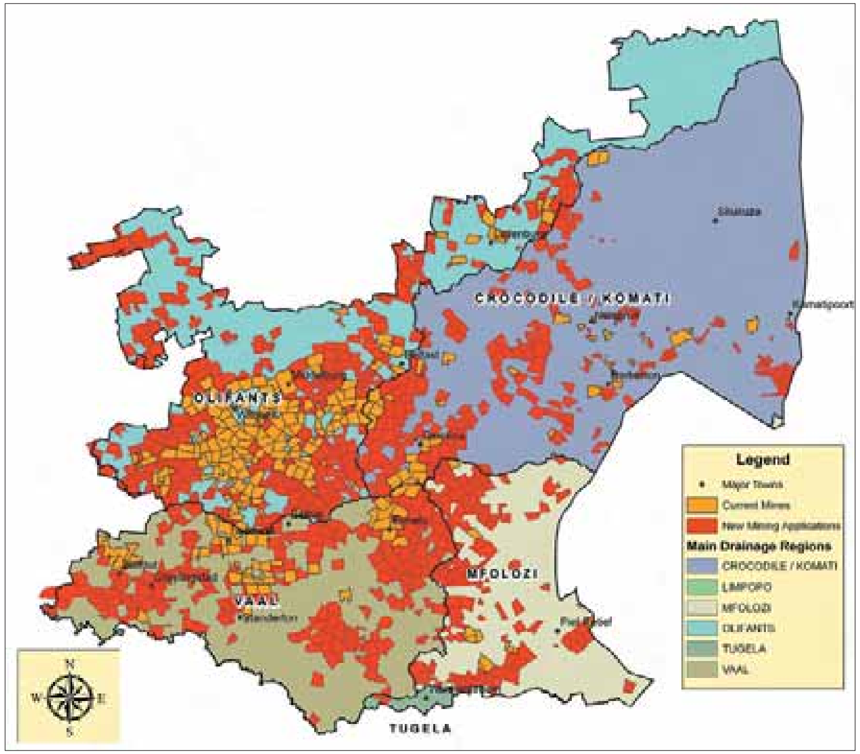


Figure 3.93 Distribution of farms currently under application for mining permits at the Department of Minerals and Energy.

Conclusions

What does the future hold for the Witbank coalfield? Perhaps a century from now, all of the mines will be flooded and leaking acid water. In their upper reaches the rivers will run red (Figure 3.86) and both river and ground water will be undrinkable. Aquatic animal life will be minimal and only very hardy aquatic vegetation will survive. The rivers will also be choked with sediment. Extensive areas of the region will have become devoid of vegetation due to acidification of the soil (Figure 3.87), setting in motion severe erosion, which will strip the soil cover and eat into the backfill of the old opencast workings. The eroded sediment will choke the rivers and all dams will be filled with sediment. In short, the region could become a total wasteland.

The Olifants River catchment is in trouble, but the most serious long-term threat that coal mining poses is to the water resources of the Vaal River basin, which provides drinking water to possibly a third of the country's population. Rivers rising on the escarpment, which supply the Lowveld as well as neighbouring southern Mozambique and Swaziland, are also under threat. In the absence of adequate, fail-safe environmental protection procedures, we believe that a moratorium should be declared on new mining applications in all of these catchments until the cumulative impact of mining is fully understood and adequate mitigation can be guaranteed. In addition, there should be a concerted research programme to assess the future impact of current and past mines, to find ways of reducing acid discharge from mines and of passively treating sulphate-rich mine water. If adequate, low cost mitigation procedures cannot be discovered, then no further mining should be permitted in sensitive catchments.

MINING

Managing poor quality coal-mine water

Is irrigation part of the solution?

John G. Annandale
Yacob G. Beletse
Richard J. Stirzaker
Keith L. Bristow

Coal is an important industry and foreign exchange earner for South Africa and provides the raw material for most of our power generation, as well as employment for many. However, coal extraction impacts heavily on the landscape and soil and water resources in particular, generating large volumes of saline mine drainage, with the potential to degrade rivers and farmland. Several technologies exist to treat polluted mine water, but these are costly and the water volume is difficult to manage. Irrigation of agricultural crops could be part of the solution to this mine water problem. Irrigation uses large volumes of water, produces food, and more importantly, can create jobs, especially at post mine closure, when communities need to diversify away from mining. However, the environmental cost needs to be made explicit and should be understood by all stakeholders. We conclude that irrigation with certain mine waters, on carefully selected and managed sites, could be a cost effective component of a long-term mine and catchment water management strategy. However, to ensure that any environmental impact remains acceptable, it is crucial that mines institute long-term monitoring strategies that involve other interest groups in the catchment.

Mining impacts landscapes and water systems

South Africa's coal industry is the second biggest mining sector after gold. Mining impacts on our landscapes and water systems and its effect may be manifest throughout the life cycle of the mine and long after mine closure. Potential impacts of mining on the water environment are (a) disruption of hydrological pathways, (b) seepage of contaminated leachate into aquifers, (c) depression of the water table around the dewatered zone, and (d) disposal of saline mine water into rivers [1]. The impacts of mining arising from the first three tend to be relatively localised and limited compared to the disposal of untreated mine water.

Mine waters

The quality of mine water depends largely on the chemical properties of the geological materials it interacts with [2]. Coal-mine water can be highly acidic or alkaline, is usually saline, and is typically dominated by calcium sulphate ($CaSO_4$), sodium sulphate (Na_2SO_4), magnesium sulphate ($MgSO_4$) or sodium bicarbonate ($NaHCO_3$) [3].

It is estimated that 360 million litres per day (Mℓ d^{-1}) may be generated after closure of the entire Mpumalanga coalfields [4]. For the Olifants Catchment, it could be 170 Mℓ d^{-1}. Not all this water will move to the same locality, and several sub-areas where between 12 and 40 Mℓ d^{-1} is expected to decant from the mines are envisaged. These decant volumes have the potential to support in excess of 6 000 ha of irrigation in the Olifants Catchment alone. Yet the Olifants is already an over-allocated catchment with relatively high river salinity, so mine wastewater irrigation needs to be viewed within its catchment context.

Irrigation with mine water

Management options for saline mine water in South Africa can be summarised as (a) pollution prevention at source, (b) reuse and recycling of water to minimise the volume of polluted water being generated, (c) treatment of effluents if the problem cannot be solved through prevention, reuse and recycling, and (d) discharge of treated effluent (which is considered the last resort because of the enormous expense) [5]. Utilisation of certain poor-quality waters for irrigation is also suggested as a water reuse strategy, especially in the post-closure phase [5]. If successfully implemented, irrigation could create jobs, and an income could be realised from the water instead of incurring a cost for treatment.

In the early 80s, Du Plessis used a steady-state chemical equilibrium model to evaluate the potential of using calcium sulphate rich mine water for irrigation of field crops in South Africa [6]. It was found that the amount of salt predicted to leach, and which could potentially contaminate groundwater, was far lower with calcium sulphate rich water than for irrigation using chloride rich water of otherwise similar ionic composition. This could be attributed to precipitation of gypsum – a sparingly soluble salt – in the soil. This was an exciting realisation, as gypsum precipitation provides a mechanism to remove salt from the water system with minimal unwanted impacts on soil. Sodium based salts, however, are far more soluble than calcium salts, so there is no opportunity to capture and store them in the soil profile.

The potential use of mine water for agricultural crops was then tested in a series of field trials from 1993-2007 [3, 7]. Higher crop yields were obtained under sprinkler irrigation with mine water compared to dryland production, without foliar injury to the crop (Figure 3.94). Clearly recognisable leaf symptoms associated with specific nutritional disorders were not observed, but it is essential to take into account what ions are being added to the soil with the irrigation water when working out a fertilisation programme. Crops like sugar-beans, wheat, maize and potatoes proved highly successful under irrigation with $CaSO_4$ and $MgSO_4$ rich mine water.

Soil salinity increased compared to the beginning of the trial and a seasonal fluctuation was observed due to rainfall in the summer season with dry winters. In the rainy summer season, low soil salinities were maintained because the salt load is low (less irrigation) and the opportunity for flushing salts out of the root zone, higher, than in winter. Measurements taken between 1997 and 2007 showed that soil salinity increased from a low base and oscillated around a relatively low level of 250 milli Siemens per metre (mS m^{-1}), as predicted a decade earlier [3]. Gypsum precipitation was also shown to be taking place in the soil, but did not create any noticeable physical or chemical changes that would adversely affect crop production and soil productivity (Figure 3.95).

Figure 3.94 Centre pivot irrigated field crop in the Emalahleni (Witbank) coalfields using mine water.

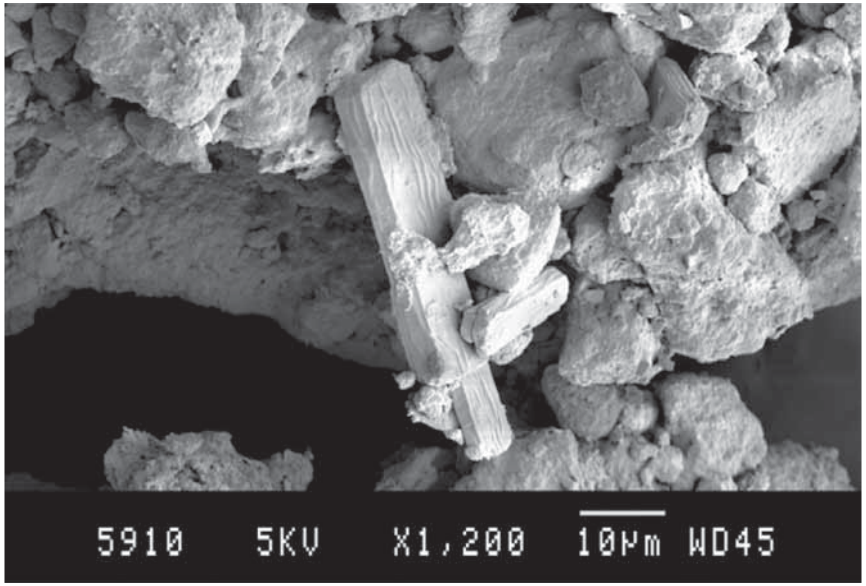


Figure 3.95 Magnified gypsum crystal illustrating precipitation of this salt in mine water irrigated soil.

In the short-term (two to eight years), irrigation with calcium sulphate rich mine water proved successful with a negligible impact on groundwater quality. The system is flexible and can be managed to achieve a specific objective, be it maximum crop production, water use, job creation, economic return or maximum gypsum precipitation and minimum salt leaching. (Figures 3.96 and 3.97)

Figure 3.96 Beef cattle on mine water irrigated pasture at Syferfontein Colliery.

Although crops were successfully grown with sodium rich waters in the short-term, there is clearly less opportunity for responsible irrigation as part of a water management strategy, compared to using calcium sulphate rich waters where salt build up is reduced through gypsum precipitation.

Since the impact of calcium sulphate rich mine water on crop and soil seemed minimal and manageable, it was reasonable to focus on the impact on groundwater quality. Boreholes drilled inside or in close proximity to irrigated fields have shown very little salt moving through the soil profile in the short-term. Salt plumes are attenuated by different mechanisms between the soil surface and aquifers, often by clay layers [8]. This monitoring was on a localised scale and cannot be used to unequivocally determine larger-scale irrigation impacts. It was therefore necessary to simulate the expected impact of large-scale irrigation with mine water on groundwater resources [9]. Several long-term simulations using the Soil Water Balance (SWB) model suggest it could indeed be feasible to irrigate carefully selected areas with calcium sulphate rich mine water [3, 7].

Figure 3.97 (a-b) Mine water irrigation research trials (with mining in the background).

Conclusions and recommendations

We argue that there are four components to managing irrigation with saline water. These are (a) chemical quality of the irrigation water, (b) hydrological setting of the irrigated area, (c) management of the leaching fraction, and (d) the fate of the drainage water. Normally, water quality and hydrological setting are fixed for a given irrigated area and these constrain the management of leaching and the fate of drainage water. In the case of mine water irrigation, this is not necessarily so. We can decide to irrigate with certain mine waters and not with others. We can, for example, require water treatment involving neutralisation of acid mine drainage before using it. Our hydrological setting is also somewhat flexible, especially when dealing with relatively small areas, often less than 1 000 ha per mine. We can choose, for example, if we are to irrigate over spoil or not, and can select the site carefully so that percolation can be intercepted, reused and isolated. Isolated water can be stored on site or considered for controlled release. Finally, once the water quality and hydrological setting are fixed, a responsible irrigation management programme must be implemented. Our work has shown that the use of calcium sulphate rich water is agronomically feasible, with no adverse impact on soil or groundwater in the short-term. When social aspects like job creation, especially after mine closure, are considered, we conclude that irrigation with certain mine waters on carefully selected and managed sites could form an important, cost-effective component of a long-term mine and catchment water management strategy (Figure 3.98). However, it is crucial that long-term monitoring strategies around such irrigation areas be instituted to provide early warning for unforeseen events from mine water use. This will allow implementation of adaptive management strategies to ensure that any environmental impact remains acceptable.

Figure 3.98 Mine water irrigated potatoes can create several job opportunities, which is especially important post closure.

Acknowledgements

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Environmental changes are progressively affecting the future of South Africans through their combined impacts on human livelihood, security and prosperity.

This book is about environmental change in South Africa, its causes, trends, implications, suggested solutions and the technologies and methodologies of observation and analysis. It draws together work from as many scientific disciplines as possible to inform not only the private sector and political decision makers, but also the general public on current environmental issues and challenges.

Observations on Environmental Change in South Africa provides pertinent scientific evidence to assist the people of our country in formulating intelligent and responsible policies and practices for the betterment of our society and to ensure the long-term sustainable futures of South Africans.

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