Understanding Environmental Change in Complex Systems: SAEON Core Science Framework

UNDERSTANDING ENVIRONMENTAL CHANGE IN COMPLEX SYSTEMS: SAEON CORE SCIENCE FRAMEWORK

South African Environmental Observation Network (SAEON)
TG O'Connor
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FOREWORD

This document stems from the need for SAEON and its partners to clarify our scientific approach across the spectrum of disciplines and ecosystems. It is a guiding and high-level statement by SAEON at this early stage of its development and follows on the document "Design of SAEON" which was produced by the SAEON Technical Steering Committee in 2003, as well as Van Jaarsveld & Biggs (2000).

Research leaders and funders should find in the document a useful reference for decision making as it elevates priorities for a question-driven approach to environmental change monitoring and research in complex systems. Prospective research students and partnering researchers will be able to contextualise and motivate their research work by referring to this document.

The "Framework of the Core Science Plan" is intended to provide momentum and substance to the wide-ranging long-term environmental research and monitoring programmes that have been and are still being developed by SAEON and its partners. The document is expected to have a 3–6 year lifespan and will be reviewed and refined by SAEON as our scientific understanding improves and to accommodate relevant changes and realities in the National System of Innovation.

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Johan Pauw
Managing Director, SAEON
Pretoria, November 2009

An understanding of ecosystem responses to anthropogenic and natural drivers requires detailed, long-term observation and documentation. Drivers of environmental change are not always as immediately obvious as the one shown above. The nature of response might require additional investigation of the ecosystem under observation.

EXECUTIVE SUMMARY

The mandate of the South African Environmental Observation Network (SAEON) is “to develop and sustain a dynamic South African observation and research network that provides the understanding, based on long-term information, needed to address environmental issues”. Observation focuses on aspects of ecosystem functioning which benefit society. These include biodiversity, hydrology, biogeochemical cycling and production, soils and sediments, and disturbance regimes.

A primary objective of observation is to distinguish natural variability of ecosystem functioning, including extreme events, from response to anthropogenic impact resulting from global change. Global change drivers encompass CO_2 loading, climate change, changing marine geophysical patterns, sea-level rise, ocean acidification, land or sea use and management, harvesting, nutrient loading, acid deposition, hydrological functioning, sedimentation, alien organisms, diseases, pests, and pollution. Discrete yet integrated observation programmes are conducted for the main biomes or environments of the country, including large marine systems, coastal habitats, savanna, fynbos, grassland, wetland, forest, arid ecosystems, and freshwater aquatic environments.

This document describes a number of complementary approaches for meeting this mandate. Particular emphasis is placed on understanding the response of each aspect of ecosystem functioning to anthropogenic or natural drivers. Observation design seeks to differentiate individual effects. This includes detailed observation of a single or few sites, comparison across a set of sites, and geographically distributed observation, depending on the response or process under consideration.
Two additional approaches are more holistic. First, observation is made of ecosystems which function as relatively discrete entities, such as Algoa Bay, the Drakensberg, and Lake St Lucia. Secondly, cross-cutting themes are investigated, including degradation of dryland environments and sustainability of harvesting. Finally, flexibility is ensured through responding to special cases which might arise.

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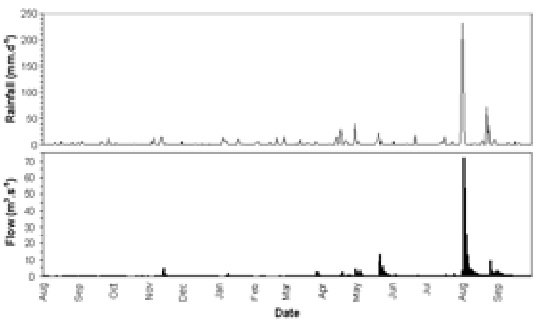

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Extreme drought and floods, as large infrequent events, impact severely on ecosystems. The rainfall and hydro- graphs on the left clearly record a flood event at Swartvlei near Knysna, Western Cape (2006). The picture illustrates the impact of such an event on the terrestrial environment of the Keisie River near Montagu, Western Cape (2008).

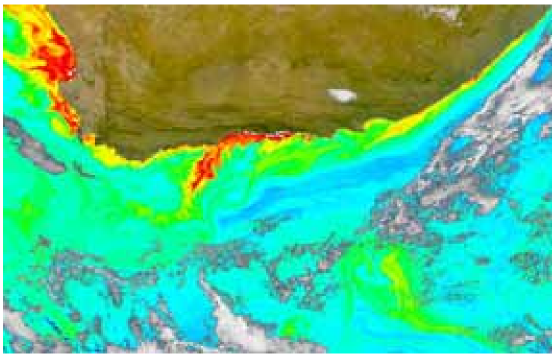
1. INTRODUCTION

Global environmental change refers to human-induced transformations of the composition, structure and functioning of the world's ecosystems. Concern about the global effect of these changes on human well being has led to a number of initiatives to identify key knowledge requirements for adaptation to and mitigation of global change. The reader is referred to a number of recent reviews for appropriate background (e.g. Fischlin et al. 2007; Scholes et al. 2008; Burns et al. 2008). Society's response to environmental change requires sound information and understanding about long-term patterns of change. The South African Environmental Observation Network (SAEON) was formed to meet this need. Its mandate is "to develop and sustain a dynamic South African observation and research network that provides the understanding, based on long-term information, needed to address environmental issues" (SAEON Advisory Board 2003).

This document describes the framework of SAEON's core science plan for meeting its mandate. The following features have influenced this plan. First, a global response has been to establish remote-sensing based Earth observation systems. *In situ* observation is required to validate remote-sensing products and to address issues which cannot effectively be addressed by remote sensing. SAEON's mandate is to concentrate on *in situ* observation. Where possible, however, an appropriate combination of *in situ* and remote-sensing observation, aided by modelling, is sought for each objective. Second, observation needs to distinguish natural variability from human-induced directional change. Third, South Africa contains a rich diversity of biomes and ecosystems that are impacted in complex ways by humans. This presents a threat of environmental observation developing as a set of fragmented and poorly integrated activities unless there is an integrated approach. The structure of this summary is as follows.

- Section 2 identifies SAEON's scope of interest.
- Section 3 describes the main drivers of change of interest to SAEON.
- Section 4 comprises the bulk of the document and describes the intended approach to observation of individual responses to multiple drivers.
- Section 5 describes the general approach to integration of observation results both within an individual node and across nodes.
- Section 6 addresses some cross-cutting themes and activities, including observation of discrete ecosystems.

2. SAEON THEMES



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A colour-enhanced satellite image* (above) shows growth of algae (red) around the South African coast while the graph** shows seasonal spikes in zooplankton abundance in response to increases in phytoplankton abundance.

* http://oceancolor.gsfc.nasa.gov/FEATURE/IMAGES/S2003135100038.L2_HPRE.SouthAfrica.jpg

** L. Hutchings, M.R. Roberts and H.M. Verheye. 2009. Marine environmental monitoring programmes in South Africa: a review. In: *South African Journal of Science* 105, March/April.

A set of ecological themes was identified for SAEON during the course of its development. This history is briefly recounted in order to provide a perspective. The original intention (pre-2000) was to establish a set of Long-Term Ecological Research (LTER) sites based on the American model but adapted for the South African scientific landscape (Biggs et al. 1999). The proposed structure of this initiative was formulated by a committee over a number of years which culminated in a workshop held at Skukuza in 1999. The resulting publication from this workshop (Van Jaarsveld and Biggs 2000) sketched the template of both SAEON's themes and organisational structure. The main aim expressed then remains the core aim of SAEON: "to formally establish a network of research sites in South Africa that can answer long-term ecological questions relevant to society, particularly those elucidating the effects of anthropogenic opposed to natural change in the environment (e.g., climate change)" (p63, Van Jaarsveld and Biggs 2000). It further identified a strong need to observe ecosystem functioning that related to societal benefits – in other words ecosystem services. An emphasis on ecosystem services was further promoted by the Millenium Ecosystem Assessment (2005). When an LTER programme was proposed to government, it requested that it be adapted to a long-term environmental observation network, a request influenced in part by the World Summit on Sustainable Development of 2002 (Anon 2002). Early formulation of the SAEON concept continued to emphasize ecosystem functioning and services. Following the constitution of SAEON in 2002, a task team was commissioned to review further SAEON's scientific themes and organisational structure (SAEON Advisory Board 2003). The resulting set listed below retained the previously identified themes and made some additions.

- Water
- Carbon/nutrient cycles (including primary and secondary productivity, nutrient loading and deposition)
- Soils and sediments
- Biodiversity
- Disturbance regimes and their outcomes (including large, infrequent events)
- Climate/atmosphere

This list was the basis for developing the structure of the observation plan described in the following sections. A number of complementary approaches have been adopted. First, an observation design is described in Sections 3, 4 and 5 which treats each response separately and seeks to isolate the effect of a specific driver on that response.

However, ecosystems are complex and respond to multiple drivers acting together. Accordingly, complementary approaches are described in Section 6 that are more holistic in nature, being based on observation of ecosystems, special case studies, and cross-cutting themes.

© Dewald Reiners

A number of anthropogenic drivers may impact an environment such as this river and its riparian fringe, in combination with natural drivers of change. For prioritisation of which drivers need to be observed, enumeration of all anthropogenic and natural drivers of change is a necessary first step.

3. OBSERVATION APPROACH

3.1. Introduction

In addition to detecting change, SAEON seeks to identify the main causes of environmental change through its observation activities, which presents a major challenge for designing an observation approach. For example, if a variable of interest (e.g., primary production, species richness) showed directional change, then this would be considered evidence for global change rather than natural variability. But demonstrating directional change would not necessarily reveal the cause of that change. It may result from a single driver, or a number of anthropogenic drivers acting simultaneously, or from interaction of anthropogenic drivers with patterns of natural variability. Sections 3 and 4 describe an observation approach designed to distinguish the impact of individual drivers as well as to elucidate some of their interactive effects.

3.2. Environmental Change as Driver and Response Variables

For the purpose of developing an observation design, the set of ecological themes described above was redefined as a set of driver and response variables following Van Jaarsveld and Biggs (2000) (Table 1). The driver variables reflect the most important anthropogenic and natural drivers forcing long-term change of the main ecosystems of the country; the response variables represent ecosystem components or processes of interest. Representing the structure in this manner makes it easier to include any additional driver or response variables that might have to be considered in the future. The main anthropogenic and natural drivers of change to be considered are briefly described in Box 1 (p.16–17). Eighteen are listed, which highlights the potential complexity that an observation system needs to address.

A main component of planning observation has been to make projections of each driver's impact on a response of interest, and then further to consider interactions if possible. Projections serve to profile potential spatial and temporal patterns of change, and conditions for change, that are used for consideration of geographic distribution of observation, frequency of sampling, and other design elements. These efforts are not presented here but are accessible on the web. Interested parties are encouraged to offer revision which may then be incorporated into observation design.

Box 1 highlights the following features.

a. There are too many different impacts on ecosystems for all of them to be accommodated in an observation design.

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SAEON seeks to recognise the main causes of environmental change through its observation activities. Here high school learners are immersed in the intricacies of ecosystem monitoring during a SAEON Science Camp in Phalaborwa. Monitoring of this nature is invaluable for ensuring sustainable resource use by communities which are directly reliant on natural resources for their well-being.

Table 1. List of driver and response variables considered by SAEON. The driver variables reflect the most important anthropogenic and natural agents forcing change of the main ecosystems of the country; the response variables represent the key pre-determined areas of interest for SAEON.
A response variable may be affected by multiple driver variables but the identity of these would depend on the ecosystem in question.

Drivers	Response variables
• Climate change	• Biodiversity (biome, ecosystem, species)
• CO_2 loading	• Biogeochemical cycling
• Marine geophysical patterns	• Primary production
• Sea-level rise	• Secondary production
• Ultra-violet radiation	• Sediments
• Land use and management	• Hydrological functioning
• Coastal/marine use and management	• Disturbance regimes
• Harvesting	• Marine geophysical patterns
• Acid deposition	
• Nutrient loading	
• Pollution (plus poisons)	
• Disease	
• Pests	
• Alien organisms	
• Disturbance regimes	
• Hydrological functioning	
• Sediments	
• Large infrequent events	

Enumerating all anthropogenic and natural aspects of change is, however, a necessary first step for prioritisation of which drivers need to be observed.

b. The task is simplified because not all drivers will affect a particular ecosystem, nor will all operate all the time or at the same time. Design of SAEON's observation approach has attempted to maximise use of differences in the spatio-temporal pattern of drivers and responses in order to distinguish the individual and relative impact of drivers on a response of interest.

c. A variable may function as both a driver and a response, depending on context. For example, hydrological functioning is a driver of river systems but itself responds to climate change and land use.

d. The listing in Table 1 indicates only the direct effects of a single driver but indirect effects and interactions between drivers are expected to result in the greatest change. Uncovering these is a major challenge facing science.

The response variables in Table 1 cover ecosystem structure and functioning. These variables were originally proposed (Van Jaarsveld and Biggs 2000; Scholes et al. 2004) because they underpin ecosystem services. The observation design for each response variable is described below in Section 4.

Box 1. Drivers to be considered by SAEON: The following is a list of what are considered to be the most important agents of anthropogenic change and of natural variability affecting South African ecosystems.

- **Climate change** refers to human-induced changes in the patterns of precipitation, temperature, wind, and radiation. Climate affects every facet of ecosystem structure and functioning of terrestrial, aquatic, coastal and marine ecosystems. Climate change is therefore expected to result in directional change that needs to be distinguished from patterns of natural variability.

- **Increase of atmospheric CO_2 concentration** (CO_2 loading) has direct effects through 'carbon fertilisation' of the growth of some plants and not others, and is responsible for ocean acidification.

- **Other atmospheric gases**, including particulates, are monitored because of their contribution to climate change.

- **The marine geophysical environment** may be altered by climate change. Changes in winds, heat and freshwater fluxes will alter currents and upwelling patterns that would affect the composition, structure and functioning of marine and coastal ecosystems. These, in turn, will have feedbacks on climate.

- **Sea level rise** is a direct consequence of climate change that is impacting coastal environments and possibly adjacent inland ecosystems that are influenced by inundation or salinisation of groundwater. Sea level is currently rising at 3 mm per annum along the South African coast and may rise more than 0.5 m during the forthcoming century.

- **Ultra-violet radiation** can disrupt physiological functioning of organisms that may affect population processes and ecosystem functioning.

- **Land use and management** are distinguished. Land use is the choice which is made for a parcel of land. Change in land use may be characterised by land transformation. Land management refers to the choice of approach for pursuing a specific land use, such as the grazing and burning system adopted by a livestock rancher.

- **Coastal/marine use and management** is comparable to land use in that discrete geographic areas of coast or open sea may experience a specific form of use such as mining, protection, controlled or uncontrolled access, or aquaculture. Each of these forms of use may be managed in different ways.

- **Harvesting** of marine, coastal, freshwater, or terrestrial resources is the targeted exploitation of specific organisms, such as medicinal plants or animals, or of coastal or marine resources for food. The manner in which harvesting is undertaken may be important.

- **Acid deposition** resulting from dry or wet fallout of atmospheric emissions can affect freshwater aquatic and terrestrial systems through its effect of biogeochemical cycles and consequent biological effects.

- **Nutrient loading** refers to the increased concentration of elements in soil, freshwater, or coastal waters that may perturb biogeochemical cycling and consequently disrupt ecosystem composition and productivity. Nitrogen and phosphorus receive the most attention.

- **Pollution (plus poisons)** is a catch-all term for the multitude of contaminants which are released into the environment. Contaminants as different as oil pollution, heavy metals, or pesticides are very different in their dynamics and effects on ecosystems and therefore need to be addressed individually.

- **Disease epidemics** may reshape ecosystems through their affect on the abundance of key species (e.g., rinderpest pandemic during the late 1800s). Disease outbreaks may be naturally variable while some may be alien introductions (e.g. rinderpest) that can spread rapidly. They are usually infrequent events.

- **Pests** are usually indigenous organisms such as locusts which may attain outbreak proportions as a result of other human impacts on the environment. They are usually infrequent events that may leave a significant imprint on an ecosystem.

- **Alien organisms** are plant and animal species which have invaded habitats outside of their natural range of distribution through dispersal by humans. Their success in a new habitat is a threat to indigenous biodiversity and they may substantially alter ecosystem functioning.

- **Disturbance regime** refers to a range of biotic agents and abiotic events that may temporarily restructure an ecosystem. For terrestrial environments, the most conspicuous agents of disturbance are fire and herbivory. Disturbance regimes are therefore confounded with land use and management. By contrast, extreme weather events are the main disturbance experienced by marine environments.

- **Hydrological functioning** refers to the amount, quality, and seasonality of river flow. It is a driver of aquatic, estuarine and nearshore systems but is itself influenced by climate change, land transformation and use, impoundments, and water abstraction.

- **Sediments** are also an important driver of aquatic, estuarine, nearshore and coastal dune systems. Sediment dynamics depend directly on hydrological functioning in fluvial environments.

- **Large infrequent events** differ in their nature depending on environment or biome. Droughts and floods are conspicuous such events in terrestrial and coastal environments. Coastal and marine areas are also occasionally impacted by extreme storms and tsunamis, that are expected to change with climate change.

The monitoring of long-term trends in biodiversity includes the investigation of the impact of changes in land-use and management on species diversity. The impact of, for instance, alien invasive plants on indigenous biodiversity, is revealed by observation over time.

4. RESPONSES TO CHANGE

4.1. Introduction

In this section an observation design is outlined separately for each of the main response variables of interest to SAEON. In reality these variables all function in an interconnected manner, which is addressed further in Section 6.

4.2. Biodiversity

4.2.1. Introduction

The South African National Biodiversity Institute (SANBI), in conjunction with conservation agencies, is responsible for developing a national strategy for biodiversity conservation. Part of its mandate is biodiversity monitoring, whereas SAEON will seek an understanding of long-term trends in biodiversity in response to natural and anthropogenic drivers (Table 1). Biodiversity has been defined by SANBI as biomes, ecosystems, species, and genes.

The ecosystem units used by SAEON are the terrestrial ecosystems used by SANBI (Mucina and Rutherford 2006), the three main biogeographic regions along the coastline (Brown and Jarman 1978), and the three large marine systems surrounding southern Africa (Sherman and Hempel 2009). Observation of biodiversity therefore needs to recognise its different units and the manner in which they might show change.

Accordingly, observation is conducted at four distinct, yet inter-related, hierarchical levels.

a. Shifts in the extent and position of terrestrial biomes, coastal biogeographic regions, and large marine ecosystems.
b. Shifts in the extent and position of terrestrial ecosystems (vegetation types) within biomes; changes in the extent of coastal habitats.
c. Changes in biodiversity integrity (richness, composition, structure) across trophic levels of terrestrial ecosystems, coastal habitats, and large marine ecosystems.
d. Changes in the distribution and abundance of individual species.

The aims of observation are to quantify change and to understand the drivers primarily responsible for change of different hierarchical levels of biodiversity. Different drivers would have a different effect at each level. An individual node would therefore aim to observe a set of selected cases of change of each of these elements that were best suited for understanding causes of biodiversity change. Accordingly, an approach to observation is described separately for each biodiversity level.

4.2.2. Shifts of biomes, coastal bioregions, and marine ecosystems

4.2.2.1. Terrestrial biomes

Changes in the position of terrestrial biomes are expected in response to climate change because biomes each occur within a well-defined climatic envelope. Other drivers potentially promoting a shift in biome position are the effect of carbon loading through benefiting woody C_3 plants at the expense of C_4 herbaceous species; change in the fire regime, which usually limits woody plants; patterns of land degradation resulting from livestock management; and loss of natural asset through land transformation. The most conspicuous projected changes are:

a. Invasion of grassland by savanna;
b. Expansion (or retreat) of karoo bushes into grassland;
c. Expansion (or retreat) of forest into grassland;
d. Possible increase of savanna elements in arid grassland;
e. Contraction of succulent karoo; and
f. Loss of lowland fynbos.

Observation of biome shifts is conducted using a combination of remote sensing and *in situ* monitoring along biome boundaries. Expansion of large woody plants in response to increasing atmospheric CO_2 concentrations, which have increased substantially since the 1940's, could have occurred and will be examined using the aerial photographic record.

4.2.2.2. Coastal biogeographic regions

Three distinct biogeographic regions are recognized along the 3000 km of our coastline: a cool-temperate bioregion along the west coast; a warm-temperate bioregion along the southern coast; and a sub-tropical bioregion along the eastern coast. Thirteen coastal regions are recognised across the three bioregions. These regions are defined by climate, currents, and water properties. Change in the geophysical character of the coastline will be observed as a first indicator of potential shifts in these bioregions and coastal regions. Observation in coastal regions is based on distinct habitats such as estuaries, rocky inter-tidal, rocky sub-tidal, beaches and coastal dunes, and focuses on well-defined transition zones between bioregions as these are the expected location of rapid change.

4.2.2.3. Large marine ecosystems

The three large marine ecosystems surrounding southern Africa (Benguela, Agulhas, Southern Ocean) are monitored for change in their geophysical character (e.g. current patterns and oceanic fronts, heat flux) that would drive changes in their ecosystem structure, with additional focus on meso-scale variability within each system. Data are derived from remote-sensing and *in situ* observation using floats, buoys, and ships. Modelling is an essential tool for data processing.

4.2.3. Biodiversity changes of terrestrial or coastal ecosystems

Different approaches are required for observing changes in the position of an ecosystem and for assessing changes in its biodiversity integrity. Observation of shifts in an ecosystem boundary is similar in approach to that for biome shifts, and will be most easily observed for ecosystems with distinct composition and sharp boundaries. An example is the proposed shift of *Colophospermum mopane* woodland in the savanna biome in response to climate change. Its woody vegetation is almost mono-specific and its boundary is abrupt. The main anthropogenic drivers which might affect a boundary or result in loss of area of a terrestrial vegetation type includes climate change, carbon loading, land transformation, land use and management, fire regime, and alien plant invasion. The position and extent of terrestrial units can be observed using remote sensing in conjunction with ground truthing. Change in sea-level rise or marine geophysical conditions are likely to be particularly important in forcing change in coastal ecosystems.

Change in biodiversity integrity (richness, composition, structure) of a marine, coastal or terrestrial ecosystem requires direct site-based sampling of appropriate indicator taxa of that system. Commonly employed approaches attempt to capture a system's variability by sampling along the main environmental gradients. Observation of biodiversity integrity is used to illustrate some of the challenges common to observation of all responses. It would be an easy matter to establish observation of biodiversity change in a system of interest by mapping its distributional shift over time and obtaining corresponding information on its integrity from site-based sampling. But this will not meet the aim of identifying which anthropogenic or natural drivers were responsible for forcing change. To this end the observation plan has adopted an approach which will isolate, as best can be done, the effect of individual drivers of change.
Box 2 (p. 16–17) provides a brief outline of the means whereby the impact of some drivers can be distinguished from that of others. In circum-stances where observation of one impact

Box 2. Distinguishing individual anthropogenic impacts.

- The impact of **climate change** on biodiversity integrity is revealed when other anthropogenic impacts can be minimised. Large protected areas offer the best environment for achieving this, using sites distributed along a climatic gradient, or geophysical gradient in the case of marine or coastal systems. There is a higher likelihood of detecting climate- (or geophysical) induced changes sooner rather than later where sharp gradients occur over short distances, such as along altitudinal transects in mountains or through coastal biogeographic transition zones. Examples of currently existing biodiversity monitoring that should reveal climate change impacts on biodiversity integrity are found within Kruger National Park, Kgalagadi-Transfrontier Park, Maloti-Drakensberg Transfrontier Park, Richtersveld National Park, Tsitsikamma National Park Marine Protected Area, and Table Mountain National Park Marine Protected Area. Similarly, change of the marine geophysical environment and consequent change of the distribution and composition of marine biota across trophic levels (pelagic and benthic) can be revealed by sampling along cruise lines. Associated species-based observation would reveal the consequences of such shifts for top fish predators, birds and mammals dependent on these fisheries. Modelling projections are a key tool for anticipating patterns of change of all these variables.

- **Sea-level rise** will inundate coastal habitats thereby reducing radiation, displace tidal systems landward, salinise groundwater and freshwater, and promote increased landward penetration of storm surges. Examples of appropriate indicators for such impacts include: displacement or attrition of salinity-sensitive mangroves; composition of rocky inter-tidal and sub-tidal communities; extent and condition of coastal wetlands; and undercutting of vegetated sand dunes through elevated erosion.

- Impact of **ocean acidification** is becoming evident through change in the abundance and condition of organisms with calcified exoskeletons (e.g. corals, thecosome pteropods), and is expected to influence phytoplankton growth.

- An effect of **carbon loading** on terrestrial systems should be evident from an increase in life forms benefiting from carbon fertilization (e.g. bush invasion).

- **Land uses** that rely mainly on natural vegetation are the primary matrix for biodiversity in the country. Different land uses are compared across a landscape within a region of relatively uniform climate and soils. The main land uses are commercial livestock or game ranching, communal rangeland, and protected areas; the main biomes are savanna, grassland, Nama-Karoo, and succulent Karoo. Monitoring loss of natural asset to development and transformation relies on national remote-sensing efforts.

- **Coastal or marine use** addresses regions where different levels of harvesting pressure or use are found adjacent to one another, or where a specific use is made of an area (e.g. mining, harbours). These environments require in situ observation.

- **Land management** choices of grazing and fire regime for rangelands affect more than 70 % of the country's land surface. Observation is based on comparison across properties. Long-term experiments are monitored for describing the extent and rate of change occurring under a defined management level. Biome-specific management actions are observed as appropriate, such as water distribution using gradient studies, bush clearing or elephant impact in savannas using comparative approaches, and the effect of fragmented landscapes on fire regime.

- **Sea management** concerns decisions such as opening or dredging of estuaries has a direct effect on the structure and functioning of these ecosystems.

- **Nutrient loading and acid deposition** of terrestrial environments result from atmospheric emissions of sulphur- or nitrogen-based compounds whose main sources are urban-industrial complexes and coal-based power stations in Mpumalanga. The well defined spatial pattern of deposition allows for a gradient approach to observing impacts on surrounding terrestrial ecosystems, concentrating on vulnerable low nutrient ecosystems of grassland, fynbos and forest. Current long-term fertilisation experiments provide a special opportunity for determining the nature of biodiversity change in response to nutrient loading and soil acidification.

- **Nutrient loading and acidification** of freshwater systems owes to atmospheric and terrestrial inputs from point and diffuse sources, which are observed along a river system based on monitoring of water quality and biological indicators by DWAF.

- **Nutrient loading** in coastal environments is an outcome of supply via rivers, direct waste discharge and upwelling patterns. Comparative and gradient approaches of river and discharge impacts are possible for estuaries, beaches, and rocky sub-tidal or inter-tidal habitats, taking upwelling patterns into account. Harmful Algal Blooms are specific events, usually marked by mass mortalities of fish and invertebrates, resulting from increased nutrient availability.

- **Ultra-violet radiation** is expected to become more intense as a consequence of effects on the ozone layer, some of which have abated over the past few decades. Increasing UV may perturb photosynthesis and nutrient cycling of certain species, which would be difficult to distinguish from other impacts on these processes.

- Response of **alien invasive plants or animals** to all impacts described above is revealed by observation of biodiversity response. Their impact on indigenous biodiversity is revealed by observation over time. For terrestrial environments, this is complemented by comparison of sites with differing degrees of infestation, and of cleared sites.

- Levels of **pollutants and poisons** in the environment may be monitored but ascribing an impact to a specific poison requires a level of understanding (e.g., DDT and egg shell thickness) that is not available for most. Individual cases where contaminants originate from point sources (e.g. waste, sewage, smelter fallout) will be approached using gradient approaches. Individual nodes would identify cases worthy of observation.

- **Large infrequent events** may not be spatially predictable but a geographically distributed observation network is more likely to 'capture' events such as disease or pest outbreaks, or discrete pollution events such as oil spills at sea.

(e.g. land management) can be nested within that of another (land use), there would then be some measure of interactive effects.

4.2.4. Species changes

The ecology of many individual species is well understood, which offers an opportunity for improving our understanding of the influence of anthropogenic drivers and natural variability on changes in the distribution and abundance of individual species, and the remixing and formation of communities. Reliance on well studied species will bias observation toward plants and vertebrates. Species subject to harvesting (Table 2) are amongst the most closely studied and monitored, providing an opportunity for determining the impact of this effect alone or in conjunction with other anthropogenic impacts using tools of population study such as modelling. Furthermore, these species often index the state of biodiversity in their respective systems. Observation approaches need to be individually devised for different species on account of differences in rates of population turnover, meta-population structure, drivers of relevance, and differences in life form and motility.

Table 2. Examples (not intended to be comprehensive) of current monitoring efforts relating to harvesting of individual species or groups of species and indirectly affected species or groups.

Environment/group	Species or group
Pelagic	Krill
	Main species of commercial fisheries
	Long-lived sea birds
	Top fish predators
	Turtles
	Sea mammals, including whales
Coastal	Prawns
	Squid
	Abalone
	Line fish
Terrestrial vertebrates	Parrots
	Oribi
	Aardvark
	Vultures
	Selected reptile species
Terrestrial plants	Selected species of medicinal plants
	Selected timber species
	Cycads

4.3. Biogeochemical Cycling and Productivity

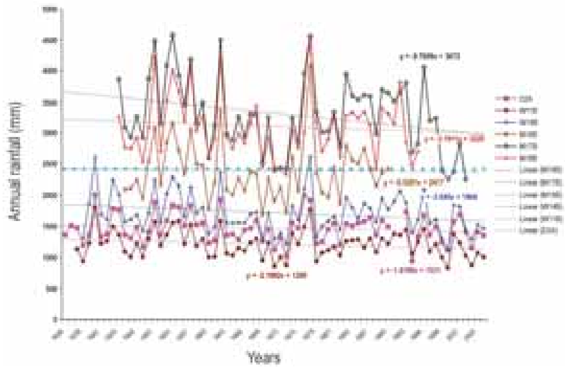
4.3.1. Introduction

A need for observation of anthropogenic impact on biogeochemical cycling and productivity stems from the central role these processes play in the fate of greenhouse gases and hence climate change, and in the supply of provisioning services. Secondary production, whether it is in the form of viewing wildlife in a reserve or consuming livestock reared on rangeland or marine fish, is of obvious importance to society. Long-term changes in secondary production depend directly on changes in biogeochemical cycling and primary production. Observation therefore attempts to address these related processes as a whole. Similarly, the fate of carbon and other greenhouse gases is an outcome of biogeochemical cycling and production.

4.3.2. Carbon cycling

Climate change is driven mainly by an increasing concentration of atmospheric CO_2 and other greenhouse gases, both carbon-based (e.g., methane) or not (e.g., nitrous oxide). Atmospheric CO_2 has risen from a pre-industrial level of 280 ppm to over 380 ppm today, and is set to continue to rise. An improved understanding of climate change therefore depends directly on improving understanding of the ability of different environments across the globe in sequestering atmospheric carbon. This has formed the basis of a number of globally coordinated observation initiatives such as GCOS, GTOS and GOOS of GEOSS, amongst others. A strong methodology for observation has been developed linking remote-sensing with detailed and intensive *in situ* observation of carbon flux, productivity, and bio-geochemical cycling in order to better understand the fate of carbon. South Africa has an important contribution to make to this global effort for both terrestrial and marine environments on account of our geographical position and the limited number of observation initiatives across Africa and its surrounding oceans, despite their importance for global climate. The uniform approach and methodology of international efforts would be adopted. Intensive observation is conducted on a core site of limited size for terrestrial environments whereas a distributed observation approach is employed in the marine environment. Capital outlay and maintenance costs are high so that observation would be conducted only in priority biomes. The marine environment is considered particularly important for uptake of annual CO_2 emissions, with the Southern Ocean playing a conspicuous role. The country's sub-tropical savannas and grasslands are important because

Inter-annual rainfall variability impacts on primary and secondary production and it is critical for hydrological functioning. Long-term observation is needed in order to distinguish patterns of natural variability from directional changes induced by global change for informing decision-making for management and policy. The graph shows variable rainfall measured at six different stations in the Jonkershoek area over a period of 69 years, thus providing a rare opportunity for determining whether directional change might be occurring (DC Le Maitre, pers. comm.).



similar vegetation occurs throughout much of the non-forested portion of sub-Saharan Africa. A core site would be located where it is broadly representative of a biome's climate, soils, and land use.

4.3.3. Primary and secondary production

4.3.3.1. Introduction

The preceding section outlines a global approach of determining primarily the impact of climate change and carbon loading on primary production through its effect on biogeochemical cycling. In this section an approach for observation on primary and secondary production is outlined separately for each environment. In all cases choices of an approach are grounded in what is desirable and what can realistically be achieved.

4.3.3.2. Marine environment

The three large marine ecosystems or regions (Benguela, Agulhas, Southern Ocean) are monitored for changes in productivity of all levels of the trophic web for both the photic pelagic zone and benthic environment, in conjunction with changes in climate and geophysical character (section 4.2.2.3.) including ocean acidification, sea surface temperature, ocean circulation and upwelling, and ultra-violet radiation. Monitoring of primary productivity and some key geophysical variables are based on remote-sensing, whereas *in situ* sampling from ships is used for surveillance of geophysical variables, carbon, nutrient availability, zooplankton, fish stocks, and top fish predators. Populations of a number of bird and mammal species have been monitored for a long time. Significant changes in fish stocks are expected to result from climate change in conjunction with harvesting; harvest is recorded by operators. Remote-sensing will ensure surveillance of infrequent events, whether climate-related, geophysical, or oil pollution spills.

4.3.3.3. Coastal environments

Functioning of coastal environments is addressed on a habitat basis (e.g., rocky reefs, rocky shores, estuaries, salt marshes, soft sediment, coastal pelagic). The influence of drivers relevant to each of these habitats on nutrient stocks, as well as phytoplankton, macroalgae, zooplankton and fish production will be monitored. The main drivers whose effect would be monitored include seawater temperature, salinity, and pH, ocean circulation and upwelling patterns, ultra-violet radiation, seawater-freshwater exchange, sedimentation, and nutrient loading. Harmful algal blooms will receive special attention.

4.3.3.4. Savanna, Grassland and Arid Systems

The influence of inter-annual rainfall variability on primary and secondary production has presented a major management challenge in these three biomes in which natural vegetation supports large mammalian herbivores. These patterns of natural variability need to be understood if human-induced directional change is to be detected.

The use of a core site, in addition to investigating carbon flux (section 4.3.2), would provide detailed insight about biogeochemical cycling and primary productivity in relation to climate change and carbon loading, and possible consequent changes in dominant life form. Only a handful of sites can be established nation wide. Additional efforts are required for surveillance of the impact of other drivers on primary production, and for understanding responses in secondary production. Affiliated sites, especially long-term experiments and fence-line contrasts, would be used to observe effects of land use, fire, herbivory, and biome-specific management practices such as water point distribution, bush clearing, or alien plant invasion and control. The use of affiliated sites would increase the likelihood of observing the impact of infrequent weather events, or pest or disease outbreaks.

4.3.3.5. Forest

Forest primary production has a history of monitoring because of an interest in timber, for which stem wood has been the main variable monitored. This variable is also useful for indexing carbon storage in forests. The existing network of monitoring stands will be expanded across the climatic and topo-edaphic gradients over which forests occur in South Africa.

The distribution of this network is suitable for observing the impact of the following on forest primary production: carbon loading; climate change; infrequent weather or climate events; forest use (e.g., protected, controlled harvesting, communal access); nutrient loading and acid deposition; forest fire; alien invasive plants; and elephants and other large herbivores.

4.3.3.6. Production systems

Production crops are closely managed in terms of nutrient availability, genetic diversity, pest impacts, and in other ways that serves to minimise variability in production. They are therefore fine-scaled indicators of change in production by comparison with natural systems and will serve to provide additional evidence of certain anthropogenic impacts.

Interpretation of trends is enhanced by the depth of physiological understanding of these species by comparison with indigenous plant species.

- The *plantation forestry* industry maintains a network of plots for detailed monitoring of tree and stand growth that covers the climatic and topo-edaphic gradient of afforested areas in South Africa. As with indigenous forests, continued monitoring of these plots is adequate for revealing changes in production in response to carbon loading, climate change, rare weather events, nutrient loading and acid rain.
- Production of key *cereal crops*, namely maize and wheat, plus sugarcane is similarly monitored and could provide further evidence of the impact of the same impacts affecting plantation forestry.

4.4. Hydrological Functioning and Sediments

4.4.1. Introduction

Hydrological functioning is defined as the quantity, seasonality, and quality of water flowing through a drainage system. The quantity of water flowing through a stretch of river can be reduced through impoundments, abstraction, and increased evapo-transpiration; whilst increases in the amount of flow may result from inter-basin transfers, increased runoff from changed land surfaces, and decreased evapo-transpiration.

Impoundments may further alter the seasonality of flow. Hydrological flow is a well understood physical process which can be successfully modelled at a catchment level. Water quality may deteriorate from accelerated soil erosion, or from increased inputs of nutrients, waste, and pollutants, or simply from reduced flow because of lessened dilution. The many different drivers which may affect water quality have resulted in assessments in South Africa being based mainly on the biological state of the river.

Sediments affect ecosystem structure and functioning of rivers, dams, wetlands, estuaries, rocky shores and reefs, whilst a supply of sediment is essential for maintaining sandy beaches and for creating coastal dunes. The supply of sediment in all these cases depends on soil erosion and sediment transport by rivers. Changes in land use or management in the catchment are the principal cause of changes in the extent of soil erosion by water. The amount of sediment transported through a fluvial system will depend further on the amount of water flow, and may be substantially reduced by impoundments. Wind patterns along the coast have an additional direct effect on the building or decline of beaches and coastal dunes. Similarly, wind patterns determine the dynamics of dune systems in arid areas.

Soil erosion usually results in a decrease in water and nutrient availability, hence primary productivity of impacted terrestrial environments. The effect of different agricultural practices on soil erosion has been a concern for over a century. This concern highlights our poor knowledge of the rate of soil formation, a process which requires long-term study.

4.4.2. Hydrological flow

Observation of long-term changes in river flow requires gauging weirs, which are expensive to construct and maintain. Maximum use therefore needs to be made of already existing infrastructure.

Climate change. Pattern of river flow in response to changes in precipitation and evapo-transpiration are best observed on catchments under a stable natural vegetation cover that has been consistently managed. Long-term experimental catchments in protected areas offer the best means of identifying an influence of climate change as soon as possible. This includes currently operational catchments (e.g. Jonkershoek) and others that were abandoned but are still potentially functional (e.g. Cathedral Peak). DWAF's national network of monitoring river flow would supplement efforts. Currently available

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infrastructure would serve mainly the fynbos and grassland biomes, whereas semi-arid and arid areas would be poorly represented.

Land use, management, and alien invasives. The effect of different land uses, or different forms of management for the same land use, or areas infested with woody alien plants or not, can best be observed by comparing two or more catchments that are otherwise similar. Observation is best based on first-order or micro-catchments because these are the only units which are likely to match the spatial scale of land uses and management areas.

Large, infrequent events. The DWAF national network of monitoring river flow would capture such events.

4.4.3. Water quality

Impacts on water quality include nutrient loading (mainly phosphorus and nitrogen), increased turbidity resulting from sedimentation, pollutants and other contaminants. A river functions as a continuum of flow from source to mouth, thus upstream inputs can affect downstream functioning. The impact of any of the above therefore depends on the amount entering the river and the point of entry. Sources may be of a point nature, such as waste outlets, or of a diffuse

Human settlement frequently develops in close proximity to water sources with a resulting impact on water quality. Hydrological functioning is affected by this kind of land use with changes in water quality caused by (human-induced) accelerated soil erosion, or from increased inputs of nutrients, waste and pollutants. The effect of different land uses can best be observed by comparing two or more catchments that are otherwise similar

nature, such as fertilizer input from agricultural fields. Impacts may become diluted downstream depending on patterns of river flow. Effective observation of water quality therefore requires monitoring quality throughout the course of a river but it may be difficult, if not impossible, to distinguish different anthropogenic impacts.

Water quality of the main rivers, large impoundments, and river stretches in the vicinity of significant point impacts (eg wastewater works, mines) of the country is monitored by DWAF, water boards, CSIR, and metropoles, amongst others. DWAF monitor both bio-indicators and water physico-chemical variables. These efforts would form a basis for observation of the net effect of a multitude of impacts without necessarily being able to distinguish the effect of individual anthropogenic impacts. Point-source impacts (e.g. wastewater) would be assessed by upstream-downstream comparison. Similarly, impact of a certain land use might be defined by change in water quality of a river passing through a region dominated by a single land use. For example, deteriorating water quality would be expected along a stretch of river flanked by irrigation cropping, whereas water quality might be expected to improve when flowing through a protected area.

The following specific impacts could best be observed based on comparison of impacted versus non-impacted first- or higher order catchments, including experimental catchments:

- *Plantation forestry.* A number of experimental sites afford comparison of planted versus indigenous vegetation.
- *Acid deposition.* Extant experimental catchments could reveal such effects over time. An opportunity would be provided by any new industrial development that would impact a relatively pristine catchment, for example the proposed development of coal fields and power generation in the Limpopo Province.
- *Acid mine drainage.* The current and expected increase of coal mining, especially in Mpumalanga, offers an opportunity for examining the impact of acid mine drainage.

Water quality of impoundments offers an overall indicator of the state of a catchment but does not necessarily reveal the impact of different drivers.

4.4.4. Observation of river systems

Observation of hydrological flow (section 4.4.2) and water quality (section 4.4.3) were designed to gain insight of the relative impact of individual drivers

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on these responses. Observation of individual impacts on hydrological functioning cannot necessarily be aggregated into total system impact because of synergistic, interactive, conditional, and indirect complex effects. Observation of a heavily impacted river from source to mouth can reveal the net effect of all drivers. The scale of this impact can be assessed by comparison with an otherwise similar, but lightly impacted, river. Initially, a comparison is planned for each of KwaZulu-Natal, Eastern Cape, Western Cape, and Mpumalanga. A number of heavily impacted rivers have a long history of monitoring. Hydrological modelling would provide an essential tool for study of the effect of climate change, land use and management, impoundments, and waste-water release on hydrological functioning. Associated observation would reveal consequences of changes in hydrological functioning for biodiversity and functioning of its dependent aquatic, wetland, riparian, and estuarine systems.

4.4.5. National index of fluvial sediment transport

Dams present an opportunity for monitoring whether soil erosion is increasing or decreasing in a catchment. Bathymetric measurement of changes in dam volume can indicate the approximate volume of sediment which has collected over a period. DWAF routinely monitors a

Fire is an essential disturbance agent affecting more than 60 % of the land surface of the country. Our grassland, savanna, fynbos, and Nama-Karoo vegetation is adapted to a fire regime described by type and intensity of fire, and season and frequency of burning. Any alteration of this regime would have consequences for biodiversity, biogeochemical cycling, productivity, carbon sequestration and storage, hydrological functioning and sediment dynamics.

number of major impoundments in this manner. Rates of sedimentation would be interpreted using ancillary monitoring of river flow and land use patterns.

4.5. Fire Regime

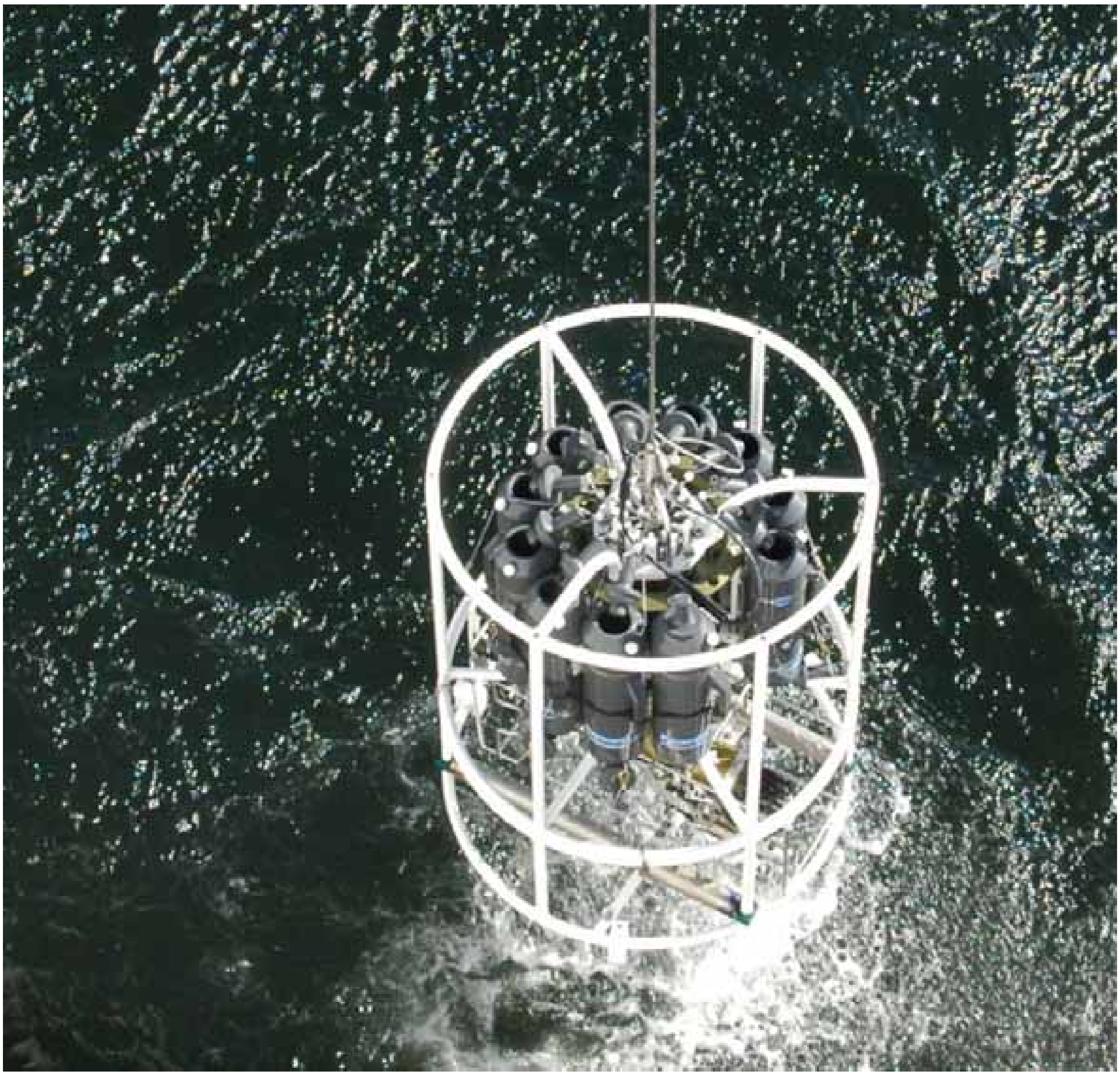
Fire is a key determinant, hence primary management tool, of the structure and functioning of fynbos, grassland and savanna biomes, and a threat to forests. It may become more significant in the Nama-Karoo biome in response to climate change. Fire is arguably the most important driver of disturbance affecting more than 60 % of the land surface of the country. Any change in the fire regime (defined as type and intensity of fire, season and frequency of burning) may therefore have widespread consequences for biodiversity, biogeochemical cycling and productivity, carbon sequestration and storage, hydrological functioning and sediments. Regions far removed from biomes in which fires occur, such as estuaries, might also be affected.

Drivers that may induce a substantial change in the fire regime include those that could affect availability of fuel or conditions for ignition and burning.

- Climate change – especially amount, inter-annual variability, and season of rainfall, winds, and temperature;
- Land transformation through the loss of fire-prone vegetation;
- Land use and management – especially grazing regime; and
- Increases in alien woody plants and bush encroachment.

Observing changes in a fire regime have to be made at a landscape scale. This would be based on remote-sensing in conjunction with ground mapping and recording of individual fires.

The response of ecosystem integrity or species diversity to climate-related versus other anthropogenic agents can be compared across all biomes, and also across habitats within a biome. The picture below illustrates sampling of a marine ecosystem from a ship in a monitoring programme of geophysical variables, carbon, nutrient availability, zooplankton, fish stocks, and top fish predators.



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5. INTEGRATION AND SYNTHESIS

5.1. Within Nodes

The set of observation activities described in section 4 for an individual node will provide an integrated statement of the pattern of change in response to anthropogenic drivers and natural variability. An example is presented in Table 3 (p.36–37) of a minimum set of information for the savanna biome. The approach is similar for the other nodes. The following are some features of this approach that should be noted.

- Different responses are observed at different spatial scales. For example, intensive observation of a core site (± 100 ha) serves mainly the purpose of improving understanding of the effect of climate change and carbon loading on carbon cycling. This cannot be achieved without detailed observation of biogeochemical cycling and primary production. By contrast, observation of secondary production is undertaken at a property scale while observation of biome shifts occurs on a widespread geographic basis.
- The choice of where to undertake observation will assist in providing a measure of the strength of effect of certain drivers acting alone or in combination with other drivers. Protected areas are particularly important for revealing the impact of climate change and carbon loading because other human impacts are reduced.
- A comparative approach is ideal for understanding the impact of land use and management.
- Impact of infrequent events which are poorly predictable in space and time are most likely to be captured in a geographically distributed set of observation efforts, provided the temporal resolution of sampling is appropriate.

5.2. Across Nodes

The use of a driver-response structure for observation provides a consistent framework for integration across nodes that differ markedly in their biophysical character. Individual response variables can be compared in terms of which drivers have the greatest effect. Climate change is a driver expected to affect all environments and it is therefore used as a starting point for integration across nodes.

A question common to all nodes would be whether climate-related variables have had a greater impact than other anthropogenic drivers on a

Table 3. Outline of observation design for the savanna node, illustrating that each response variable is observed in a manner which indicates the effect of individual driver variables. The table represents a shell for observation design, to which additional components might be added that increase the drivers under surveillance for a specific response if deemed to be necessary.

Response	Agents	Observation design
Biome shift	i. Climate change and CO_2 loading	i. Woody ingress into grassland along altitudinal transects and savanna-grassland interface at multiple localities.
	ii. Land use and fire regime	ii. Direct loss of savanna to land transformation, and effect of altered fire regime on savanna shift, observed at grassland-savanna interface using mainly remote sensing.
Biodiversity: ecosystem shifts	i. Climate change and CO_2 loading	i. Displacement of ecosystem types with sharp boundaries within protected areas (e.g., mopane within KNP)
	ii. Land use (confounded with fire regime)	ii. Comparison of response across land uses (e.g., KNP, communal, private conservation). Difference over time reveals interaction. Separate effect of fire regime revealed through comparison of properties with same land use that differ in fire regime.
Biodiversity: ecosystem integrity	i. Climate change and CO_2 loading	i. Site-based (GRADSECT) monitoring of richness, composition and structure across trophic levels within KNP; special attention paid to tree-grass ratio.
	ii. Land use	ii. Comparison of response across land uses (e.g., KNP, communal, private conservation). Difference over time reveals interaction.
	iii. Management: fire and grazing regime	iii. Comparison of the most common regimes used for a specific land use across properties in a locality; observed using site-based monitoring across trophic levels.
	iv. Management: water distribution	iv. Site-based monitoring of richness, composition and structure across trophic levels along gradients from water points within KNP. Interaction of land use and water management revealed by comparison of such gradients in different land uses.
	v. Management: bush clearing	v. Use of experiments and cleared areas with paired 'control' sites.
	vi. Alien invasive species	vi. Comparison over time of sites that differ in the degree of invasion; monitoring of biodiversity response on cleared sites.
	vii. Large infrequent events	vii. Response assessed by above efforts ensuring appropriate temporal resolution of surveillance to capture the specific effect of a large infrequent event.
Biodiversity: species	i. Climate change and CO_2 loading	i. Changes in the distribution and abundance of selected plant and animal species.
	ii. Land use	ii. Comparison among land uses of population abundance of plant and selected animal species (operating at an appropriate spatial scale).
	iii. Management	iii. Comparison among properties of a given land use which differ in fire/grazing management, of population abundance of plant and selected animal species (operating at an appropriate spatial scale).
	iv. Alien invasive species	iv. For invasive plant species, comparison of areas of differing infestation using plant and animal taxa operating at that spatial scale.
	v. Harvesting	v. Population response of a selected set of species (e.g., medicinal, food) that are intensively harvested, assessed using observation and modelling to accommodate other drivers.
	vi. Large infrequent events	vi. Response assessed by above efforts ensuring appropriate temporal resolution of surveillance to capture the specific effect of a large infrequent event.

Response	Agents	Observation design
Carbon	i. Climate change and carbon loading	i. Intensive observation of a core site according to GTOS protocol: biogeochemical cycling and primary production
Primary production	i. Climate change and carbon loading ii. Land use and management	i. In addition to a core site, surveillance of peak phytomass on experimental plots under consistent management. ii. Comparison of patterns of primary production across different land uses and and management regimes using remote-sensing in combination with site-based sampling.
Secondary production	i. Land use ii. Land management iii. Other	i. Comparison of land uses occurring at a locality over time for conspicuous or selected components of secondary production (e.g., large mammals). Entire property constitutes an observation unit. ii. Comparison of different management regimes (fire, grazing) for a specific land use within a general locality over time for conspicuous or selected components of secondary production (e.g., large mammals). iii. Other effects on secondary production such as extreme weather events or disease outbreaks are captured by above efforts provided the temporal resolution of surveillance matches that of the event.
Fire regime	i. Climate change and carbon loading ii. Land use iii. Land management	i. Changes in the distribution of burnt areas and types of fire in KNP over time. Carbon loading has an indirect effect through increasing woody vegetation affecting production of a fuel load. ii. Comparison of large protected areas with other land uses occurring at that general locality, e.g., with communal or private conservation areas adjacent to KNP. Observation is based on remote sensing and ground inspection of area burnt, season of burn, landscape characteristics, and fire-return period. iii. Comparison of properties of a specific land use which have adopted different grazing or fire management approaches, or have undergone a change in approach (e.g., block to mosaic burning in KNP). Observation approach as for land use.
Hydrological regime: flow	i. Climate change ii. Land use iii. Land management iv. Large, infrequent events	i. Revealed by flow records for a protected high-order catchment. ii. Comparison of otherwise similar high-order catchments that are under different land uses. iii. Comparison of micro-catchments that are under different management regimes. iv. Captured by the above-described observation.
Hydrological regime: quality (nutrients & sediment)	i. Land use ii. Land management	i. Comparison of otherwise similar high-order catchments that are under different land uses. Change over distance when river flows from one land use to another (e.g., value of protected areas in 'cleaning' water). ii. Comparison of micro-catchments that are under different management regimes.
Sediment	i. Land use or management	i. Comparison of soil loss and slope transport across properties using *in situ* measurement.

Meeting the need for essential socio-economic services is recognised as a key anthropogenic driver of environmental change in South Africa. An example is the generation and distribution of energy, as signified by the electricity pylons shown below. The pressure for increased power generation in the future will result in further land transformation, additional impoundments to meet water requirements, acid mine drainage, soil acidification, and acid deposition.

response of interest. For example, the response of ecosystem integrity (site sampling) or species diversity to climate-related versus other anthropogenic drivers can be compared across all nodes, and also across habitats within a node. Some of the other anthropogenic drivers (e.g., harvesting, land use) can be compared for a subset of nodes and a subset of response variables. Some key drivers are obviously relevant to only one or a few environments, such as the effect of ocean acidification on marine and coastal systems, or of sea level rise on coastal systems.

6. COMPLEMENTARY APPROACHES

6.1. Introduction

The design described thus far is compartmentalised in that different responses to different drivers are observed in different places. This structure is best suited for improving understanding of a specific response to the separate and collective influence of multiple drivers, but relations among response variables are not properly addressed. Ecosystems, however, function as an integrated unit and complementary approaches to observation are therefore required. The following sections briefly describe the main means whereby additional observation and study of change will be made. The first is observation of a selected set of discrete ecosystems. The second is pursuit of a select number of cross-cutting themes.

6.2. Observation of Ecosystems

A set of distinct ecosystems will be observed in order to gain insight about the nature of each system response to multiple impacts. Ecosystem here refers to a geographically defined area of the earth's surface (e.g., Algoa Bay, St Lucia estuary, Drakensberg) that functions as a relatively discrete entity. Case studies such as these provide the opportunity of gaining deeper understanding of complex responses to multiple drivers acting concurrently and synergistically. Ecosystems selected for observation should be well studied and understood. It is particularly useful if the ecosystem is to be subject to a large perturbation or influence. For example, in the near future Algoa Bay will have a large port constructed on its shore, while freshwater input into St Lucia may be engineered.

6.3. Cross-cutting Themes

6.3.1. Degradation of rangelands and other systems

Rangelands cover more than 70 % of the land surface of South Africa and are critical for sustained provision of essential ecosystem services including agricultural products, water provision, carbon sequestration, and biodiversity. Degradation, defined as natural and anthropogenic processes resulting in loss of the land's biological or economic productivity, has been identified as a key threat to sustainable delivery of these services. A main challenge is to separate directional changes in degradation from the effects of pronounced inter-annual rainfall variability. A large number of biophysical indicators have been identified for observing degradation, including variables covering climate, soil, water, vegetation, domestic animals, wild animals, and socio-economic factors. Some indicators, for example botanical composition and animal performance, have a particularly strong history of study. These and other selected indicators would form the basis of investigation over the long-term of degradation in relation to land use, management, biophysical character of the region, climate change, and changing socio-economic conditions. Palaeo-ecological study is a required component of this observation effort.

Wetland and riparian systems are of especial importance for water-related services but these systems have similarly been subject to a host of human impacts. They have not enjoyed the depth of study that dryland environments have, and the reasons for degradation relate mostly to impacts on hydrological regime and direct transformation, but the overall approach is similar to that used for rangelands.

6.3.2. Sustainable productivity of harvested systems

Harvesting of naturally produced secondary productivity is the characteristic pattern of resource use in marine, coastal and freshwater aquatic systems, and also for some terrestrial systems whose biotic resources are not under private ownership. The question of what is required for sustainable harvesting of selected species is common to all systems. Despite differences in environment, tools for studying population biology and dynamics are similar and would allow comparative study across species and systems.

6.3.3. Special case studies

The approach to environmental observation described in this document has in effect pigeon-holed activities. Observation of special cases that may arise is one means of ensuring flexibility and of responding to new interests that fall within SAEON's mandate. This is not developed further in this document but potential examples include:

- development of a biofuels industry and its impact on land transformation, biodiversity, and ecosystem services; and
- pressure for increased power generation and its environmental consequences such as acid mine drainage, soil acidification, and acid deposition.

Observation of these is accommodated in the main observation design but would require targeted data collection and analysis.

7. About SAEON

The Southern African environment is characterised by high levels of variability and biodiversity. For example, rainfall is a primary driver of the ecosystems, but its high variability limits its usefulness as an indicator of environmental change. Rainfall outcomes are complicated by the timing, frequency and intensity of rainfall events, as well as conditions of surface temperature, humidity, soil, slope and vegetation. These complexities, coupled with differential responses by thousands of species, cause uncertainty about the direction and extent of rainfall-induced change (Pauw, 2007).

Southern Africa's indigenous biodiversity, landscapes and oceans are continuously changed by diverse and adjoining land uses such as mining, farming, conservation, forestry, urban sprawl, communal resource management, fishing and golf estates. Time-series data covering the spectrum of spatial scales is essential for reliable data on significant environmental changes, some of which are slow, while others may be sudden. Data obtained over short periods and at single locations offers limited value.

The advance of climate change is already being observed but how and where it will impact on Southern African society remains uncertain. Rural communities, commonly desperate for resources and information, are particularly vulnerable to climatic variability, which is often aggravated by unsustainable agricultural and fishing practices, not only by those communities themselves, but also by commercial and illicit enterprises.

Earth observation science is thus urgently required to bring more certainty about environmental change, and to enable formulation of adaptive and mitigating management policies and practices, for themes ranging from food production to population health.

The South African Environmental Observation Network (SAEON) was established in 2002 after a process of deliberation within the research community. Following extensive consultation with its sister departments, the Department of Science and Technology (DST) took the lead by mandating and funding the National Research Foundation to develop SAEON as an institutionalised network of departments, universities, science institutions and industrial partners.

According to the SAEON mandate, its responsibilities rest on three mandates: observation, information and education.

Integrating Earth Observation Systems

The Department of Science and Technology's vision was to establish a long-term *in-situ* environmental observation platform supporting the various mandates of the different participating organisations, and overall for the public good.
It is vital for a national environmental observation system to be durable in its design and management. SAEON's network design promotes the integration of existing environmental observation systems, while it is stabilised by core funding from DST and a diverse range of participants.

SAEON seeks to coordinate and support long-term *in-situ* environmental observation systems through three tiers of stakeholder advisory committees — political, technical and operational. The Department of Environmental Affairs (DEA) and other relevant departments are members of the SAEON Advisory Board and Technical Steering Committee.

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).

Six SAEON nodes have been established, not only at locations selected for geographical spread, but also in different host organisations for organisational spread. These organisations are:

- Marine and Coastal Management (MCM)
- South African National Biodiversity Institute (SANBI)
- South African National Parks
- Ezemvelo KZN Wildlife
- South African Institute for Aquatic Biodiversity (SAIAB)

The nodes are field centres coordinating and facilitating observation and information systems for four biome-based terrestrial regions, the coastal zone (divided into three bio-geographic regions) and offshore-marine systems (divided into three large marine ecosystems). Once established, they become centres of gravity attracting world-wide research interest.

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The mandate of 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, connsistent and reliable long-term environmental databases; promote access to data for research and/or informed decision making; and contribute to capacity buidling 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 knowlдge 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 (DS&T) 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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