









# Synthesis and Outlook on Future Research and Scientific Education in Southern Africa 32

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## Abstract

The sustainability of southern Africa's natural and managed marine and terrestrial ecosystems is threatened by overuse, mismanagement, population pressures, degradation, and climate change. Counteracting unsustainable development requires a deep understanding of earth system processes and how these are affected by ongoing and anticipated global changes. This information must be translated into practical policy and management interventions. Climate models project that the rate of terrestrial warming in southern Africa is above the global terrestrial average. Moreover, most of the region will become drier. Already

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there is evidence that climate change is disrupting ecosystem functioning and the provision of ecosystem services. This is likely to continue in the foreseeable future, but impacts can be partly mitigated through urgent implementation of appropriate policy and management interventions to enhance resilience and sustainability of the ecosystems. The recommendations presented in the previous chapters are informed by a deepened scientific understanding of the relevant earth system processes, but also identify research and knowledge gaps. Ongoing disciplinary research remains critical, but needs to be complemented with cross-disciplinary and transdisciplinary research that can integrate across temporal and spatial scales to give a fuller understanding of not only individual components of the complex earth-system, but how they interact.

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## 32.1 Introduction

“We are not living in a stable world. Science needs to unravel the nature, causes and consequences of this change in a way that can lead to transformative change with positive impact on society.” This was the closing challenge from the South African Department of Science and Innovation’s (DSI) Prof Yonah Seleti at the SPACES II Programme Synthesis Meeting in Pretoria June 2022. This view strongly supports the idea that environmentally focused policy-related research, especially in developing regions such as southern Africa, be motivated by and embedded in the need to enhance the social-ecological basis to advance human well-being. While environmentally focused research addresses important unknowns about the functioning of the natural (ecological) world, such research thus cannot be decoupled from pressing social issues, such as the security and sustainability of food production, water supply and its quality, and how these issues link with poverty and developmental challenges. However, strengthening the relevant links between explanatory scientific research and its policy implications remains a difficult and complex challenge (Stringer and Dougill 2013; von Maltitz 2020).

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It is now almost certain that the southern African social-ecological system, like several other regions of the world, is approaching potentially consequential “tipping points,” sets of conditions that entrain self-perpetuating changes that have adverse impacts (Chap. 7; IPCC 2022). These could include, for example, prolonged and intense drought leading to major cities and their surrounding regions running out of water, the collapse of food production systems and related food insecurity, novel intense weather events such as category 4 cyclones making landfall on southern Africa’s east coast ever further southward, and toward major cities and centers of human settlement, or unprecedented heatwaves (Mbokodo et al. 2020; Chaps. 6 and 7). The impacts of such events would have extensive health and social consequences including loss of human life, disease, human displacement, human migration, infrastructure damage and related food and water insecurity, and increases in poverty and deprivation. These impacts would adversely impact on the region achieving the United Nations Sustainable Development Goals (SDG) (Chap. 3). A well-developed predictive understanding of such climate change-driven impacts enables society to develop strategies, approaches, and policies that can anticipate and avoid, adapt to, or mitigate against impacts. Working toward this goal underpins the Science Partnerships for the Adaptation to Complex Earth System Processes (SPACES II) program, with key outputs from this research and important gaps in knowledge highlighted across the chapters of this book.

The southern African region is highly complex in terms of its environmental and socioeconomic setting and its diverse flora and fauna, and this is a fundamental condition that challenges explanatory scientific work in its efforts to tease out a predictive understanding at a level of credibility sufficient to inform appropriate societal responses. The region is an area of convergence of several global scale geophysical drivers of climate, ecosystems, and ecosystem processes. The mid-latitude southerly extent of this region gives rise to a globally unique meeting of warm, high salinity, and nutrient-poor waters carried polewards by the Agulhas Current down the east coast and the cold, nutrient-rich waters of the Benguela Current originating from the Antarctic Circulation and feeding the Benguela Upwelling System along the west coast. These currents have major impacts on precipitation, with the warm Agulhas Current bringing rainfall to the east, while the cold Benguela Current inhibits rain on the west. Two distinct climatic systems, partly linked to these ocean currents, exert seasonally variable impacts on the region. Midlatitude cyclones bring rainfall to the western Cape region with high predictability, and sometimes further northward and inland with lower dependability, during the austral winter months. The seasonal southward migration of the Inter-Tropical Convergence Zone (ITCZ) as summer months approach tends to enhance summer convective rainfall, as well as displacing the path of the midlatitude cyclones from their winter landfall track to the southern ocean. This West-East winter-summer seasonality pattern is overlaid by a roughly orthogonal trend in rainfall amount, with arid and semiarid conditions in the southwest transitioning over semiarid grasslands and savannas to subtropical woodlands and tropical forests in the north. High interannual variance in rainfall is associated with the lower influence of predictable winter rainfall regime, and annual rainfall total throughout the region. These climatic gradients, together with related

disturbances like wildfire, have had major impacts on the biodiversity that has evolved in the region over millennia. The spatial variation in interannual variability in rainfall also poses multiple challenges for both agriculture and the provisioning of water for human and industrial use (Chaps. 5, 6 and 12).

Southern Africa's diversity in ocean currents, topography, including the ocean shelf, climate, geology, and disturbance regimes, has resulted in southern Africa having unique and high levels of biodiversity, with a disproportionate number of endemic species in both the marine and terrestrial environments (Chap. 2). This diversity is under increasing pressure from global change drivers (Chap. 3) including anthropogenic land cover and land-use change (Chaps. 3, 4, 13, 15, 17, 20 and 22), spread of invasive alien plant and animal species (Chaps. 3 and 24), and overexploitation of terrestrial and marine biological resources (Chaps. 3, 11, 16, 19, 25 and 26). Critical feedbacks of these impacts on the global climate system derive from resulting trends such as land degradation (Chaps. 13, 20 and 23), which is a CO<sub>2</sub> source to the atmosphere (Chaps. 14, 17, 23, 25 and 30). Loss of biodiversity and ecosystems goods and services has profound impacts on local livelihoods (Chaps. 3, 4, 20, 22 and 23). Sustainable agriculture, ecotourism, and other nondepleting uses of natural resources are strategic imperatives for the region and would ensure the persistence of large contributors to individual livelihoods and countries' Gross Domestic Products (GDPs), with varying priority in different countries (Chaps. 4 and 20). Both agriculture and tourism are disproportionately large contributors to job creation and livelihoods opportunities, in any region where unemployment is a key concern (Chap. 4). Direct access to natural resources is important to rural communities and is especially a safety net for the poor (Chaps. 19, 20, 21, 22, 23 and 25). Despite this, the region has a distinct tension between developmental needs versus biodiversity protection and nature conservation (Chaps. 3, 4, 20, 22 and 23). While biodiversity is the mainstay of a large number of both formal and informal livelihood opportunities in sub-Saharan Africa, for example, Shumsky et al. (2014), from a policy perspective, environmental concerns are often perceived as constraints to economic development (Chaps. 4 and 31).

From a social-ecological perspective, a merging of vastly different resource management systems has occurred over four millennia in sub-Saharan Africa (Bjornlund et al. 2020). Colonialist practices from Europe converged with or dominated traditional Khoisan and Bantu tenure, land use, and land management systems, resulting in complex and often contested land management regimes in the region. Ancient traditional land management systems have been replaced or modified along with the conflicted history of land ownership in the region. Land tenure in sub-Saharan African countries is a postcolonial mix of private land holdings with their history in the colonial occupation of the region, mixed with a number of different forms of customary tenure with roots in traditions of the Bantu tribes that were resident in the area at the time of colonization. Some of these traditional approaches have themselves been modified through colonial and postcolonial processes.

These differences in tenure and management legacies link to vastly different land-use practices, which range from large-scale high intensity farming through

to small-scale subsistence types of farming (Chaps. 3, 15, 20–23). By far the single largest land use is rangelands for livestock or game production (Chaps. 15–20). Rangeland management systems differ substantially with rangeland being either commercially managed, often using livestock rotational techniques reliant on fencing and with relatively low stocking densities, or being communally managed where livestock stocking rates can be close to the ecological carrying capacity (Chaps. 16, 19, 20, and 23). Increasingly, rangeland is also being managed for wildlife-based agri- and nature-based tourism industries (Chaps. 15 and 18). This diversity of agricultural practices poses multiple research priorities and challenges to support management decision-making in these varied land-based subsectors. The urgency for solutions is growing with the need to reconcile demands for increasing agricultural productivity with resource use constraints and environmental concerns (Chaps. 19–23).

There is clear evidence that near-shore marine resources have been exploited by humans dating back at least to the late Pleistocene as evidenced by analysis at Pinnacle Point (Marean 2010; Wren et al. 2020). The advent of the commercial fisheries industry in the late seventeenth century greatly increased the levels of marine exploitation and gave rise to thriving fisheries industry, which can be divided into four main sectors: subsistence fishing, small-scale (artisanal) fishing, large-scale commercial fishing, and recreational fishing. The fishing industry is important in terms of supporting local food security, and the provision of job opportunities (Baust et al. 2015). However, it remains a politically contentious industry with ongoing disputes around licensing among main sectors and the associated access to resources, with clear historical evidence of discrimination against the artisanal sector (van Sittert 2017). Deep-sea, mostly commercial, and inshore (mixed commercial and artisanal) trawling target hake is a key component of the commercial fishing industry, while pelagic purse-seine fisheries target sardine, anchovy, and herring. Other important, largely artisanal sectors include shrimps, chokka squid, and numerous line fish species. The high value of crayfish and abalone creates a disproportionate revenue and amount of jobs for the biomass harvested (Baust et al. 2015), and pressure from poaching. Harvest levels have fluctuated greatly over time: between the different sectors and between the west and east coasts. Due to upwelling, the west coast has a globally high rate of net primary production and has been the main contributor to the tonnage of fish caught. Initially, this was mostly based on hake, with catches peaking in the late 1960s, but declined substantially thereafter. In Namibia, the small pelagic (mostly sardine) fisheries industry had largely collapsed by 1977 (Paterson et al. 2013). On a tonnage basis, the east coast contributes far less to the fishing catch, but it has far greater involvement of small-scale and subsistence fisheries, which play a proportionately more important role than on the west coast (Baust et al. 2015). Stricter management and quota systems reduced fishing pressure but have not resulted in a complete recovery of stocks (Paterson et al. 2013).

## 32.2 Overview

### 32.2.1 Climate Change

Climate change is a global challenge that manifests differently across and between regions and subregions. The southern Africa region is anticipated to be subjected to severe impacts (Chaps. 3, 7, 20–23), being largely warm and dry. The interior, especially to the west, has historically warmed at twice the global average, a trend that is projected to continue for years to decades (Chaps. 6 and 7). Rainfall projections are less certain, but there is growing consensus that almost all of the region is likely to become more arid, with this effect being strongest in the already arid west. The combined impact of warming and reduced rainfall will greatly increase drought stress, an impact that will be felt both within the natural environment as well as in crop agriculture and rangelands (Chaps. 6, 7, 14, 19–23 and 26). The climate of the region already has high interseasonal variance, and this is likely to increase. Maximum, rather than mean, impacts are likely to have the greatest short-term social and ecological consequences, with more prolonged and intense droughts likely to occur. Despite overall projections of greater aridity, the warming of the Indian Ocean is likely to result in tropical cyclones of greater strength that move further south, bringing episodic flooding and related impacts on built infrastructure and the natural environment (Chap. 7).

Southern Africa has two distinct rainfall regimes: the winter rainfall, Mediterranean-like climate of the Fynbos, and semiarid Succulent Karoo of the southwestern tip of the continent, where rainfall is dependent on midlatitude cyclones that sweep over the region in winter, and the summer rainfall interior region that is dominated by convection rainfall (Chaps. 5–7). These regions are separated by a zone with all-season rain. The winter rainfall region's rainfall is projected to be reduced, because the path of the midlatitude cyclones will be displaced southward. This circulation pattern has occurred in years when the Western Cape has experienced severe drought, such as during the 1920s, and more recently during the 2015–2018 drought that almost resulted in a “day-zero” scenario, that is, the depletion of an urban water supply to the Cape Town metropolis. Climate change projections indicate a high likelihood of decreased rainfall and even more severe drought over the next few decades (Chap. 7).

A key feature of the summer rainfall region is a high interannual variance in rainfall. There is good evidence that this is linked, in part, to El Niño Southern Oscillation (ENSO) events, with dry periods associated with the El Niño phase, and wet periods associated with La Niña phase. This relationship is not perfectly dependable, however, and can only be used as a partial predictor of annual rainfall in the summer rainfall region (Chaps. 5, 6 and 12). Additional influences of rainfall variability include oceanic conditions in the Angola-Benguela region, the Agulhas Current and its behavior within the Mozambique Channel, and the Indian Ocean (Chaps. 5–9).

Reasons for the low correlation between the strength of ENSO events and realized rainfall remain unresolved. A better understanding of the drivers of climate

is therefore imperative to fully understand climate change impacts, or to be able to accurately conduct seasonal weather forecasts. Chapter 8 considered changes in what is termed the Agulhas leakage and how this has a relatively small but important impact on local climate. The extent of Agulhas leakage is likely to increase as a result of climate change. The need to regionalize climate drivers that are often at scales below those of large-scale climate models is highlighted by this work. Feedbacks from vegetation cover to the climate system were explored in Chap. 10 where models were used to show that wide-scale land cover change (in this case, deforestation) would have direct and negative feedbacks on precipitation patterns. This preliminary evidence provides some justification for action to reduce deforestation and to promote reforestation in Angola and Zambia, and could add a novel interpretation to the impacts of exotic commercial plantations in South Africa if confirmed by credible modeling of the processes involved.

Understanding past climate (Chaps. 5, 27 and 28) is important for calibrating future climate models and can also be directly used to better understand both current vegetation patterns and how vegetation has responded to climate variance in the past. Proxy climate data shows that there has been a succession of cooler and warmer periods over the past millennium with rainfall in the winter rainfall region negatively correlated with temperature, and the opposite in the summer rainfall region. This trend could not be replicated by modeling efforts, suggesting further research is required to explain this discrepancy (Chap. 5).

### 32.2.2 Climate Change Impacts

The combined impact of a hotter and drier future on an already arid region will have adverse impacts on net primary production (Chap. 26), biodiversity (Chaps. 15–17), agricultural systems (Chaps. 17–23), water provision, tourism, and many other natural resources (Chap. 3). Severe extremes, such as heat waves, droughts, and floods, which are assumed to be associated with this long-term trend, are expected to further increase these devastating negative impacts on the terrestrial biosphere (Chaps. 6, 7, 20, 22 and 23).

Climate change also influences ocean currents, upwelling systems, and marine biogeochemical cycles. These changes become evident in oceanic warming with increased stratification within the upper ocean and a lowered supply of oxygen from the atmosphere. Since the marine fauna responds to temperature variations and are sensitive to oxygen levels, such changes can directly affect exploitable fish stocks (Chaps. 2, 11 and 25). Decreasing oxygen concentrations have, for instance, been linked to the southward shift of the rock lobster distribution and an increased frequency of rock lobster walkouts in response to associated events during which dissolved oxygen is completely consumed in the water column (e.g., Hutchings et al. 2009).

Additionally, changes of upwelling systems are expected to influence primary production but due to the complex interplay of upwelling, mesoscale oceanographic features, and frontal zones, the link between upwelling intensity and primary

production may not be linear (e.g., Rixen et al. 2021). Ocean changes are also likely to have direct feedbacks into the local climatic systems, but these feedbacks are far from fully resolved (Chaps. 8 and 9).

### 32.2.3 Carbon Cycles

The fate of atmospheric CO<sub>2</sub> is critical in understanding climate futures. The vast extent of the southern African land surface and the surrounding oceans means that small changes in overall trends in emitting or sequestering carbon are important for understanding global carbon dynamics. Thus, both oceanic and terrestrial realms are potentially important global carbon sinks (Chaps. 2, 15 and 25).

The global ocean is a critical sink of carbon, through what is termed the solubility pump and the biological carbon pump, and while the solubility pump is well studied, the response of the biological carbon pump to global change remains poorly understood. Currently, neither the magnitude nor the direction of its expected change is predictable. However, the Benguela Upwelling System along the west coast is known to act as CO<sub>2</sub> source to atmosphere in the north and as a CO<sub>2</sub> sink in the south due to varying relative strengths of these two marine carbon pumps (Chaps. 2 and 25; Siddiqui et al. 2023). While in both systems, the solubility pump increases CO<sub>2</sub> concentrations in the surface water due to the warming of upwelled water, the biological carbon pump lowers the CO<sub>2</sub> concentration, because it fixes CO<sub>2</sub> into biomass through primary production. Carbon is exported via the produced organic matter into deeper parts of the ocean and the underlying sediments. The CO<sub>2</sub> uptake by the biological carbon pump was estimated to be  $18.5 \pm 3.3 \text{ Tg C year}^{-1}$  and  $6.0 \pm 5.0 \text{ Tg C year}^{-1}$  for the Namibian and South African part of the Benguela Upwelling System, sizeable numbers that confirm the accumulated effect of small changes of CO<sub>2</sub> exchange that could be of great relevance for national carbon budgets (Chap. 25).

Bottom trawling for fish and the associated remobilization of sedimentary organic carbon could potentially impact CO<sub>2</sub> uptake both by the biological carbon pump and through changes in the pelagic food web structure (Chap. 25). A near-collapse of the fishing industry due to overharvesting has resulted in the system having currently a relatively low secondary production of fish relative to primary production, with a significant change in fish species dominance (Chaps. 2, 11 and 25). There is also an order of magnitude increase in neritic copepods, though it is unclear if this is due to climate change or changes in fish stocks (Chap. 2).

With respect to terrestrial trends in carbon sequestration, it was found that in the semiarid Karoo, grass-dominated, degraded, and less diverse sites had higher carbon sequestration rates than the more typical dwarf-shrub-dominated sites. This raises important questions about the preferred state of the landscape and how it might be managed. It also appears that slight changes to the management regimes can tip such systems from being a net carbon emitter to being a net carbon sink. Annual precipitation patterns both in terms of magnitude and seasonal distribution are also



critical in this regard, with wet years resulting in net CO<sub>2</sub> sinks, while arid years tend to show a net emission (Chap. 17).

In savanna systems, both empirical data and modeling found that the vegetating productivity was able to recover rapidly from artificially created prolonged drought periods (Chap. 26). Landscape level changes in standing biomass due to tree encroachment in savanna are seen as a degradation of the natural vegetation and have major adverse impacts on ranching industries. It does however lead to large, but poorly quantified amounts of carbon sequestration, and Namibia has quantified this trend in its greenhouse gas inventory, reporting that the country is carbon neutral largely due to the wide-scale occurrence of bush encroachment. This raises important questions around trade-offs among carbon sequestration, biodiversity, livelihood opportunities, and other environmental goods and services (Chaps. 14–16 and 26).

### 32.2.4 Marine Systems

In contrast to the terrestrial system where the ecology is largely determined by precipitation, temperature, disturbance regimes, and the nature of the soil, within the marine environment, the physical and biogeochemical properties of the sea water are the key determining variables affecting the marine ecosystem. Climate change impacts the thermal structure of the ocean with enhanced temperature increase near the surface, increasing stratification and reducing oxygen levels. Climate-warming-driven changes to global and local wind patterns will impact both ocean currents and the strength of ocean upwellings. The nature of the southern African marine environment is largely determined by the contrasting ocean currents, the Agulhas Current transporting warm, salty, and nutrient-depleted tropical waters along the east coast, while the Benguela current system on the west coast is associated with cold and nutrient-rich water that upwells to the surface impacting the ecology of the region, particularly as it relates to regionally enhanced primary production (Chap. 25). The southern tip of Africa is where these transition zones between Atlantic and Indo-Pacific water bodies occur, giving unique habitats with high levels of both speciation and endemism (Chap. 2). The marine habitat also differs from the terrestrial habitat in that it can be zoned by depth of the water column and depth of the seabed. Obviously, the nature of the seabed at each depth is also of importance. As discussed above, there is a level of mixing of the converging ocean currents in the form of rings of the Agulhas water “leaking” into the Benguela, which result in 300-km wide swirling masses of Indian Ocean water moving northwestward within the Atlantic and that may persist for 3 years (Chap. 8).

As in the terrestrial environment, southern Africa has above-average endemism within its marine waters (Chap. 2). This makes the region biologically important from a conservation perspective. As in the terrestrial biomes, it is the combined impacts of past and current human disturbances, in this instance pollution, bottom trawling, and overharvesting, combined with the impacts of climate change, that pose major threats to the region’s marine biodiversity in the longer term (Chap.

25). Already there are clear impacts in changes to trophic chains due to the intensity of fish harvesting, with possible feedbacks into the biogeochemistry cycles as discussed before. Since the 1950s–1960s, there have been substantial, long-term changes in abundance, biomass, production as well as species and size composition of neritic (on the shelf) mesozooplankton communities in both the Northern Benguela Upwelling System (nBUS) and Southern Benguela Upwelling System (sBUS) subsystems (Chaps. 2 and 25). Long-term changes in zooplankton communities from the mid-1990s to mid-2000s, are likely to have fundamental effects on biogeochemical processes, food web structure, and ecosystem functioning of the BUS as well as on the ecosystem services, for example, carbon sequestration and fisheries, supported by the plankton (Verheye et al. 2016).

Decoupling the climate change impacts on zooplankton and fish stocks from the management impacts on fish stock depletion remains an important question for the long-term sustainable harvesting and management of these globally important fish resources. This will also require a better understanding of what appears to be a jellyfish dominated dead-end food chain (Ekau et al. 2018).

These changes have been described for the nBUS by Bode et al. (2014) and Verheye et al. (2016), for the sBUS by Huggett et al. (2009), Blamey et al. (2015) and Verheye et al. (2016). Abundances of neritic copepods have increased by at least one order of magnitude in both subsystems, with turning points reached around the mid-1990s in the south and around the mid-2000s in the north, but declining afterward. At the same time, there were marked changes in copepod community structure, with a gradual shift in dominance from larger to smaller species in both subsystems.

### 32.2.5 Terrestrial Environment

At the regional scale, a combination of climate change and enhanced CO<sub>2</sub> concentrations was modeled to have profound biome level shifts in vegetation structure (Chap. 14).

Loss of soil through soil erosion has long been identified as a threat to South Africa as soil loss in the region can be one to two orders of magnitude higher than soil genesis (Chap. 13). Conserving soil is fundamental to long-term sustainable agriculture, including adapting to climate change impacts (Chaps. 20 and 23). This critical and basic aspect of land management, though not new, must not be overlooked when focusing on new climate smart land management solutions (Chap. 20). However, a reanalysis of potential erosion rates suggests that previous estimates may have been an order of magnitude too high (Chap. 13). Land transformation and degradation impact on the natural environment, potentially reducing net primary production (NPP) and causing a loss of biodiversity. The combined impact from land degradation, when coupled with climate change, may be more severe than when considering these impacts in isolation (Chap. 3).

The process of increasing density of indigenous woody vegetation, locally referred to as bush encroachment, was identified as a major threat to current range-

land livelihood activities. Its occurrence is widespread over most savanna areas, and increased woodiness within grasslands is also widely reported. Although SPACES II projects did not consider bush encroachment specifically, it is a background theme to many chapters considering rangeland management (e.g., Chaps. 15–19).

Drought is a natural aspect of the savanna environment (Chaps. 5 and 6), and predictions are that droughts are likely to intensify with climate change (Chap. 7). Savanna vegetation responses to drought were investigated in Chap. 26. Drought causes substantive production and biomass loss, and a shift from perennial to annual species of grasses, but no signs of tipping points to alternative states were observed. Recovery from drought occurred rapidly, even after an artificial 6-year prolonged drought period. Resting periods from grazing were, however, identified as important. The methodology used could help identify undesirable vegetation shifts and recommend management interventions.

### **32.2.5.1 Natural Rangelands and Agriculture**

Use of the terrestrial landscape ranges from total resource conservation through to land transformation for crop-based agricultural production. All countries in the region have complex land tenure arrangements where there is a dualism of tenure with some farmers having freehold or leasehold on vast individually owned farms, whereas other land users exist on areas of customary tenure where the rangeland resource is communally used, though small crop plots are privately used and managed, at least during the growing season (Chaps. 2–4). In addition, there are vast areas of state-owned and managed national game reserves, especially within the savanna biome (Chaps. 15 and 18). Within the private and communal sector, there has been a move from almost all land being used for livestock, to much of the dryer areas now being used for wildlife (Chaps. 15, 16, 18 and 19). It is suggested that wildlife is the economically optimal use for areas of low rainfall (Chap. 18).

### **32.2.5.2 Primary and Secondary Production and Use in the Terrestrial Environment**

Given that the savanna biome is by far the largest biome within southern Africa, it received a disproportionately large focus in the SPACES II program. Use of the savanna ranges from pure conservation through wildlife and livestock management to food crop production. Much of the savanna is used by local communities who have traditional tenure to the land and use it for livestock, game, and a multitude of other natural products including woodfuels. However, large commercial farms, including game farms and private reserves, are also common. Chapter 15 gives an overview of rangeland use within the savanna biome and the threats and degradation challenge it faces. Bush encroachment is identified as one of the biggest threats to livestock and tourism dependent linked livelihood activities. Drivers of bush encroachment are complex and traditionally are attributed to livestock and fire regime management. The direct impact of raised CO<sub>2</sub> levels in promoting bush encroachment is being increasingly recognised as one of the contributing factors to bush encroachment (Bond and Midgley 2012; Chap. 15).

### 32.2.6 Understanding Rates of Change

Monitoring and the critical importance of long term datasets was a common theme running through almost all chapters of this book, with monitoring data either being the basis of the studies, an identified shortcoming in resolving long term impacts or developed as part of the methodologies. Although our understanding of the degree and rate of environmental change as a consequence of climate change has advanced tremendously over the past three decades, many of the current studies highlight the degree to which uncertainty still remains. Fortunately the southern African region has extensive long term climatic and natural history data creating a sound baseline for some variables from which to track further change. The southern African region in general, and especially the Cape Floristic region, has attracted extensive botanical research which is mostly well archived (Chap. 2). The local avian research community, using citizen science approaches in addition to more traditional approaches has long term, extensive and replicated bird distribution data resolved to a quarter degree spatial scale and covering most of the subregion (Hugo and Altwegg 2017). In common with marine data, sampling intensity varies greatly and tends to bias to the more accessible areas. Most other taxa also have reasonable data sets due to a large and active population of environmental scientists in the region, linked to almost all of the main universities and additional research institutions.

The need for ongoing and increased levels of monitoring in both the terrestrial and marine environments is critical for tracking and better understanding the long-term impacts that the region is experiencing from climate change and human interventions. This needs to include both abiotic monitoring of climate, the atmosphere and oceans, as well as monitoring of key biological variables such as net primary production and the associated sequestration of atmospheric CO<sub>2</sub> (Chap. 25). Earth based or ocean based, location specific monitoring is needed to calibrate satellite based observations. In this context, SPACES contributed with long-term greenhouse gas (GHG) measurement infrastructures to overcome the limits of our understanding of the temporal dynamics of the biosphere-atmosphere exchange of carbon (Bieri et al. 2022). This requires highly sophisticated monitoring equipment and well-educated scientists and technicians for data-analysis and maintenance. However, in the ocean, we have not yet reached this stage and further efforts are needed to understand the exchange processes.

In the South African context the newly approved Expanded Freshwater and Terrestrial Environmental Observation Network (EFTEON) and the South African Polar Research Infrastructure (SAPRI) within the South African Earth Observation Network (SAEON, van Jaarsveld et al. 2007) is a major commitment by the South African government to further its monitoring and research network for the terrestrial, freshwater and marine environments.

Despite this, across the subregion there is still insufficient long term commitment to long term environmental and climatic monitoring given the high probability of adverse livelihood and environmental impacts that will be experienced from climate

change. This shortfall is probably most pronounced in the vast marine environment, partly due the cost of installing and servicing permanent monitoring sites being orders of magnitude more expensive than for terrestrial based monitoring sites.

Global change drivers, including climate change, are impacting and changing natural environments in novel and fairly unpredictable ways. Understanding the nature of the change and the rates at which this change is taking place is critical for long-term sustainable management of these systems (e.g., Challinor et al. 2018).

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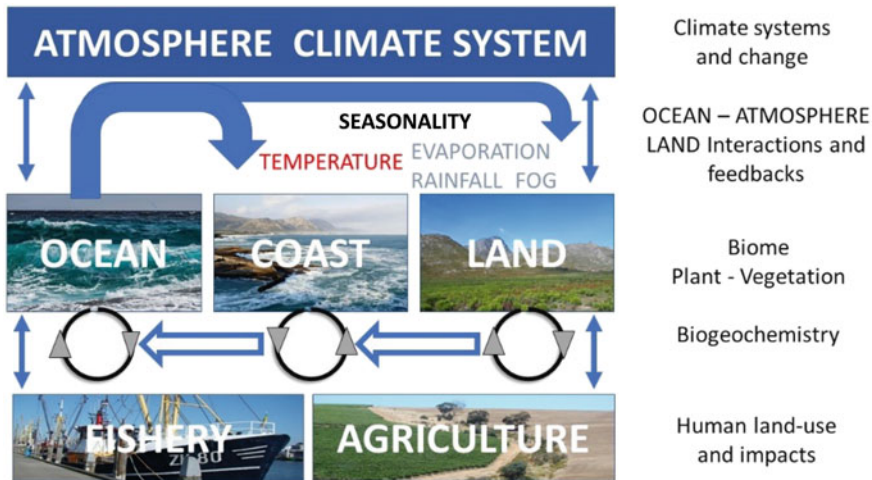
### **32.3 Emerging Issues for Integrated Ecosystems Research**

As is common in attempting to understand complex coupled human-environmental (or socio-ecological) systems, much uncertainty remains. Despite the considerable advances in knowledge from the previous studies, most of these studies have tended to be stand-alone investigations on single or few components of the system, and have not attempted integration across the entire system. Future studies should not only increase the depth of knowledge within systems components, but also develop an understanding of the linkages between (sub-)systems. Understanding of the linked ocean–climate–land interactions in southern Africa is not fully resolved, despite this triggering the climate change responses of the entire system. For a better understanding of climate change impacts and feedbacks and development of land management and climate-smart agriculture in the region, an integrated research approach supported by due involvement of, and interaction with, different stakeholder groups will be the next step.

#### **32.3.1 Ocean–Atmosphere–Land Interactions and Feedbacks**

The interactions between ocean, atmosphere and land are complex, with many feedbacks between the three components (Fig. 32.1). The ocean surrounding southern Africa has direct but still purely quantified feedbacks into the climate of the subregion as they influence air temperatures, rainfall, and the west coast fog banks. The seasonality of precipitation is also of high ecological relevance and controls the development of the vegetation and the biome. Climate change impacts on ocean currents could therefore have profound and poorly understood impacts on local weather and climate.

Transports from the terrestrial landscape into the oceans via river discharges and eolian dust deposits strongly influence the ocean currents as, for example, seen in front of Congo river mouth (Chap. 9) as well as seawater chemistry and the sedimentation (Chap. 2). As illustrated in Chaps. 12, 27, and 28, sediment studies can indicate the major changes to biodiversity, land use, and pollution. Anthropogenic changes in the terrestrial environment from land use (Chaps. 20–22), increased erosion (Chap. 13), and other forms of pollution are transported by rivers and as eolian dust into the ocean (Chaps. 28 and 29). Eventually, these



**Fig. 32.1** Ocean–atmosphere–land interactions and feedbacks

components are deposited at the continental shelf, potentially with multiple impacts on the marine environment and its biodiversity (Eckardt et al. 2020).

Climate change and other human activities will directly impact on the intensity and nature of land–atmosphere–ocean linkages. For example, climate change is likely to increase drought conditions, which lead to dust storms where large quantities of dust are transported off-shore into the oceans (UNEP 2016; Eckardt et al. 2020). Land management practices, including a move to nontill agriculture, together with large-scale adoption of windbreak technologies, could greatly reduce wind speed, soil erosion, and have positive effects on the microclimate (Chap. 21; Veste et al. 2020).

A feature of both savanna and fynbos vegetation is that the vegetation burns naturally at intervals ranging from twice a year to only once in 20–30 years, depending on vegetation type and rainfall. Timing and frequency of fires has direct anthropogenic links. The fires produce vast smoke plumes, which have direct and indirect climate feedbacks (Lu et al. 2018; Ichoku 2020).

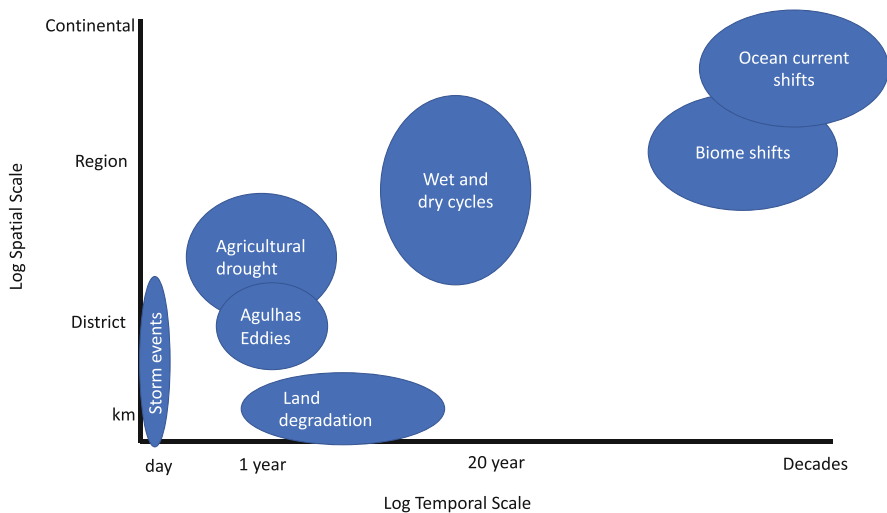
Wind-driven pollutants, soil, and smoke also enter the oceans, with both positive and negative effects. Extensive rangeland fires are the norm over much of the savanna during the late winter. During this period, a high-pressure system forms over the interior, with the smoke typically circulating out over the Atlantic and back again in what is termed the gyre effect, but also leading to extensive deposition over the Atlantic. At odd periods, especially during neutral El Niño Southern Oscillation (ENSO) events, there is also an observed fast flow of what has been termed a “river of smoke” that exits the east coast, travelling in a southeast direction over the Indian Ocean toward Australia (Kanyanga 2009). The actual smoke clouds have direct albedo effects, particles act as nuclei for cloud formation, and in addition there

are nutrients, including soluble forms of iron, that are deposited in the oceans and leading to extensive algal blooms (Piketh et al. 2000).

### 32.3.2 Mesoscale Effects and Across Scale Effects

Many drivers of local climatic impacts (Fig. 32.2), and particularly precipitation, are driven by, or occur, at a spatial scale far smaller than can be determined from global circulation models. Examples include, but are not limited to, localized convective thunderstorms, which are the mainstay of the summer rainfall precipitation; deep mixing of surface and subsurface waters in the southern oceans due to localized events (Nicholson et al. 2016, 2022); the Agulhas leakage, which brings warm and salty waters as well as multiple organisms into the Benguela Current (Chap. 8); and the Benguela Upwelling System, which are critical to driving the high primary production along the west coast (Chap. 9). Resolving the impacts of these mesoscale events on both climate and ecological function is critical for a full understanding of the risks posed from climate change.

Complex interactions occur between processes at different scales and from different drivers (Fig. 32.2). Clearly, global circulatory patterns impact on local drivers of climate such as the formation of convective storms. Equally prevailing winds and their strength along the west coast of southern Africa have impacts on the location and intensity of upwelling systems (Chap. 8). A multitude of small, localized fires cause smoke plumes to extend far into the Atlantic and Indian oceans. These localized impacts feed directly into ecological processes, effecting for instance net primary production (NPP) at the local scale. Feedbacks can be in



**Fig. 32.2** The temporal and spatial scales of important climate change related processes

both directions, and very direct, for instance increased evapotranspiration being a trigger for local thunderstorm development. Equally feedbacks can be slow and very weakly coupled, for instance increased NPP resulting in CO<sub>2</sub> uptake from the atmosphere and hence feeding back into global CO<sub>2</sub> dynamics and climate.

Identifying the key mesoscale drivers of climatic and environmental processes as well as the way these are driven by and impact on processes at both the local and global scale remains poorly resolved within the southern African context.

### **32.3.3 Biogeochemical Processes in Hydrosphere–Biosphere–Lithosphere**

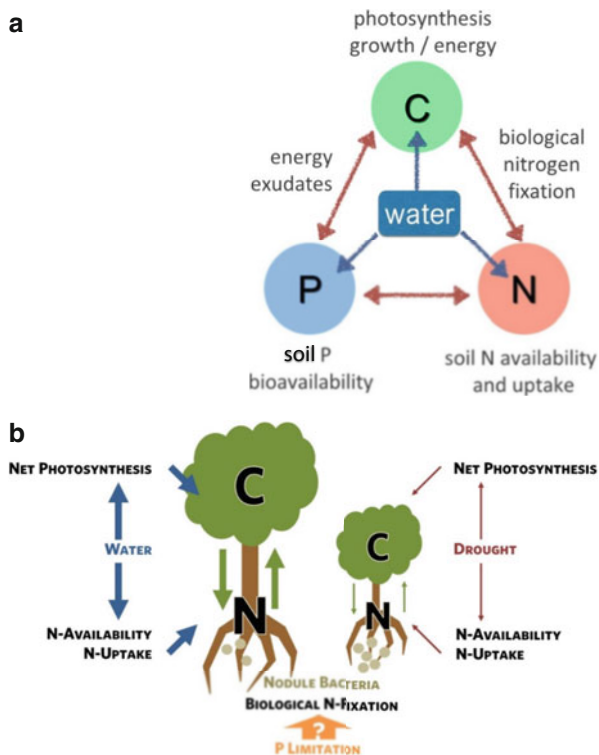
Climate change leads to an increase in precipitation variability with changes of dry-wet cycles and thus controls vegetation development and compositions in biomes. Previous studies have mainly focused on the carbon cycle (Chaps. 17 and 25), which is also linked to the increased atmospheric CO<sub>2</sub> concentration, and the hydrological cycle (Chap. 6). Less attention has been paid to the interactions and feedbacks between carbon and other biogeochemical processes (particularly those including nitrogen, N, and phosphorus, P), water availability, and changes in vegetation in southern African biomes. Generally, southern African soils are characterized by a low nitrogen and phosphate content. The P-bioavailability is largely affected by adsorption and desorption processes of Fe- and Al-hydroxides in acid soils and P immobilization by Ca in alkaline soils. The mineral crystallinity is one important aspect, affecting P adsorption and desorption processes. Biological nitrogen fixation (BNF) with symbiotic bacteria plays an important biological role to overcoming the low soil nitrogen levels in nutrient-poor soils, and allows plants to build up their own N pool even in dry conditions, but under the conditions of larger portions of plant carbon transported toward the symbiotic microorganisms to maintain their BNF. Little information is available on the interconnected biological and soil chemical processes in the soil-plant system for most biomes in southern Africa. Studies in the fynbos show specific adaptations of plants depending on soil conditions (e.g., Griebenow et al. 2022).

The biogeochemical processes on the ecosystem level are externally controlled by the precipitation (Fig. 32.3a). Beside the rainfall amount, the frequency of drought and wet conditions is crucial for the ecological processes in the soil-plant systems. Therefore, changes in dry-wet cycles have drastic consequences for the uptake of macro- and micronutrients by the plants, but also the entire biogeochemical cycles and vegetation. Increasing droughts will alternate the carbon fluxes in plants and ecosystems and reducing productivity (Fig. 32.3b); however, for the coupled changes of P and N uptake and cycling by the vegetation and soil microbes, only few investigations were carried out.

The implication of climate change for hydrological, biogeochemical, and ecological processes in the different biomes is more complex due to the different rainfall amounts and the seasonality in the summer, winter, and year-round rainfall zones. In general, spatiotemporal characteristics of the various weather systems and



**Fig. 32.3** (a) Water is the most critical factor for the interactions among carbon (C), nitrogen (N), and phosphate in soil-plant systems. (b) Schematic illustration of the interactions and transport of N and C with good water supply and drought stress (modified after Gypser and Veste 2019)



the biomes are broadly understood. However, the transition between these rainfall zones under climate change in southern Africa remains an open question and the transition zones are complex (Conradie et al. 2022). Changes in the rain seasonality and the length of dry-wet cycles were observed in the recent decades (Roffe et al. 2021, 2022), which are coupled to the complex ocean–climate–land interactions in the different seasons (Sect. 32.3.2). Furthermore, there is clear evidence that with climate change, the frequency of extreme events will increase, like the extreme droughts in the Western Cape in 2015–2017 (Theron et al. 2021; Wolski et al. 2021; Chap. 7) or heavy rainfalls and floodings in the Karoo recently in summer 2022 and the KwaZulu-Natal floods in April 2022.

Therefore, a better understanding of these changes in relation to the ocean and their impacts on terrestrial ecosystem functioning is needed. These requires a transcontinental study approach across the summer, winter, and year-round rainfall zones in southern Africa on the influence of changes of rainfall seasonality and their feedback on biogeochemical processes, vegetation composition and dynamics, biome development, and land-use systems. Such information is also important for the development of resilient and climate-smart agriculture in the region.

### 32.3.4 Thresholds of Change, Tipping Points, and Impacts from Unique Events

Much of the southern African flora and fauna has evolved in a situation of high variance in climatic drivers, and especially related to annual precipitation (Chaps. 2, 5, 6, 16 and 26). Some biomes, such as the savanna, are considered by many to represent disequilibrium systems, maintaining their structure because of, rather than despite the high levels of disturbance (Chap. 15). Ecological theory speculates that many systems experience critical thresholds, or tipping points, and if pushed to beyond these points, the system may collapse or change to a new stable state (e.g., Walker and Salt 2006). In Chap. 16, it was found that savanna systems exhibit high resilience to drought and despite artificially enforced intense drought, there was still high potential for recovery. However, in Chap. 14, it was shown that there is likely to be shifts in entire biomes as a consequence of climate change. Aspects such as bush encroachment have traditionally been seen as vegetation responses to overgrazing, but there is growing evidence that this might be a precursor to increased woodiness over much of the savanna and grassland biomes. The situation is different in the winter rainfall areas in the Western Cape and the Succulent Karoo. Even though a significant decrease in rainfall is expected here, seasonality plays an important role for the ecosystem. This is clearly linked to the ocean–land interaction, but its variability of dry-wet cycles and its importance for vegetation and land use is not understood. In general, temporal fluctuations in precipitation (rain and fog) in combination with spatial heterogeneity of water supply due to run-on and run-off processes are important factors for plant communities. A model developed by Reineking et al. (2006) shows that spatiotemporal variation of resource supply can maintain diversity over a long time. Furthermore, the importance of fire disturbances (Hebbelmann et al. 2022) and invasive plants (van Wilgen et al. 2020) for changes in natural ecosystems as well in agri-systems will be increased under climate change. These dramatic changes to thresholds in several stable ecosystems can be irreversible if caused by humans. The characteristic return time to equilibrium increases as a threshold is approached (Wissel 1984). Thus, in addition to information on the effects of stress on systems, we also need studies on the length of recovery phases, whose ecological importance has been underestimated.

The environment is not in isolation of humans, and operates in a complex coupled human environmental system. Human population density has increased by between one and two orders of magnitude over the past 200 years. This has been accompanied by large scale replacement of indigenous mammals with domestic livestock, extensive deforestation, clearing of natural vegetation for crop fields, impoundment of streams, extensive fencing and provision of artificial water which change natural animal migration patterns and many other impacts (Chaps. 3, 4, 18 and 29). Systems wide consequences of these changes are hard to model. Both climate change and anthropogenic activity are resulting in new and unique pressures on the environment. Responses of the environment to unique events that fall outside

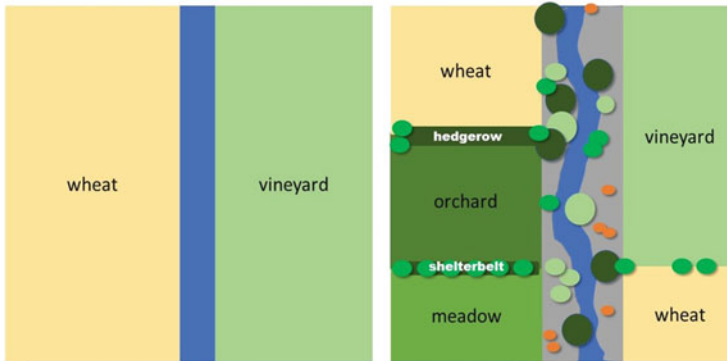
of the envelope in which the environment evolved may result in unanticipated environmental change. Breaching thresholds and tipping points in the climate and ocean systems could have even greater consequences for the region.

### **32.3.5 Distinguishing Signals from Complex Drivers**

As discussed above, there are many complex changes taking place in the subregion driven by a mix of climate change and other anthropogenic impacts. We also are slowly developing better monitoring tools and building long term sequences of environmental data, including a better understanding of natural cycles of change. Disentangling the causes of observed impacts remains hugely difficult and problematic, especially since there may be synergistic, or dampening effects from alternate drivers of change. For instance, the CO<sub>2</sub> fertilization effect from anthropogenic emissions can to some extent offset impacts from poor land management. In the west-coast fisheries, the impacts from overharvesting may be difficult to distinguish from changes in the frequencies and intensities from near-shore upwellings (Blamey et al. 2015). To overcome this, there is a need for a combination of enhanced systems' understanding of the drivers of systems dynamics, use of experimental manipulation, improved and enhanced long-term monitoring, and the use of modeling to understand probable consequences from specific impacts.

### **32.3.6 Multifunctional Land Use and Integrated Landscapes**

It is expected that due to climate change, high rainfall variability and water scarcity will increase in the future, and this will affect the water use patterns in agricultural production (Chap. 7). Water resources in the region are limited and a more water-efficient landscape is needed to mitigate negative effects of climate change. An integrated approach to water and landscape management needs to combine agricultural, forestry, and natural ecosystems to increase ecosystem resilience, to optimize water use efficiency, to ensure a sustainable bioeconomy, and to strengthen conservation of biodiversity during the next decades. Land-use systems of the future have to be holistic to support different needs of the society. Systems must be able to balance ecosystem services such as water and food provision, carbon sequestration, and biodiversity (O'Farrell et al. 2010; Mastrangelo et al. 2014; Grass et al. 2020). Complex trade-offs are inevitable and so-called win-win solutions are not guaranteed, though some choices have less societal and ecological consequences than others. Coordinated actions between different stakeholders are needed to improve recent farming practices, while reducing the pressure on land conversion and improving food security in a sustainable way (Rötter et al. 2016). An improved understanding of the water-land-use relations is essential to develop strategies for integrating resource-efficient land use, agricultural productivity, sustainable water management and conservation of the natural ecosystem and ecosystem functioning (Quinn et al. 2011; Rötter et al. 2021; Pfeiffer et al. 2022). As the region urbanizes,



**Fig. 32.4** Scheme of the concept of differentiated land use on a farm/landscape level: (a) state of development with large-scale agriculture and (b) ideal image of differentiated land use in integrated landscapes with the integration of natural habitats (modified after Veste and Böhm 2018)

complex trade-offs between urban and rural needs intensify, with water allocation already identified as a critical resource to the region (Matchaya et al. 2019). The recent increase of renewable energy from photovoltaic and wind parks needs to be integrated in a sustainable way as part of a multifunctional land-use system (Murombo 2022).

To develop more sustainable and resilient farming systems, there is a need to redesign agricultural landscapes and to integrate different land-use types including natural and seminatural areas from the farm to the landscape level (Chaps. 20, 22 and 23; Landis 2017; Pfeiffer et al. 2022). A differentiated land use with complex landscape structure (Fig. 32.4) has been previously proposed for Central European agricultural landscapes (Haber 2007) but has rarely been realized in practice. A key challenge for implementing sustainable and resilient agricultural systems is to develop appropriate governance structures and set appropriate incentives for land users (Leventon et al. 2017).

A particular challenge is the integration of habitats for the conservation of biodiversity within the farmed landscapes (see, Chap. 23). Depending on the species, different scales and demands must be considered. The combination of utilized agricultural landscapes and natural habitats has various advantages for the use of the landscape (Chaps. 21–23; Rötter et al. 2021). In the last decades, various initiatives have been developed in southern Africa, but more integration of biodiversity into the landscape and management is needed. There is clear evidence that transformation of farmlands and the integration of wildflower vegetation, old fields, or patches of natural vegetation within crop fields or orchards supports a wide range of insects and spiders and enhances pollinator activity and pollination services to crops and fruit trees (Chap. 22; Theron et al. 2020; Ratto et al. 2021). A recent study by Eckert et al. (2022) emphasizes the importance of small-scale spatial heterogeneity for soil arthropod biodiversity in two different regions in South Africa. For many African big game species, on the other hand, larger habitats and

routes are needed to enable migration. Restrictions and direct confrontations often lead to conflicts between humans and wildlife, which must be regulated accordingly. However, smaller mammals, insects, birds, and even plants will need to migrate as a consequence of climate change and a more integrated landscape will aid in facilitating this movement (von Maltitz et al. 2007).

In addition to the integration of biodiversity, the interactions and feedbacks of biogeochemical processes between the subcomponents must also be increasingly taken into account in the analysis of integrative landscapes (Chaps. 20–23; Rötter et al. 2021). In this context, agroforestry (Chap. 21; Sheppard et al. 2020) or adjacent riparian forests/woodland are combined land use that also has positive impacts on soil and hydrology. Furthermore, intercropping systems with diversified crop cultivation can enhance yield, environmental quality, production stability, and ecosystem services.

To meet these challenges, more transdisciplinary research is needed to better understand the land-water-climate nexus and linking different ecological processes, including nature conservation research. Moreover, innovative methodologies and decision-support tools to manage land for a balanced provision of food, feed, timber, fiber, and fuel, a sustainable bioeconomy and conservation of biodiversity and development of natural ecosystems are urgently needed. A recent study by Chrysafi et al. (2022) emphasized the importance of understanding the Earth system interactions for sustainable food production.

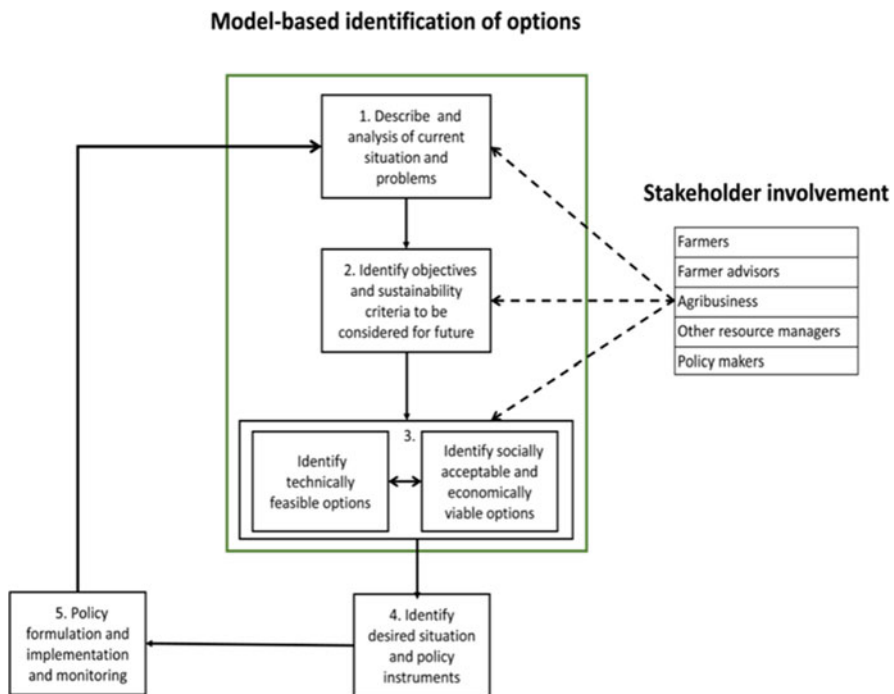
### **32.3.7 Connection Between Different Research Topics and Approaches: The Need for Integration Across Disciplines and for Interdisciplinary and Transdisciplinary Collaboration**

The complexity of climate change and environmental sustainability forces researchers to draw on interdisciplinary knowledge that spans social and natural sciences (Schipper et al. 2021). Climate change and its impacts on the socio-environmental system is often referred to as a “wicked problem” (Rittel and Webber 1973), and there is a growing branch of science around how to best deal with wicked problems (e.g., Wohlgezogen et al. 2020; Daviter 2017; de Abreu and de Andrade 2019). Solutions to resolving climate change impacts to achieve environmental and social sustainability require a system-based approach integrating across multiple environmental and social disciplines (Stock and Burton 2011). As illustrated throughout the book chapters, there are complex bidirectional feedbacks between the climate and the environment, as well as between different environmental systems, and subsystems. Clearly, there are also strong linkages between the oceans and the terrestrial environment, adding additional complexity. Further, in both the terrestrial and marine environments, there is a long history of human-led environmental change, much of this likely to interact in synergy with climate change to amplify the climate change impacts on the environment (Chap. 3).

An example of how transdisciplinary approaches have been implemented in agricultural science is given in the following section. Ecological science is influencing agricultural management choices—for example, climate smart agriculture/soil health/carbon.

In agricultural systems science, for quite some time, integrated system modeling for ex-ante evaluation of agro-technologies involving multiple disciplines has been an important research topic. For instance, the approach has been applied to support explorations of alternative agricultural development scenarios, and constituted an important building block of generating information to feed the development cycle of policies on land use and natural resource management (Van Ittersum et al. 2004; Rötter et al. 2016). Such an inter- and transdisciplinary collaboration approach—supported by modeling—is described in the following section and illustrated in Fig. 32.5.

To identify technically feasible land management options, first, biophysical modeling (step 3, left) is needed as shown in Fig. 32.5. Integrated agro-economic modeling (step 3, right) can then deliver valuable inputs for identifying technically feasible as well as socially acceptable and economically viable options in close interaction with (key) stakeholders. Modeling frameworks for such kinds of anal-



**Fig. 32.5** Schematic development cycle of policies for natural resource management and land use (steps 1–3 in the green box) supported by agricultural system modeling studies and stakeholder interaction (Rötter et al. 2016, modified from van Ittersum et al. 2004)

yses have been developed in different contexts (see Van Ittersum et al. 2004); in the framework of climate change and land-use dynamics in southern Africa, such a framework has been designed and partly realized in the SALLnet project (Chap. 23; Hoffmann et al. 2020; Rötter et al. 2021; Nelson et al. 2022; Pfeiffer et al. 2022).

### 32.3.8 Societal Impacts: Visions for the Future

Although there is an intrinsic benefit from conserving ecosystems and understanding climate risks, it is the direct impacts on human well-being that is one of the key justifications of environmental research. Large parts of southern Africa can be considered developing, with countries varying in their level of development. Despite this, all the countries share many key developmental needs including job creation, ensuring food security, reducing inequalities, and the provisioning of basic services such as water. Although the level of agricultural dependency varies between the countries (see Chap. 20), all of the southern African countries have a high reliance on the agricultural sector for support of the economy and job creation. Throughout the region, the agriculture section is predicted to have negative impacts from climate change unless substantive adaptation measures are implemented (Chap. 20). Increasingly, the role of nature based tourism is also becoming an important component of most countries' economies, and is seen as an important component of rural job creation. Reducing climate risk through adaptation interventions is critical. These interventions can take many forms and have been given multiple names but, in most instances, relate to enhancing the resilience of the landscape or farming activity through improved management. This often involves reducing land degradation, enhancing water and soil conservation, and restoring biodiversity. In the biodiversity sector, this is referred to as ecosystem-based adaptation (EBA), while in the agriculture sector, sustainable agriculture practices such as conservation tillage, agroforestry, or climate smart agriculture may be used. Ensuring land based adaptation practices are implements and increasingly important for the sustainable future of livelihoods in the region. Two recent examples illustrate how critical this is. The 3 years of drought culminating in the 2018 water crisis in the city of Cape Town, which almost culminated in Cape Town becoming the first major city globally to totally run out of water (Sousa et al. 2018; Burls et al. 2019). This same problem is now occurring in a number of other towns and cities within the region, and predictions are that the situation is likely to become worse in the future. Secondly, the 2022 floods in KwaZulu Natal have illustrated the devastating impacts that can be anticipated from increased frequencies and intensities of storm events. In both cases, integrated management of the catchments would have helped mitigate the severity of the impacts.

Impacts of bad management are less obvious in the marine environment and might only manifest through secondary measures such as fish yields per harvest effort. Sustainability of the marine resources is critical to many coastal industries as well as providing a critical source of protein. The marine resources need to be managed so that they can provide sustained social benefit in the future. In areas

where the marine resource is already severely degraded, management strategies to allow for the recovery of the resource are needed, which will require a sound understanding of the ecological dynamics.

There is an ongoing need to link results coming out from theoretical environmental research to the actual livelihood impacts of individual people and communities. This can take place in a number of different ways. Short-term weather forecasting can assist in avoiding impacts from floods, dry spells, and heatwaves. Medium-term predictions can assist farmers in determining planting patterns for the season. Apart from these tactical decisions, strategic decisions need to be supported by transdisciplinary approaches. For example, projections on long-term climate change impacts will guide in the types of land-use systems that are biophysically and technically feasible for the future. In addition negotiation with various stakeholders (different interest groups) must also be considered to ensure social acceptability. (see Fig. 32.4), may even impact on spatial planning for settlement and investments.

### 32.3.9 Governance

Achieving sound environmental governance is a critical component for effective environmental management and conservation (Bennett and Satterfield 2018). Achieving sound governance is complex and although it involves many processes, at its core should be sound scientifically based decision making. Governance is generally considered to require institutions, structures, and processes that determine how, by whom, and for whom decisions are made (Bennett and Satterfield 2018). Clearly, for any decision making to be effective, it is critical that appropriately skilled and capacitated human resources are in place. Many aspects of governance, such as law enforcement, fall outside of the realms of environmental science; however, where possible, all aspects of governance from the initial formation of policy, rules, and norms through to on-the-ground implementation of policies and plans should be based on the best available scientific evidence. This requires both that policy relevant environmental research is being undertaken, and that there are appropriately skilled human resources within relevant government departments to assimilate this knowledge into governance processes.

The fact that environmental issues are split across what are typically multiple government departments (e.g., Environment, Agriculture, Water, Forestry) and have impacts on many other departments (e.g., Health, Rural Development, Tourism, Industrial Development, Economics) means that sound environmental management requires integration across departments and cannot be achieved in isolation. Effective integration requires special skills as well as appropriate research to understand these cross sector linkages. Further, it requires political will and appropriate policies and structures to facilitate intergovernmental department collaboration.

Given that our scientific understanding is not perfect, and that the environment is constantly changing, an adaptive management process is recommended. Over-arching environmental objectives are likely to be based on national and global policy consideration. These need to be translated into operational and verifiable



goals, which guide action that is taken. A monitoring system is then required to understand if the verifiable goals are being achieved as anticipated. If not, the action and potentially the goals (if they are unachievable) need to be reassessed. This entire system needs to be based on the most up-to-date scientific understanding, with the science underpinning the management assumptions being reassessed based on new data and the outcomes from the monitoring and evaluation process. Capacity building of both state and academic staff within the southern African region remains critical in ensuring the above process (see Chap. 31).

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## **32.4 Mutual Learning, Capacity Development, and Citizen Science**

Interdisciplinary programs such as SPACES play an important role in developing skills within young emerging scientists in the region. Southern Africa has world-class expertise relating to its fauna and flora, and has also established itself as a continental leader in terms of climate change research. This makes it an ideal location for collaborative research with European partners in joint endeavors to understand the new challenges that global change is placing on the environment. European partners bring access to the most modern research ideas as well as access to advanced monitoring and modeling equipment and skills. The long-term data records from the region, together with good local infrastructure, make the region ideal for ongoing climate change research in a southern hemisphere developing world context.

Developing and retaining new scientific capacity in southern Africa has its unique challenges. High turnover in national departments is a reality of the region, driven in part by the transitional nature of expertise put in place during the colonial past, which is being replaced by new appointees aligned to national transformation priorities. Currently, there is high demand for the relatively limited pool of top-class graduates from what are termed previously disadvantaged racial groups. One unfortunate consequence is that many emerging young scientists are promoted into managerial positions at a relatively young age, and the capacities they have gained around the science need replacing. The benefit is that they are bringing their scientific background into the management arena. This, coupled with decreasing local funding for scientific research, means that partnering with European institutions can greatly facilitate this local capacity generation.

Climate change in particular is leading to new constellations and new ecological systems that cannot be understood in this form with previous knowledge alone. Mutual learning can better link previous experiences and point to new common paths for research and application. This also applies to knowledge transfer to Europe, where increased heat waves and drought will change living conditions. Joint summer schools and the exchange of students and scientists also offer the opportunity to get to know the other perspective between the continents. The newer IT-based technologies allow for shared classrooms and (blended) e-learning for certain courses (e.g., socio-ecological modeling). However, these learning methods

cannot replace classical field work and experience in nature, but should be used in a complementary way in future projects.

A high upcoming potential for scientific projects has the integration of citizen science. These formats can mobilize specific long-term local knowledge and have additional benefits for the interactions among science, stakeholders, and policy (Peter et al. 2021; Vohland et al. 2021). Particularly, in biodiversity research, the involvement of individuals or natural history societies is a growing source for long-term monitoring and science. In the future, the direct involvement of people with expertise as citizen scientists should be supported in scientific projects in the context of land-use, landscape development, and climate change. These groups provide a link between research and education and, furthermore, thus are also multipliers of scientific results into society and for policy makers.

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## 32.5 Lessons Learned and Recommendations for the Future

This book summarizes a very wide range of primary experimental, synthesis, and analytical work that has been generated over 5–10 years by a large group of authors. The composition and relationships between these authors has changed, in some cases dramatically (Chap. 1; Bieri et al. 2022), careers have been launched, new capacity has been created, and some strong long-term collaborative relationships have been built. Many new insights have been gained, new scientific findings have been made, and many important scientific and policy-relevant questions can now be asked from a new perspective and with a deeper background understanding.

At a higher level, self-analysis (Chap. 31) provides many guidelines on how future multi- and transdisciplinary cross-national collaborative programs could be further enhanced. In an era when capacity building and skills transfer are paramount in international negotiations like the UNFCCC, UNCCD, and UNCBD, this learning is valuable indeed. While the conception behind this collaborative work lies more than a decade in the past, the fruits of this work show that much of that conception was sound, and despite the many changes in regional and global political and environmental imperatives, the results presented here add great value to the fundamental understanding of regional functioning, risks, and potential solutions to the essential challenges facing the region.

Quoting Butts et al. 2016: “as we enter a world where extreme events, from natural disasters to deliberate attacks, become ever more common, sustainability and resilience become essential elements of our national security strategy. We ignore these values at our peril”. The concept of environmental security is not new, but with an increased certainty of the adverse impacts of climate change on both the environment and livelihoods in the southern African region (IPCC 6th report, Chap. 7), it is clear that the work summarized here provides increased support for addressing the environmental impacts that pose major risks to the security of the region. Substantive social disruption and displacements due to extreme weather events, and longer-term risks such as from a biodiversity perspective confirm that the products of this work are of increasing value.

Climate-related risk has often been expressed in terms of the nature of the hazard, the vulnerability of the environment (or human population) being impacted, and the level of exposure. The work described here is particularly motivated by this framing. However, a fourth component to understanding risk was added recently, among others by WGII of IPCC (2014), and further elaborated by Simpson et al. (2021). This relates to the ability of society to respond to or manage the risks. Under this framing, there are complex interactions within and between the risk components and the responses to them that can amplify or reduce the final outcomes. Simpson et al. (2021) state “Indeed, recent evidence indicates how some of the most severe climate change impacts, such as those from deadly heat or sudden ecosystem collapse, are strongly influenced by interactions across multiple sectoral, regional, and response-option boundaries.” It is with these complexities that the chapters in this book have only, in some instances, started to grapple.

Understanding risk and determining response options is now seen as increasingly requiring a more integrated understanding of the dynamics of the complex systems involved (see also Challinor et al. 2018). The model of collaboration that the work described here followed could be applied to better understand the interlinkages between components that have been addressed here, and to answer the more complex questions that arise from a strong theoretical basis of understanding the components themselves.

The SPACES I and SPACES II programs focused on key elements of the complex coupled earth system processes in the southern African region and have advanced our understanding on both the likely nature of future impacts as well as management and policy interventions that may assist communities in mitigating the effects of global environmental change. In this regard, these and previous international and national programs (e.g., BMBF-BIOTA, SAEON) have made substantive progress in understanding key and prioritized aspects of the environment and its climatic drivers. Looking further into the future, it is clear that while an understanding of ecological processes remains the basis for robust policy recommendations, the critical feedbacks and influences of human responses at multiple spatial and temporal scales must become much more seamlessly integrated into such work.

Taking the above into account, it becomes clear that the southern African region lacks a well-integrated view on the implications of the wide range of policy options now proposed and being implemented to address biodiversity loss, climate change, and development imperatives. There is no credible set of projections, for example, on how these will interact at the regional level to influence land-use change and ecological sustainability. Not only is this view lacking, the region does not have the predictive means to inform such a view, beyond some partial analysis. In the northern Hemisphere, many integrated modeling approaches have been developed along these lines, and this is now a critical skills gap that needs to be filled to allow the work presented here to be leveraged for better decision making.

This synthetic view of the results of SPACES thus emphasizes more than ever the urgent need for integrated approaches to predictive modeling of coupled processes between the ocean, atmosphere and land, their feedback to the biosphere, and the outcomes as extrapolated spatially and taking into account a range of social-

ecological responses. It is on this basis that concepts and plans for sustainable use of ecosystems on land and in the ocean, and related issues of climate protection, can be credibly developed in the future while taking into account social and economic development imperatives. Such approaches can provide guidance for implementation in practice without oversimplifying the scientific insights and findings that more properly represent a complex and dynamic world .

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