Research Infrastructures as Anchor Points for Long-Term Environmental Observation

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Abstract

In this chapter, we highlight the importance and value of key Environmental Research Infrastructures, and how these can act as anchor points for long-term environmental observations and facilitate interdisciplinary environmental research. We briefly summarize the development of these efforts in South and southern Africa over the last three decades and from this perspective discuss how their successful maintenance and further implementation may turn such RIs into important anchor points for long-term environmental scientific work in support of environmental sustainability, national commitments under selected international policy discussions, and societal well-being. The fundamental role of Environmental Research Infrastructures is multifold and includes the provision of data that enable reporting and policy development, the provision of validation sites in the development of new observational sensors, measurement techniques and models, and the provision facilities for training of scientists and technicians. Humanity currently faces a number of global crises, including the impact of

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changes in the climate, resulting in droughts, floods, fires, storms, and other extreme events. These crises are significantly stressing and transforming the lives and livelihoods of the vast majority of humanity. The societal response to these events is dependent on the availability of scientific knowledge and its effective transfer to governance structures, industry, and the broader society. In order to effectively address these challenges, large amounts of long-term social-ecological data are required across a broad range of intersecting disciplines that are available for analysis by the scientific community. Research Infrastructures have the ability to act as anchor points in the provision and utilization of this data, and the development of indigenous capacity to develop the observations and technical skills.

30.1 Introduction

The well-being of modern human societies is deeply dependent on natural resources (Angelstam 2018; Mirtl et al. 2018; Loescher et al. 2022), and recent global assessments have strongly advanced the predictive understanding of multiple, interacting dependencies (e.g., Díaz et al. 2015; Diaz 2019; Pörtner, Hans-Otto et al. 2021). Ecosystem processes and structures (both geophysical and biological) themselves interact in complex ways across various temporal and spatial scales, and it is important to understand these processes and how they are responding in a rapidly changing environment. This is especially important when trying to understand some of the grand challenges facing human societies, such as climate change, loss of biodiversity, land-use change, pollution, and eutrophication (Mirtl et al. 2018; Loescher et al. 2022). Many regions worldwide are experiencing the impacts of increasingly frequent and damaging climatic events such as heat waves, extended droughts, storms, or changes in rainfall distribution and intensity with increasingly adverse consequences for ecosystem functioning, biodiversity, and ecosystem services that support livelihoods (Masson-Delmotte et al. 2021).

A number of research activities deployed since the 1990s have been enhancing knowledge of the functioning of biophysical components of the Earth system and their interactions. These enhanced understandings of fundamental processes now inform the implementation of mitigation and/or adaption measures for climate change impacts through guidelines, regulations, or policy briefs. Among the best developed, and most vital for global climate stability, is the science behind the global carbon cycle (e.g., Friedlingstein et al. 2022). However, significant regional gaps in the coverage of such research limit a fuller understanding, resulting in a reliance on the use of extrapolation and assumptions that have not been tested in these underrepresented regions. This weakens important global level insights into optimal policy development and implementation of planned responses. This is particularly true in southern Africa (López-Ballesteros et al. 2018; Nickless et al. 2020), which has historically had limited amounts of data collection and remains inadequately integrated with respect to key research infrastructure, human capacity, and networks to support this regionally and globally important work.

The contribution of Africa to the global carbon cycle is characterized by its low fossil fuel emissions (with the exception of South Africa), and its rapidly increasing and urbanizing population, which is expected to change the fuel use patterns. However, due to the limited number of long-term measurements conducted in Africa, this region contributes significantly to the uncertainty in the global CO_2 budget (Ciais et al. 2011). Indeed, it is still not known if Africa is a net carbon source or a sink of carbon to the atmosphere, nor how it is likely to change in the future (Merbold et al. 2009; Ciais et al. 2011). Current risks include an expansion in cropland and increased rates of degradation and deforestation in the extensive dryland and savanna systems and the tropical forests of central Africa (Ciais et al. 2011).

Key questions that are increasingly highlighted for study in an African context include the ways in which ecosystems and biological communities are changing and potentially adapting as a result of both local and global drivers of change. These studies include analyses of factors that result in ecosystems approaching or crossing tipping points beyond which irreversible change may occur (Taylor and Rising 2021) and the related determination of ecosystem resilience vital for reducing environmental risks. These questions are also highly relevant for broader global and national policy commitments by African nations, providing evidence-based support for national positions including international UN conventions under which increasingly stringent requirements for credible data are needed, such as the Paris Accord of the UNFCCC, targets under the CBD, and the Sustainable Development Goals (United Nations 2021).

Research Infrastructures include facilities, resources, and related services used by the scientific community to conduct cutting-edge research, knowledge transmission, knowledge exchange, and knowledge preservation (European Strategy Forum on Research Infrastructures 2018). In this chapter, we aim to highlight the importance and value of key Environmental Research Infrastructures focused on land surface–atmosphere interactions, with relevance for the carbon cycle and associated biogeochemical functioning, and challenges inherent in building and maintaining these efforts. Our contribution is based on experience gained in South Africa, and more broadly across the subcontinent, with regard to the installation, maintenance, and long-term sustainability of such infrastructures, including capacity building (e.g., Bieri et al. 2022; Chap. 31). We briefly summarize the development of these efforts over the last three decades and, from this perspective, discuss how their successful maintenance and further implementation may turn such RIs into important anchor points for the positioning and long-term development of environmental scientific work in support of environmental sustainability, national commitments under selected international policy discussions, and societal well-being.

30.2 Rationale for Coordinated Terrestrial Research Infrastructure in Southern Africa

To obtain an Earth systems' view of environmental processes, large amounts of diverse data are required that are often measured over the long term in a consistent manner. This is beyond the capacity of individual scientists or research sites to maintain and synthesize. Therefore, collective efforts have been needed to create Environmental Research Infrastructures (ERIs) at a large enough scale to provide data to answer the types of large ecosystem-scale questions being asked (Mirtl et al. 2018; Loescher et al. 2022).

Research Infrastructures that focus on biogeochemical cycles must confront the challenge of measuring relevant aspects of systems with a high degree of temporal and spatial complexity. For example, understanding changes in atmospheric composition requires information about the sources and sinks of terrestrial and marine ecosystems as well as the processes governing the surface–atmosphere exchange.

Biogeochemically focused research infrastructure in a region like southern Africa cannot focus merely on biophysical aspects, but must also consider the complexity of the region's biological diversity and ecosystems, and the vital activities of people in these landscapes. The status of multiple drivers of ecosystem structure and functioning are particularly relevant, including vegetation, soil, land-use and disturbance regimes, hydrological flows, and the omnipresent role of human activities in all aspects. For this reason, independent research projects focusing on subelements of the greater Earth system may not capture important linkages to factors that are beyond the scope of the specific project aims, even when coupled to larger-scale models of frameworks. By contrast, well-coordinated efforts supported by RIs designed to provide comprehensive platforms of deliberately monitored variables can enhance the potential for improved systems' understanding. These are to be supported by RI staff to provide and operate the platform, while external researchers have access to the infrastructure for undertaking additional research, on a project basis.

These concepts are being addressed by a number of national or regional science programs such as the Integrated Carbon Observation System (ICOS) in Europe (Heiskanen et al. 2021), the National Ecological Observatory Network (NEON) of the United States (Keller et al. 2008; Metzger et al. 2019), the Terrestrial Ecosystem Research Network (TERN) of Australia (Cleverly et al. 2019), the Chinese Ecosystem Research Network (CERN) (Li Shenggong et al. 2015), and the international Long-Term Environmental Observation Network (ILTER) (Haberl et al. 2006; Mirtl et al. 2018). Within Africa, the establishment of such continental scale networks is not as advanced and there is a marked shortage of observations that cover the variety of natural and human-altered biomes that occur in Africa. This is detrimental in the assessment of the drivers of global change of feedback interactions. This is also of consequence to understanding the contribution of the African continent to global processes, such as its contribution to the global carbon cycle (López-Ballesteros et al. 2018; Nickless et al. 2020).

Long-term Environmental RIs have been noted to have four characteristics or “Conceptual pillars” (Loescher et al. 2022), including long-term time horizon of decades to centuries, the need for in situ observations at different spatial scales across ecosystem compartments of in natura sites, zones, and socio-ecological regions, strong process orientation on the study of ecosystem processes as they respond to both internal and external drivers related to ecosystem and social processes, and the use of a systems approach where abiotic and biotic components interact at different scales and human use of the systems is highlighted. For such a challenging set of characteristics to be met in a southern African setting, strong networking within and between research and academic institutions will be needed, and this would need to be supported by commitments to funding support and investment in human capacity on a time scale of at least a decade.

The fundamental position of Environmental RIs in the scientific value chain is the provision of reliable long-term observational data. This data is then available to support research into the process-level understanding of ecosystem interactions, the development of remote sensing and modeling products, data applications, and the support of national and global policies (Fig. 30.1).

One of the core roles of Environmental RIs is to drive and facilitate further research, through a number of processes including the provision of data for use by national and international researchers, and the provision of a research platform on which local and international researchers can conduct studies and train students, a set of sites and infrastructure to train environmental observation technicians, and a focal area to establish citizen science projects and engagement (Ramoutar-Prieschl and Hachigonta 2020). The research platform nature of many RIs allows for

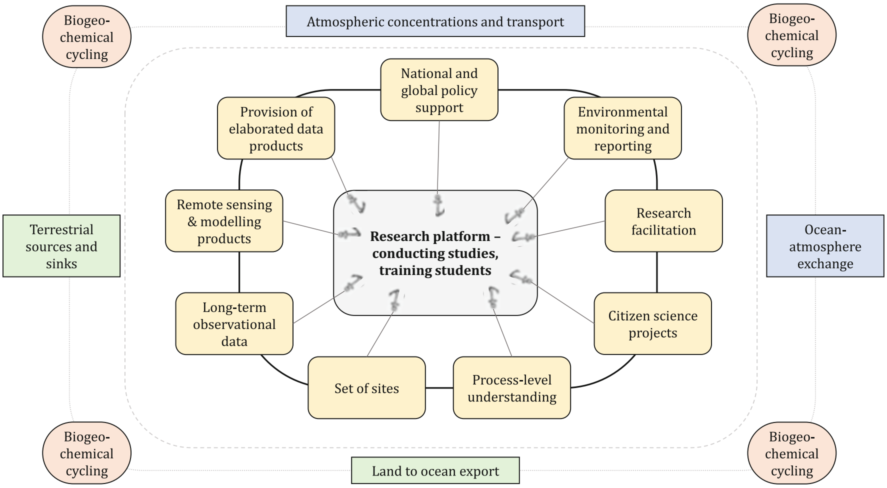

Fig. 30.1 Conceptual diagram illustrating the foundational components of an environmental Research Infrastructure and their interaction embedded in natural processes of global biogeochemical cycling

collaboration with universities and other research organizations to conduct research at the higher levels of the knowledge generation pyramid.

The provision of long-term large-scale data is one of the core functions of environmental RIs. These data can be used in a myriad of ways, including providing essential background and contextual data for research at the RI sites and supplementary observations for national and international routine environmental monitoring and reporting. For example, specific output in terms of the carbon fluxes and ecosystem carbon storage will support efforts to comply with the United Nations Framework Convention of Climate Change (UNFCCC) Paris agreement reporting regulations (Edenhofer et al. 2014). Data from the observations of C exchange and environmental carbon stocks will provide an independent observational-based estimate of the state of annual CO_2 inventories in understudied sections of the Agriculture, Forestry and Other Land Use (AFOLU) sectors, complementary to the traditional activity-based emissions estimates, and it could help in assessing the efficacy of CO_2 mitigation strategies.

The large suite of environmental observations will provide much of the necessary background information and will allow researchers to build on the data being produced in order to develop ecological theory and delve into process-based studies. This in turn will drive theory development, with a stronger emphasis on incorporating processes related to the functioning of the ecosystem in which the RIs operate into the global knowledge base.

By design, RIs offer innovation platforms for the development and validation of novel sensing and data acquisition technologies, instruments, and methods. Examples of this may be the provision of essential validation datasets for researchers to use in the development of remote sensing products for vegetation and ecosystem functioning and the hydrological cycle: for example, evapotranspiration data is essential in validating components of the Earth system and hydrological models and there are limited observation sites on the African continent (Khosa et al. 2019, 2020; Gokool et al. 2020). In the development of novel observational instrumentation, it is necessary to compare the instrumentation to well-established measurement methodologies under field conditions. The availability of RI platforms facilitates such intercomparisons and instrument development.

Moreover, RI Platforms provide a human capacity development facility to train students and young researchers on the use of, and operation of advanced environmental observation instrumentation and provide a facility where undergraduate students can be introduced to the various measurement techniques and operations. The datasets generated through these RIs will provide ample opportunities for postgraduate level students to work with large and integrated data sets in order to develop Data Science competencies and provide scientific value to the operations of the RI. Many parts of the world have a shortage of skilled environmental observation technicians, particularly in areas related to air quality management, hydrological, climate, and biodiversity observations. The operations at the environmental RIs will need to train and develop the skills of junior technicians in maintaining these observation networks. This effectively functions as a pipeline for the development of trained and experienced environmental observation technicians who will be able to move into roles in other spheres of government or industry.

30.3 Status of a Coordinated Terrestrial Environmental Research Infrastructure in Southern Africa

Over the past three decades, a number of land surface atmosphere flux-related infrastructures have developed across the African continent. While these have provided some early indications of the relevant carbon cycle functioning, the density of these installations across the continent is well below the level required to derive globally credible insights, especially given the diversity of ecosystems, land uses, and soil and climatic gradients within this vast region. The first of these were developed through the SAFARI 2000 project (Scholes and Andreae 2000; Scholes et al. 2001; Scholes 2006), which established the Skukuza (South Africa) and Mongu (Zambia) towers (Gatebe et al. 2003). Further observations in southern Africa were established by Veenendal et al. (2004) in Botswana and Brümmer et al. (2008) for Burkina Faso. This individual work was eventually consolidated through the CarboAfrica project (Ciais et al. 2011); however, this has not continued as a coherent integrated network of observation platforms, thereby limiting the interoperability between these measurements, nor has it allowed for the development of a cohort of skilled technicians and researchers. Besides the need for highly skilled staff for installing and maintaining an eddy flux tower as well as large investment costs for instruments, limited implementation is likely due to funding limitations and conflicting priorities for scarce funds. The limited funding is illustrated in that africa receives less than 5% if the global-climate-related funding (IPPC) of which less than half goes to the maintenance of institutions.

At present, there are only seven flux measurement sites on the continent that are reporting to Fluxnet (https://fluxnet.org/), and many of these are out of date (Table 30.1). FluxNet is an international “network of networks,” tying together regional networks of Earth system scientists who use the eddy covariance technique to measure the cycling of carbon, water, and energy between the biosphere and atmosphere.

The challenge of maintaining and growing this capability has constrained the further elaboration of these African RIs, but in 2016, South Africa selected an ecosystem flux RI called the Expanded Freshwater and Terrestrial Environmental Observation Network (EFTEON) as one of its key national investments in environmental monitoring. The roll-out of this program has been a vindication of SPACES and SPACES II investments in similar components, and the landscape scale approaches taken in the SPACES II program, in particular.

With the rising need for developing environmental observation and research capacity in Africa, there have recently been a number of projects initiated. Particular emphasis has been placed on how the in-house skills are developed and how the operational transfer of the infrastructure to local institutions can be accomplished (Bieri et al. 2022). Within the context of highlighting several research activities in

Table 30.1 List of African sites on Fluxnet (https://fluxnet.org/)

Country	Site name	Lat	Long	Ecosystem (IGBP)[M2]	Elevation (masl)	Reference	Time period
Ghana	Ankasa	5.2685	−2.6942	Evergreen broadleaf forest	124		2011–2014
Senegal	Dahra	15.4028	−15.4322	Savanna	40	Tagesson et al. (2015a, b)	2010–2013
South Africa	Skukuza	−25.0197	31.4969	Savanna	359	Scholes et al. (2001), Kutsch et al. (2008), Archibald and Kirton (2009), Williams et al. (2009), Fan et al. (2015)	2001–2016
	Malopeni	−23.8366	31.2137	Savanna	389	Khosa et al. (2020)	2008–2016
	Welgegund	−26.5698	26.9393	Grassland	1480	Räsänen et al. (2017)	2010–2013
Zambia	Mongu	−15.4378	23.2589	Deciduous broad leaf	1053	Gatebe et al. (2003)	2000–2009
Republic of Congo	Tchizalamou	−4.2892	11.6564	Savanna	82		2006–2009

this book, the BMBF program Science Partnerships for the Adaption to Complex Earth System Processes in Southern Africa (SPACES) offered the opportunity to coestablish both equipment and capacity for scientific monitoring that is intended to operate beyond typical project lifetimes, thereby eventually turning into an RI or becoming a part of an already existing network coordinated by a national science institution. With regard to greenhouse gas (GHG) flux measurements, the projects ARS AfricaE (Adaptive Resilience of Southern African Ecosystems, https://ars-africae.org/) and EMS Africa (Ecosystem Management Support for Climate Change in Southern Africa, (https://www.emsafrica.org/) were designed to set up flux towers for continuous observation of CO_2 and energy exchange between the land surface and the atmosphere in managed and (semi-)natural South African ecosystems. An example of the variety of research options provided by operating flux towers over the long term is given by Rybchak et al. (in Chap. 17). The authors demonstrate the effect of grazing intensity and weather on the CO_2 sequestration potential and biodiversity in typical Nama-Karoo ecosystems. In that chapter, they offer useful suggestions and a roadmap for a transfer of project infrastructure and capacity into a longer-term initiative, such as the described RIs.

Recent experience gained during the initial establishment of an RI in the EFTEON network (Benfontein Nature Reserve) revealed the potential to capture the impact of rare extreme events. An extreme wildfire event occurred in the footprint of the flux tower sites, following thorough vegetation sampling and a lead-up period of 2 years of flux measurements. The impact of the fire on the magnitude of the CO_2 Fluxes can clearly be seen in Fig. 30.2 where the flux response before and after the fire can be seen (Fig. 30.3).

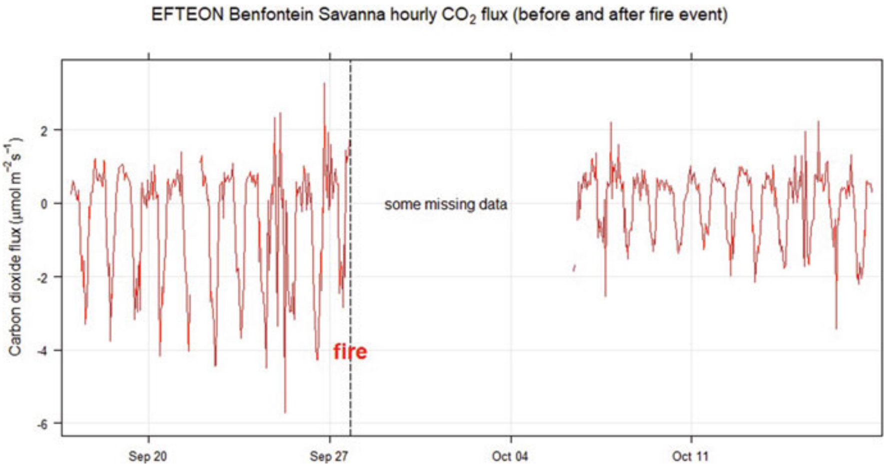

Fig. 30.2 Eddy-covariance flux data for the Benfontein Site before and following the rare fire event of the 28 September 2021

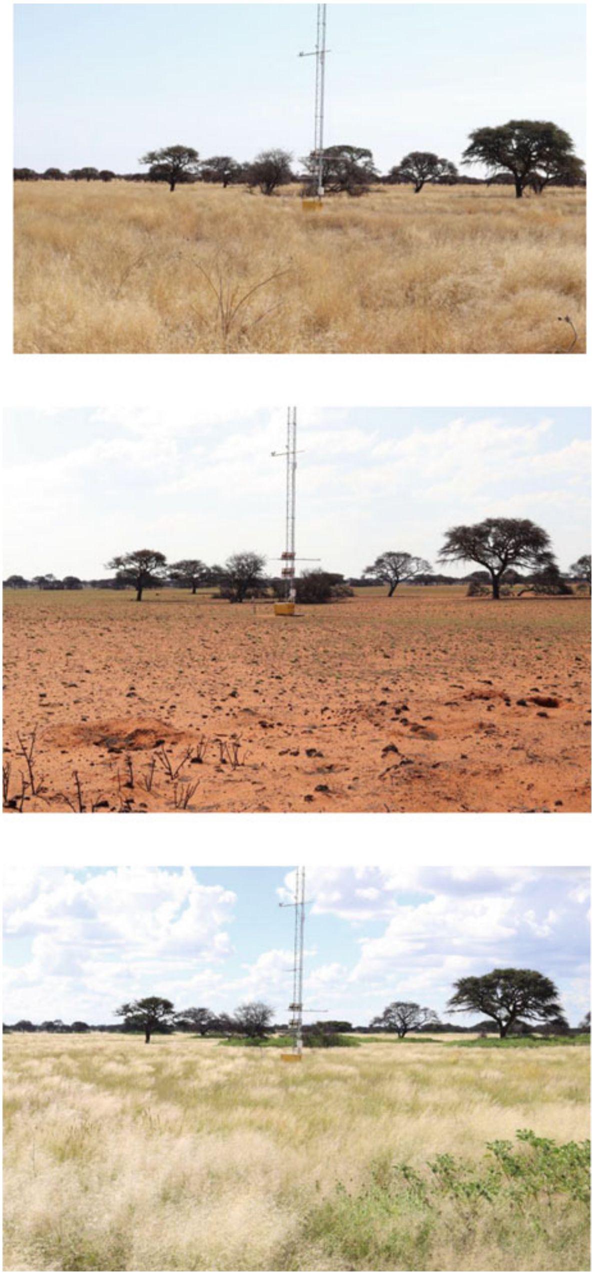

Fig. 30.3 Repeat photographs for the Benfontein Tower, top taken on 24 August 2021 (1 month prior to the fire), middle 6 October 2021 (7 days post-fire) (courtesy Amukelani Maluleke), and bottom 9 March 2022 (at the end of the following growing season)

30.4 Design and Observational Aims of an Environmental RI

Environmental RIs are designed to implement a broad set of observations and allow for the deployment of additional research through projects. This provides the opportunity to study processes through identifying and quantifying the drivers of environmental change and the ecosystem response to those drivers.

In the recent paper on the development of a Global Ecosystem Research Infrastructure (GERI), a number of key features of environmental RIs include that they estimate and provide essential environmental observations (including GHG flux), they adopt a cause and effect paradigm, they implement a focus on understanding spatial and temporal variability in ecological drivers and processes, they have implemented a scaling strategy and a focus on reporting observational uncertainty (Loescher et al. 2022). The initial questions of an environmental RI are important and influence the scope and design, however much of the greatest value in a RI may be derived from opportunistic studies that build on the baseline of the infrastructure that has been set up and operated. Therefore, it is imperative that environmental RIs accommodate researchers and research questions outside the original scope of the design.

In the context of the South African Environmental Observation Network (SAEON), the drivers of terrestrial environmental change that have been considered include

- Weather and climatic conditions, such as long-term climatic change, the impacts of ultraviolet radiation, and hydrological functioning and sediments.
- Changes in atmospheric composition as drivers of environmental change include issues such as an increase in atmospheric CO_2 concentration, changes in the concentration of other atmospheric gases and particulates, the deposition of acidic species to the land and water surface, and changes in nutrient loading (eutrophication) through atmospheric deposition processes.
- Land-use change is an important management option through alteration in the way land is used and valued, and the activities (economic and otherwise) that occur on the land.
- Biotic changes can drive ecosystem processes; classic examples include events such as disease epidemics or pests and the introduction and spread of invasive alien organisms.
- Finally, disturbance events can drive changes in ecosystem structure and function; these might include issues such as fires (see Fig. 30.2), droughts or floods, or other large infrequent events.

The establishment of long-term environmental RIs in the landscape with a detailed record of baseline characteristics to benchmark impact of changes is essential to document and elucidate the magnitude of the drivers. At the same time, the geographic distribution of terrestrial South African RIs allows one to monitor and quantify large-scale ecosystem responses through various thematic studies including inter alia:

- *Biodiversity:* Observations of changes in biodiversity are conducted at four (interrelated) hierarchical levels, with the aim to quantify changes and understand the drivers responsible for observed changes, such as shift in extent and position of biomes, shifts in the extent and position of ecosystems within biomes, changes in biodiversity integrity (richness, composition, and structure) across trophic levels within ecosystems, and changes in the distribution and abundance of species.
- *Biogeochemical cycling and productivity:* Biogeochemical cycling plays a central role in the fate of greenhouse gases and the supply of provisioning ecosystem services; observational foci relate to carbon cycling and storage, primary and secondary production and other biogeochemical cycles, such as (the N and P) cycles.
- *Hydrological functioning and sediments:* These processes play a crucial role in the provisioning and quality of water; observational foci relate to the hydrological flow regime, the quality of the water in the various components of the system, and other impacts such as redistribution of sediments.
- *Fire Regime:* Fire is a key determinant and management tool of the structure and function of many terrestrial biomes, and changes in the fire regime (type, intensity season, and frequency of burning) may have widespread consequences for biodiversity, biogeochemical cycling, carbon sequestration, and hydrological functioning.
- *Social response:* How do societies drive and respond to a changing environment?

These themes highlight, for example, a number of overarching research questions that would be appropriately underpinned by terrestrial RIs:

- *Provisioning ecosystem services:* How do different land use, disturbance regimes, soil fertility, and climate constrain the capacity of South African ecosystems to deliver human needs such as clean water, clean air, nutrition, energy, and a safe, productive, and attractive environment?
- *Biogeochemistry and productivity:* What is the potential for South African ecosystems to sequester CO_2? What is the likely size of the change in carbon pools and fluxes in South Africa as a result of changes in land cover and land use, and what trends are observable? What is their resilience under changing climatic and land-use conditions?
- *Biodiversity:* What are the biodiversity and ecosystem services implications of using South African landscapes in different ways?
- *System variability:* What are the spatial patterns in South Africa of diurnal, seasonal, annual, and interannual ecosystem pools and fluxes of C, water, nutrients, and energy and how are they changing?
- *Ecosystem resilience:* What are the implications of changing biodiversity for the resilience of the ecosystem functioning and ecosystem service delivery, under ongoing climate and land-use change? How do various land management approaches affect ecosystem productivity, efficiency, and sustainability? Which strategies maximize societal resilience to climate extremes and other shocks?

With these considerations in mind, when South Africa embarked on developing an environmental RI for freshwater and terrestrial processes (EFTEON) (Feig 2018), the following principles were considered essential in the infrastructure planning:

Long-term environmental research (LTER) The EFTEON is intended for long-term continuous operation and the primary purpose of the network is to provide long-term environmental data for the national and global research community. Site operations need to undertake measurements and observations that are of value at both the short and long term. As a result, the selected landscapes need to be available for multidecade operation and allow regular (daily) access to the core site by the EFTEON staff and researchers using the platform.

Research Platform EFTEON is intended as a research platform with an open data and open platform use policy. This is in order to facilitate the use of the infrastructure and data by other researchers, both nationally and internationally. The selected landscapes must allow for the use of the facilities by multiple researchers or partners from multiple research organizations (managed by rules of site usage and selected via evaluation of submitted project proposals).

Spatial diversity coverage Landscapes selected for the network are to represent South African biomes and human-transformed ecosystems and their embedded aquatic systems, this design concept places a focus on lived-in landscapes and landscapes in transition (driven by climate change or land-use change). The selected landscapes shall enable the long-term observation of the coupled terrestrial/aquatic systems in the face of change and shall include a number of relevant land uses, such as conservation, urbanization, agriculture, post-mining rehabilitation, etc.

Historical observations and experimental datasets Incorporation of existing research and linking to existing socio-ecological datasets is a strong focus of the EFTEON design concept. The availability of long-term existing social-ecological and Earth system data sets would be considered an advantage in the selection of the landscapes. There is a strong emphasis on data archiving and data archaeology to ensure long-term availability and continuity of datasets.

Experiments and manipulations The use of experiments and manipulations provides considerable insight into environmental processes. The landscapes 2*must* offer the opportunity to implement and sustain appropriate experiments, at a scale matched to the scales of key processes, to help elucidate process-level understanding of ecosystem changes. They could include things like disturbances, irrigation or fertilization, withholding or adding herbivores, excluding fire or increasing fire frequency. These may be experiments undertaken and managed by the EFTEON staff or those experiments operated by landscape users from one or many institutions (managed by rules of site usage and selected via evaluation of submitted project proposals). Landscapes that *only* consist of strictly protected land covers failed this principle.

The general situational characteristics of the landscape These include the opportunity to observe the coupled terrestrial and aquatic (fluvial and groundwater) systems, the opportunity to observe social-ecological systems in the South-African developmental context, the opportunity to act as a National RI allowing and encouraging the use of these landscapes by multiple research organizations (both nationally and internationally), and spatial coverage across important biomes.

The landscape location in the face of Global Change This focused on the presence of representative near-natural land cover (i.e., land uses where most key ecological processes are autonomous, rather than imposed by human agents) and modified land uses (e.g., cultivation, plantation, urbanization, mining, etc.), the climatic impacts (e.g., anticipated climate change hotspots), or gradients, which can be optimally observed (altitudinal gradients/projected climate change hotspots), transition zones between biomes, which occur within the proposed landscape, and the expected development pathways for the landscape (including any evidence or published plans for regional developments or other evidence as may be appropriate).

Logistical and operational suitability of the core and associated sites This includes, inter alia, security of tenure for the operations, particularly for the core site, existing facilities for hydrological observations such as gauging weirs, dams, testing boreholes et cetera, suitability for the deployment of micrometeorological observations (i.e., the assumptions of horizontal heterogeneity and steady-state conditions are met), any existing long-term observations or experiments, including details of the research, availability of the data, data users and key findings, and the availability of office facilities for staff and guest researchers.

Stakeholder analysis This includes an in-depth analysis of the relevant stakeholder communities within the nominated landscapes, including land owners and land custodians, communities and residential areas, engagement with relevant authorities or resident groups, and assessments of current land uses.

30.5 Toward the Regional and Multidisciplinary Integration of Terrestrial Biogeochemical Research Infrastructures

In order to meet the long-term environmental research and monitoring needs, a number of authors have suggested the concept of essential variables. Essential Climate Variables (ECVs) were first defined by GCOS as “Physical, chemical or biological variables or groups of linked variables that critically contribute to the characterization of the Earth’s climate” (Reyers et al. 2017; López-Ballesteros et al. 2018). A number of organizations have published lists of essential variables, including the Global Climate Observation System (GCOS) for ECVs (WMO 2015), the Group on Earth Observations Biodiversity Observation Network (GEOBON) for Essential Biodiversity Variables (EBVs) (Guerra et al. 2019), the Ecosystem and Socio-Ecosystem Functional Types project (ESEFT) for essential social-ecological functional variables (ESEFT 2019) and the EU funded SEACRIFOG project (Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations, reference) has published essential variables for GHG observations in Africa. The Global Climate Observation System (GCOS) stipulates a suite of 54 essential climate variables: these are divided into the components for the land and atmosphere (reference). GEOBON lists 6 classes of essential biodiversity variables with 21 variables identified, the classes include genetic composition, species and populations, species traits, community composition, ecosystem function, and ecosystem structure (Guerra et al. 2019). ESEFT lists the Essential Social-Ecological variables in classes (Components and Functional Dimensions): the social system, the ecosystem, and interactions (ESEFT 2019).

The availability of long-term observations aligned to the applicable essential variables mentioned above is of crucial importance in the development of, and the validation of, ecosystem models and remote sensing products. A prime example of a closely linked relationship between the flux observations infrastructure and the modeling community can be found in the link between Oz Flux and the CABLE model development team (Kowalczyk et al. 2006; Haverd et al. 2013, 2016a, b; De Kauwe et al. 2015). In South Africa, this same dynamic has been demonstrated with the flux measurements at Skukuza and the CSIR CABLE development team (Khosa et al. 2019, 2020).

A wider fitting frame for the SPACES projects and the above-mentioned activities form the BMBF-initiated and funded science centers, that is, SASSCAL, and its West African sister organization WASCAL. SASSCAL is the Southern African Science Service Centre for Climate Change and Adaptive Land Management, a joint initiative of Angola, Botswana, Namibia, South Africa, Zambia, and Germany in response to the challenges of Global Change. The center understands the role of science as a service to societies that are most severely affected by climate change and to provide decision-makers with evidence-based results and advice. Hence, SASSCAL may act as a facilitator for supporting research infrastructures as it is conceptualized and operationalized to complement the existing research and capacity development and research initiatives in the region. Very similar objectives, although a bit more tailored to the regional conditions, are pursued by WASCAL, the West African Science Service Centre for Climate Change and Adaptive Land Management, thereby likewise offering opportunities for supporting RIs in the long term. Cooperation within all these activities and among the several groups involved is a key aspect for the success of the work and for achieving the specific aims of the infrastructure. Critical issues like unbalanced resource distribution, paternalism, or misuse of good scientific practices have been observed in the past and must be combatted in all present and future endeavors. A review of North–South relationships and recommendations on how to avoid mistakes of the past are given in Chap. 31 by Lütkemeier et al.

In South Africa, the South African Environmental Observation Network (SAEON) has been tasked with the development of long-term environmental in-situ research infrastructure and the data management facilities that support such research. Recently three Research Infrastructures have been awarded to SAEON:

these include the Expanded Freshwater and Terrestrial Environmental Observation Network (EFTEON), the Shallow Marine and Coastal Research Infrastructure (SMCRI), and the South African Polar Research Infrastructure (SAPRI). These RIs all focus on facilitating interdisciplinary environmental research. In the terrestrial sphere, the EFTEON RI is establishing six research landscapes, with a thematic focus on (1) *Biogeochemistry*, including eddy covariance measurements and atmospheric deposition in order to quantify the exchange of CO_2, nutrients, and energy between the land surface and the atmosphere, (2) *Biodiversity*, to quantify the abundance, diversity of a diverse range of biological communities, including vegetation, avifauna, invertebrates, and others, (3) *Hydrology*, with a focus on quantifying water quantity and quality and the movement through the landscape, (4) *Climatology and Atmospheric Processes*, to establish a detailed climatological record and understanding of atmospheric chemical exchanges, and (5) *Social Ecological Systems*, to gain an understanding of how humans interact with and make decisions relating to the ecosystems in which they operate (Feig 2018).

Similarly, the SMCRI is developing infrastructure across four Sentinel sites; these include (1) the Algoa Bay Site, located around Gqeberha (Formally Port Elizabeth), (2) the Two Oceans Sentinel Site, around Cape Town, (3) the Natal Bight Sentinel Site, located north of Durban, and (4) the Marion Island Sentinel site in the South Indian Ocean. SMCRI is developing a number of research platforms that include airborne remote sensing, a Coastal Biogeochemistry Laboratory, acoustic telemetry arrays, and marine remote imaging. In addition to the science platforms, they operate a number of platforms that facilitate the work, including a Coastal Craft Platform, a Hyperbaric Chamber, and a Science Engagement Platform.

The SAPRI is in the early stages of development and will facilitate research in the Southern Ocean and the Antarctic.

30.6 Impact of a Research Infrastructure and Its Assessment

Setting up an environmental RI like outlined above requires comprehensive coordinated effort and resources including a variety of communities. Expectations from operators, scientists, the private and the public sector, and other stakeholders may vary with individual perspectives and aims. Therefore, it is important to understand and assess what impact on the environment, science, and society a fully functional RI is able to cause.

Broad types of impact usually fall under one of the following categories:

- Science and technology
- Social impact
- Human capital impact
- Economic and innovation impact

For environmental RIs, these can be more specifically tailored to the main strategic objectives of the groups involved. As an example, ICOS has undergone an impact assessment in 2018 where key indicators were defined along these strategic lines (Heiskanen et al. 2021):

- Producing standardized high-precision long-term observational data
- Stimulating scientific studies and modeling efforts and providing a platform for data analysis and synthesis
- Communicating science-based knowledge toward society and contributing timely information relevant to the greenhouse gas policy and decision making
- Promoting technical developments
- Ensuring high visibility of the RI

It is then possible to fully grasp the RI impact at various levels by evaluating specifically designed indicators such as, but not limited to, lengths of the acquired data sets, degree of harmonization of the data sets, number of related articles published, media appearances, provision of policy-relevant data, publications used outside the scientific domain, new knowledge generated on carbon sources and sinks, investments mobilized by the RI, and application of data in globally leading models. Two further, highly important indicators are the improvement of long-term decisions through enhanced political discourse based on evidence and a reduction of damage by extreme weather events and through more effective climate mitigation policy.

30.7 Conclusion

In this chapter, we aimed to highlight the importance and value of key Environmental RIs focused on land surface–atmosphere interactions, with relevance for the carbon cycle and associated biogeochemical functioning, and challenges inherent in building and maintaining these efforts.

It is clear that the presence of long-term environmental RI provides a strong opportunity for furthering a wide range of environmental research. In some cases, these observations can be undertaken by the RI itself; however, the nature of the questions to be asked and the techniques that may be employed in these RIs advocate for the role of the RIs acting as a research platform where they provide the long-term high-quality baseline observations, while other research entities such as universities, science councils, and others build off of the base that the RIs create and build the knowledge base through short-term projects that either elucidate process level questions, the link between fields in a multi- or interdisciplinary manner, or utilize different or novel observation techniques to fill in the observational gaps left in the initial RI design.

Studies presenting a synthesis of available methods and data for estimating the African carbon budget stressed the associated large uncertainties due to a very limited number of long-term observations (Ciais et al. 2011). The contribution of Africa to the global carbon cycle is characterized by its low fossil fuel emissions, a rapidly increasing population concomitant with cropland expansion, potential degradation, and deforestation. Published estimates are in the range of −0.6 to −0.2 $PgCyr^{-1}$ associated with uncertainties in the same order of magnitude indicating a small net sink of carbon for the whole African continent (Valentini et al. 2014). Coordinated endeavors such as environmental RIs will help reduce the large uncertainties in the continental-scale carbon budget. In this chapter, we briefly summarized the development of these efforts over the last three decades and, from this perspective, discussed how their successful maintenance and further implementation may turn such RIs into important anchor points for long-term environmental scientific work in support of environmental sustainability, national commitments under selected international policy discussions, and societal well-being.

Humanity currently faces a number of global crises, including the impact of changes in the climate, resulting in droughts, floods, fires, and other extreme events. These crises are significantly stressing the lives and livelihoods of the vast majority of humanity. The societal response to these events is dependent on the availability of scientific knowledge and its effective transfer to governance structures, industry, and the broader society. In order to effectively address these challenges, large amounts of data are required across a broad range of intersecting disciplines that are available for analysis by the scientific community. Research Infrastructures have the ability to act as anchor points in the provision and utilization of this data.

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