Technical article

Integrating project-based infrastructures with long-term greenhouse gas observations in Africa

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Abstract

There is a lack of long-term greenhouse gas (GHG) measurement infrastructures in Africa. This limits our understanding of the temporal dynamics of the biosphere-atmosphere exchange of carbon in response to climate change. Where relevant infrastructures have been established in externally funded research projects, they have often not been successfully transferred to local institutions at project termination, nor maintained in the long term. This leads to loss of capacity and continuity in primary data. We describe a collaborative approach where eddy-covariance (EC) towers for continuous long-term observation of carbon dioxide and energy fluxes were constructed under two consecutive German-funded research projects and designed to complement existing South African infrastructures. They will be transferred to partner institutions at project termination, supported by deliberate capacity building actions for long term sustainability. Joint activities were implemented to i) strengthen technical expertise for infrastructure maintenance, ii) introduce a new generation of academic scientists to the topic, iii) co-develop a training concept to enhance local capacity to continue teaching the topic, iv) improve the uptake and use of data by the research community, v) improve data use and access by stakeholders, and vi) facilitate knowledge exchange between institutions. Co-designed activities included training, apprenticeships and knowledge exchange, student exchange, co-supervision, and public outreach. Following a similar model in international research projects could significantly benefit 1) national capacity for emission inventories, 2) development of long-term GHG observation networks, and 3) the global scientific community via improved availability of data. While we specifically focus on a network of GHG observations, the principles are applicable for the infrastructure to observe other surface/atmosphere exchange processes or other long term observational infrastructure.

Keywords

capacity development, eddy covariance, research collaboration, climate change, South Africa

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Authors’ contributions

All authors contributed to the study conception, design and methodology. The first draft of the manuscript was written by MB and all authors participated in revisions. In addition, JdT, GF, NEM, BM, MM, GFM, SM, GvM and CB were responsible for funding acquisition, and MB and CB for project administration. CB acted in a supervisory role and as project leader.

Introduction

The African continent makes a relatively small contribution towards the global carbon emissions from fossil fuels, however its emissions from land use and land-cover change are significant (Davis-Reddy and Vincent 2017; Kutsch et al. 2011; Valentini et al. 2014), and its vast tropical and subtropical ecosystems contribute significantly to the global carbon and water cycle (Ciais et al., 2011; Hickler et al. 2005; Scheiter and Higgins 2009). Africa was suggested to act as an overall small sink for atmospheric carbon (Valentini et al. 2014), but the estimations are uncertain due to a lack of long-term greenhouse gas (GHG) observations in many of the important ecosystems (López-Ballesteros et al. 2018; Quansah et al. 2015). Eddy Covariance (EC) towers are used to measure fluxes of trace gases, water vapour, and energy between the land surface and the atmosphere on a continuous basis. In combination with data collected by ecologists, remote sensing scientists, hydrologists, and other disciplines, flux measurements can be used to validate vegetation or ecosystem models and to understand the patterns of carbon and water fluxes between the biosphere and atmosphere. At the larger scale, coordinated tower networks can be used in quantifying the response of biomes to the impacts of climate change and land use, and in the estimation of regional carbon budgets when coupled to larger-scale climate or ecosystem models.

Most EC measurements in Africa have been associated with field campaigns of research projects, and as such, have been of limited duration (Ago et al. 2014; Brümmer et al. 2008; Quansah et al. 2015; Tagesson et al. 2015; Tagesson et al. 2016; Veenendaal et al. 2004). Collaborative international research initiatives on land-atmosphere interactions include for example the Southern African Fire-Atmosphere Research Initiative 1992 (SAFARI 92), the Southern African Atmosphere Research Initiative 1994 (SAFARI 94), and the Southern Africa Regional Science Initiative (SAFARI 2000), along with the Miombo network (Desanker et al. 1997) and several collaborative efforts by e.g. the Max Planck Institute. These collaborations have contributed significantly to the generation of new knowledge and helped to spin off further initiatives. Still, a very limited number of the established EC towers have continued long past the original project that established them. A prime example of a successfully continued, active site is the Skukuza flux tower; this is one of several sites established in 2000 as part of the SAFARI 2000 campaigns (Scholes et al. 2001; Swap et al. 2003). It is still operational and maintained by the Council for Scientific and Industrial Research (CSIR) (Khosa et al. 2019).

López-Ballesteros et al. (2018) recorded several inactive EC stations associated with past projects in their recent assessment of GHG monitoring infrastructures in Africa. This could be partially attributed to the costly maintenance of the towers and the associated demand of specialist technicians, but also to the fact that projects are often not co-designed with local partners, and sustainable capacity building activities are not sufficiently incorporated in project planning.

The abandonment of project-related EC towers leads to loss of opportunity to strengthen national infrastructures in target countries, and also loss of globally valuable long-term data. Long-term data records through networks of measurements are important for understanding complex ecosystem processes including the extent to which the land contributes towards being a carbon source or sink (Baldocchi 2014). The lack of long-term data is particularly problematic in African ecosystems, such as shrublands and savannas, because these systems are highly dependent on rainfall and periodic fires. However, these environments experience large interannual differences in precipitation and disturbance regime, and hence require long timeseries to understand trends (e.g. Ahlström et al. 2015; Brümmer et al. 2008; Brümmer et al. 2009; Davis-Reddy and Vincent 2017; Merbold et al. 2009; Veenendaal et al. 2004).

We describe one route by which an externally funded research project in Africa has attempted to address these limitations by better implementing long-term capacity building and partnerships with EC tower infrastructures. We present our approach in which site selection was designed to complement national infrastructure and align with national level processes and in which strengthening the relevant technical and academic capacities received equal attention along with the production of research outputs and suggest that such an approach could be used by other similar, externally funded research projects as well. We describe the specific South African-German research project and the main collaborating institutions, the evolution of research, knowledge generation and capacity building activities, and their value and impact within the South African applied scientific landscape. Finally, we briefly discuss the limitations of the approach and suggest general operational steps for projects that may be of use in similar future initiatives.

Project collaboration and design

South Africa hosts the majority of currently operational EC towers within Africa (López-Ballesteros et al. 2018) (Table 1). The Skukuza tower in the Kruger National Park (KNP) is the longest running African EC tower, in operation since 2000 (Feig et al. 2017). The Skukuza tower, along with another EC tower within the KNP, the Malopeni tower at Phalaborwa, operational since 2008, are maintained and operated by the CSIR. These towers have been used for numerous studies from local level physiological studies (e.g. Kutsch et al. 2008) to facilitating model (Khosa et al. 2020; Martínez et al. 2020) and remote sensing development (Khosa et al. 2019; Ramoelo et al. 2014) as well as emission inventory development (Feig 2008).

The South African Environmental Observation Network (SAEON) also runs operational towers with long-term stations established in 2016 at Cathedral Peak in the Drakensberg and in 2019 at Jonkershoek - both part of the Long-Term Ecological Research (LTER) network. SAEON is currently engaged with the development of a long-term landscape level research infrastructure (RI) in the process of establishing six long-term RI sites across South Africa (Feig 2018). The RI, termed the

Extended Freshwater and Terrestrial Observation Network (EFTEON) follows a landscape-based approach that attempts to link flux measurements at selected points representing utilized and relatively less utilized sites to a wide range of environmental and social measures, with a special focus on links to freshwater systems.

The South African-German research project 'Adaptive Resilience in Southern African Ecosystems' (ARS AfricaE) (2014-2018) installed three additional EC towers in South Africa through a collaboration of the German Johann Heinrich von Thünen Institute and local partners, the University of Venda and the Grootfontein Agricultural Development Institute (GADI) (Figure 1; Table 1). Furthermore, one additional tower, Agincourt, was installed by the CSIR during project implementation. The location and site design were chosen to complement the existing tower network in South Africa and appear to have informed the developing strategy for the EFTEON RI, given that several local partners were variously engaged in this cluster of activities (see Feig, 2017).

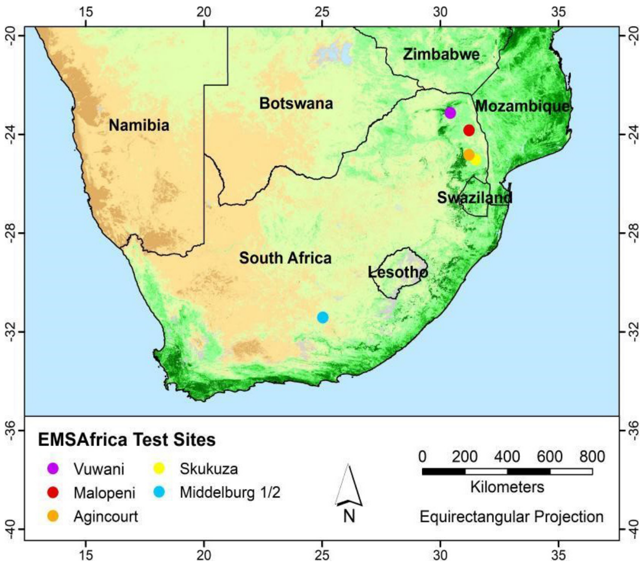

Figure 1: *The field design of the ARS AfricaE/EMSAfrica projects. Skukuza and Malopeni represent the towers that were part of the South African monitoring infrastructure, Agincourt, Vuwani and Middelburg towers were built during the ARS AfricaE project.*

The field design of ARS AfricaE and its follow-up project 'Ecosystem Management Support for Climate Change in Southern Africa' (EMSAfrica, 2018-2021) is based on six research sites, each with an EC tower as the central infrastructure. The sites are situated along a precipitation gradient, with paired sites allowing comparison between a natural-like environment with a human-modified site. This makes it possible to begin quantifying the separate and combined impacts of land use and climate on the structure and function of ecosystems. Importantly, this approach complements the previously existing tower network, where most sites were located on natural ecosystems.

Following the multidisciplinary, multi-scale approach of EMSAfrica, EC flux data are linked with a variety of on-site measurements, such as ecophysiological experiments, and coupled with remote sensing data to produce models on Southern African vegetation patterns and carbon balance (for a more detailed description of the approach, see Berger et al. 2019).

Capacity building approach and activities

In their recent assessment of an integrated strategy for an African GHG observation infrastructure, Ndisi et al. (2020) emphasise that investments in infrastructure form only one part of the process. The development of human resources capacity and long-term infrastructure maintenance strategies are of equal importance for successful operation (Ndisi et al. 2020). In this context, we define capacity building as an approach to develop

Table 1: *Summary of the currently operational long-term eddy covariance flux towers in South Africa.*

Name	Location	Operational since	Approach	Operated / established by
Skukuza	-25.02°, 31.49°	2000	Savanna / conservation area	CSIR
Malopeni	-23.83°, 31.21°;	2008	Savanna / conservation area	CSIR
Welgegund	-26.56°, 26.93°;	2010	Grassland / commercial agriculture	North-West University
Cathedral Peak	-28.98°, 29.24°	2012	High-altitude grassland	SAEON
Middelburg (1 and 2)	-31.52°, 25.01°	2015	Nama Karoo / paired setup, heavy and lenient grazing	GADI/ ARS AfricaE through Thünen Institute
Agincourt	-24.82°, 31.21°	2016	Savanna / communal area	CSIR
Vuwani	-23.14°, 30.43°	2016	Savanna / communal area	University of Venda / ARS AfricaE through Thünen Institute
Benfontein Savanna	-28.89°, 24.86°	2020	Kimberly Thornveld, paired setup, transition from Savanna-like to Nama-Karoo-like vegetation	SAEON
Benfontein Nama-Karoo	-28.86°, 24.84°	2020	Kimberly Thornveld, paired setup, transition from Savanna-like to Nama-Karoo-like vegetation	SAEON

long-term skills and commitment towards the sustainable employment of the EC infrastructures, data, and applications. Ika and Donnelly (2017) define 'conventional' means of capacity building as training, workshops, and technical advice. Capacity building conducted in association with research projects has been criticized for overemphasising the conventional view, often reduced to just training (e.g. Potter and Brough 2004).

Following Ika and Donnelly's (2017) classification, advanced forms of capacity building relate to fostering increased engagement and dialogue between stakeholders; facilitation of processes and networking belong to this type of capacity building. The key conditions to successful capacity building were proposed to include well-established commitment from stakeholders, successful collaboration, and aims based on stakeholder needs (Ika and Donnelly 2017).

Our attempt was to design the project and its capacity building activities as a collaborative effort, designed primarily to address locally identified priorities regarding training needs, data accessibility and use, and the strengthening of international collaborations and development of new projects. We used a range of conventional and advanced forms of capacity building, with strong collaborations between institutions and individuals at the centre of the approach. Our aims were to:

1. Strengthen the technical expertise required for the maintenance of the EC towers in the long term;
2. Introduce a new generation of academic students to the topic;
3. Strengthen the local capacity to teach and coach the topic;
4. Improve the uptake and use of EC data by researchers working on relevant fields;
5. Improve the access and use of the infrastructures and data by the various stakeholders;
6. Facilitate knowledge exchange between institutions in Germany and South Africa, including co-supervision of students and the development of joint scientific publications.

In the following subsections, the specific activities are described in more detail.

Training workshops on Eddy Covariance Flux Measurements

The concept of a five-day intensive course on EC flux measurements was initially based on demand defined at a 2018 meeting of the South African 'Carbon Connections' community, i.e. researchers and stakeholders working on the topic of carbon exchange. Following the recommendations, the development of the technical capacity to operate EC towers, as well as an improved capacity of researchers and data scientists to manage and utilise data were defined as priorities. The course concept was further developed based on experiences gained via a land-atmosphere interactions training workshop organised by the global research initiative 'Integrated Land Ecosystem Atmosphere Processes Study' (iLEAPS).

Funding for the three planned courses was secured via the German Ministry of Education and Research (BMBF) programme for training and knowledge exchange (coordinated by the EMSAfrica project) with significant in-kind support in personnel, equipment and the provision of facilities by the South African partners. The course aims were to enhance participants' skills and understanding of: 1) EC theory including fetch area requirements and experimental design, via lectures and practical examples; 2) operation and function principles of equipment, such as the gas analyzer and sonic anemometer, via hands-on demonstrations; 3) how to set up and operate an EC system, via hands-on sessions and demonstrations as well as Q&A sessions at a tower site; 4) technique and relevance of ancillary measurements, such as soil chamber measurements and meteorological measurements, via hands-on sessions; 5) how to process raw flux data, via demonstrations and hands-on sessions; and 6) various ways of applying EC systems and data in research projects and models. The aim was to link the mechanistic understanding to the drivers of ecosystem and atmospheric processes and drivers at a larger scale, and to increase the participants' understanding of how they can take advantage of the data in their own projects.

The course advertisement was distributed online (www.spaces-training.org) and via the networks of the collaborating institutes, as well as the project partners and stakeholders. Early-career researchers and technicians applying for the training were asked to describe how they used or were planning to use EC measurements or data in their project, and this information was used in tailoring course content. The aim was to have a combination of students planning their research career, technicians needing to strengthen their skills, and young researchers of different fields needing to understand the production of the data, to be able to apply it in their research. All course materials, background materials and additional resources were made available to the participants, many acting as lecturers and teachers at their home institutes in southern Africa.

The first of the three workshops was realised as a Winter School in 2019 under a shared academic leadership of SAEON and the Thünen Institute, with strong input and several co-lecturers from the CSIR, and contributions from a variety of collaborating universities and research institutes in southern Africa. It was hosted by the University of Venda at the Vuwani Science Resources Centre. The course was attended by 25 students from a number of southern African countries, including Angola, Botswana, Namibia, Zimbabwe and South Africa. It was realised in collaboration with the EU-African project 'Supporting EU-African Cooperation on Research Infrastructures for Food Security and Greenhouse Gas Observations' (SEACRIFOG) and the regional initiative 'Southern African Science Service Centre for Climate Change and Adaptive Land Management' (SASSCAL). Consequently, the course incorporated a strong overview of the status of overall GHG measurements in the African continent and climate adaptation and mitigation.

The second workshop was initially postponed due to the COVID-19 pandemic, and finally organised as an online intensive course on the 24.-26.11.2021. The course was again co-designed by the Thünen Institute, SAEON and CSIR partners, with invited lectures from a variety of South African and German colleagues. A total of 25 participants, representing eight different countries, attended the course, which had an even stronger emphasis on data processing and analysis. The third course (drafted for 2022) intends to incorporate a stronger input from the multidisciplinary research community, ecosystem modellers, earth observation scientists and others applying EC data into their research.

Knowledge and staff exchange

The collaboration between the Thünen Institute and partners from CSIR, SAEON and the University of Venda benefited from regular knowledge exchange and joint field visits. For the three EC towers built by the Thünen Institute together with South African partners during the project ARS AfricaE, maintenance and data transfer were conducted by the local partners with regular visits from the German team. This was in conjunction with on-site training, maintenance manuals and regular exchange, and in the case of the University of Venda, also student apprenticeships.

Southern African researchers' and students' exchanges were made possible during the EMSAfrica project via a grant programme CaBuDe (Capacity Building and Development) of the DAAD (German Academic Exchange Service), funded by the BMBF. These included four-year grants given to doctoral researchers to complete their degree in Germany, sandwich degrees for co-supervised doctoral programmes, as well as shorter grants for BSc and MSc students and varying lengths of research visits. Despite delays in the programme caused by the global COVID-19 pandemic, we used some grants for collaboratively supervised doctoral and MSc projects, as well as to strengthen collaborations and specific capacities of individuals through visits to German academic institutes. For example, two doctoral students working full-time on project-relevant topics in South Africa and Germany were both co-supervised by a South-African-German supervision committee, and field trips and research exchanges were organised both ways (see www.emsafrica.org). In addition, several research and grant proposals were initiated as a direct result of the collaborations and expanded networks between Germany and southern Africa.

Infrastructures such as EC towers can act as valuable anchor points to attract further research initiatives and projects. The Middelburg site has gained significant attention from collaborating institutions during the EMSAfrica project, both locally and internationally, and is now hosting several short- and long-term projects as a 'regional hub' of experimental research. The University of Stellenbosch has graduated one MSc student and has two further MSc students working on the site and has assigned two post-doctoral staff to provide analytical support over the past four years, funded by the South African National Research Foundation (NRF). The EMSAfrica project is also working together with local land-users through stakeholder workshops to explore ways in which its data and products can be useful to either the livestock and/or game industry, or the conservation organisations and researchers in the area. The data collected via the EC towers helps to assess the impact of livestock grazing on carbon balance in the semi-arid ecosystems (Rybchak et al. 2020) and is of long-term interest to the planning of sustainable management practices. First results, including broader discussion on land-use history and management implications, are published as a case study in an up-and-coming handbook on Southern African ecosystems, especially aimed at policy makers and those working on the science-policy interface (Rybchak et al. 2022).

All data from the EC towers hosted by the Thünen Institute are made accessible via the Open Access Data Centre (OADC) of SASSCAL (https://www.sasscal.org/prototype-oadc-open-access-data-center/) and FLUXNET (https://fluxnet.org/). Ancillary data measured by the EC towers, for example radiation and soil moisture, are used in various student projects at South African universities.

Stakeholder engagement and long-term sustainability

EMSAfrica is a multidisciplinary project, with a diverse group of stakeholders in research, governmental and non-governmental institutions in South Africa. The stakeholders are incorporated into steering the project's outputs to better contribute to sustainable land management and climate mitigation efforts and processes in South Africa via workshops and discussions. The main aim of stakeholder work at this level is to enhance knowledge exchange, to strengthen the use of existing infrastructures and resources, and to better integrate the data products into policy and decision-making frameworks.

As form of public outreach, EMSAfrica also engages school and community educators via the collaboration with the University of Venda. Vuwani Science Resource Centre, where one of the EC towers is located, is a flagship community outreach project of the University of Venda. Climate change and renewable energies are the centre's focus areas, and the EC tower adds to its uniqueness as an educational site to both students and the public. At this site, a request was presented by the site manager to produce additional EC tower information materials, for increasing the general awareness of the rural learners and community in the Limpopo province in climate change impacts and research. As a result, information posters explaining the EC tower's principles of function and links to climate change research were produced. Furthermore, a GHG demonstrator – a glass chamber with miniature landscape and an interactive "blow-in CO_2" component demonstrating the impacts of increasing GHGs – along with an explanation board, was constructed by the German team engineers as part of the physical demonstrations at the Vuwani exhibition hall.

The EMSAfrica project preceded the development of the EFTEON Landscapes, a National Network of environmental research infrastructure sites, where the site selection was based on proposals put together by research consortia (https://efteon.saeon.ac.za/landscapes/). The connections made during the EMSAfrica program acted as nodal points for the development of strong proposals, and while not all of these were successful, the networks, and thinking that went into the development of these proposals is likely to facilitate further research engagement in the future. When EMSAfrica ends in 2022, two of the recently built EC towers in Middelburg are planned to be transferred to the newly launched (2021) Stellenbosch University School for Climate Studies. This interdisciplinary academic structure seeks to link specialist skills and approaches across multiple departments and faculties to provide a platform for integrated research and training at post graduate level that is relevant to climate variability and change. An institution such as this School could integrate the infrastructures and equipment into its program and continue to develop the data-intensive, long-term research in landscape level functioning and its relevance to landscape management and policy development. The Vuwani EC tower will be transferred to the ownership of the University of Venda, remaining at the Vuwani Science Resources Centre, where it will strengthen the existing climate change measurement infrastructures, with planned research collaboration with the Stellenbosch University School for Climate Studies and technical maintenance support from EFTEON.

It is expected that the legacy from these projects will be felt in the South African Environmental Research community for the foreseeable future. The flux towers that have either been established or supported through these projects will continue providing essential long-term data in a data sparse region; the impetus for their establishment was strongly driven by these projects. In terms of the training, many of the technical staff that will continue the management of these infrastructure will

Figure 2: *Summary of the key activities at each project stage from project planning to the transfer of infrastructures to local collaborators at project end.*

have gone through the EMSAfrica training workshops, and we are beginning to see the establishment of a cohort of technically capacitated researchers able to utilise these data in South Africa. This will feed into the long-term research direction in South Africa.

The connections that have been made through these projects continue. A Memorandum of Understanding was signed between SAEON and the Thünen Institute; it facilitated exchange of students and staff, as well as the submission of joint proposals for funding calls, with plans to continue such activities also in the future.

Limitations

It must be noted that the structures and organisations present in South Africa are already well developed, which greatly improves the likelihood of success of efforts such as those described here. A key issue in maintaining tower operability after project end is the continuity of funding. As described under Section Stakeholder engagement and long-term sustainability, South Africa's recently established long-term research platforms, their associated technical personnel and further research collaborations, will be crucial in the long-term sustainability of the legacy EMSAfrica project infrastructure.

Generally, little information is available on the success of capacity building for GHG observation infrastructures in the least developed countries with poor infrastructures (see e.g. Umemiya et al. 2020). Recent initiatives, such as the integrated strategy for African GHG observation infrastructure (Ndisi et al. 2020) can help guide collaborative efforts. In the case of the EMS Africa efforts, early planning of the larger research program (SPACES) did involve technical German-South African discussions at inter-ministerial level, as well as engagement with academic leaders at least in South Africa, as the agendas were shaped. It remains to be seen if this will permit the legacy EMS Africa infrastructure to continue to serve its purpose.

Conclusions and recommendations

There is a clear urgency to develop long-term GHG observation infrastructures and technical and academic capacities related to climate change in Africa (Niang et al. 2014; Ndisi et al. 2020). We suggest that international research projects should better align their aims with building national capacities to conduct emission inventories, even when this is not the primary aim of the project. Long-term planning of infrastructures such as EC flux towers as part of regional observation networks would have a major role in helping the scientific community answer the large unanswered questions on the fluxes of carbon and water in African ecosystems. Open sharing of data and building collaborative partnerships would increase the impact and sustainability of projects and could best spur the careers of young researchers in all collaborating countries.

We summarize our collaborative approach in Figure 2, by identifying a "check-list" of key activities at the different project stages. We suggest that such a list could help other third-party funded research projects with the combining of short-term aims with sustainable outcomes.

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