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Linking scales and disciplines: an interdisciplinary cross-scale approach to supporting climate-relevant ecosystem management

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Abstract
Southern Africa is particularly sensitive to climate change, due to both ecological and socio-economic factors, with rural land users among the most vulnerable groups. The provision of information to support climate-relevant decision-making requires an understanding of the projected impacts of change and complex feedbacks within the local ecosystems, as well as local demands on ecosystem services. In this paper, we address the limitation of current approaches for developing management relevant socio-ecological information on the projected impacts of climate change and human activities. We emphasise the need for linking disciplines and approaches by expounding the methodology followed in our two consecutive projects. These projects combine disciplines and levels of measurements from the leaf level (ecophysiology) to the local landscape level (flux measurements) and from the local household level (socio-economic surveys) to the regional level (remote sensing), feeding into a variety of models at multiple scales. Interdisciplinary, multi-scaled, and integrated socio-ecological approaches, as proposed here, are needed to compliment reductionist and linear, scale-specific approaches. Decision support systems are used to integrate and communicate the data and models to the local decision-makers.

1 Introduction

Observed temperature increases over large parts of South Africa during the period 1931–2015 have occurred at rates of about twice the global mean, and this trend is projected to continue into the future (DEA 2017). Other projections across Southern Africa include changes in rainfall amount, variability, intensity and seasonality, and increases in the likelihood of extreme

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Extended author information available on the last page of the article weather events (DEA 2017; Tadross et al. 2017). These changes are likely to alter the carbon sink/source strength of the ecosystems exposed to them. The effects of climate changes on individual organisms translate to changes in populations and, through altered interactions with other species, to changes in communities and ecosystems. Indirect effects can also occur via climate change impacts on disturbance regimes, such as fire frequency, intensity or season, flood exposure, wind storms, and droughts (Davis-Reddy and Vincent 2017).

The complexity of climate-management interactions in Southern Africa is well illustrated by increasing woody biomass in savannas and former treeless grasslands (e.g. Stevens et al. 2016; Skowno et al. 2017). This phenomenon, called bush encroachment, greatly affects the portfolio of ecosystem services provided by the system. It has traditionally been attributed to inappropriate land management, for instance the suppression of fires due to excessive grazing pressure. However, the impacts of increasing atmospheric CO_2 might be particularly strong in savanna ecosystems, characterised by an uneasy co-dominance by trees and grasses. In experimental situations, increased atmospheric concentrations of CO_2 create a competitive benefit for C_3 woody vegetation in relation to C_4 grasses (Bond and Midgley 2012; Midgley and Bond 2015). Stevens et al. (2016) showed a strong trend of woody plant encroachment across various savanna and former grassland land-use types in South Africa over the past 70 years, indicating that the trend is unlikely to be attributable solely to poor management. However, the frequent observation of bush encroachment on a managed site, but not on an adjacent one, suggests that management factors also contribute to the phenomenon. Similarly to the indirect effects described above for climate change, CO_2 enrichment that leads to woody encroachment will influence grass productivity with cascading effects on agricultural production (Anadon et al. 2014), fire frequency and intensity (Langevelde et al. 2003), and biodiversity (Smit and Prins 2015; Stanton et al. 2018).

Southern African terrestrial ecosystems are strongly affected by human activities, for instance through grazing and browsing by domestic livestock, cultivation, and fuelwood collection (Niang et al. 2014; Stevens et al. 2015). Fuelwood collection has resulted in substantial changes in savanna composition and structure in many parts of South Africa where large rural populations either occur in the absence of modern energy services or are unable to afford them (Higgins et al. 1999; Giannecchini et al. 2007; Fisher et al. 2012; Kahn et al. 2012; Matsika et al. 2013). Humans also influence the fire regime, which largely controls tree dominance in savanna ecosystems (Scheiter and Higgins 2009; Midgley and Bond 2015; Archibald 2016). Land cover transformation, such as the expansion of settlements and rangelands, is very evident in certain regions (Coetzer et al. 2010; Schoeman et al. 2013).

2 Knowledge gaps and research needs

The abovementioned multiple, interacting, and contrasting impacts of climate and human management make projections of vegetation change in Southern African ecosystems difficult, emphasising the need for long-term monitoring in conjunction with carefully designed experimentation (Bond and Midgley 2012; Midgley and Bond 2015; López-Ballesteros et al. 2018). A comprehensive analysis of possible Southern African vegetation shifts due to climate change does not yet exist. Moreover, our understanding of the carbon dynamics of African ecosystems is incomplete due to a paucity of long-term observations in major ecosystem types (Valentini et al. 2014). Even though savanna ecosystems cover more than half of the Southern African land area (Cowling et al. 2004), their carbon budget and its projected changes are uncertain. A further third of the area is occupied by semi-arid dwarf-shrublands (the Nama-Karoo and Succulent Karoo Biomes), even less well studied with respect to climate responses and carbon dynamics. Knowledge of CO_2 fluxes is particularly lacking for areas under human land-use (e.g. Ciais et al. 2011), even though four-fifths of South African savanna, grassland, and shrubland ecosystems are under some form of agriculture, usually involving livestock (Kotze and Rose 2015).

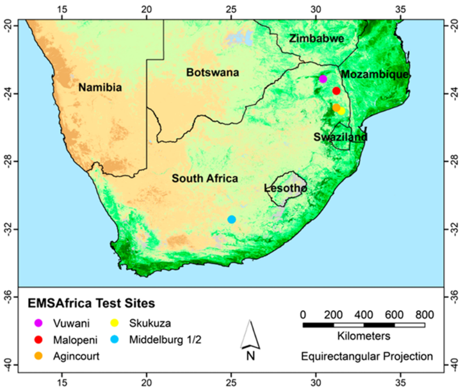
Land-use approaches that respond to ecosystem change are based on managing the resilience of the local socio-ecological system (e.g. Linkov et al. 2014) and could be made more robust by incorporating the knowledge of local land users. At the same time, land management tools must be informed by credible disciplinary knowledge, since the future circumstances may be outside the range of variation experienced in the past. However, outside of formal conservation lands, communication between researchers and local land users and land managers is often inadequate in Southern Africa (Ziervogel et al. 2014).

Ecosystem management support needs to allow for interaction and exchange between researchers of different disciplines, and between the formal scientific approaches and the experiential reality of affected stakeholders. Many knowledge gaps exist in the continuum from local- to global-scale change drivers and their consequences. These gaps compromise the development of both optimal local adaptations and national, regional, and global mitigation objectives. There is considerable complexity in the way the various components of these socio-ecological systems interact. Potentially nonlinear interlinkages between climate change impacts and land management make the response of the systems difficult to predict, especially since the feedbacks between ecosystem responses to climate and land-use changes, and atmospheric greenhouse gas concentrations, are poorly known. The resulting complexity requires innovative thinking and best-of-breed technology, e.g. social-ecological models and decision support information systems (Linkov et al. 2014).

3 Design of a cross-scale interdisciplinary approach

The complexity described above can only be understood through a scientific approach that combines several disciplines, conducts observations at a range of scales from single plants to ecosystems, and integrates land management activities. Using our two consecutive projects—Adaptive Resilience in Southern African Ecosystems (ARS AfricaE, 2014–2018) and Ecosystem Management Support for Climate Change in Southern Africa (EMSAfrica, 2018–2021)—as examples, we discuss the approach with a specific focus on the interlinkages between the different disciplines and scales.

The ARS AfricaE and EMSAfrica field site designs allow us to distinguish between land-use and climate-induced impacts on the structure and function of ecosystems. We established three focal areas along an aridity gradient in South Africa, with each area containing two contrasting observation sites based on different intensities of land use (and thus disturbance regimes), for instance, protected ecosystems compared with livestock grazing or peri-urban landscapes (Fig. 1). On these sites, we measure plant ecophysiological traits, monitor ecosystem-scale carbon fluxes, characterise the spatial dynamics of vegetation structure using remote-sensing, and conduct socio-economic surveys on human use of the ecosystems. The data are used to (i) create, calibrate, and test local ecosystem models, (ii) scale up the information to the biome level, and (iii) provide information adapted to the needs of land-use decision-makers by employing state-of-the-art multi-agent modelling and simulation techniques to integrate spatiotemporal ecological data with social-ecological data (Fig. 2).



Site	Land use type	Mean annual precipitation (mm)
Vuwani	Peri-urban	~ 500–1000
Malopeni	National Park	473
Agincourt	Village/ communal area	550-800
Skukuza	National Park	547
Karoo/ Middelburg 1	Lenient grazing	372
Karoo/ Middelburg 2	Heavily grazed	372

Fig. 1 Overview of the ARS AfricaE/EMSAfrica project research sites. The image backdrop is based on the Aqua Moderate-resolution Imaging Spectroradiometer (MODIS) data (product ID GMYD09Q1) and represents a composite of Normalized Difference Vegetation Index (NDVI) values observed between April 30 and May 7, 2018. The NDVI is a dimensionless indicator of live green vegetation and ranges between − 1 and 1. Here, light to dark green colours represent a higher abundance of healthy vegetation, whereas light to dark brown tones suggest lower amounts of photosynthetically active plant biomass. Land-use type and mean annual precipitation are provided in the table on the right

3.1 Studying ecophysiological responses to climate change at the plant level

By using ecophysiological approaches, we can explore small-scale mechanisms at leaf or plant level, underpinning changes at higher organisational scales such as the community or ecosystem scale (Ainsworth et al. 2016). In our cross-level approach, ecophysiological field experiments are used to improve our understanding of how higher-level responses, such as canopy flux, are related to changes in short-term drivers such as humidity, temperature, and soil water. We collect data for key shrubland, savanna, and grassland species using manipulation experiments and in-field sampling. The traits examined include (1) vegetation structure; (2) water use and leaf-level gas exchange under a range of soil, water, and temperature conditions, and following herbivory; and (3) soil respiration at a range of soil, water, and temperature conditions.

In our cross-scale approach, the results are used to parameterise ecosystem models (the "Modelling ecosystem dynamics at various spatial and temporal scales" section) in order to predict the functioning of entire ecosystems under future climatic and management conditions. The soil respiration and photosynthesis measurements support the partitioning of net ecosystem carbon exchange (NEE) efforts from the nearby eddy covariance (EC) flux tower into its various components (the "Monitoring biosphere-atmosphere exchange of carbon dioxide and water vapor" section): gross primary production (GPP) and net primary production (NPP), and auto- and heterotrophic respiration. The results allow us to deduce responses under the varying environmental conditions brought about by climate change. Similar comparative experiments undertaken at the other project sites allow us to draw conclusions about how general or specific the responses to environmental factors are.

3.2 Monitoring biosphere-atmosphere exchange of carbon dioxide and water vapor

Understanding ecosystem carbon fluxes and stocks is important for predicting the responses to climate change and choosing climate change adaptation measures. We established EC flux towers at all six of our project sites (Fig. 1), providing continuous and long-term monitoring of

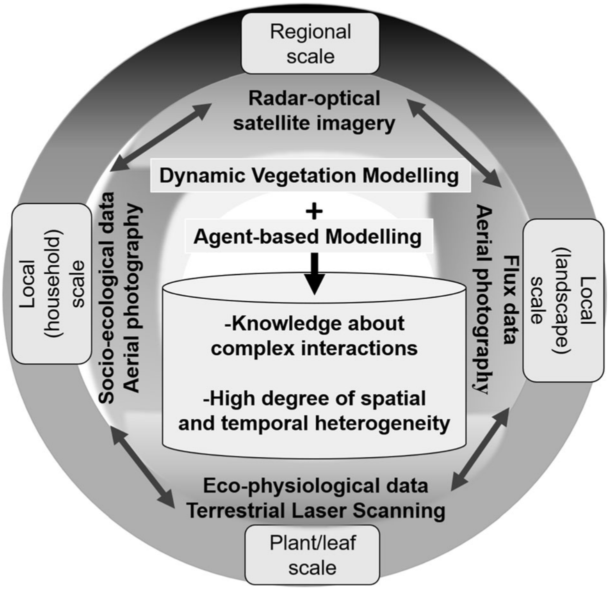


Fig. 2 Summary of the integrative project approach, showing the multi-level observations of carbon fluxes (the "Monitoring biosphere-atmosphere exchange of carbon dioxide and water vapor" section) and plant ecophysiology (the "Studying ecophysiological responses to climate change at the plant level" section), remote-sensing (the "Leveraging Earth Observation data to support ecosystem monitoring, modelling, and management" section), and socio-economic surveys (the "Understanding human impact in ecosystem change" section). These data are used to create, calibrate, and test vegetation (the "Modelling ecosystem dynamics at various spatial and temporal scales" section) and agent-based models which, in turn, are used to simulate and up-scale relevant information products for land-use decision-makers (the "Integrating models to support climate-relevant decision-making" section)

biosphere-atmosphere exchange of CO_2 and water vapor along the chosen aridity gradient as well as under different land-use management regimes.

Networks of EC flux towers with their associated meteorological measurements allow GPP and evapotranspiration to be quantified in a variety of climate zones and vegetation types (e.g. Brümmer et al. 2012). EC is the currently preferred method for continuously measuring exchanges of CO_2, water vapor and sensible heat between ecosystems, and the atmosphere over time scales of hours to decades and at the landscape scale, thus enabling the evaluation of seasonal and interannual variability as well as the elucidation of their climatic controls (Baldocchi et al. 2001). As the productivity of water-limited ecosystems such as shrublands and savannas is highly dependent on rainfall, and interannual differences are typically significant (e.g. Veenendaal et al. 2004; Brümmer et al. 2008, 2009; Merbold et al. 2009), long-term measurements are essential to detect significant trends.

In our cross-scale approach, by linking flux data with on-site ecophysiological measurements and employing combined approaches from Earth Observation (EO) (the "Leveraging Earth Observation data to support ecosystem monitoring, modelling, and management" section) and vegetation modelling (the "Modelling ecosystem dynamics at various spatial and temporal scales" section), we are able to improve our interpretation and understanding of the carbon fluxes between the biosphere and atmosphere, and study the consequences of ecosystem change for processes such as NPP, which is the basis of many ecosystem services. Continuous measurements allow us to observe the impacts of short-term ecosystem perturbations, such as changes in management regime or weather anomalies, on the CO_2 exchange of entire ecosystems. In the long term, the measurements will help to improve our understanding of the net carbon balance of Southern African ecosystems.

3.3 Leveraging Earth Observation data to support ecosystem monitoring, modelling, and management

EO data and products enable interdisciplinary studies at all scales of analysis, from the plant and household to the landscape and regional level (cf. Fig. 2). A comprehensive set of analysis-ready EO time series data, so-called space-time data cubes (cf. Baumann 2017) are collected on each of the project field sites (cf. Fig. 1) and for larger geographical areas (e.g. Kruger National Park). They consist of multi-temporal geospatial data from ground-based, air- and space-borne platforms at various sensing schemes. The pre-processed time series data comprise multispectral, thermal infrared, synthetic-aperture radar (SAR) as well as light detection and ranging (LiDAR) imagery and products that serve our diverse project applications and research topics. They are obtained at multiple spatial resolutions, with ground sampling distances (i.e. pixel sizes) ranging from a few centimetres to kilometres.

We further develop and test data fusion and analysis schemes by extracting image products, thematic maps, and spatial statistics from available EO data sets (e.g. Urbazaev et al. 2015; Odipo et al. 2016). Further emphasis is on computational approaches taking advantage of and adding value to publicly available satellite imagery such as data from NASA's Landsat missions and ESA's Sentinel (Copernicus) programme (e.g. Cremer et al. 2018; Urban et al. 2018). The resulting methods are used to derive land surface parameters related to the status and dynamics of South Africa's terrestrial ecosystems (e.g. fuel biomass, woody cover, vegetation heights, land use) to implement environmental and socio-ecological mapping, monitoring, and management with direct societal benefits (e.g. Urbazaev et al. 2015; Odipo et al. 2016; Urban et al. 2018). An example application is the spatiotemporal characterisation of fuel biomass and fuel moisture content for improved fire management in the Kruger National Park.

In the cross-scale interdisciplinary approach, the EO data and products support the interpretation of EC fluxes (the "Monitoring biosphere-atmosphere exchange of carbon dioxide and water vapor" section), ecophysiological experiments (the "Studying ecophysiological responses to climate change at the plant level" section) and socio-economic surveys (the "Understanding human impact in ecosystem change" section). Moreover, they help to parameterise, calibrate, and validate our agent-based simulations, vegetation models (the "Monitoring biosphere-atmosphere exchange of carbon dioxide and water vapor" section) and biome shift predictions. Furthermore, they form an integral part of our anticipated system for data-driven and science-informed decision-making (the "Integrating models to support climate-relevant decision-making" section).

3.4 Understanding human impact in ecosystem change

The paired sites approach of the two projects aims at allowing comparisons between ecosystems under little human impact and those under high-intensity human management in all measurement scales. In addition, a case study on the local use of fuelwood is conducted around one of the observation sites, Agincourt village in Bushbuckridge. The socio-economic conditions in the Agincourt site are well researched due to the existence of the 27-year Agincourt Health and Socio-Demographic Surveillance System (HDSS). Surveys conducted on fuelwood collection and use and the monitoring of fuelwood removal in the areas surrounding the villages allow us to accurately quantify carbon removal from local ecosystems. Longitudinal survey data enable the study of interannual variation in the provision of ecosystem services to local communities, as well as the key socio-economic drivers of household dependence on these. In the interdisciplinary approach necessary for socio-ecological inquiry, the results are used in conjunction with vegetation models (the "Modelling ecosystem dynamics at various spatial and temporal scales" section) to construct a case study of resource use in local communities impacted by climate change. To investigate whether local resource extraction and carbon removal by human appropriation can be tracked from space, a further case study on the linkage between remotely sensed dynamics of woody vegetation and the Agincourt household survey data is envisaged.

3.5 Modelling ecosystem dynamics at various spatial and temporal scales

Dynamic Global Vegetation Models (DGVMs) integrate processes from the leaf level to the ecosystem and the biosphere level (Prentice et al. 2007; Smith et al. 2014). They simulate the distribution of competing plant functional types (PFTs) and different biome types, vegetation dynamics and structure, and the fluxes of carbon, water, and, increasingly, nutrients between the soil, vegetation, and the atmosphere. Disturbances, such as fire (Scheiter and Higgins 2009; Rabin et al. 2017) and grazing (e.g. Pachzelt et al. 2015) are included in some DGVMs. Site-scale or even farm-scale applications (e.g. within the ARS AfricaE project) make it necessary to adjust the models for local conditions (e.g. Hickler et al. 2012; Seiler et al. 2014).

Several DGVMs have limited applicability in savanna and shrubland ecosystems, because they do not allow for an accurate representation of the vulnerability of woody plants to fire (Scheiter and Higgins 2009) and the vulnerability of woody plants and grasses to herbivory (Scheiter and Higgins 2012). In addition, most DGVMs do not represent shrub growth forms adequately (Gaillard et al. 2018). In our projects, we use the adaptive Dynamic Global Vegetation Model (aDGVM), an individual-based model that was developed to simulate the response of tropical vegetation to impacts of climate change, fire (Scheiter and Higgins 2009; Higgins and Scheiter 2012), and human management, e.g. grazing and wood harvesting (Scheiter et al. 2019), as well as LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator) (Smith et al. 2001), a global-scale model that will be adjusted for applications in southern Africa.

In our cross-scale approach, information obtained from ecophysiological (the "Studying ecophysiological responses to climate change at the plant level" section) and EC measurements (the "Monitoring biosphere-atmosphere exchange of carbon dioxide and water vapor" section) collected at the project sites is used to parameterise the models for local vegetation under varying grazing pressures. Remote-sensing data (the "Leveraging Earth Observation data to support ecosystem monitoring, modelling, and management" section) are used to test and benchmark model outputs. After successful model parameterisation and testing at various spatial scales, the aDGVM is used to estimate recent past, present, and future climate-driven changes in vegetation and ecosystem functioning.

3.6 Integrating models to support climate-relevant decision-making

A decision support system (DSS) is a platform for integrating, analysing, and displaying complex information to assist decision-making (Gibson et al. 2017). These systems typically consist of software components and complex algorithms, designed to support decision-making with the visualisation of different decision outcomes or scenarios.

In our interdisciplinary cross-scale approach, we use DSSs to integrate the various data and models in a way that allows exchange between the researchers and the local decision-makers.

The DSSs cover the entire workflow from model development to result analysis and visualisation. Since agent-based modelling and simulation systems have a well-proven record to handle the complexity of coupled human-environmental systems (Le et al. 2012; Lenfers et al. 2018), the MARS (multi-agent research and simulation) framework (Dalski et al. 2017) is used in the projects described here. MARS is particularly well suited for the simulation of large-scale scenarios with a high number of individual agents (Hüning et al, 2016).

We implement decision support via specific case studies at core project research sites. The first study involves local land-use decision-makers at the Agincourt village, and the second focuses on livestock farming systems in the Karoo (Fig. 1). The related decision support systems are, from the outset, designed collaboratively by the MARS developers, the interdisciplinary team of researchers, and the local stakeholders. The active participation of such a diverse group requires the inclusion of a wide range of knowledge and values (Reed 2008; Hugé and Mukherjee 2018). We use stakeholder workshops and focus group discussions as the main way of facilitating exchange between researchers and local decision-makers at the early stages of planning (Nyumba et al. 2018). The information contained in the land-use planning tool as well as the format of the tool are designed together with the end users and adapted to local needs. This is a way to avoid one of the main limitations of many existing DSSs, i.e. their inability to represent available scientific knowledge in the most appropriate way for the intended local users (Dicks et al. 2014).

In addition to generating a practical, hands-on simulation tool for use by land users and/or decision-makers, this collaborative approach is also an important step towards scaling up information on the socio-ecological systems and their local impacts on climate into regional and global level assessments.

4 Conclusion

With multiple pressures of climate change (e.g. Kruger and Shongwe 2004) and land-use change (e.g. Schoeman et al. 2013), Southern African ecosystems are undergoing substantial changes. These challenges need to be addressed through an approach that links different disciplines and measurements at various scales. This paper presents a blueprint for such an approach, while contributing towards a better understanding of the future of Southern African biodiversity, carbon sequestration potential, ecosystem services, and livelihoods under the combined impacts of human land use and climate change. This serves as a basis for developing sustainable and climate-resilient land-use strategies in cooperation with stakeholders at different levels.

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