Modeling the multi-functionality of African savanna landscapes under global change

Reimund P. Rötter[1,*], Simon Scheiter[2], Munir P. Hoffmann[1,3], Mirjam Pfeiffer[2], William C.D. Nelson[1], Kingsley Ayisi[4], Peter Taylor[5], Jan-Henning Feil[6], Sara Yazdan Bakhsh[6], Johannes Isselstein[7], Anja Lindstädter[8,9], Kai Behn[8], Catrin Westphal[10], Jude Odhiambo[5], Wayne Twine[11], Ingo Grass[12], Paolo Merante[1], Gennady Bracho-Mujica[1], Thomas Bringhenti[1], Sala Lamega[7], Issaka Abdulai[1], Quang Dung Lam[1], Mina Anders[10], Valerie Linden[5], Sina Weier[5], Stefan Foord[5], Barend Erasmus[13]

[1] Tropical Plant Production and Agricultural Systems Modeling (TROPAGS), University of Göttingen, Göttingen, Germany

[2] Senckenberg Biodiversity and Climate Research Centre (SBiK-F), Frankfurt, Germany

[3] AGVOLUTION GmbH, Göttingen, Germany

[4] University of Limpopo, Risk and Vulnerability Science Center, Polokwane, South Africa

[5] University of Venda, School of Agriculture, Thohoyandou, South Africa

[6] Department of Agricultural and Rural Economics, University of Göttingen, Göttingen, Germany

[7] Grassland Sciences, University of Göttingen, Göttingen, Germany

[8] Institute of Crop Science and Resource Conservation, University of Bonn, Bonn, Germany

[9] University of Potsdam, Institute of Biochemistry and Biology, Potsdam, Germany

[10] Functional Agrobiodiversity, University of Göttingen, Göttingen, Germany

[11] University of Witwatersrand, Wits Rural Facility, Acornhoek, South Africa

[12] University of Hohenheim, Department of Ecology of Tropical Agricultural Systems, Stuttgart, Germany

[13] University of Pretoria, Faculty of Natural and Agricultural Sciences (NAS), Pretoria, South Africa

*Correspondence: Reimund P. Rötter, Tropical Plant Production and Agricultural Systems Modeling (TROPAGS), University of Göttingen, Göttingen, Germany. Email: reimund.roetter@uni-goettingen.de

1 PROBLEM STATEMENT AND CHALLENGES

Various recent publications have indicated that accelerated global change and its negative impacts on terrestrial ecosystems in Southern Africa urgently demand quantitative assessment and modelling of a range of ecosystem services (Chaplin-Kramer et al., 2019; Conway et al., 2015; IPCC, 2019) on which rural communities depend. Information is needed on how these Ecosystem Services (ES) can be enhanced through sustainable land management interventions and enabling policies (Rötter et al., 2005; Sikora, Terry, Vlek, & Chitjja, 2020). Yet, it has also been claimed that, to date, the required system analyses, data and tools to quantify important interactions between biophysical and socio-economic components, their resilience and ability to contribute to livelihood needs do not exist (Midgley & Bond, 2015;

Sikora et al., 2020). We disagree, but acknowledge that building an appropriate integrative modelling framework for assessing the multi-functionality of savanna landscapes is challenging. Yet, in this Letter-to-the-Editor, we show that a number of suitable modelling components and required data already exist and can be mobilized and integrated with emerging data and tools to provide answers to problem-driven questions posed by stakeholders on land management and policy issues.

High population growth, persistent low agricultural productivity and poverty, severe land degradation, and high climate variability, among other things, have already led to a decline of essential ES in many regions of Africa. The situation is particularly critical in the savanna regions of Southern Africa, which are considered hotspots of global change impacts that lead to a deterioration of ES (Conway et al., 2015; IPCC, 2019; Sikora et al., 2020). Accelerated climate change is putting additional pressure on their multi-functionality (Conway et al., 2015; Midgley & Bond, 2015). ES such as provision of food, feed, fuel, carbon sequestration, nutrient cycling, habitat quality, pollination, and natural pest control are under threat (IPCC, 2019; Sikora et al., 2020). Southern Africa has also been identified as a hotspot for biodiversity, whereby agricultural expansion is seen as a key driving force for the declining species diversity (IPBES, 2018). The projected doubling of the African human population by 2050 and the climate change-induced increased frequency of extreme droughts underline the urgent need for science-informed assessments as a prerequisite for identifying sustainable land management options (IPCC, 2019; Sikora et al., 2020).

About 70% of the population of southern Africa relies on agriculture. Most of these people are smallholders of which about 94% depend on rainfed agriculture. Around 16% of the rural population has been characterized as 'food insecure' during the last 5 years (Sikora et al., 2020). Climate variability, climate change, changes in land-use, technological advances, institutional and policy constraints as well as the current status of ES determine whether and to what extent the most relevant sustainable development goals (SDGs) can be achieved, specifically: No poverty (1), Zero hunger (2), Clean water (6), Climate action (13), and Life on land (15). Southern African savanna landscapes are composed of arable land, rangelands and orchards/homegardens and host unique nature parks (IPBES, 2018; Midgley & Bond, 2015; Sikora et al., 2020), which are, however, excluded from our analysis. Rural livelihoods, especially those of smallholders, who commonly perform mixed crop-livestock farming largely depend on the ES these three major land use types provide. Smallholders in the region are highly diverse in terms of resource endowments such as land and water. The generally huge yield gaps (with yield levels at 20% of the attainable), food insecurity and shrinking land holdings call for radical changes in land use policies and management to avoid societal unrest growing in the future. In national plans on sustainable development, sustainable intensification (Cassman & Grassini, 2020) of these systems, not surprisingly, has the highest policy priority (Sikora et al., 2020). It is seen as an important means to provide incentives to the younger farmer generation, boost agricultural development and to set land aside for nature conservation.

A broad range of management interventions has been suggested for promoting sustainable intensification (Cassman & Grassini, 2020), including cereal intercropping with legumes, site-specific fertilizer application and irrigation. Most experimental studies on testing such interventions have just looked at impacts on dry matter production and yield, but a few also looked at other ecosystem functions such as carbon sequestration and water and nutrient use efficiency. Yet, to date, no study has looked in an integrated manner at the complexity of smallholder systems with a broad range of interacting ES at the landscape level.

There is an urgent need to develop and apply an appropriate analytical framework to assess the current status of ecosystems and their functions. Land management interventions must be identified that can reverse the decline of ES and work toward the achievement of the SDGs in the face of climate change and other global change processes such as population growth and biodiversity decline.

2 AVAILABLE AND EMERGING DATA AND TOOLS

On that background, the Southern African Limpopo Landscapes network (SALLnet) set out to perform field studies, develop and apply system approaches and modelling tools to gain a deeper understanding of the interactions and multi-functionality of different land use types (arable land, tree orchards/homegardens, rangelands) and develop sustainable land management scenarios jointly with stakeholders.

Process-based (eco-)systems modeling for crops and rangelands offers the option to conduct scenario analyses in order to examine the interaction between management and environment for given crop and rangeland systems (e.g., Hoffmann et al., 2018; Pfeiffer et al., 2019). These models generate output on dry matter production, crop yield, water and nitrogen dynamics, carbon sequestration, and vegetation dynamics. Output of crop and livestock models can be combined (Descheemaeker, Zijlstra, Masikati, Crespo, & Homan-Kee Tui, 2017) whereby livestock models generate data on meat and milk, depending on age, gender, etc. Farm level economic modelling (Reidsma et al., 2015; Rötter, Fanou, Höhn, Niemi, & Van den Berg, 2016) allows for the *ex-ante* evaluation of the outcomes of different scenarios of land use management and enabling policies including proposed risk management strategies at regional level (Reidsma et al., 2015; Rötter et al., 2005, 2016).

The process-based crop model APSIM (Akinseye et al., 2017; Hoffmann et al., 2018; Holzworth et al., 2014), and the vegetation models aDGVM/aDGVM2 (Scheiter, Gaillard, Martens, Erasmus, & Peiffer, 2018; Scheiter & Higgins, 2009; Scheiter & Savadogo, 2016) have been previously parameterized and tested for crop and rangeland systems in several savanna regions of Western, Eastern, and Southern Africa. Based on comprehensive groundwork such as agronomic trials on water conservation and irrigation, integrated nutrient management, new crop cultivars, and crop rotations (e.g., Hoffmann et al., 2020), drought or grazing experiments in rangelands (e.g., Pfeiffer et al., 2019), it was possible to further extend modeling capabilities for crops and rangelands and evaluate them for the Limpopo region in South Africa. For example, in addition to the simulation of carbon sequestration, dry matter production, and water fluxes, the trait-based aDGVM2 vegetation model can now also simulate vegetation dynamics as a function of specific local management actions such as grazing and fuelwood harvesting. This makes it suitable for the simulation of rangeland dynamics (Pfeiffer et al., 2019; Scheiter et al., 2019).

Prototype agent-based bio-economic models (Rötter et al., 2016) are currently being tested in three subregions of Limpopo with explicitly different agricultural risks. These models are based on new farm survey information collected from villages along a climatic gradient and can be applied to examine the economic performance of different farm types and analyze the effects of policy interventions on management decisions from the farm household level to the regional scale.

3 TOWARD AN INTEGRATED MODELLING FRAMEWORK AND RELEVANT USE-CASES ON SUSTAINABLE LAND MANAGEMENT

Based on the considerations such as data availability and agro-ecological diversity, we have chosen the province of Limpopo to develop and operationalize an integrated modelling framework for multi-functional savanna landscapes. The Limpopo region is highly diverse in terms of biophysical conditions, biodiversity, and land use, and comprises some of the former homelands of the Republic of South Africa. It is characterized by a high climatic variability (CV) of seasonal rainfall in many areas >25%, poverty (headcount 11.5% in 2016), and food insecurity (12.9%) as well as by a high level of land inequality—and as such is quite typical for many other regions in southern Africa (Sikora et al., 2020). Therefore, it truly is a hotspot of global change impacts and suitable for generalizing the findings for similarly managed ecosystems in Southern Africa.

For making the modelling framework complete for numerous potential applications, it is necessary to combine available data and tools with new or emerging state-of-the-art databases. The latter include high resolution remote sensing products (land use data), iSDA digital soil map, IoT (Internet of Things)-based micro-climate maps, rapid plant health detection by smartphones, new regional climate modelling products, and additional biophysical modelling components such as the hydrological model SWAT (Arnold, Srinivasan, Muttiah, & Williams, 1998) and the LIVSIM (LIVstock SIMulator) model (van de Ven, De Ridder, Van Keulen, & Van Ittersum, 2003).

Figure 1 illustrates how the data and model components already developed can be supplemented with additional tools and integratively linked to quantify interactions between different land use types, management decisions, and environmental change from the field- to the landscape-level.

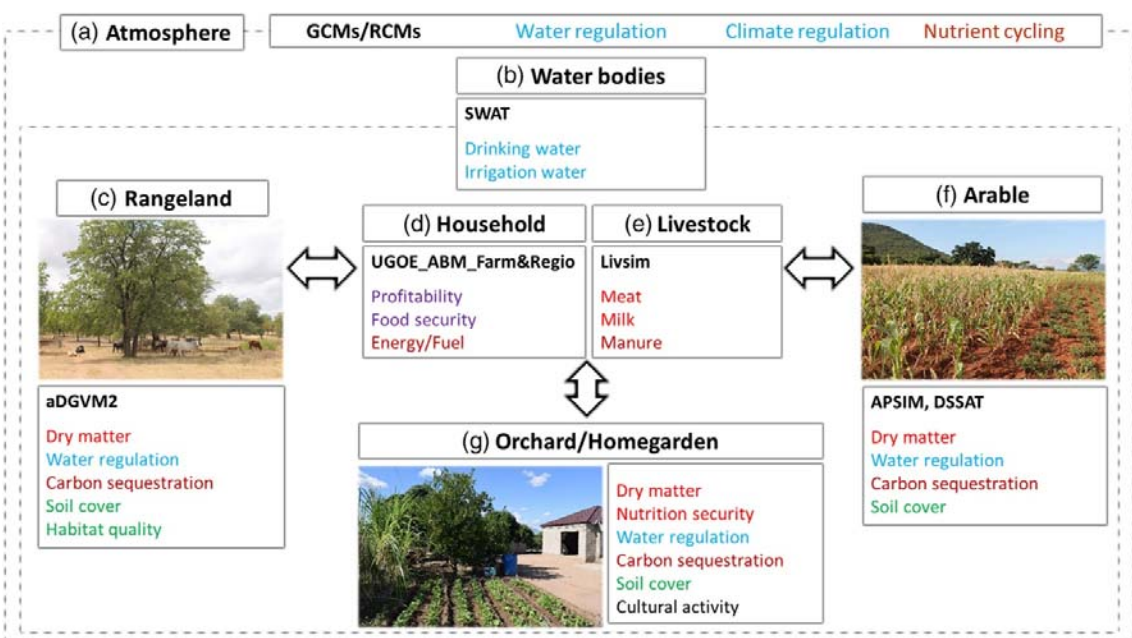

FIGURE 1. UGOE—Integrated Landscape Approach. The predominant land use systems in the savanna regions (of Limpopo Province) are represented with their core ecosystem services: Rangeland (c), arable (f), and orchard/homegardens (g). Matter fluxes between the systems are driven by humans (d) and livestock (e). The

overall systems are simultaneously closely interacting with water bodies (b) and the atmosphere (a). In addition, we indicate available models for the different land use types respectively drivers (first word in black & bold in the boxes). GCMs, global climate models; RCMs, regional climate models

However, before coupling models or combining their outputs within such analytical framework, its components need to be tested with local data and use-cases. Based on the discussions with stakeholder platforms established by SALLnet, the following relevant use-cases have been defined, most of which have relevance for the wider domain of Southern African savanna landscapes:

1. Sustainable management of smallholder crop-livestock systems.
2. Potential of deficit irrigation for sustainable intensification of maize-based systems for so-called 'emerging farmers'.
3. New crops for filling the winter livestock feed gap.
4. Sustainable management of macadamia (*Macadamia ternifolia* F.Muell) orchards.

With a system perspective in mind, we compiled the tools and defined data flows necessary for quantifying the crucial ecosystem services (Figure 1) for different alternative management interventions and policy views. In doing so, we especially focused on use-cases 1, 2, and 3 (above). Work on these is currently in progress for Limpopo, utilizing supportive tools such as sensitivity analysis and expert judgments to check the plausibility of results.

The purpose of the framework is to *ex-ante* assess what effects sustainable intensification measures such as improved management practices (see above) and enabling policy interventions (such as investments in agricultural extension services, irrigation, or communication infrastructure) could have. The framework examines the effects of such interventions on interactions between land use types and the ecosystem services they provide from plot to landscape scale—and thus on the functioning of the whole land use system. Such land use optimization has to be done in a spatially explicit manner and with a long-term perspective, and should allow to quantify potential trade-offs and synergies between short-term economic viability and long-term ecosystems functioning.

4 OUTLOOK

Our integrated modelling framework and systems approach to analyzing the multi-functionality of savanna landscapes contains several novelties. Here, we emphasize two aspects: (a) closing the missing link between biophysical analysis, farm level decision-making and policy intervention scenarios, and (b) developing and evaluating the framework jointly with stakeholders and a multi-disciplinary team with problem-oriented use-cases.

We propose the following steps for developing, evaluating, and operationalizing such framework for any given savanna region in Southern Africa:

1. Monitoring and assessing spatio-temporal patterns of ecosystem functions and services at landscape level.
2. Developing a framework linking crop, livestock, and rangeland systems with farm-economic models enabling integrated analyses.
3. Using assembled field experimental, survey and monitoring data as well as advanced sensitivity analysis and expert knowledge to evaluate the framework.

4. Perform land management and policy scenario analyses for alternative interventions as jointly defined with stakeholders.

Research opportunities to extend the applicability of the framework lie in: further model-data fusion, integration of high-resolution remote sensing, soil and micro-climate sensor data, as well as distinct improvements of crop and vegetation models, in particular, for capturing the impacts of climate extremes and elevated CO_2. Likewise, extended (agent-based) model capabilities incorporating insights into human decision behavior under risk/uncertainty, and their use in sensitivity analyses and for alternative stakeholder-defined scenarios will allow us to better explore sustainable land use options.

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