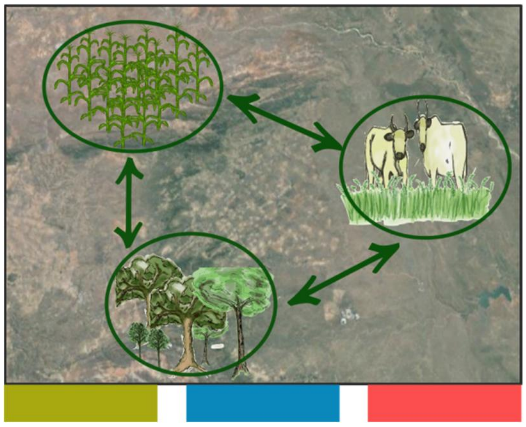
South African Limpopo Landscapes Network



Acronym: SPACES-SALLnet

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Thematic area

Theme 2: "Management options for multi-use landscapes and their component ecosystems for building ecosystem and social resilience to environmental changes"

Deutsche Zusammenfassung

Auf der Basis rezenter Modellprojektionen ist zu erwarten, dass klimabedingte Risiken im südlichen Afrika in Zukunft noch ausgeprägter als heute auftreten werden, mit tiefgreifenden Auswirkungen auf essentielle Ökosystemdienstleistungen (ESs) wie, z.B. Produktion, Biodiversität und Bestäubung, sowie Kohlenstoffsequestrierung. Diese ESs werden im südlichen Afrika typischerweise durch die drei räumlich eng miteinander vernetzten Landnutzungstypen (LNT) bereitgestellt, sprich durch Weideland, Ackerland und Obstplantagen. Eine starke Zunahme der menschlichen Bevölkerung wird die Nachfrage nach diesen Dienstleistungen, die wesentlich essentiell zur Sicherung der lokalen Existenzgrundlagen beitragen, erhöhen. Die übergreifende Forschungsfrage des SALLnet lautet: "Wie und in inwieweit kann die Funktionalität und die Widerstandsfähigkeit (Resilienz) der multifunktionalen Landschaften im südlichen Afrika unter möglichen alternativen Zukunftsszenarien verbessert werden?" Zur Beantwortung dieser Fragestellung wählen wir Südafrikas Limpopo- Region als Studiengebiet, da diese sich aufgrund ihrer hohen raumzeitlichen Klimavariabilität und vielfältigen Landnutzung besonders gut als Fallstudie für unsere Zwecke eignet. Nach Auswertung der Fallstudienergebnisse werden wir diese so verallgemeinern, dass sie für ein größeres Gebiet im südlichen Afrika als Empfehlungsgrundlage dienen können. Wichtige Innovationen von SALLnet sind (i) ein starker Fokus auf Interaktionen zwischen den verbundenen LNT Ackerland, Weideland und Obstplantagen; (ii) eine integrierte multiskalige Bewertung von LN-Szenarien und der damit verbundenen Management-Optionen zur Verbesserung der Resilienz von Ökosystemen und sozialen Systemen, die mit diesen LNTs einhergehen; und (iii) ein grundlegend transdisziplinärer Ansatz, der Stakeholder in den gesamten Forschungsprozess mit einbezieht. Die Grundlagenarbeit in jedem der drei LNT-Typen (in den Teilprojekten (TP) 1 und 3) wird als Basis dienen, um experimentell die Auswirkungen von Management-Innovationen auf die Verbesserung der LNT-spezifischen Resilienz zu bewerten. Die Ergebnisse werden in biophysikalische und sozioökonomische Modelle (TPs 1,2 und 4) eingespeist, um die Effekte von aktuellem (Status Quo) vs. innovativem Landnutzungsmanagement auf ESs in Limpopo auf höhere Skalenebenen zu extrapolieren. TP 1 wird diese Analysen integrativ zusammenführen, um zusammen mit den Stakeholdern iterativ eine Gesamtrisikobewertung und Synthese von Handlungsimplikationen zu erzielen. Das abschließende Gesamtergebnis des Projektes wird eine Reihe von gemeinsam erarbeiteten Risikomanagementstrategien sowie dokumentierte Szenario-Analysenergebnisse beinhalten. Ebenso wird es ein computergestütztes System zur Ermöglichung gemeinsamen Szenario-Analysen, als auch zur Unterstützung von Diskussionen, gemeinschaftlichem Lernen, und Erarbeitung von Handlungsempfehlungen umfassen.

English Abstract

Climate-induced risks in southern Africa are expected to become even more prominent in the future than they are already today. This will have tremendous effects on essential ecosystems services (ESs), e.g. production, biodiversity, pollination, and carbon sequestration, provided by the three intertwined land use (LU) types, rangelands, arable lands and orchards. At the same time, strong increases in human populations in the region will put increasing demands on these services that are crucial for supporting local livelihoods. The overarching research question of SALLnet is: “How and to what extent can the functioning and resilience of the multi-functional landscapes in southern Africa be enhanced under possible alternative futures?” To answer this, we select the Limpopo region as case study area because it is particularly appealing for our purpose due to its high spatiotemporal climatic variability and diverse land use. Following evaluation of case study results, we will generalize the findings for a larger recommendation domain in Southern Africa. Key innovations of SALLnet will be (i) a focus on interactions between the connected LU types, i.e. arable lands, rangelands, orchards; (ii) an integrated multi-scale assessment of LU scenarios and associated management options aimed at enhancing ecosystem and social resilience at the LU type level as well as at the landscape level, and (iii) a truly transdisciplinary approach involving stakeholders in the entire research process. Groundwork in each of the three LU types (SPs 1 and 3) will serve as a basis to evaluate effects of management innovations experimentally on improving LU type specific resilience. Outputs will be fed into bio-physical and socio-economic models (SPs 1, 2, 4) to upscale the effect of status quo versus innovative LU management across Limpopo on ESs. SP 1 will integrate these analyses for an iterative overall risk evaluation and synthesis of policy implications with stakeholders. Final outcome will be a set of jointly developed risk management strategies, a computer-based system for facilitating scenario analysis, discussions and joint learning, and documented scenario analysis results and policy recommendations.

1. Objectives

1.1 Overall goal of the project

The overall goal of SALLnet is to answer the overarching question: “How can the resilience of the multi-functional landscapes in South Africa’s Limpopo region be enhanced under future climate conditions?” This will be explicitly investigated under different socio-economic pathways. To do so, SALLnet will design an inter- and transdisciplinary framework to develop and evaluate alternative land use management (LUM) scenarios at multiple scales. In this context, we will identify, select and investigate a set of different possible LUM scenario options, that in different ways, aim to enhance the resilience of land use, ESs and landscapes, to anticipated changes in climate and socio-economic drivers; thereby special attention will be given to link these scenarios to the relevant range of Sustainable Development Goals (SDGs) and local policy objectives. For each scenario, we will analyze the degree of accomplishment towards the relevant SDGs, and evaluate synergies and trade-offs among the multiple development goals. Assessing the effectiveness of management options is key to enhance the resilience of different land use systems and reduce

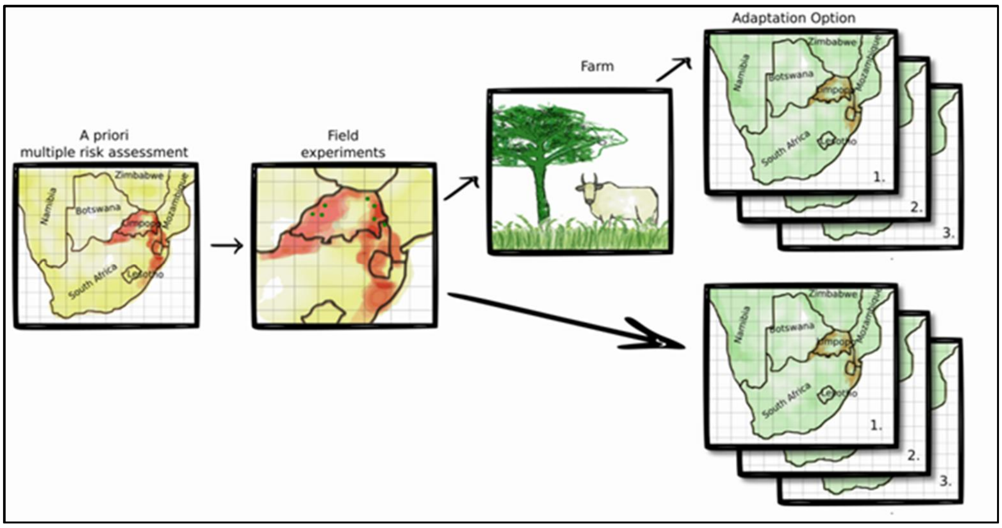

Fig. 1 Schematic illustrating the study approach in SALLnet. (from left to right:) (i) A-priori, large-scale area assessment of multiple risks related to biophysical and socio-economic drivers affecting impacts on ecosystem services (ESs), (ii) groundwork on the supply and demand of critical ESs via observational studies and field experiments; in parallel, participatory experimentation and/ co-innovation of management options for enhanced resilience and risk reduction, (iii) scaling of observations, experimental results and co-developed risk management options along two different pathways: biophysical factors only (lower branch); both, biophysical and socio-economic factors (farm-level) taken into account (upper branch).

risks to ecosystem services (ESs). In SALLnet we consider climate variability and change as the main source of risk, but approach them as a multiplier of existing socio-economic risks, while we pay due attention to other drivers of land use change such as urbanization processes. SALLnet focuses on Limpopo's dominant land use types (i) arable lands, (ii) rangelands and agroforestry, and (iii) orchards, and connects these LU types in an integrated analysis. SALLnet aims to (see Fig. 1):

1) Conduct an a-priori, large area assessment of the multiple risks that may threaten ESs.
2) Carry out required groundwork to identify, assess and quantify the delivery and demand of critical ESs, and evaluate promising options through participatory experimentation and /co-innovation.
3) Develop, test and apply modelling frameworks, model components, associated databases and scaling methods to extrapolate and scale groundwork results in space and time and identify management options at higher aggregation levels under a baseline and alternative future land use management and policy scenarios.
4) Perform an integrated analysis of connected land use systems and their interactions, with a synthesis for different land use scenarios to provide policy recommendations in support of improved ecosystem management and enhanced resilience of land use systems.

The scenarios will be developed in close interaction with local stakeholders, and evaluated and compared with respect to a set of pre-defined sustainability indicators (ecological, economic and social). The scenarios will build on issues that have emerged in previous or ongoing science-policy dialogues in/about Limpopo region, such as the propagation of agricultural intensification (along different pathways) or the consideration of specific policy interventions such as measures (investments, programs) to promote increase of biofuels, a wild-life economy or climate-smart management practices. According to a broad consensus on the need to intensify land use, we will analyze three basic land use management (LUM) scenarios and their associated (LU-type) specific management practices: (LUM 0) Business-As-Usual, (LUM 1) Efficiency-Oriented and (LUM 2) Diversification-Oriented. Additionally, specific policy scenarios will be analyzed on top of the three basic LUM scenarios.

LUM 0 reflects the present situation or status quo; LUM 1 and LUM 2 reflect two alternative pathways of LUM for sustainable intensification. While LUM 1 focuses on the achievement of further efficiency gains (in water use, nitrogen use, labor use, etc.), higher production and specialization, LUM 2 focuses on diversification of agricultural production on a farm or social-ecological system level aiming at a high degree of resilience to climate-induced risks.

The policy scenarios will include specific intervention strategies:

- Scenario A: the “agricultural intensification scenario” (land-sparing): This scenario is in line with global efforts of agricultural intensification (Godfray et al. 2010); it concurrently will enable to increase the proportion of land for nature conservation. This scenario can be considered a governmental strategy in South Africa, specifically in support of small-scale and emerging farmers. There is still considerable scope for increasing agricultural productivity with reduced or similar environmental footprint through various technological and institutional innovations such as new crops/cultivars, efficiency gains in the use of water and nutrients, land consolidation and infrastructural measures.
- Scenario B1: the “biofuel scenario”: national policy (the Integrated Resource Plan 2016, Green Economy Accord, National Strategy for Sustainable Development, the National Development Plan, SA Climate Change Response Strategy, and others) may result in extensive investments in biofuels, mainly from shrubs and timber, with major implications for regional land use (Gasparatos et al. 2011).
- Scenario B2: the “wildlife economy” scenario: wildlife-based tourism and income from game farming has been suggested as poverty-relief mechanism. However, such initiatives do not recognize the wide variety of ecosystem services that rangelands and agroforestry systems provide.

The results from the LUM scenarios in conjunction with spatial analyses will also provide a quantification of what could be achieved in terms of ESs and the various associated sustainability indicators if all land bought according to the Land Rights act would be redistributed and managed according to the alternative LUM scenarios. “Land restitution” addresses historical inequalities in land ownership due to apartheid legislation (the Restitution was promulgated in 1994). So far, application of the Land Rights Act, to restore social justice and resilience has led to some positive developments, but also led to unintended land use outcomes – the consequences and possible amendments of which we will quantify for the Limpopo region in our LUM analysis. Our LUMs are quite much in line with what the climate-impact research community tries to establish world-wide under the term “Representative Agricultural Pathways (RAPs) (see e.g. Claessens et al. 2012). We will consider various future GHG emissions/ Representative Concentration Pathways (RCPs) (Vuuren et al. 2011) and associated climate model projections (using CMIP5 data sets)(see e.g. McSweeney and Jones 2016; see also the descriptions in SP1&2) and pay due consideration to how the various LMU scenarios’ will contribute to the 1.5° and 2.0°C climate policy goals for a selected range of future climate projections (Schleussner et al. 2016; Griscom et al. 2017).

1.2 Relation to funding policy objectives

Combating poverty and hunger, ensuring food security, strengthening agriculture and rural development as well as promoting sustainable urbanization are key targets regarding the Sustainable Development Goals (SDGs) (see, below), as identified in the Africa-related political guidelines of the German Federal Government. A holistic understanding of both natural and agricultural landscapes is thus needed to accommodate the legitimate but often conflicting needs of improving human livelihoods and ensuring biodiversity conservation. SALLnet will perform integrated regional assessments and make use of local knowledge in a bottom-up approach with tight links to existing initiatives on biodiversity and ESs, as postulated by IPBES. Our integrated land use analysis approach is consistent with the IPBES philosophy of the value of nature's contribution to people, as a more inclusive framing of ESs. SALLnet will gain a collective and balanced understanding via a biosphere approach. To this end, biosphere reserves in South Africa's Limpopo Region will be used as test cases in accordance with UNESCO Man and the Biosphere scopes in order to reconcile environmental protection and sustainable development (Coetzer et al. 2014; Reed et al. 2016). It will allow more informed projections of the likely negative impacts of climate change and other man-made pressures, and help to identify mitigation and adaptation strategies required to ensure sustainability in all its dimensions (ecological, economic and social). Field work within SALLnet will thus, among other representative locations, focus on the Vhembe and Kruger-to-Canyons Biosphere Reserves (two of the four biosphere reserves in the province, >50% of which are covered by biospheres). Moreover, proposed activities across LU-types (arable lands, rangelands, orchards) will explicitly address six of the 17 SDGs (https:/sustainabledevelopment.un.org/sdgs) on Poverty, Hunger, Consumption & Production, Climate Action, Life on Land, Partnerships (i.e. SDGs 1, 2, 12, 13, 15 & 17, respectively) and a few more indirectly, such as on Health (e.g. SDG 3).

In order to disseminate research results, data gained in SALLnet will be transferred to SASSCAL's Open Access Data Centre/Knowledge Exchange. SASSCAL's network for hosting and providing data and information makes it a perfect multiplier for raising awareness and ensuring implementation and consideration of SALLnet outputs. Making use of SASSCAL's established infrastructure will facilitate communication between higher education institutions and a wide range of stakeholders. Establishing multi-stakeholder platforms that will be directly tied into the SALLnet research process will be a second, local multiplier for the dissemination of research findings and science-based recommendations. Furthermore, we will promote open access publishing of the study results as much as possible. The South African Research Infrastructure Roadmap (SARIR) recently made two awards for national research infrastructure: the South African Population

Research Infrastructure Network (SAPRIN) and the Expanded Terrestrial and Freshwater Environment Observation Network (ETFEON). The objectives of SALLnet are well-aligned with the aims of both and will be able to contribute data to these networks. The SA partners in SALLnet have submitted a funding proposal to the Alliance for Collaboration in Climate & Earth Systems Science (ACCESS), in support of the Global Change Research Plan of the National Research Foundation. SALLnet is congruent with themes 4 & 5 of the ACCESS call (i.e., impact of seasonality on the provision of ecosystems goods and services, and the policy and regulatory responses to such impacts). The ACCESS proposal will focus on the role of climatic seasonality, and possible shifts in seasonality due to climate change, with the aim to increase societal resilience to such shifts, ensuring human well-being, and mitigating land degradation processes. The role and nature of ESs for human well-being, their links to the main land use types in the Limpopo region, and the interplay between land use, ESs and land degradation are key aspects where the SA ACCESS proposal could interlink with SALLnet activities. SALLnet and the ACCESS proposal together enable, to mutual benefit, a close integration of distinct, but complementary and mutually supportive objectives. These objectives will be tackled by a consortium with a proven high capability to deliver and advance knowledge in response to policy requirements.

1.3 Scientific and/or technical goals of the project

In SALLnet, the quantitative evaluation of innovative management options developed in consultation with local stakeholders (see e.g. Van Ittersum et al. 2004) will be a major goal. We will, in particular, investigate management effects on ecosystem performance under anticipated futures that we coin “land use management scenarios”.

In addition, the potential land use impact of selected policy scenarios will be explored. We will explicitly analyze options for three major land use types, aiming to enhance their resilience to climate variability and change by identifying effective options for climate adaptation and mitigation. In a first step, we will identify prominent climate-induced risks and their potential impacts on the SDGs (see Fig. 1).

On the basis of that risk assessment and previous research in LLL, targeted field observations, experiments and a synthesis of accumulated science-based information will be conducted. We will specifically consider landscape-scale interactions of different land use systems (see, Fig. 2) by advancing integrated assessment approaches of ESs and their management. Considering such interactions is vital for sustainability assessments (Raudsepp-Hearne et al. 2010). Crop and rangeland modelling and different modes of scaling will be applied to evaluate risk management options from field to regional scale. This information will then be utilized to develop risk

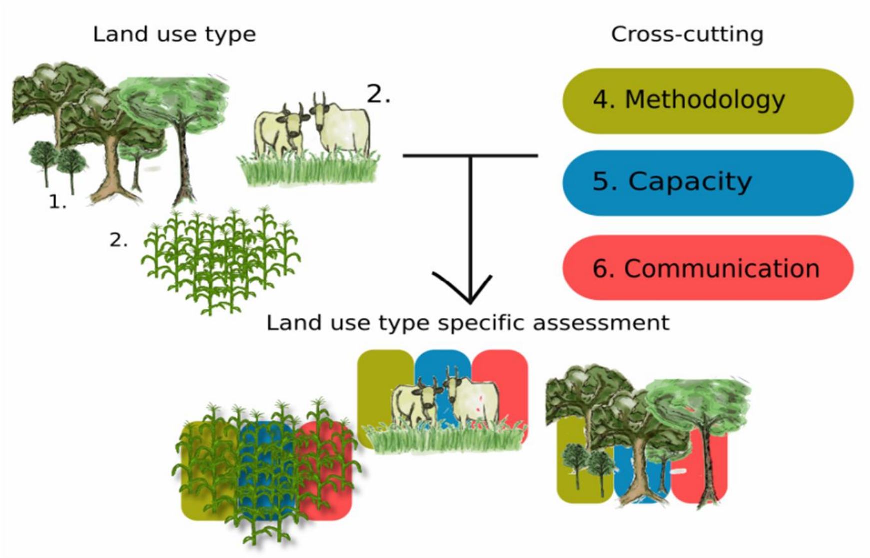

Fig. 2 Research matrix: land use type related research topics (1-3) and associated cross-cutting topics (4-6) leading to specific assessments in the three major land use types in the Limpopo Region (1. arable lands, 2. rangelands and agroforestry systems, and 3. orchards)

management strategies that are technically feasible, ecologically and economically viable, and socially acceptable for the baseline as well as for alternative future land use management scenarios. Finally, to facilitate identification and agreement among stakeholders on sustainable land use pathways while taking into account scale interactions, we will develop modelling frameworks and supportive user interfaces for interactive analysis of multiple goals. This will include identification of trade-offs and synergies between the goals. Our approach furthermore explicitly addresses the three cross-cutting issues (1) methodology development (green), (2) capacity building (blue), and (3) communication with stakeholders or clients at each step (red; see Fig. 2).

Specific technical and scientific objectives and innovations of SALLnet are:

- To develop a SALLnet toolkit for an assessment of ecosystem multifunctionality, combining quick, standardized, quantitative assessments of multiple ecosystem services with trait-based approaches;
- To identify synergies and trade-offs of ESs both within and across interlinked land use types, with direct implication for conservation and best management practices;
- To conduct integrated experimentation on management options in the face of drought to prevent system shifts towards desertified or bush-encroached states;
- To establish innovative methods to aggregate/scale and connect results from ground work and various modelling approaches in different land use types;

- To develop a first-ever macadamia model within a crop modeling environment
- To provide improved and extended ecosystem representation in process-based dynamic vegetation modelling by accounting for the role of nutrient availability and dynamics;.
- To develop a framework and platform for integration and synthesis of risk assessment
- To develop portable (across scales and land use types) qualitative and quantitative sustainability indicators
- To develop a user interface for dissemination of research results and policy re-commendations
- To establish mechanisms for interacting with different types of stakeholders
- To provide guidelines for decision support on sustainable land use (scientific goal)
- To provide insights for addressing policy questions on land use, food security, biodiversity, resilience (ecological and societal), and adaptation/mitigation strategies in response to climate variability/change (scientific goal)

Ground-based work (in subprojects (SPs) 1, 3) will focus on the three major land-use types within Limpopo's multi-use landscapes and their socio-economic context and performance (SP 4)(Fig. 3). These SPs will integrate their ground-based activities via a common study design and harmonized methodology. SP 4 will collect socio-economic data (tailor-made farm surveys) in the target villages and farms of SPs 1 & 3.The integrated field work will be scaled up (in SPs 1, 2 and 4) to various decision levels (farm, province); generated data will be integrated into agro-economic (SP 4) and agro-ecosystems models (SPs 1 & 2) for land use type-specific analysis as well as for an overall risk evaluation and scenario analyses with stakeholders (in SP 1). This eventually will result in a synthesis for the land use types, their interactions and policy implications (SP 1).

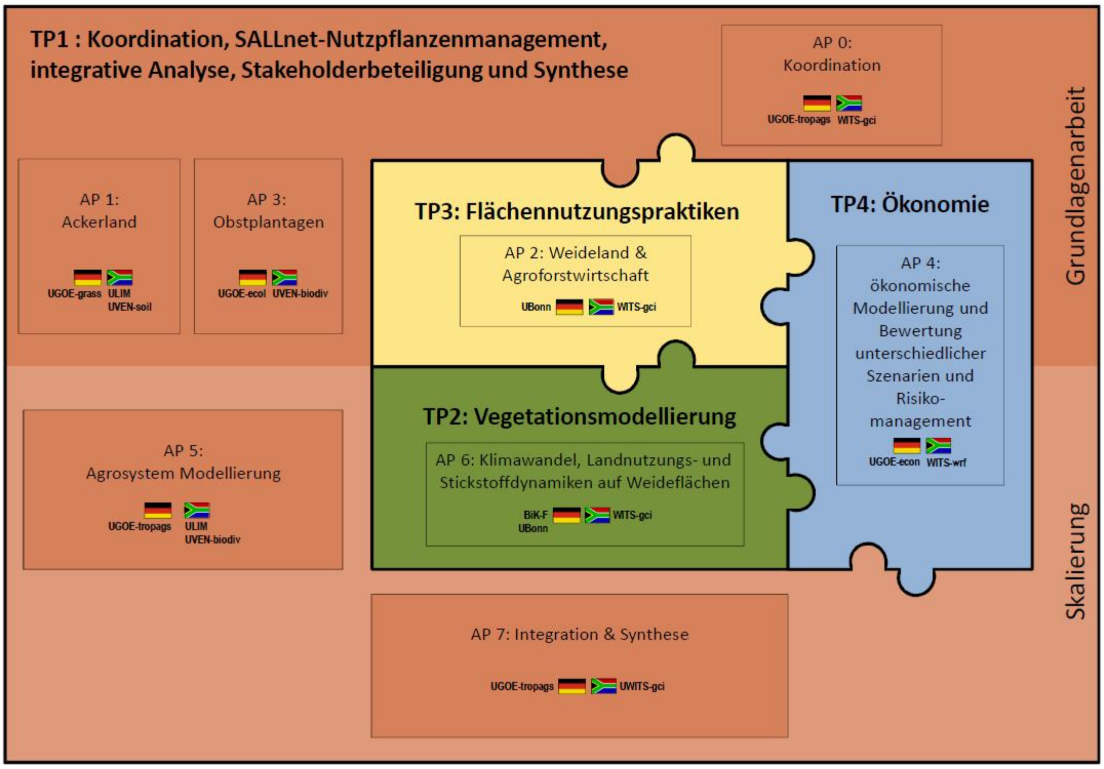

Fig. 3 SALLnet Sub-projects 1, 2, 3, 4 and their interactions

2. State of the art & previous work

2.1 State of the art

All terrestrial life on our planet inherently depends on the management of the available land resources. The study and modelling of future land use and associated management options for building ecosystem and social resilience requires an integrative understanding of how ecological, economic and socio-cultural drivers interact and thereby affect the provision of ecosystem services (ESs) for human well-being. Moreover, the interests and objectives of different stakeholders have to be taken fully into account for any management and policy intervention to be successful and sustainable (e.g. Van Paassen et al. 2007). The various drivers of land use change are coupled by interactions and feedbacks. To model these interdependencies, among the existing approaches (Verburg et al. 2016) socio-ecological systems theory has been increasingly applied and there are initiatives extending this into quantitative and dynamic modelling approaches (Berger and Troost 2014; Schlüter et al. 2014). For southern Africa, climate variability and change has been identified as a major driver threatening the achievement of most – if not all – of the 17 SDGs by 2030 and beyond (e.g. Dai 2013). Many studies exist on future land use and sustainable development pathways for distinct time horizons and spatial scales (Rötter et al. 2007; Verburg et al. 2009; Popp et al. 2017). However, while some methodological advancements have been made in terms of land use scenario analyses (Van Ittersum et al. 2004; Laborte et al. 2007; Van Paassen et al. 2007; Reidsma et al. 2015; van Vliet et al. 2016), to our knowledge, an approach combining novel aspects such as multi-scale assessment with transdisciplinary co-innovation at local scale for highly diverse interlinked land use systems so far has never been attempted.

In the following we will in particular address the state-of-the-art in each of the three major components of SALLnet research project: (1) Groundwork, (2) Scaling and (3) Integration & Synthesis.

(1) State-of-the-art in assessing multiple ecosystem services in African drylands groundwork on land use management

Ecosystem multi-functionality, i.e. the ability of ecosystems to provide society with the multiple ecosystem services (ESs) needed to prosper, are closely connected to biological diversity (Cardinale et al. 2012; Duffy et al. 2017). Empirical studies focusing on global drylands have shown evidence that in these vulnerable ecosystems, a loss of biodiversity may considerably impair the delivery of critical ESs such as carbon storage, productivity, and the build-up of nutrient pools (Maestre et al. 2012). Recent studies suggest that biodiversity at multiple trophic levels is needed for ecosystem multi-functionality (Lefcheck et al. 2015; Wood et al. 2015; Soliveres et al. 2016). However, it is a challenging task to capture multiple ecosystem functions and services, including those mediated by trophic interactions. This leads to a clear gap between the data available and those needed to identify best management options to sustain critical ESs. To fill the ‘ecosystem function data gap’, sets of easy-to-use standard methods, such as the REFA (Rapid Ecosystem Function Assessment) protocol, seem promising (Meyer et al. 2015) but need to be tested. The underlying idea is addressing a range of functions to represent overall functioning, rather than measuring single functions in detail.

Among more elaborate approaches, trait-based research is particularly useful, and is even considered by some (e.g. Martin and Isaac 2015) as a key for an improved understanding of agroecosystem functions and ES delivery in the face of land-use intensification and climate change. A ‘trait matching’ i.e. the identification of those functional traits that mediate linkages between adjacent trophic levels, may help to understand the translation of functional diversity across trophic levels (Le Provost et al. 2017) – however, such has rarely been applied in Southern African agroecosystems.

Ecosystem multi-functionality of savanna ecosystems may be considerably threatened by bush encroachment (D'Odorico et al. 2013; Soliveres et al. 2016). Unfortunately, the design of appropriate management interventions to avoid massive tree establishment is still impaired by our limited understanding of the ecological mechanisms behind encroachment (Joubert et al. 2008; O'Connor et al. 2014). Contrasting conceptual models have been proposed, and are still controversially discussed. In recent years, top-down (or demographic-bottleneck) models of savannas have gained favour over traditional, bottom-up (or competition-based) models (Bond 2008; Sankaran et al. 2008). Top-down models argue that the critical problem for savanna trees is of demographic nature: Climatic stresses and/or disturbances such as fire and grazing limit successful tree seedling germination, establishment and/or transition to mature size classes (Higgins et al. 2000; Wiegand et al. 2006). These models put a main emphasis on direct (negative) effect of disturbances on tree seedling establishment and survival. For arid and semi-arid savannas, the models particularly highlight the importance of drought events (Sankaran et al. 2004), but reject indirect (bottom-up) effects of drought events on tree establishment (Higgins et al. 2000).

Results from field and pot experiments on factors causing bush encroachment in Africa's semi-arid savannas, however, have provided evidence that among various factors tested (grazing, and fire as top-down factors; nitrogen addition and irrigation as bottom-up factors), bottom-up factors such a high rainfall frequency and nitrogen deficiencies may also be responsible for an increased tree germination and survival (Ward 2005). This suggests that top-down and bottom-up effects may jointly be responsible for tree establishment. In this context, indirect effects of drought may also play a role: As severe and/or prolonged drought may considerably increase the mortality of perennial grasses, seedling establishment may be facilitated in post-drought years (Fredrickson et al. 2006). Surprisingly, experimental studies have rarely explored the relative importance of bottom-up mechanisms (such as nitrogen limitation or competitive release in post-drought years) and top-down mechanisms (such as severe grazing and drought).

(2) State-of-the-art in the modelling of land use management options for crops and orchards, rangelands & agroforestry, their economic implications as well as effects of selected policy interventions

Process-based crop simulation models such as the Agricultural Production System Simulator (APSIM) are increasingly developed and applied to understand the effect of management and genotype change on productivity and other ecosystem services of arable land in a changing environment (e.g. Holzworth et al. 2014). Such analyses have been successfully done especially for the major crops such as wheat, rice and maize. Key advantage of crop simulation models is their ability to extrapolate effects across space and time. However, recently, model intercomparisons have shown that individual model predictions often contain high uncertainty (Asseng et al. 2013). To overcome the various modelling deficiencies (Rötter et al. 2011), model predictions are increasingly done by using multi-model ensembles. Secondly, more specific and targeted field trials designed for crop modelling improvements are needed (Rötter et al., in review). Another major point for the crop modelling community currently is the application of these models spatially; running them at high resolution grid cells by using super-computer facilities (Hoffmann et al., *accepted*). In SPACES-LLL, we have taken this argument up, and have tested the APSIM peanut model, a so far neglected crop in modelling. Based on model evaluation with field data we applied it for simulations for whole Limpopo (see, Fig. 5). However, much more work is still necessary to better present forage crops in APSIM. Furthermore, crop models have to be improved with respect to modelling crop rotation effects, rather than testing them just with single season runs. Improving rotation modelling would enable to more realistically simulate management adaptation options for climate change. Moreover, in line with global efforts, applying a range of crop models (multi-model ensemble modelling) would allow to indicate model uncertainty.

Last, but not least, when it comes to eco-physiological modelling of tropical and subtropical perennials, there is a huge gap in terms of available models and required process-knowledge, despite the fact that these crops often play a key role for the local economy in these countries. There are currently only very few models available for some perennials such as oil palm, coffee, cocoa and coconut (Hoffmann et al. 2014; Luedeling et al. 2016) – but not a single model for macadamia, which is very important in the study area.

Dynamic global vegetation models (DGVMs, Prentice et al. 2007) are process-based models that simulate eco-physiological and ecological processes based on environmental conditions. DGVMs simulate vegetation dynamics at large temporal and spatial scales and allow quantifying vegetation changes induced by climate and land use change. As most DGVMs do not adequately capture the complexity of grass-tree interactions in savanna rangelands, the adaptive dynamic global vegetation model version 2 (aDGVM2, Scheiter et al. 2013; Langan et al. 2017) has been specifically developed to represent tropical ecosystems. As a distinct key feature in aDGVM2, plant communities are composed of individual plants and dynamically adapt to biotic and abiotic environmental drivers through evolutionary processes and trait filtering.

In “Limpopo Living Landscapes”, the implementation of both the grass layer and the tree layer was improved to account for the diverse vegetation of the Limpopo province (see Fig. 4 for key

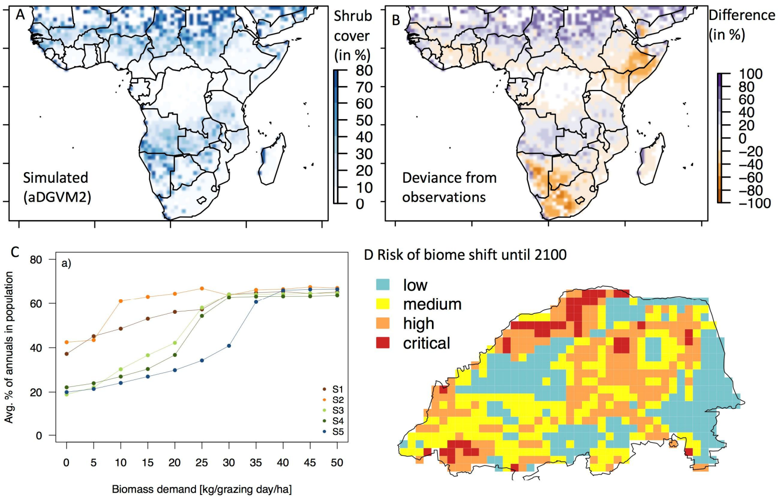

Fig. 4 Key results from previous work. The aDGVM2 allows to simulate observed patterns of shrub distribution in Africa (A and B). The novel implementation of annual and perennial grasses simulates changes in the grass community in response to grazing (C). Under climate change (here for RCP 8.5) the aDGVM simulates high risk of biome shifts in the Limpopo province until 2100, in particular in open ecosystems (grasslands, savannas).

results). While the original version of the aDGVM2 simulated only perennial grasses and single-stemmed trees, the improved model version simulates annual and perennial grasses (Pfeiffer et al. in prep) as well as single-stemmed trees and multi-stemmed shrubs (Gaillard et al. submitted). Model projections using aDGVM2 and aDGVM (Scheiter and Higgins 2009, predecessor of aDGVM2)) for different IPCC emissions scenarios, i.e. RCPs 2.6, 4.5 and 8.5 show that in the absence of land use, simulated vegetation shifts towards more wood-dominated biomes with the highest risk of vegetation change in grasslands and open savannas (Scheiter et al. submitted). While this trend of woody encroachment is supported by empirical evidence (Buitenwerf et al. 2012; Stevens et al. 2017), previous aDGVM studies have several limitations: (1) land use and management was not considered in future projections; (2) nutrient limitation was not considered; (3) unexplained deviations between simulated and observed shrub patterns remained; (4) previous studies did not use a large ensemble of climate change projections. Yet, resolving these limitations is necessary to reduce uncertainty in integrated analyses in SALLnet.

Economic modelling and risk management. To map and predict interactions of heterogeneous firms and their joint reactions to climate change and policy interventions in the agricultural sector, agent-based models have been increasingly developed and applied throughout the past two decades (e.g. Balmann 1997; Barreteau and Bousquet 2000; Berger 2001; Evans and Kelley 2004; Happe et al. 2008; Berger and Troost 2014). In general, an agent-based model is defined as a system of interacting agents, who react autonomously to external influences

(Russell and Norvig 1995 p. 33). With regard to the agricultural sector, each farm can for instance be described as an agent. Agent-based models provide a considerably higher flexibility than formal-analytical models based on neoclassical theory, because various assumptions are not prescribed by the modelling approach and, instead, can be tailored to the problem at hand (e.g. Balmann and Happe 2001). The agents can be provided with a high bandwidth of individual characteristics and behaviors. Hereby, the heterogeneity of farms, for instance with respect to their type, location, factor endowment and management capabilities, can be explicitly considered.

To account for the increasing issues of agri-relevant risks and policy interventions, Feil and Musshoff have developed and applied an agent-based market model, which explicitly considers these aspects (Feil and Musshoff 2013, 2017a, b). In specific, the optimal long-term market entry, growth, shrinkage, exit and land-use decisions of heterogeneous farms are analyzed in a competitive environment under uncertainty and different political schemes. However, more work needs to be done to properly model farm level adaption to climate change and other agri-relevant risks in Limpopo according to the overarching project goals. For instance, to date just one type of agri-relevant risks can be considered in the model at a time. The simultaneous integration of various risks, such as weather, demand and policy related ones, could considerably increase the relevance of the modelling results for the region. Moreover, the model as is does largely not allow for the short and midterm adoption of risk management options at farm level, like investments in irrigation technologies or the extension of the cultivation program by new cover crops. The additional consideration of such risk management options could provide important information with regard to their effectiveness and, thus, further enhance the relevance of the results both for farmers and politicians.

(3) State-of-the-art in the integrated assessment and modelling of land use management options and synthesis of scenario analyses with stakeholders

During last decades several frameworks for integrated assessment and modelling (IAM) of agro-ecosystems have been developed for different target scales, decision makers and research questions (see e.g. Van Ittersum et al. 2008) including such that address multi-scale assessments of climate change adaptation options (e.g. Lehtonen et al. 2010; Reidsma et al. 2015). Alongside with this, improvement of scaling methods for IAM has been initiated (Ewert et al. 2011). Different approaches for integrating biophysical and socio-economic analysis for land use management and policy design have been developed and tested under different environmental conditions (e.g. Aggarwal et al. 2001; Castella et al. 2007; Rötter et al. 2007; Van den Berg et al. 2007; Van Ittersum et al. 2004), some of these explicitly for addressing questions around climate change adaptation and mitigation for agricultural systems (Berger and Troost 2014; Reidsma et al. 2015). The involvement of stakeholders in research on land use scenarios has been pioneered by the SysNet project ((Van Ittersum et al. 2004; Van Paassen et al. 2007) which, already early on, developed web-based user interfaces for facilitating the interaction between scientists and different other stakeholder groups (Laborte et al. 2001; Rötter et al. 2005). To date, however, to our knowledge, a framework for integrated regional assessment of land management and policy scenarios affecting a range of land use types, taking into account the views of different stakeholders and including different decision and spatial and temporal aggregation levels, does not exist. Yet, designing, evaluating and operationalizing such as system together with stakeholders is a pre-requisite for providing relevant science-based information that can be applied to support technically feasible and socially acceptable decisions on sustainable land use management, design enabling policy interventions, and facilitate success in their implementation.

2.2 Previous work of the applicants

The German partners are tightly connected to their SA partners. The majority of the consortium has been jointly active in the region since November 2013 within the SPACES "Limpopo Living Landscape" (LLL) project providing a very strong base for institutional cooperation and investigation of sustainability issues. Most proposed activities build on previous work carried out in the LLL project, and on established cooperation between individual scientists. LLL has created partnerships in a region where so-called "Historically Black Universities" (ULIM & UVEN) are located and has performed active research in two UNESCO biosphere reserves. UWITS maintains a rural research station in the Kruger-to-Canyons Biosphere where an extensive human demography surveillance program and an environmental monitoring program have been in operation for the last 25 years, providing detailed insights into long term change and socio-ecological system coupling. Taking advantage of the infrastructure of the experimental farms at ULIM and UVEN, well-organized experimental and modelling platforms have been established (e.g. DroughtAct exploring rangeland resilience and management options in the face of drought). LLL has developed a vivid communication infrastructure and has been active in capacity building and teaching (for details, see https://www.uni-goettingen.de/en/555723.html). All relevant stakeholder groups ranging from individual farmers to local communities and policy makers had been involved in LLL. However, in spite of all these achievements, lessons learned from LLL indicate that it is essential to put a much stronger focus on the interactions between land use types in delivering ESs, integrate biophysical with socio-economic analyses at multiple scales, and strengthen stakeholder engagement already at early stages in the research process. SALLnet will make use of and further develop the inter- and transdisciplinary network as well as expand the scientific expertise of the consortium by integrating socio-economic research. Already in 2016 the consortium invited SASSCAL for discussing future exchange and collaboration. Collaboration with SASSCAL will be expanded. SALLnet is thus building a sound basis for tackling the challenges for research and development identified above, and described in more detail in the following sections. For a detailed overview of comparing activities from SPACES-LLL and SPACES II- SALLnet please see Tab 1, for details on individual expertise and previous work of working groups and PIs please see ANNEX I.

Tab. 1 Comparing activities and themes in SPACES-LLL with SPACES II-SALLnet

	LLL	SALLnet and assigned WPs	Partners involved in SALLnet
Integration & Synthesis Analysis across land use types	-	To develop a SALLnet toolkit for an assessment of ecosystem multifunctionality, combining quick, standardized, quantitative assessments of multiple ecosystem services with trait-based approaches (WP2) - To analyze synergies and trade-offs in multiple ecosystem services across land use types - To develop a framework and platform for integration and synthesis of risk assessment across and between land use types (WP7) - To operationalize and apply land use management information system (LUIS) for interactive scenario analyses with stakeholders (WP7) - To develop transferrable (across scales and land use types) qualitative and quantitative sustainability indicators (WP7)	ALL, Lead: UGOE-tropags and WITS-gci with specific contributions from UoBonn
Time frame	Mainly current climate conditions	Current as well as future climate change projections with specific link to HAPPI climate change scenarios (1.5°C target of COP21)	
Target group	- Smallholder farmers	Smallholder, commercial and emerging farmers	
Capacity building	- APSIM workshops for annual crops - Training of students in DroughtAct experiment	- To develop a user interface for dissemination of research results and policy recommendations (WP7) - Workshop for modelling macadamia (WPs 5 and 3) - Workshop on crop modelling (WP 5 and 1)) - Workshop on vegetation modelling (WPs 6 and 2) - Workshop for students regarding agricultural risk management in Limpopo (WPs 4, 1 and 5) - Workshop on assessment and analysis of multiple ecosystem services (WPs 1,2, 3 and 7)	ALL
Stakeholder involvement	- Meetings at workshops (3x)	- Workshops and individual consultations and regular visits of local and national stakeholders (WP 7 with contributions from all other WPs) incl. the following groups: - agribusiness, farmers, farmer advisors, NGOs, other resource managers, policy advisors and policy makers (local and national)	ALL

Socioeconomics	- Interviews on the use of ecosystem goods in four villages (1 MSc thesis)	- Large scale socioeconomic survey (n= 600+)on all farm types (WP4) - Assess ecosystem service demand (household questionnaires in villages) as a means to upscale and to match ecosystem service demand and supply - Efficiency analysis on the basis of farm-level data - Application of agent-based market model to three exemplary sub-regions of Limpopo region	UGOE-econ WITS-wrf WITS-gci
Arable land (modelling + experimentation)	- Field trials and modelling (one crop model APSIM) for testing new drought tolerant local legume crops in the field (lablab, cowpea, groundnut), 1 MSc thesis ongoing, 1 paper in press (Hoffmann et al) - On-farm trials testing these crops, not continued after 1 year due to severe drought (El Nino) - Water harvesting technique as adaptation for maize cropping (PhD thesis G Lekalakala finished)	- Modelling and experimentation of new forage and cover crops (WPs 1 and 5) - Monitoring effects of management on production and environment (WP1) - Upscaling of results using multi-model ensembles (WP5) - Extensive survey on forage crop use in the region (WP1) - Specific assessment of the trade-off between feed supply for livestock and using the residue for soil fertility improvement(WP1)	UGOE-tropags UGOE-grass UVEN-soil ULIM
Orchards/fruit trees (modelling + experimentation)	Impact of landscape context on ecosystems services in subsistence mango farms and commercial macadamia plantations (2 MSc thesis) Carnivores and rodents in the agro-ecological matrix (1 MSc thesis) Importance of birds and bats for natural biocontrol in macadamia production (2 PhD thesis, ongoing) Seven manuscripts (published and submitted) on animal diversity, responses to land-use change and management of ecosystem services	- Develop a first-ever macadamia model within a crop modeling environment (WP5 with WP3) - Monitor soil water and productivity of macadamia (WPs3 and 5) - Monitor of management effects on production and environment (WPs3 and 5) - Assessment of regulating ecosystem services along a climatic gradient (WP3) - Trade-offs and synergies between regulating ES (WP3) - Economic valuation as well as the management and upscaling of ESs in these systems (WP3) - Resource utilization of managed honeybees and native wild bee pollinators (pollen analysis) to identify spatial and temporal variation in resource use and to optimize pollination services within macadamia (WP3)	UGOE-tropags UVEN-biodiv UGOE-ecol UBonn

Rangeland (modelling + experimentation)	Experimentation: Set-up of DroughtAct experiment on rangeland management in the face of drought (one PhD thesis ongoing; one manuscript ready for submission) - Grazing effects on ecosystem structure and productivity (grazing gradients at four sites; analysis ongoing) - Diversity of selected taxa (plants, spiders, ants, rodents, bats) in two villages (3 MSc theses; 2 papers submitted) Modelling: - Dynamic vegetation model aDGVM2 extended to better represent biodiversity in Limpopo Province (grass layer simulates annual and perennial grasses; representation of trees and shrubs, i. e. multi-stemmed woody plants; representation of tree crown architecture improved; sub-model for grazing implemented) - Dynamic vegetation model aDGVM1 used to simulate potential biome shifts in Limpopo Province under IPCC RCP 4.5 and 8.5 climate change scenarios	Experimentation: - Conduct integrated experimentation on management options to prevent system shifts towards desertified or bush-encroached states, including bottom-up effects (N limitation, competitive release in post-drought years) and top-down effects (severe grazing) of tree establishment. (WP2) - Use existing infrastructure from the DroughtAct experiment - Implement novel treatments (nitrogen fertilization, planting of tree seeds) - Record parameters on demographic and ecological processes conceptually and / or empirically linked to tree establishment, such as vital rates of tree seedlings, and nearest neighbour effects on them; Assess effects of climate change and land use intensification on multiple ecosystem services (e.g. forage quantity and quality, carbon sequestration, decomposition, pollination, biocontrol) focusing on three land use types (rangelands, homegardens, arable land) nested within 15 villages along a climate gradient (3 levels of aridity) (WPs 1,2 and 3): - Rapid Ecosystem Function Assessment (REFA) - Ecosystem services provided by higher trophic levels with a trait-based approach - Dendrometry for trees' climate resilience - Analyse synergies and trade-offs of ESs Modelling (WP6): - Integration of nitrogen cycling into aDGVM2; necessary to understand impacts of elevated CO2 on future vegetation, greenhouse gas emissions and vegetation-herbivore interactions - Model testing and parameterization by replicating field experiments (DroughtAct) with models and using ground data from consortium - Assessment of climate and land use change impacts on multiple ESs (e.g. C and N dynamics, habitat structure, diversity, biome state) at landscape scale - aDGVM/aDGVM2 simulations for Limpopo province for a large ensemble of climate change projections and land use scenarios, in particular with respect to 1.5°C/2°C target of COP21 - Data integration into SASSCAL databases	UBonn UGOE-ecol ULIM WITS-gci BIK-F UGOE-tropags UVEN-biodiv UVEN-soil WITS-gci

3. Detailed description of the subproject/work packages

Ground-based SPs will focus on three major land-use types within Limpopo's multi-use landscapes (SPs 1 & 3), their socio-economic context and performance (SP 4). These SPs will integrate their ground-based activities via a common study design and harmonized methodology. Taking advantage of the steep climatic aridity gradient in South Africa's Limpopo region, the SPs will use a space-for-time substitution to evaluate effects of climate-induced risks on multiple ESs under conditions of climate change, and to assess the risk of undesired losses of ESs due to direct and indirect consequences of land-use change. A higher variability and a higher incidence of drought shocks can be expected under increasing climatic aridity (Ruppert et al. 2015). As done in previous dryland studies evaluating climate change effects via a space-for-time substitution (e.g. Guuroh et al. 2018), we will use the UNEP aridity index (AI; defined as precipitation/potential evaporation) to stratify sampling into three zones of climatic aridity: dry sub-humid (AI 0.50-0.65), moist semi-arid (AI 0.36-0.49), and dry semi-arid (AI 0.20-0.35). In each of these "climatic zones", five villages will be selected (15 target villages in total), where SPs 1 and 3 will sample in three LU-types (arable land, rangeland and agroforestry systems represented by homegardens). SP 1 will add data on adjacent orchards if applicable. Data on multiple ESs mediated by soil, vegetation and by higher trophic levels will be recorded in each land-use type. Based on previous work and on existing protocols (e.g. Meyer et al. 2015), a SALLnet toolbox will be established and applied to allow rapid field assessment of ESs.

SP 4 will collect socio-economic data (tailor-made farm surveys), among others, in the target villages and farms of SPs 1 and 3. In SPs 1, 2 & 4, the integrated field work will be scaled up to various decision levels (farm, province); generated data will be integrated into agro-economic and ecosystems models (SPs 1 & 2) for land use type-specific analysis, as well as for an overall risk evaluation and scenario analyses with stakeholders, which eventually will result in a synthesis for the land use types, their interactions and policy implications (SP 1). The assignment of the different work packages to subprojects is shown in Fig 3, for consistency we refer in the following paragraphs to work packages only.

Coordination (WP 0) will be managed by Prof. Rötter supported by a 75% 'project manager' position located at UGOE-tropags. A communication strategy will be developed to maintain effective communication within the project team and with relevant stakeholders. A kick-off meeting and annual workshops will be platforms for presenting project findings and networking amongst the project teams and with local stakeholders. Additional public outreach will be maintained via a project website and regular press releases.

3.1 WP 1: Arable lands [lead by UGOE-grass, ULIM and UVEN-soil]

3.1.1 Resource planning for WP 1: Arable lands

The overall aim of WP 1 is to analyze and develop the arable – ruminant livestock interface of smallholder and commercial farms along a climatic gradient in Limpopo to overcome the regular occurring feed shortages and to diversify farm management. On-farm investigations and in-depth on-station field experimentation will be combined to assess the spatio-temporal variability of available feed resources and to explore the potential of cover and neglected forage crops to sustain on-farm ruminant livestock production. The on-farm research will also comprise an assessment of soil fertility and production potential of the arable land in the 15 target villages. The applied methodology will comprise extensive farm surveying, field trials and crop and farming systems modelling. The research within WP 1 will be done in close co-operation with WP 4 (household survey) and WPs 2 and 3 (assessment of ecosystem services of the different land-use types). Data from WP 1 will feed in SALLnet integrative analysis of WP 7.

Livestock husbandry is a key agricultural activity in Limpopo and contributes to 30% of the average gross farm income which is more than twice as high as the contribution of field cropping. Apart from poultry, cattle and goat are common on the farms. They are kept by all categories of farms, i.e. the subsistence, smallholder (or emerging), and commercial farmers. While for the subsistence farmers ruminant livestock is predominantly kept as an insurance against household emergency situations, smallholders (in particular the emerging farmers) and commercial farmers provide livestock products to local and regional markets and thereby generate an important source of income. There has been considerable research in semi-arid southern Africa over the last 20 years to improve the forage basis of ruminant husbandry in South Africa and Zimbabwe. The adoption of research results focusing on tropical forages, mainly forage shrubs and tropical legumes (Whitbread and Pengelly 2004) in the farming practice was low, and the referring crops are not grown to any appreciable extent. As a main reason for this the resource limitation in particular of the subsistence farmers was identified (Whitebread and Pengelly 2004). Therefore, in the research proposed here, the focus will be on emerging smallholder and commercial farmers with an open access to markets and with the necessary land, financial and qualification resources.

Employing cover crops in arable systems to bridge phases of fallow bare soil in crop rotations has not been considered in Limpopo in any depth. (i) Potential advantages of such cover crops are: diversification of crop rotation – possibly increasing resilience/stability towards climate change/land degradation, (ii) soil conservation, reduction of erosion risks, supporting nutrient cycling, and provision of additional feed to ruminants in times where forage from crop residues and rangelands is scarce. WP 1 includes the following work package tasks (WP-tasks):

WP-task 1.1: Extensive farm surveying: to assess the spatio-temporal availability of feeding resources on smallholder and commercial farms that have ruminant livestock. A farm survey will be performed across a climatic gradient in Limpopo in the SALLnet 15 target villages. The focus will be on forage gaps and the conditions how they develop. Data on farm structure, livestock numbers, forage availability and forage quality, and livestock performance will be sampled on three occasions during the year and a feed balance will be established. The farm sample will be a subset of households that are analyzed within WP 4 (economics). The data will be used to analyze the relationship of site condition and farm structure and the forage basis and livestock performance at the farm level.

The research within WP-task 1 will be conducted in close co-operation with WPs 2, 3, 4 and 7. Farm selection and data acquisition on-farm will jointly be organized with WP 4 and will be aligned with the assessment of multiple ESs in WP task 1.2 and WPs 2 and 3. The results of the feed and livestock study will be used in an overall analysis in the integrative WP 7.

WP-task 1.2: Measuring of soil fertility and estimating production potential of the arable sites: As part of the joint and integrated assessment of ecosystem multi-functionality, this WP-task will focus on soil fertility and production potential with the aim to analyze synergies and trade-offs among feed provision on arable land and other ESs. This will be done in co-operation with WPs 2 and 3 on the selected arable sites of the 15 SALLnet target villages. The analysis will comprise soil physical and soil chemical variables (organic carbon and nitrogen, main soil nutrients, soil pH, soil texture and bulk density). Arable soil fertility data will be analyzed in relation with site and farm conditions as well as arable and livestock performance. The site selection and the organization of the survey will be done in close co-operation with the stakeholders as well as with the SALLnet partners from WPs 2 and 3. Data from WP-task 1.2 (arable land) will be merged with similar assessments of the other land-use types to understand synergies and trade-offs between critical ESs delivered by Limpopo's multi-functional landscapes (see WP-task 2.2). Results will feed into WP 7 for an overall analysis and synthesis of findings of the different WPs.

WP-task 1.3: On-station field experimentation on neglected forage and cover crops: field experiments at the experimental stations of ULIM and UVEN to test the potential of underutilized, and for the region, novel cover crops to provide additional forage for livestock. A series of field experiments will be set up on the experimental farms of the Universities of Limpopo and Venda to test the potential of cover crops to provide additional forage for livestock. Therefore a range of fast growing forage legumes and non-legume fodder crops including those from temperate climate mainly from the botanical families of *Poaceae, Fabaceae, Brassicaceae* will be grown in a crop rotation followed by maize under rainfed and irrigated conditions. The date of sowing will be varied. Data on germination and establishment, leaf area development and yield formation will be sampled in addition to climatic and soil water conditions. Forage quality will be assessed by proximate analysis. Nutrient and water use efficiencies will be deduced from the data. The measurements and analysis will also comprise the growth of the following main crop maize. Growth data will be used for the development of a "cover crop growth model" within the APSIM framework.

WP-task 1.4: Integrative analysis of data of WP-tasks 1, 2 and 3 to explore the relevant factors associated with feed shortages and livestock constraints on-farm and development of mitigation strategies. Data from on-station field experimentation with cover crops will feed the crop model (to be operationalized in WP 5) to evaluate the effect of changing climate (in particular water availability) on herbage yield and forage quality and compare management strategies on the long run. The water consumption of the crop and the carbon sequestration to the soil will also be assessed. In close co-operation with WP 4 farming system modelling will be used to evaluate the potential of cover crops to support the ruminant livestock husbandry and to close forage gaps. Results will feed in WP 4 (farm economics) and WP 7 (Integration & Synthesis).

Tab. 2 Timing of activities in WP 1 Arable lands [SP 1 – UGOE]

WP		2018				2019				2020				2021			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1.1	Extensive farm surveying																
1.1.1	Farm and site survey		■	■	■	■											
1.1.2	Data analysis of survey						■	■	■	■	■	■					
1.2	Analysis of soil fertility and production potential of arable sites																
1.2.1.	Site selection, development of common protocol			■	■												
1.2.2	Field data acquisition					■	■										
1.2.3	Sample preparation and data analysis							■	■	■	■						
1.3	On-station field experimentation																
1.3.1	Field experiments		■	■	■	■	■	■	■								
1.3.2	Sample preparation, labotatory analysis					■	■			■	■						
1.3.3	Data analysis, Setup of cover crop model							■	■			■	■				
1.4	Integrative crop and farming systems analysis																
1.4.1	Specific data analysis							■	■	■	■	■					
1.4.2	Data transfer									■	■						
1.4.3	Joint analysis and evaluation										■	■	■	■			

3.1.2 Major Milestones for WP 1: Arable lands

M1.1 Farm survey accomplished [project month 12; 03/2019]

M1.2 On-station field experiments, data acquisition and sample analysis accomplished [project month 23; 2/2020]

M1.3 Data transfer to WP7 [achieved in project month 27; 06/2020]

M1.4 Reporting of results [accomplished by project month 34; 03/2021]

3.2 WP 2 Rangelands & agroforestry [lead by UBonn and UWITS-gci]

3.2.1 Resource planning for WP 2 Rangelands & agroforestry

WP 2 focuses on the delivery of multiple ESs of Limpopo's rangelands and agroforestry systems, and evaluates ecosystem stability in the face of climate change. To this end, space-for-time substitutions for climate change (WP-tasks 2.1 and 2.2) will be combined with field experiments (WP-task 2.3) to explore suitable management options. To fill research gaps from the first phase, a main focus will be put on the tree layer. Beyond the land-use type related research of this WP, individual assessments of ES delivery from rangelands and agroforestry systems (this WP), arable land (WP 1) and orchards (WP 3) will be jointly analyzed to understand synergies and trade-offs between critical ESs delivered by Limpopo's multi-functional landscapes (WP-task 2.2). This integrated assessment of ecosystem multi-functionality is essential for a spatial upscaling in WPs 5 and 6, and for the synthesis in WP 7. WP 2 includes the following work package tasks (WP-tasks):

WP-task 2.1: Assess climate change effects on multiple ESs in rangelands and agroforestry systems: This WP-task is part of the integrated, cross-WP activity on ecosystem multi-functionality. Field work will concentrate on 15 target villages along the steep gradient of climatic aridity in Limpopo. Using a random sampling scheme, five plots will be established in villages' rangelands and homegardens (5 plots × 2 land-use types × 15 villages = 150 plots), complementing plots on villages' arable land (see WP-task 1.2) and in adjacent orchards (c.f. WP-task 3.1). Soil- and vegetation mediated ESs will mainly be assessed via a Rapid Ecosystem Functioning Assessment, REFA (Meyer et al. 2015) while ESs provided by higher trophic levels will mainly be evaluated with a functional trait approach.

Soil- and vegetation-mediated ESs: Here, (i) provisioning ESs (forage quantity and quality, and the provision of timber and non-timber forest products) will be quantified along with the related ESs of (ii) primary production, (iii) carbon storage, (iv) erosion control, and (v) disturbance regulation, using non-destructive methods. For the tree layer, we plan for 20 × 50 m plots, but will adjust plot size to tree density. We will record trees' and shrubs' species identity and measure trunk diameter and canopy metrics (area, density and height). Adult trees (stem diameter >5 cm) will be marked to allow repeated observations. Generic allometric models will be used to estimate aboveground biomass from stem diameter, canopy height and wood specific gravity (Chave et al. 2014). The latter will be obtained from literature and validated via wood samples to account for regional-scale differences in specific gravity. Woody root biomass will be estimated with a fixed root-shoot ratio (Addo-Danso et al. 2016). Ecosystem services from the grass layer will be sampled on 100 m² subplots nested within plots. We will set up three sampling quadrats of 1 m² equipped with moveable cages to estimate herbaceous species' aboveground biomass from cover, height and phenology (Guuroh et al. 2018). A field spectrometer will be used to assess quadrats' forage quality (metabolizable energy) from spectral models recently established for African savanna rangelands (Ferner et al. 2015).

Biomass data will be aggregated on the level of species, functional groups and vegetation layers, and used to estimate (i) provisioning ESs, (ii) primary production, and (iii) carbon storage in plant biomass. Carbon storage in soils will be quantified via soil analyses. Topsoil samples (0-10 cm) will be pooled from five randomly placed corers per plot. Besides soil organic carbon, we will analyse various soil physical and chemical properties (soil N, main soil nutrients, soil pH, and bulk density) to assess soil fertility (similar as in WP-task 2.1). Soil texture will serve as a rough proxy for water availability (Meyer et al. 2015). For the ES ‘erosion control’ (iv), we will use the cover of perennial plants as a proxy (Rietkerk et al. 2000; Guuroh et al. 2018), as well as visible signs of erosion such as the length of exposed tree roots. For ‘disturbance regulation’ (v), climate resilience of important tree species towards the severe drought from 2013-2015 will be assessed with dendrometric methods.

ESs provided by higher trophic levels: As the REFA protocol puts little emphasis on ESs provided by higher trophic levels; we will additionally sample data with alternative methods. Considering the key role of trait-based research in understanding the causes and consequences of changes in agroecosystem function and ES delivery (Martin and Isaac 2015), the basic proxies suggested by REFA for saprophagous food webs and consumer-plant interactions will be complemented with a functional trait approach. REFA methods will be used to assess (i) litter decomposition via standard wooden sticks, (ii) belowground secondary productivity via a heat extraction of soil fauna from soil cores; (iii) aboveground secondary productivity via standardized suction samples of invertebrates; (iv) vertebrate herbivory via paired plots (grazed plots adjacent to cages to estimate grazing offtake); (v) invertebrate herbivory, and (vi) plant infection via a scoring of leaf damage, (vi) invertebrate predation via attack rates on artificial caterpillars, (vii) pollination via pan traps, and (viii) seed dispersal via removal rates of standard seeds.

For functional trait measurements, we will put emphasis on plant-pollinator interactions, but also consider biological control by invertebrates. Our field work will focus on rangelands, homegardens and on arable land. It complements the experimental assessment of pollination and biological control in macadamia plantations (c.f. WP 3). A nested plot design facilitates trait matching (Le Provost et al. 2017). Standard protocols will be used for sampling plant functional traits (Perez-Harguindeguy et al. 2013), and invertebrate functional traits (Moretti et al. 2017).

We assign 6 person months for the scientific coordination and harmonization of the various ground-based activities in WP2 (and in WPs 1 and 3). This demanding work requires a postdoctoral researcher who is familiar with the challenging field research conditions in rural Africa, with the REFA methodology and with non-destructive estimations of provisioning ESs including field spectroscopy. Soil- and vegetation mediated ESs will be assessed by tandem of a German PhD student (N.N.) and a South African PhD student. For the German PhD student, we assign 7.8 person months to WP-task 2.1. The South African student (N.N.) will be funded by the Alliance for Collaboration on Earth System Science (ACCESS) Annual Cycle and Seasonality Project (ACyS), and will be co-supervised by B. Erasmus (UWITS-gci) and A. Linstädter (UBonn). Tree layer ESs will be analysed in the PhD thesis of Vincent Mokoka funded by DAAD, supervised by A. Linstädter (UBonn) and K. Ayisi (ULIM). The study on trees’ climate resilience will be done by a DAAD-funded MSc student (N.N.) at UGOE-tropags (supervised by E. Fichtler). Cascading effects of land-use intensification on ecosystem services within trophic networks will be evaluated by a DAAD-funded

German PhD student (N.N.). He/she will be jointly supervised by A. Linstädter (UBonn) and C. Westphal (UGOE-ecol).

WP-task 2.2: Analyze synergies and trade-offs of multiple ESs on landscape level: The extensive field data collected with our SALLnet toolbox in the 15 target villages constitute an excellent data basis for an integrated assessment of ESs delivered by Limpopo's multifunctional landscapes. The data set allows addressing interactions (synergies and trade-offs) of multiple ESs within and across land-use types, and under future climate conditions. In a first step, ES bundles will be identified via multivariate methods such as Principal Components Analysis (PCA). This approach will also allow to capture synergies and trade-offs of ESs at different scales (Raudsepp-Hearne et al. 2010). Trade-offs will be further quantified with a statistical approach developed by Bradford and D'Amato (2012) and already applied in drylands (Lu et al. 2014; Feng et al. 2017). This method extends the traditional meaning of trade-off from a negatively correlated relationship to the inclusion of uneven rates of same-direction changes. We will use Structural Equation Modelling to explore direct and indirect effects of environmental conditions (including changing climate and land-use) on individual ESs, ES bundles, and ecosystem multi-functionality.

In a next step, synergies and trade-offs in the supply of multiple ESs will be matched to social preferences. To this end, interviews with farmers (done in close collaboration with WP 4) will be used to analyze factors influencing land users' awareness and valuation of different ecosystem service categories (Martín-López et al. 2012). We envisage that this analysis will considerably improve our understanding of how climate and land-use changes will jointly affect ecosystem service delivery in savannas. Results will be integrated into models for the development of land-use and policy scenarios (with WPs 4 to 7). Based on model results and discussions with farmers, recommendations will be drawn on the sustainable use of land-use systems in the face of climate-related risks.

We assign 7 person months for WP-task 2.2. The planned work is very demanding (especially the synthesis of multiple ESs) and requires an experienced postdoctoral researcher who is familiar with state-of-the art statistical analyses such as Structural Equation Modelling.

WP-task 2.3: Evaluate land-use options under (post-) drought conditions: This WP-task will take advantage of the large-scale field experiment DroughtAct that was established in the LLL project on ULIM's Syferkuil Experimental Farm. After a pre-treatment year (growth period 2013/14), passive rain-out shelters and grazing exclosure fences were set up in the growth period 2014/15 to simulate a severe drought in combination with differing resting schemes of the rangeland. The experiment is currently in its fourth treatment years; and manuscripts describing the experimental set-up and results to date are in preparation (Mudongo et al. in prep.). DroughtAct offers a unique experimental platform that will be used in SALLnet to explore the relative importance of bottom-up mechanisms (nitrogen limitation and a competitive release in post-drought years) and top-down mechanisms (severe grazing and drought) for tree establishment.

Starting in the growth period 2018/19, seeds of the encroacher species *Acacia mellifera* will be planted in four treatment plots per block. Two of these plots per block have a history of severe drought (DH+; i.e. a two-year experimental drought followed by a non-drought year and a one-year drought), while the other two plots were not subject to experimental drought (DH-). This enables us to assess if previous drought events may open up a time window for tree establishment due to competitive release.

We will implement nitrogen fertilization treatments (N+ and N-) in a full factorial design with four treatment combinations: DH+N+, DH+N-, DH-N+, and DH-N-. Fertilization treatments will be performed on those plots that are already bounded by trenches to avoid nutrient leaching to adjacent areas. The layout of the N fertilization treatment is compatible with the sampling protocol of the Nutrient Network (NutNet). Facilitated by the large size of treatment plots (6 × 6 m), we will use a split-plot design to additionally evaluate grazing effects on tree seedling establishment. Hence we will have eight treatment combinations, replicated across four blocks.

Besides this new add-on to DroughtAct, the multiple-year experimental evaluation of combined grazing and drought effects will also be maintained. The drought treatment in this core experiment follows the sampling protocol of the International Drought Experiment (IDE). Grazing and drought treatments are implemented across four treatment plots per block via a full factorial design. We aim at exploring ecological conditions and (possibly) early-warning-sign of the anticipated ecosystem collapse under conditions of prolonged severe drought. During the rainy season, weekly measurements of soil moisture dynamics per plot will be maintained on all eight treatment plots per block. The methodology (soil access tubes and a portable moisture sensor) is similar to that used in WP 1. Data on daily temperature and rainfall will be taken from an existing climate station at Syferkuil Experimental Farm. In addition, air temperature and humidity within experimental treatments will be monitored with small sensors.

In the bush encroachment add-on to DroughtAct, response variables will be selected to reflect demographic and ecological processes that have been conceptually and/or empirically linked to tree establishment (see State-of-the-Art section). This includes aboveground and belowground net primary production (ANPP and BNPP). Vital rates of *A. mellifera* seedlings will be assessed to explore recruitment filters during different stages of recruitment, i.e. emergence, growth, and survival (Thuiller et al. 2008). The effect of interspecific competition with perennial grasses on tree seedling growth and mortality will also be evaluated, using a nearest neighbour approach (Zimmermann et al. 2010, 2015). We envisage that these results will allow us to elucidate functional pathways and limitations of bush encroachment, and to derive recommendations for rangeland management within favourable time windows for tree establishment.

To assess drought and grazing effects on ecosystem functioning in the core DroughtAct experiment, we will record vital rates of dominant perennial grass species. Treatment effects on changes in functional plant strategies will be recorded with a trait-based approach. We will sample six major traits that are critical to growth, survival and reproduction, as reflected in the recently established global spectrum of plant form and function (Díaz et al. 2016). These are leaf traits (leaf area, leaf mass per area, leaf N content), adult plant height, stem specific density, and seed mass. Trait measurements will be performed for dominant species of the grass layer. In addition, those REFA methods that are suitable for field experiments (such as litter decomposition, belowground and aboveground secondary productivity, and vertebrate herbivory) will be applied to link our results to those of the space-for-time substitution for climate change used in WP-task 2.1.

We request 20.6 person months for this WP. The planned implementation of an add-on experiment to DroughtAct with its eight new treatments requires the contribution of an experienced postdoctoral researcher who is familiar with designing and analyzing such field experiments. Thus, 15.6 person months for a PhD student will be complemented with 5.0 person months for a postdoctoral researcher.

Tab. 3 Timing of activities in WP2 Rangelands & agroforestry [SP 3 – UBonn].

WP		2018				2019				2020				2021			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
2.1	Assess climate change effects on multiple ESs in rangelands and agroforestry systems																
2.1.1	Target village & site selection		X	X													
2.1.2	Field campaigns in village sites				X	X	X		X	X	X						
2.1.3	Data analysis (within land-use types)						X	X			X	X					
2.1.4	Manuscript preparation											X	X				
2.2	Analyse synergies and trade-offs of multiple ESs on landscape level																
2.2.1.	Data analysis across land-use types						X	X	X	X	X						
2.2.2	Match of ES supply to ES demand										X	X					
2.2.3	Manuscript preparation											X	X				
2.2.4	Recommendations for stakeholders													X			
2.2.5	Training workshop on ES assessment													X			
2.3	Evaluate land-use options under (post-) drought conditions																
2.3.1	Data acquisition in DroughtAct		X		X	X	X		X	X	X						
2.3.2	Implementation of add-on experiment				X												
2.3.3.	Data analysis and paper preparation						X	X	X			X	X				
2.3.4	Policy brief development													X			

3.2.2 Major Milestones for WP 2 Rangelands & agroforestry

M2.1: Site selection and experimental set up completed [project month 6; 09/2018]

M2.2: Field data acquisition in rangelands and home gardens done [project month 26; 05/2020]

M2.3: Data analysis on ES supply within land-use types completed [project month 29; 08/2020]

M2.4: Manuscripts on direct and indirect effects of changing climate and land-use on ESs, ecosystem multifunctionality and trophic networks submitted [project month 33; 12/2020]

M2.5: ES synergies and trade-offs within/across land-use types analysed [project month 27; 06/2020]

M2.6: ES supply matched to ES demand [project month 30; 09/2020]

M 2.7: Manuscript on ES demand and supply submitted [project month 32; 11/2020]

M2.8: Recommendations communicated to stakeholders [project month 35; 02/2021]

M2.9: Training workshop done [project month 36; 03/2021]

M2.10: Data acquisition in DroughtAct done [project month 26; 05/2020]

M2.11: Add-on experiment to DroughtAct implemented [project month 19; 10/2019]

M2.12: Data on ecosystem functions and land-use options in (post-) drought years analysed; manuscripts submitted [project month 33; 12/2020]

M2.13: Policy brief distributed [project month 36; 03/2021]

3.3 WP 3: Orchards [lead by UGOE-ecol & UVEN-biodiv]

3.3.1 Resource planning for WP 3: Orchards

WP 3 aims to extend the previous work on the value of two ESs and their potential trade-offs (pollination and biocontrol) in macadamia, adjacent land use types and on small-holder farms along environmental gradients, including information on economic and cultural valuation, and management options. We employ both “top-down” experimental (WP-task 3.1) and “bottom-up” cost-benefit model (WP-task 3.2) approaches, and we adapt a crop-modeling approach (APSIM) to model risk in macadamia orchards (WP-task 3.3). WP 3 includes the following WP-tasks:

WP-task 3.1: Trophic interactions and networks: to quantify plant-pollinator and pest-predator interactions in macadamia plantations and adjacent land use types using experimental exclusion approaches.

We will select six pairs of macadamia farms along a climatic gradient (i.e. increasing elevation in the foothills of the Soutpansberg). One farm per pair will be located in landscapes with high agricultural land use intensity, i.e. landscape composition is dominated by agricultural land use types, such as other orchards or agricultural fields. In contrast, the paired farm will be located in landscapes that are dominated by forests. On each farm we will select a macadamia plantation for experimental exclusion of birds and bats and pollinators. To analyze the effects of the surrounding landscapes on the functional diversity and delivery of ecosystems, we will employ an experimental exclusion approach using cages surrounding macadamia trees (two treatments: total exclusion and control with no exclusion of bats and birds) at the edge and in the center of the plantation (two cages and two fences per plantation). Each treatment will comprise two macadamia trees. The control treatments will be fenced to deter monkeys and bush pigs. In addition, on each tree we will employ three pollination treatments each on ten branches with approximately 6-7 racemes (open pollination, pollination exclusion as control treatment, hand pollination to maximize pollination success). These pollination treatments (nested within the biocontrol exclosure experiment) will allow us to quantify additive and interactive effects of pollination and biocontrol ES on macadamia yields (quantity and quality). Due to great climatic variability between years in the region, we will record pollinators, pests, birds and bats in two consecutive years during macadamia flowering. Fruit damage and yields per inflorescence will be quantified during nut development and for the final harvest. The proposed methods (bat/bird exclusion, pollinator exclusion, animal surveys, yield quantity and quality estimations) have already been successfully applied in SPACES I (LLL). Significantly extending this previous work, their combination and spatial extension to different land-use contexts and over a climatic gradient will allow us to upscale our findings from local to regional scales, and to assess the contributions of multiple ES to agricultural production in Limpopo province.

Bats and birds: We will conduct monthly point bird counts and monthly deployment of twelve passively recording bat detectors (Song Meter SM4BAT Bat Detector, Wildlife Acoustics). Acoustic recordings will be analysed to quantify activity and identify species of bats using an existing regional reference library of bat echolocation calls. Additionally, we quantify trophic cascades (food webs) by estimating abundance and richness of pest species, such as stinkbugs and moths sampled by scouting methods for stink bugs and light traps for moths. Functional identity and functional complementarity of bat and bird communities will be analysed. The work on bats and birds will be conducted by a South African PhD student at UVEN-Biodiv funded by ACCESS.

Pollinators: It has been demonstrated that inadequate cross pollination and consequent poor fertilization of the ovules result in low fruit set and consequently in low yields (Heard & Exley 1994, Trueman 1994). For this reason, the pollination management with managed and wild bees is of major importance for macadamia farmers (Howlett et al. 2015). Flower-visiting insects will be recorded during and after flowering of the macadamia trees within the plantations and in adjacent flower-rich land use types with transect walks. Flower rich land use types, such as ruderal vegetation, forests or other orchards, might represent important nesting and alternative foraging sites for managed and wild pollinations. Temporal and spatial shifts in pollinator communities will be analysed to identify important habitats for pollination management of both managed and wild bees and other pollinators, for instance *Diptera* (Rader et al. 2016). This work will be conducted by a PhD student (exclusion experiment, transect walks in macadamia plantations) and a MSc student (transect walks in adjacent flower-rich habitats, trait linkages within plant-pollinator networks).

Previous work in the proposed South African macadamia orchards found that farmers strongly focus on managed honeybees for enhancing pollination services (Grass et al., in revision). However, few guidelines for the optimization of honeybee management exist. To improve the pollination by honeybees within the macadamia plantations we will manipulate colony densities and their spatial arrangement on macadamia farms that are located in the Levuvuhu Valley. We will select eight cooperating farms on which we will experimentally increase or decrease the number of honeybee colonies. The fruit set on trees at different distances from the colonies and the number of pollen grains on the stigmata will be determined (see Cunningham et al. 2016 for details).

As honeybees seem not to be very efficient pollinators of macadamia (Heard 1994), direct flower-visitor observations of open pollinated inflorescences will be conducted during day and night time to identify other potentially more efficient pollinators. The behavioural and morphological traits of flower-visitors and their individual pollen loads will be analysed and the pollination potential of most dominant species will be assessed (Ne'eman et al. 2010). This work will be conducted within the framework of a MSc thesis.

The pollination of macadamia can be enhanced through intercropping of synchronously flowering cultivars (Howlett et al. 2015). In a hand pollination experiment we will test the effects of cross-pollination with pollen and pollen mixtures from different co-flowering cultivars. Based on these results the design of macadamia orchards can be improved through the cultivation of co-flowering cultivars that facilitate cross-pollination, fruit set and yields.

WP-task 3.2: Valuing and maximising ecosystem services in macadamia production: based on avoided costs (AC) model approach, to quantify the economic value of regulating ESs (biological pest control and pollination), assess their social and cultural relevance, and develop associated management schemes for macadamia.

For biological pest control, we will build on an existing avoided cost model for stinkbug predation by bats developed in LLL (Taylor et al. in revision). We will seek to obtain more accurate parameterization of this model and to evaluate how key parameters (such as stinkbug and bat densities) vary across the landscape. Some of these parameters can be obtained in association with the experiments described in WP-task 3.1, e.g. bat detector recordings and stinkbug counts. We will model density and suitable habitat of key predator and pest species along the climatic gradient. A PhD student at UVEN-biodiv, funded by the National Research Foundation (NRF), will model population dynamics and host plant related thermal tolerance of the major stinkbug pest, *Bathycoelia distincta*.

During our exclusion trials we will monitor fruit set and damage due to the most common pest species to evaluate the relative importance and potential trade-offs between pest control and pollination services. Based on these recordings, we will extend the avoided cost-benefit model accounting additionally for costs and benefits related to pollination services. Differences in nut set between the three pollination treatments can be used to estimate the profits that result from pollination services provided by wild and managed pollinators. Additionally, potential pollination deficits will be assessed based on differences between insect- and hand-pollinated racemes.

Parameters considering avoided costs due to pesticide treatments and costs for managed pollinators and benefits due to natural pest control and wild pollinator populations will be combined in comprehensive cost-benefit model for both ecosystem services.

We will engage actively with macadamia agronomists and farmers to model the effectiveness of different management strategies (e.g. no pesticide spraying, calendar spraying, threshold spraying, retention vs clearing of natural corridors, addition of artificial bat roosts etc). Based on available economic data and knowledge of processing practices and costs, we will attempt to derive and compare economical estimates of ES of biological control and pollination from both experimental and costs-benefit model approaches (Morandin et al. 2016). This will be the first study where general wide-scale cost-benefit models will be validated by local-scale experimental exclusion approaches.

WP-task 3.3 Contribution to modelling and upscaling: to analyze the landscape-scale and climatic effects on the delivery of ESs and productivity (in collaboration with SPs 5).

In this work package, we will work with colleagues in WP5 to provide parameters for the adaptation of APSIM-type annual crop modelling system for perennial macadamia orchards. Parameters will be provided from WP-task 3.1 and WP-task 3.2 as well as economic and other data obtained directly by industry project partners in the macadamia industry. LLL enjoyed the support of the SA Macadamia Association (SAMAC) as well as numerous farmers and the country largest processor, Green Farms, and these contacts will be developed further. Knowledge of the landscape-scale variation of some of these parameters will allow upscaling from local to regional scales and the modeling of climate and other anthropogenic and market effects. In this respect, we will interact with WP7 to try to project our models where relevant in terms of the defined future land-use management and policy scenarios.

WP-task 3.4 Water use and productivity of macadamia along an altitude gradient (in interaction with WP5)

Aim: Assess water use and productivity of macadamia

We will select at two of the above mentioned sites 12 trees. The trees will have the same age and will be the same cultivar. All management should be the same. The only difference should be between the two farms to capture agro-ecological difference (dry versus wet site). At each tree sap flux will be measured continuously for 14 months. Then we measure at each site temperature and relative humidity above and below canopy. Rainfall, stem flow and through fall will be measured as well. TDR for the top 30 cm will be installed (4 reps for each site). Additionally, in monthly intervals soil water for the whole depth will be measured gravimetrically. Each tree will be monitored according to fruit development and final yield. Leaf area index will be assessed via ACCUPAR LP-80. Leaf size and weight, diameter and breast height will be measured. Productivity parameter (number of flowers, harvested nuts etc.) will be monitored. Soil profiles will be conducted for each site, which includes physiochemical properties. This work will be conducted as tandem with the PhD student employed in WP5, who will also develop the Macadamia model (Supervision of this work is done by PIs of WP5, where also expertise for this work is available).

Tab. 4 Timing of activities in WP3 Orchards [SP 1 – UGOE]

WP		2018				2019				2020				2021			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
3.1	Trophic interactions and networks																
3.1.1	Site selection and experimental set up		■	■													
3.1.2	Predator, pest and pollinator recordings				■	■	■	■	■	■	■	■					
3.2	Valuing and maximising ecosystem services in macadamia production																
3.2.3	Development of cost-benefit model for regulating ecosystem services								■	■	■	■	■				
3.3	Modelling and upscaling																
3.3.1	Contribuition to Ddevelopment of AFPSIM-type model					■	■	■	■	■	■	■	■				
3.3.2	Integration of different model approaches												■	■			
3.3.3	Recommendations to industry											■	■	■			
3.4	Water use and productivity of macadamia along an altitude gradient																
3.4.1	Monitoring of productivity and soil water dynamics					■	■	■	■	■	■	■	■				

3.3.2 Major Milestones for WP 3: Orchards

M3.1 Site selection and experimental set up [project month 6; 09/2018]

M3.2 Analysis of plant-pollinator and pest-predator interactions in macadamia plantations and adjacent land use types [project month 30; 09/2020]

M3.3 Direct and indirect effects of pest control and pollination services on yields in macadamia plantations [project month 36; 03/2021]

M3.4 Development of a cost-benefit model for regulating ecosystem services (biocontrol and pollination) along a climatic gradient [project month 36; 03/2021]

M3.5 Model integration and final recommendations to farmers [project month 36; 03/2021]

3.4 WP 4: Economic modelling and assessment of different scenarios and risk management options for agriculture in Limpopo [lead by UGOE-econ & UWITS-wrf]

3.4.1 Resource planning for WP 4: Economic modelling and risk management

The overall aim of this subproject is to investigate the effects of present and future agri-relevant risks on the production activities and the economic performance of different farm types in the Limpopo region. On the basis of this, farm type specific and spatially explicit risk management options will be developed and assessed regarding their effectiveness under different land use management and policy scenarios. Based on survey data, the biophysical results from WPs 1 and 3 as well as extended stakeholder engagements, this subproject will address the following concrete research questions:

1. What is the status quo of the agricultural sector in the Limpopo province with regard to farm structures, farm types, land-use options, agri-relevant risks, risk exposure and risk management options of farms? (addressed by WP-task 4.1)

2. How efficient are the different farm types in Limpopo and to what degree is the presence of agri-relevant risks the reason for potential deviations from their efficiency optimum? (addressed by WP-task 4.1)
3. Can risk management options be developed that support farmers in improving their long-term efficiency and/or resilience under different land use management scenarios? (addressed by WP-task 4.2)
4. How can the long-term agricultural development in the Limpopo region be modeled under explicit consideration of competition, agr-relevant risks and different policy options both at farm and regional level? (addressed by WP-task 4.3)
5. How can the effectiveness of different policy options to promote the potential land use management scenarios and risk agricultural risk management be measured and, through this, spatially explicit policy implications derived? (addressed by WP-task 4.3)

These questions will be addressed in the following three WP-tasks:

WP-task 4.1 Characterization and economic assessment of different farm types and risks: Farm-level data will be collected in a survey comprising 600 farms in total. The sampling protocol is determined largely by WP 1, 2 and 3. This WP-task will rely on this stratification of the landscape and expand the sample size to ensure that data requirements are met for both, WP 1, 2 and 3, as well as for WP 4. The sample will be stratified with regard to (i) climate, (ii) land use and (iii) soil conditions (WP 7). A standardized questionnaire will be used to collect data on socio-economic household characteristics (e.g. educational level of farm manager, farm size, farm income), factor endowment (e.g. machinery, labour, land titles), production activities (e.g. various material inputs and their timing during growing season as well as desired and undesired outputs), information on agri-relevant shocks and risks (e.g. extreme weather events or household member passing away) as well as on market and policy related conditions and issues (e.g. local market access or land restitution). Furthermore, the survey will address other land use type specific questions, contributed by WPs 1, 2 and 3.

The survey will be designed and tested by the postdoctoral researcher of WP 4 under supervision of PI Feil, PI Bruemmer, and the PIs of the other WPs during the second, third and fourth quarter of 2018. In parallel to this, field work preparation will be conducted in Limpopo by the postdoctoral researcher. For the test of the survey, a sub-sample of approximately 30 farmers of different climate, land use and soil conditions will be visited. After this, the full survey will be implemented on-site by eight trained and experienced field workers under supervision of the postdoctoral researcher during the first and second quarter of 2019, this is in order to capture perceptions at different stages of the growing season.

Afterwards, the collected data from the survey will be analyzed in two steps: First, the different farm types will be further refined if needed by estimating and analyzing probability functions for different collected variables as potential sources for farm heterogeneity (e.g. farm size, production activities, mechanization level). Second, a stochastic frontier analysis (SFA) will be conducted to quantify the efficiency level of the different farm types and to understand the reasons for potential deviations from their efficiency optimum (Coelli et al. 2005; Greene 2008). In this respect, special attention will be paid to the identified agri-relevant risks, e.g. weather or market related, as a potential source of farm inefficiency. The SFA will be conducted by the postdoctoral researcher of SP 4 (WP4) under supervision of PI Bruemmer during the third quarter of 2019.

WP-task 4.2 Development and assessment of risk management options under different land use management scenarios: We will follow a mixed method approach combining qualitative and quantitative analyses to identify, develop and assess the farm type specific and spatially explicit risk management options for the three basic different land use management scenarios. First, we will have stakeholder engagements individually or in groups as appropriate to identify and develop existing, modified and new, innovative risk management options. This will be done in the context of WP-task 4.1 and relevant outputs from WPs 1, 2 and 3.

The stakeholder platform (established in WP 7) includes farmers, land owners, members of agricultural extension services, local scientists, policy advisors and politicians of Limpopo region. The resulting risk management options will be structured into (i) farm management instruments, like the adjustment or extension of the farm production program by alternative crops or the introduction of new technologies, (ii) market-based instruments, like the development and use of crop and livestock insurances, and (iii) governmental measures, like policy changes or the facilitation of credit access for farmers. The discussions will be coordinated and moderated by the postdoctoral researcher of SP 4 under the supervision of PI Feil and PI Bruemmer in collaboration with WP 7 during the fourth quarter of 2019.

Second, the developed risk management options will be assessed quantitatively on the basis of the collected survey data, the experimental results from WPs 1, 2 and 3 as well as the outcomes of modelling from WP 5 and 6. For instance, climate zone and soil specific information on relevant crops and cropping systems for different input levels and production technologies will be generated in WP 5. The assessment of risk management options will be conducted at farm level, initially not considering interactions between the competing farms and without up-scaling of the considered measures. For this, production economics modelling will be conducted by using risk-adjusted econometric (e.g. Di Falco et al. 2007) and risk-adjusted programming (e.g. Hardaker 2004) techniques. With these approaches, it will be verified whether and, if yes, to what extent the considered measures lead to a higher efficiency and/or a higher resilience of the farms. This will be done by the postdoctoral researcher of SP 4/WP4 under supervision of PI Feil and PI Bruemmer during the first quarter of 2020.

Third, the refined list of risk management options including the results regarding their effectiveness will be conveyed back to key stakeholders from the initial stakeholder platform. In these discussions, the feasibility of the considered measures including opportunities and challenges will be discussed. The discussions will be coordinated and moderated by the postdoctoral researcher of WP 4 under the supervision of PI Feil and PI Bruemmer in collaboration with WP 7 during the second quarter of 2020.

WP-task 4.3: Modelling the effects of selected risk management options for different sets of land use management and policy scenarios: An agent-based market model, which is based on the basic models of Feil et al. (2013) and Feil and Musshoff (2017a), will be developed and applied to three sub-regions, as defined by climatic conditions (see WP 7), by using all available farm level data from this (WP-task 4.1) and previous surveys. The basic model is capable of analyzing the long-term market entry, growth, shrinkage, exit and land-use decisions of heterogeneous farms in a competitive environment (Feil and Musshoff 2017b). This modelling approach will be enhanced by the following aspects: First, it will consider not just one, but various types of agri-relevant risks that are and will be relevant to the Limpopo region in the long term, such as weather, demand or policy-related risks. This will be based on the respective findings of the farm survey (WP-task 4.1) and WP 7. Second, the farms in the model will not just interact by competing in every production period to fulfill the same exogenous, uncertain demand for their agricultural products, but additionally on an integrated market for agricultural land. Available land may become a limiting factor in the future given current patterns of urban expansion. Through this, land use changes caused by the prevalence of certain farm types against others can be explicitly considered and depicted in the sub-regions of Limpopo. Third, the agent-based model will be expanded by a quadratic programming approach, which allows every farm in the model to make adjustments or extensions of their particular production program, for instance the additional cultivation of forage and cover crops as investigated in WP 1, in every production period. Hereby, not just land-use changes on a regional level, but also at the very farm level can be modeled over time. Fourth and in connection to the previous point, the selected risk management options (see WP-task 4.2) can be integrated into the production program of the farms. Through this, the long-term effectiveness of the considered measures can be assessed in a dynamic-stochastic context under explicit consideration of competition.

In the model, different policy measures and their respective effects on the farms entry, growth, shrinkage, exit and land use decisions can also be considered (Feil and Musshoff 2013). In this work package, these will be adjusted to actual and potential policy measures in Limpopo to feature the given land use management options in the long term. Such policy measures could for instance be incentive programs for the development of a wildlife-based economy, climate smart agriculture or biofuel production. In result, the effectiveness of the considered policy measures with regard to their defined goals can be assessed. The agent-based market model will be developed and tested by the postdoctoral researcher of WP 4 under supervision and support of PI Feil, starting already in the second quarter of 2018 until the third quarter 2019. On the basis of the survey data from WP-task 4.1 and the information of refined risk management options from WP-task 4.2, the model will be applied to three exemplary sub-regions of Limpopo by the postdoctoral researcher of WP 4 under supervision and support of PI Feil from the fourth quarter of 2019 until the third quarter of 2020.

Tab. 5 Timing of activities for WP 4 Economics [SP 4 – UGOE-econ]

		2018				2019				2020				2021			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
4.1	Identification and economic assessment of different farm types and risks																
4.1.1	Field work preparation		■	■	■												
4.1.2	Development and test of questionnaire		■	■	■												
4.1.3	Survey implementation: Sampling, data collection and data preparing					■	■										
4.1.4	Analysis of collected survey data							■									
4.2	Development and assessment of risk management options under different land use management scenarios																
4.2.1.	Stakeholder engagement for identification risk management options								■								
4.2.2	Quantitative assessment of risk management options									■							
4.2.3	Stakeholder engagement about feasibility of assessed risk management options										■						
4.2.4	Paper writing										■	■	■	■			
4.3	Impact assessment of different land-use and risk management options																
4.3.1	Development and testing of agent-based market model		■	■	■	■	■	■									
4.3.2	Application of agent-based market model to three exemplary sub-regions								■	■	■	■					
4.3.3	Paper writing										■	■	■	■			

3.4.2 Major Milestones for WP 4: Economics

M4.1 Survey designed and tested [project month 9; 12/2018]

M4.2 Survey implemented in the field [project month 15; 06/2019]

M4.3 Efficiency analysis on the basis of collected farm-level data conducted [project month 18; 09/2019]

M4.4 Risk management options developed and assessed [project month 27; 06/2020]

M4.5 Paper on agricultural risk management options in Limpopo [project month 30; 09/2020]

M4.6 Agent-based market model developed and tested [project month18; 09/2019]

M4.7 Application of agent-based market model to three exemplary sub-regions of Limpopo performed [project month 30; 09/2020]

M4.8 Paper on modelling and assessment of different land use management options and policy scenarios [project month 30; 09/2020]

M4.9 Paper on modelling and assessment of selected risk management options under consideration of different land use management options and policy scenarios [project month 30; 03/2021]

M4.10 Workshop for students regarding agricultural risk management in Limpopo [project month 36; 09/2020]

M4.11 Workshops farmers, members of agricultural extensions services and politicians for presentation of results of SP 4 [project month 36; 03/2021]

3.5. WP 5: Effect of climate change and management interventions on ecosystem services of arable land and macadamia plantations in Limpopo region [lead: UGOE-tropags with ULIM and UVEN-biodiv]

3.5.1 Resource planning for WP 5: Crops, Orchards

A key focus of the overall project is to explore how management changes (intensification, diversification versus status quo) in arable land and orchards potentially affect important ecosystem functions such as carbon sequestration or productivity from field/parcel via farm and village up to regional level under current and possible future climate conditions. Maintaining or improving these services will require an efficient exploitation of crop genotype × environment × management interactions (G × E × M). It is important to note that these interactions will be strongly affected by the site specific variability in terms of soil and topography, and also by the variability in time (e.g. inter-annual variability). The climate driven variability from season to season/year to year – i.e. the climate-induced risk for farming – requires special attention in Limpopo as the recent El Nino event 2015/16 amply illustrated. This event caused an extended dry spell over two years, which turned South Africa from a net exporter of maize to an importer. While field experiments such as conducted in SP1&3 will give important insights about the processes determining G × E × M, this understanding is limited to the field sites itself. Hence, we will use in line with other studies process-based crop growth models to upscale results across the Limpopo region in line with the three overall project land use management scenarios (Business-as-usual, efficiency oriented intensification and diversification oriented). WP 5 includes the following WP-tasks:

WP-task 5.1: Development and evaluation of a process based physiological macadamia growth model: Contrary to annual crops, currently, there is no physiological macadamia growth model. Thus, the aim of this subproject will be developing a model for macadamia. We will use current modelling frameworks such as APSIM (Holzworth et al. 2014) to adopt a macadamia model, i.e. we will use existing and well established modules for soil nitrogen, and water dynamics. In addition, in particular we will make use of lessons learned from the tree modelling exercise in APSIM for Eucalyptus and oil palm (Holzworth et al. 2014; Huth et al. 2014). To parameterize the model we will use two sources: own measurements from WP-task 3.3 (Collaboration with UGOE-ecol, UVEN-biodiv) and literature data. Physiological models require a range of parameters: From the field trial we will estimate transpiration efficiency, leaf size, specific leaf weight, phenology, leaf development rate, partitioning estimates, and nitrogen content in the different organs. These will compared with data from other sites reported in the literature and also missing parameter like root data which will not collect on our own.

For evaluation of the model we will use data sets from the region. This is done again done closely in collaboration with SP3. Data will be obtained directly from industry project partners, i.e. SA Macadamia Association (SAMAC) as well as numerous farmers and the country largest processor and Green Farms. Contacts will be developed further. The WP-tasks will be fulfilled by the PhD student employed by the University of Goettingen.

WP-task 5.2 Up-scaling the effect of management interventions on macadamia productivity and related ecosystem services: Physiological models such as the macadamia model developed in WP-task 5.1 are driven by climate and soil input data. To run such models on larger scales it requires gridded data. For climate variables we will build on existing efforts in SPACES-LLL, where we sourced gridded daily data for historical periods 1980-2010 (Sheffield et al. 2006; Ruane et al. 2015). For soil data we will use the data set from Leenaars et al. (2015), which was especially developed for simulation modelling applications in sub-Saharan Africa. In addition, we have station (point) weather data available from a range of sites across Limpopo, which were quality checked in SPACES-LLL. For climate change conditions we will have a range of climate scenario data sets available, which are listed in WP6, WP-task 6.3. Model input data sets will be jointly generated with WPs 6 and 7. The input parameter for current climate, climate change and soil will be the same for our WP-tasks 5.2 and 5.4, but also for the upscaling exercise in WP 6,. These data will make it possible to run the new macadamia model for each grid cell in Limpopo. We will then use the model to *ex ante* evaluate management strategies for macadamia according to three land use management (LUM) scenarios: efficiency-oriented intensification, diversification and business-as-usual.

In the efficiency scenario (LUM1) we will increase the irrigation efficiency through better monitoring and timing (if necessary, we increase the amount at the cost of groundwater); also we will increase nitrogen use efficiency by better timing in response to demand (and if necessary the fertilizer amount at the cost of leaching losses). Priorities for this scenario would be higher yields and less input per unit of output. In the diversification scenario we would decrease irrigation and

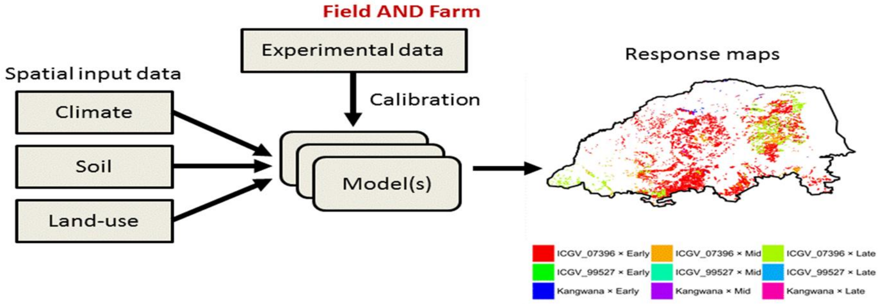

Fig. 5 Land use specific upscaling of management interventions (example modified from: Hoffmann et al. (2017). The example shows best combination of cultivar choice and planting date (response map) for peanut simulated for each 0.1°grid cell of Limpopo based on APSIM results.

fertilizer rates. Furthermore we would have lower planting area to allow additional structural plant elements like hedges in the plantation. Finally, for the business-as-usual scenario we would mimic the standard practice currently employed by the macadamia industry. For the efficiency/intensification and diversification scenarios we would assume optimal control of pests – in the efficiency/intensification scenario we would assume biocides and in the diversification scenario via biological control. This will be done jointly with WP3.

Simulation results will be used to inform the integration and synthesis work package WP7 and the economic analysis in WP4. Therefore, we will provide geo-referenced output and maps of various ESs and EFs such as productivity, carbon stocks and fluxes, nitrogen stocks and fluxes, water use, greenhouse gas emissions (CO2, N_2O) as affected by management. The WPtasks 5.2 will be carried out by the PhD student employed by the University of Goettingen supervised by the PIs of WP5.

WP-task 5.3: Model evaluation for arable cropping system: In the previous project we evaluated the capability of one important crop model called APSIM (Holzworth et al., 2014) to simulate also important (forage) legumes commonly cultivated in Limpopo (Hoffmann et al. under review ; Rapholo et al. 2017). In SPACES-SALLnet, WP 1, we propose the integration of new forage types and hence widening of the relatively narrow number of crops and crop rotations typically cultivated in the region. The modelling of both – the forage crops and the rotation – first needs calibration of the crop model and afterwards evaluation before it can be applied with some confidence. In addition to APSIM we will use also two other important crop models (WOFOST (van Ittersum et al. 2003) and DSSAT (Jones et al. 2003)) widely applied in southern Africa. This will allow quantifying the uncertainty associated with model predictions (Palosuo et al. 2011). Data for this calibration and evaluation WP-task will be derived from trials in WP1. Field trial data sets will contain important variables such leaf area index, soil water dynamics, yield components and biomass. Climate data necessary to run the models will be collected close to the sites. Important to note that this data will be collected at two distinctive sites and also in different seasons, which will enable us to evaluate the models independently from the calibration data set. The WP tasks 5.3 will be fulfilled by a DAAD funded PhD student from South Africa registered at the University of Goettingen and two MSc students registered at the University of Venda co-supervised by PIs M. Hoffmann and R. Rötter of UGOE-tropags.

WP-task 5.4 Upscaling the effect of management interventions on arable cropping system productivity and related ecosystem services: As in WP-task 5.2 and WP-task 6.3 we will use gridded soil and climate data (cf. see WP 6 data description and Fig. 5) to run the simulation models. For arable crops we will use the three crop models tested in WP-task 5.3 – WOFOST, APSIM, DSSAT to evaluate crop performance under specific management practices in line with the three pre-defined LUM scenarios for current and climate change conditions:

In the efficiency/intensification scenario we will use monoculture maize in the summer with high fertiliser input followed by a winter crop. Tillage will be applied before maize sowing. In the diversification scenario we will run more complex rotation with maize/legume intercropped, followed by a cover crop (which might vary from season to season) during winter. The crop will not be fertilised with nitrogen and no-tillage. The business-as-usual cropping will mean maize monoculture – unfertilized for smallholders and fertilised for commercial farmer's conditions. No intercropping or specific rotations will be considered.

As for WP-task 5.2 simulation results will be used to inform the integration and synthesis in WP7 and the economic analysis in WP4. Therefore, we will provide geo-referenced maps and data of various ecosystem services and functions such as productivity, carbon stocks and fluxes, nitrogen stocks and fluxes, water use, greenhouse gas emissions (CO_2, N_2O) as affected by management. In addition, we will quantify the uncertainty of our model predictions by having three models running for the same scenarios. The WP-tasks 5.4 will be fulfilled by a DAAD funded Phd student from South Africa registered at the University of Goettingen and two MSc students registered at the University of Venda, supervised by PIs of UGOE-tropags.

Tab. 6 Timing of activities for WP 5 Crops, Orchards [SP 1 – UGOE]

WP		2018				2019				2020				2021			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
5.1	Development of a process based physiological macadamia growth model																
5.1.1	Collect parameters for model development: Literature review, own measurements		■	■	■	■	■	■	■								
5.1.2	Calibrate the macadamia model against own data/historical data (Ahrends Farm)								■	■	■						
5.1.3	Evaluate the new Macadamia model against independent existing field trial data										■	■					
5.2	Upscaling the effect of management interventions on macadamia productivity and related ecosystem services																
5.2.1.	Exploring the effect of management interventions on crop productivity and soil organic carbon according to three project scenarios for current and future climate conditions climate conditions										■	■	■	■			
5.2.2	Exploring the effect of management interventions on crop productivity and soil organic carbon according to three project scenarios for climate conditions											■	■	■			
5.3	Model evaluation for arable cropping system																
5.3.1	Evaluation of the crop models WOFOST and DSSAT against generated data sets From SP1 in addition to APSIM						■	■	■	■	■	■					
5.4	Upscaling the effect of management interventions on arable cropping system productivity and related ecosystem services											■	■	■			
5.4.1.	Exploring the effect of management interventions on crop productivity and soil organic carbon according to three project scenarios for current and future climate conditions										■	■	■	■			
5.4.2	Exploring the effect of management interventions on crop productivity and soil organic carbon according to three project scenarios for climate climate conditions											■	■	■			

3.5.2 Major Milestones for WP 5: Crops, Orchards

M5.1 Working version of the new Macadamia model [project month 25; 04/2020]

M5.2 Paper describing Macadamia model development and evaluation submitted [project month 29; 08/2020]

M5.3 Paper describing the effect of irrigation management on Macadamia productivity submitted [project month 36; 03/2021]

M5.4 Paper exploring the effect of climate change on Macadamia productivity submitted [project month 36; 03/2021]

M5.5 Workshop presenting the Macadamia model to the Plantation associations [project month 29; 08/2020]

M5.6 Policy brief: Major findings from the Macadamia modelling exercise [project month 36; 03/2021]

M5.7 Paper describing model evaluation APSIM, WOFOST, DSSAT for new forage crops [project month 28; 07/2020]

M5.8 Paper exploring the effect of climate change on the new forage types [project month 34; 01/2021]

M5.9 Workshop: Introduction to APSIM [project month 10; 01/2019]

M5.10 Workshop: Upscaling of crop models [project month 22; 01/2020]

M5.11 Extension material available: New forage crops for Limpopo [project month 36; 03/2021]

3.6 WP 6: Climate change, land use and nitrogen dynamics in rangelands/shrubs [lead by BIKF, UBonn & UWITS-gci]

3.6.1 Resource planning for WP 6: Climate change, land use and nitrogen dynamics in rangelands/shrubs

WP 6 aims to project the impacts of biophysical (climate, CO_2, nitrogen) and socio-ecological factors on the provision of multiple EFs and ESs (e.g., livestock carrying capacity, maximum sustainable yield, trait/functional/habitat diversity, fuelwood harvesting capacity, C-storage, N-cycling) in the rangelands of Limpopo Province, using the vegetation model aDGVM2. The aDGVM2 allows to upscale from field campaigns (WP 2, WP 4) both in space (from sites to regional/continental scale) and in time (from historic and present to future). Model simulation runs will be designed in close collaboration with WP 5. The simulation results are indispensable for an integrated multiple-risk assessment in Limpopo (WP 7), and are aimed at the development of decision support guidelines. Integrated modelling studies will be conducted to develop guidelines for decision making. WP 6 includes three main work tasks: WP-task 6.1: model development; WP-task 6.2: model benchmarking, and WP-task 6.3: upscaling in space and time combined with impact assessment accounting for biophysical, socio-ecological and socio-economic factors. These activities will allow us to answer the following key questions:

- How do EFs and ESs in the Limpopo Province respond to climate change?
- How do multiple risks (extreme events, land use, policy change) influence future EFs and ESs?
- Does nutrient limitation mitigate or exacerbate climate change impacts on vegetation dynamics?

WP-task 6.1: Model development and nitrogen cycling: Aim: Extend aDGVM2 with routines describing nitrogen cycling; couple nitrogen and carbon cycle; adjust eco-physiological processes and anthropogenic impact models for nitrogen; extend aDGVM2 grazing routines to include browsing of woody vegetation; include fuel wood harvesting.

Nitrogen cycling has been incorporated in a variety of DGVMs, including ORCHIDEE-CN (Zaehle and Friend 2010), LPJ-DyN (Prentice 2008), or CLM4-CN (Lee et al. 2013). While nitrogen is important in all target systems of SALLnet, its dynamics is not yet accounted for in aDGVM2. To allow a more realistic simulation of (future) vegetation dynamics, explain deviation between observed and modelled shrub distribution (Fig. 4b) and to improve the representation of interactions between livestock, fire, vegetation, nitrogen and climate, the aDGMV2 will be extended by routines describing nitrogen cycling and the coupling between nitrogen and carbon cycle, using existing routines from other DGVMs (Prentice 2008; Zaehle and Friend 2010; Lee et al. 2013). We will consider relevant processes in and between plants, atmosphere, litter, soil, and microorganisms (see overview scheme in Fig. 6).

Model components describing leaf-level processes will be adjusted to account for effects of nitrogen availability on photosynthetic rates (Kattge et al. 2009) to constrain assimilatory carbon acquisition according to nitrogen availability. First steps have already been made in recent updates to aDGVM2 (Kumar et al., unpublished), albeit without accounting for limited nitrogen availability. Trade-offs linking carbon and nitrogen cycle will be introduced by linking nitrogen acquisition to the carbon costs of nitrogen fixation, uptake and re-translocation (Fisher et al. 2010). Within-plant nitrogen transport and allocation will be implemented based on the Thornley transport-resistance model (Thornley and Parsons 2014), a teleonomic approach aiming to maximize growth rate based on available resources. Work on incorporating the Thornley transport resistance model into aDGVM2 is already ongoing (Langan et al., unpublished).

Soil routines will be extended to account for nitrogen turnover through litter decomposition, microbial processes (nitrification, denitrification, symbiotic and asymbiotic fixation), root uptake, leaching and outgassing.

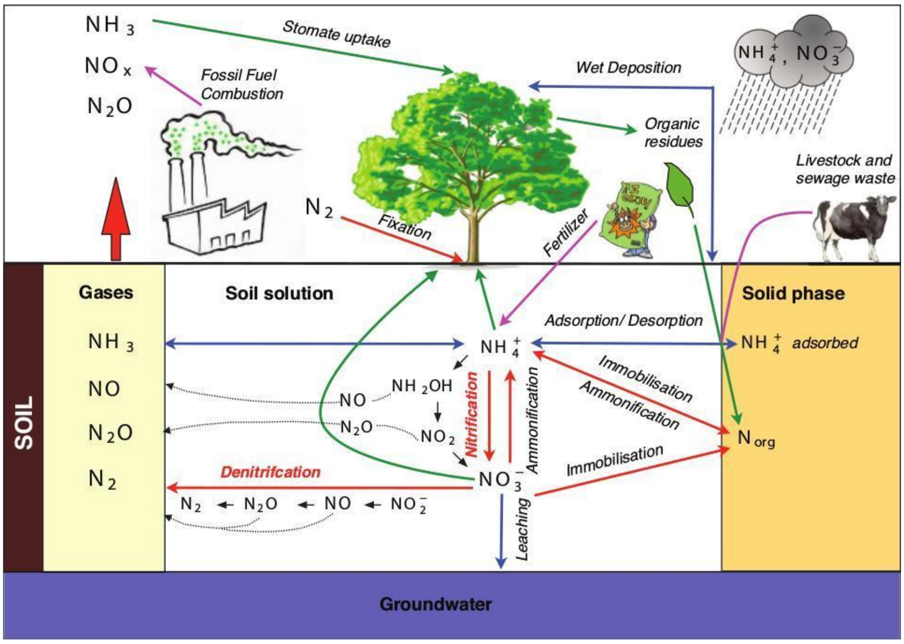

Fig. 6 Schematic overview of processes relevant to nitrogen cycling cycling that will be incorporated into aDGVM2. Red: soil-microbial; green: plant-related; blue: physico-chemical/abiotic; purple: human-related

Grazing routines will be updated to reflect the effects of leaf nitrogen content on palatability of leaf biomass (Mbatha and Ward 2010). The existing grazing routine will be extended to also simulate browsing of woody vegetation. In addition, routines to simulate fuel wood harvesting will be included and adjusted to handle multi-stemmed as well as single-stemmed woody plants.

Incorporation of a nitrogen cycle scheme into aDGVM2 will facilitate integration with APSIM (WP 5 and WP 7), as both models can be linked via C- and N-fluxes between rangelands and arable land (e.g., fertilizer application on agricultural areas; nitrogen consumed and excreted by animals; nitrogen transport to rangelands; nitrogen utilization by plants; combined greenhouse gas emissions (N_2O) from arable land and rangeland). It also facilitates cooperation with modelling in SPACES EMSAfrica where different DGVMs using or ignoring N cycling are applied.

WP-task 6.2: Model parameterization and benchmarking: Aim: To test model performance by comparing simulation results to data from field surveys conducted by the SALLnet consortium.

Model benchmarking will be conducted for the 15 target villages where assessments of the tree and grass layer are available (REFA, WP 2). We will run the aDGVM2 for the 15 study sites and statistically compare simulations and observations. Model parameters will be adjusted and calibrated to improve data-model agreement. Field and remote sensing data will be used to evaluate simulated productivity, carbon storage of grass and tree layer, habitat structure and distribution patterns of grasses, shrubs and trees.

Allometric models for tree biomass derived from field surveys (WP 2) will be incorporated to improve model performance for the study region. The model will be benchmarked against observed tree responses to drought. For this purpose, simulated tree diameter increments will be compared to dendrometric measurements.

DroughtAct experimental results (WP2) will serve to benchmark simulated drought response against observations. We will conduct simulations replicating drought conditions and land use and we will test under which conditions seedling recruitment and tree establishment is successful. Results from nitrogen fertilization and seedling recruitment experiments implemented within DroughtAct (WP2) will be used for model benchmarking, calibration and parameterization.

WP-task 6.3: Temporal and spatial upscaling and synthesis: Aim: To up-scale aDGVM2 simulations in space and time and to systematically test climate change and land use impacts.

We will conduct simulations required for the assessment of multiple risks that threaten ES delivery (WP 7). Therefore, we will systematically conduct simulations for various land use management scenarios for an ensemble of historic and future climate scenarios for the Limpopo Province. Thereby, we will focus explicitly on simulation for climate data for the Paris range of global warming from the Half-a-degree-Additional warming-Prognosis and Projected Impacts project (HAPPI scenarios, http://www.happimip.org/). This suggests analysing the impact of 0.5°C and 2.0°C warming above the pre-industrial period. Simulations will be conducted in close collaboration with WP 5 to ensure consistent simulation protocols.

Climate data aggregation will be conducted in close collaboration with WP 5 and WP 7, using historic measured and gridded data derived from interpolation and reanalysis (UGOE, Rötter, Hoffmann). Gap filled time series of weather data from ca. 30 weather station in South Africa will be used to run the model at site level. We will use the AgMERRA (Ruane et al. 2015) data set; this is a global product at 0.25° spatial resolution available for the period between 1980 and 2010 and it is commonly used for inter-comparisons of agricultural models. We will further use historic climate data compiled by the UGOE; these data sets are at daily temporal resolution and a spatial resolution of 0.25° for the period between 1955 and 2010 for South Africa. This data set was derived from interpolation and reanalysis.

In addition to model runs for historic climate, we will conduct an ensemble of future projections using climate projections from the ISIMIP project (Warszawski et al. 2014 www.isimip.org). Climate scenarios from GCMs within the CMIP5 framework cover the period between 1971 and 2099 for the RCP scenarios 2.6, 4.5, 6.0 and 8.5 and are provided at 0.5° spatial resolution. Additional future projections will use downscaled climate data provided by Francois Engelbrecht (CSIR Pretoria, South Africa) available for RCP 4.5 and 8.5 at 50 km spatial resolution and daily temporal resolution.

Soil data from ISRIC available at 1km resolution for sub-Saharan Africa will be used to run the model (Hengl et al. 2014). Variables provided in this dataset are C, N, soil depth, pH, field capacity, wilting point, saturation, and bulk density.

Different land use management scenarios will be simulated to test the impacts on large scale vegetation pattern and will be informed by the socio-economic surveys in WP 4.

- Business as usual: simulations will be conducted with different grazing and fuelwood harvesting intensities that represent current managed rangeland systems, with no change in energy mix and constant fuel wood harvesting.
- Efficiency-oriented: simulations will be conducted with increasing stocking rates and fuel wood harvesting rates reaching maximum sustainable yield.
- Diversification-oriented: for the biochar scenario, we will conduct simulations where bush clearing is maximized for biochar production; for the afforestation scenario, we will suppress grasses and fire to allow forest growth (secondary forest); for the wildlife scenario, simulations will be conducted with different grazing and browsing intensities to represent vegetation dynamics in conservation areas such as Kruger National park.

We will conduct these simulations in the presence and absence of the novel routines for N-cycling to test the impacts of N on future vegetation. This allows us to test the hypothesis that N-imitation influences vegetation patterns in Limpopo and mitigates CO_2 fertilization effects.

Simulation results will inform integration and synthesis (WP 7). We will provide data sets of various ecosystem services and functions such as vegetation type (grassland, savanna, forest), carbon stocks and fluxes, nitrogen stocks and fluxes, grass/shrub/tree cover, productivity, trait and habitat diversity, water use, and gaseous emissions (CO_2, N_2O, NO_x).

Climate and soil data as well as simulation results will be stored at the SALLnet cloud storage, hosted at the University of Göttingen and made available for WPs 5, 6 and 7.Climate and soil data will be assembled in close cooperation with SPACES EMSAfrica to allow model comparisons between SALLnet and EMSAfrica.

Tab. 7 Timing of activities for WP 6 Rangelands/Shrubs [SP 2 – BIKF]

WP		2018				2019				2020				2021			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
6.1	Model development and nitrogen cycling																
6.1.1	Implementation of N model		■	■	■	■											
6.1.2	Adjustment of fire model						■	■									
6.1.2	Adjustment of herbivory models								■	■							
6.2	Model parameterization and benchmarking																
6.2.1.	DroughtAct						■	■									
6.2.2	Remote sensing								■	■							
6.2.3	Socio-economic										■	■					
6.3	Temporal and spatial upscaling and synthesis																
6.3.1	Prepare climate data		■	■													
6.3.2	Simulations without N cycling				■	■											
6.3.3	Simulations with N cycling											■	■				
6.3.4	Data preparation for synthesis						■							■			

3.6.2 Major milestones for WP 6: Rangelands/Shrubs

M6.1 Climate forcing data prepared [project month 6; 09/2018]

M6.2 Projections of future vegetation based on biophysical factors (climate, CO_2) without N-cycling [project month 9; 12/2018]

M6.3 Projections of future vegetation based on socio-ecological factors without N-cycling [project month 12; 03/2019]

M6.4 aDGMV2 version coupled with nitrogen cycle submodel [project month 12; 03/2019]

M6.5 Fire and herbivory routines adjusted for N-cycling [project month 24; 03/2020]

M6.6 Benchmarking with ground data completed [project month 30; 09/2020]

M6.7 Projections of future vegetation based on biophysical factors (climate, CO_2) including N-cycling [project month 30; 09/2020]

M6.8 Projections of future vegetation based on socio-ecological factors including N-cycling [project month 33; 12/2020]

M6.9 Model results integrated into synthesis (SP 7) [project month 36; 03/2021]

Capacity building

M.6.10 Workshops on dynamic vegetation modeling [project months 12, 24, 36; 03/2019, 3/2020, 3/2021]

Communication

M6.11 Risk assessment and development of management recommendations for local stakeholders and decision makers [project months 9 and 36; 12/2018, 3/2021]

M6.12 Summaries/brochure with management recommendations [project month 36; 03/2021]

3.7 WP 7: Integration & Synthesis [lead by UGOE-tropags & UWITS-gci]

3.7.1 Resource planning for WP 7: Integration & Synthesis

WP7 aims to integrate results from WPs 1-6. It will develop a framework and platform for integration and synthesis, evaluate the outcomes of risk assessment, and perform analyses on land use management and policy scenarios jointly with stakeholders. Details on the identified key stakeholders is given in WP task 7.2. Special emphasis will be put on appropriate involvement of and interaction with the various stakeholder groups, multi-scale analysis and integration, e.g. synergies and trade-offs of ESs across land use types (WPs 1, 2, 3) or research for representative farm types (WP 4) with modelling results at the regional scale (WPs 5 and 6). We will consider relevant policy questions on land use, food security, biodiversity and climate protection (see WP4). WP 7 includes the following five WP-tasks:

WP-task 7.1: Development of an integrative framework: This WP-task links bio-economic modelling (from WP4) with scaling methods and databases – containing data from point to regional scale – that result from WPs 4, 5 and 6. The task furthermore includes identification of sets of different sustainability indicators/indicator groups that can be applied across scales and land use types to assess economic, ecological and social sustainability and their trade-offs.

The integrative framework describes the linkages between the outcomes of ecosystem modelling (rangelands, orchards and arable land) at multiple scales (grid and entire target region) and bio-economic modelling (farm-type specific, and scaled up to target region). It furthermore describes the required inputs for multi-scale modelling of land use management scenarios (LUM) (see, Fig. 7 for characterization of the key features of the LUMs) as well as inputs from stakeholders for scenario refinement, evaluation of scenario analysis results and formulation of policy options. Figure 7 illustrates how alternative management options aimed at sustainable intensification in agriculturally utilized land and affecting important ecosystem services could look like. Another major assignment in WP-task 7.1 is, therefore, the inventory and selection of sets of sustainability indicators quantifying the outcomes of ecosystem performance/ESs under the different land use management and policy scenarios. Envisaged indicator groups will deal with water use, carbon sequestration and emissions, biodiversity, nitrogen balances, productivity and profitability (see Fig. 8). Sustainability indicators will be further differentiated as needed (e.g., several aspects of biodiversity) and should be defined such that they are as much as possible applicable across land use types and scales.

This WP-tasks can be further divided into the following duties:

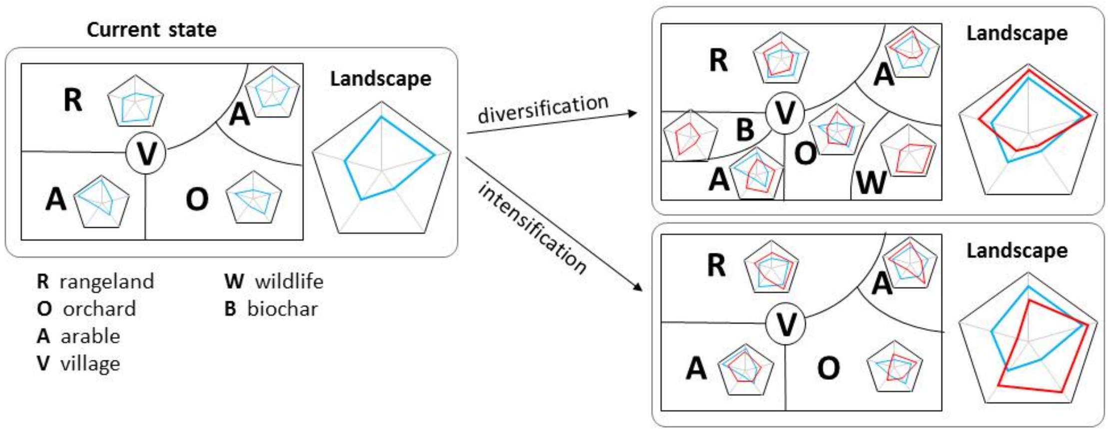

Fig. 7 Illustration of integrated ecosystem service assessment. The left panel shows how the landscape is split into different land use management (LUM9 scenarios and the spider diagrams (see also Fig. 8) illustrate provision of ES in each LU type and ES aggregated for landscape scale. Black lines in spider diagrams represent maximum provision of ES, blue lines represent realized provision. The panels on the right illustrate impacts of land use change (intensification or diversification). Intensification implies higher provision of ES in different LUM types, diversification implies more diversity in LU types but higher fragmentation. Red lines in spider diagrams indicate provision of ES in land use change scenarios, blue lines indicate ES of current state. Note, that the ES in spider diagrams are only schematic.

7.1.1 Development of an integrated framework

7.1.2 Inventory and selection of sustainability indicators

7.1.3 Identification of required input data.

The postdoctoral researcher, in consultation with all PIs and South African partners, will develop the integrative framework as well as the definitions and metrics of sustainability indicators (see IPBES 2016).

WP-task 7.2 Development of a platform of key stakeholders and mechanisms for interaction during the research process: Following earlier experience with establishing stakeholder platforms for research on land use management and scenario analysis (e.g. Van Paassen et al. 2007), we will tailor modes of interaction for the various stages of the research process to the conditions of Limpopo. That means, in personal consultations we will identify those key stakeholders involved during the entire duration of the research process. Ear-marked as key stakeholders (ca. 20 groups) are national and regional representatives of the various Ministries and research organizations (e.g. national: Department of Environmental Affairs; Department of Science & Technology, Agricultural Research Council; regional: Limpopo Department of Agriculture, Limpopo Department of Economic Development, Environment & Tourism (LEDET), University of Limpopo, University of Venda; Southern African Wildlife College), NGOs (e.g. SAEON, SANParks etc.) as well as representatives of local farmers, agri-business, policy advisors and politicians. In addition, through consultations with the major authorities and land owners in Limpopo we will identify a broader spectrum of stakeholders representing the different interest groups in the various sub-regions of Limpopo (farmers, land owners, members of agricultural extension services, local scientists) to be involved in major meeting events. The postdoctoral researcher of WP7 and the PI, RP Rötter, in close consultation with the South African research

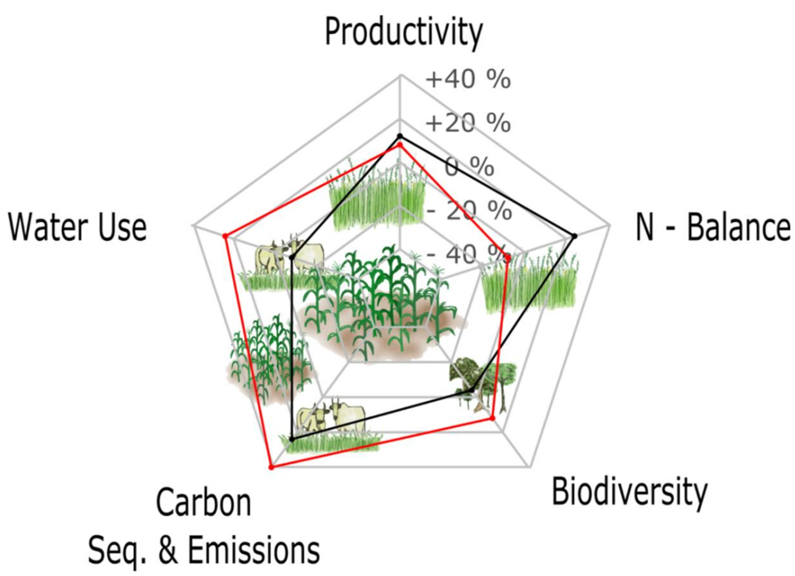

Fig. 8 Spider diagram illustrating potential sustainability indicator groups and their use in comparing different LUM scenarios

partners, will select the stakeholders and establish the platform and define the mechanisms of interaction and mode of operation (Van Ittersum et al. 2004; Van Paassen et al. 2007) (Fig 9).

In WP-task 7.2 we distinguish the following duties:

7.2.1: Inventory of relevant stakeholders and initial selection of key stakeholders to be engaged from start to the end

7.2.2: Establishment of mechanisms for interaction with the various stakeholder groups at different stages of the process 7.2.3 Extension of the stakeholder platform in the course of the project according to the interest/willingness, needs and specific issues addressed

WP-task 7.3: Establishment of databases for conducting a stratification of biophysical conditions and land-use and a large area assessment of multiple risks: The WP-task 7.3 includes following duties:

7.3.1. Create an inventory of existing spatial databases (gridded and point data) on current and future climate, soil and land use (in close collaboration with WPs 5 and 6), perform quality control and develop metadata structure.

7.3.2. Overlay the spatial data for stratification of the target region as a basis for selecting sites for experimentation and farm surveys.

7.3.3. Identify broadly the dominant potential risks in the target region through linking spatial databases for current and future biophysical conditions to ecosystem models (from WPs 5 and 6) as an input to WP 4.

7.3.4. Mirror SALLnet databases into existing data platforms like SMART, SAEON and SASSCAL Observation Net

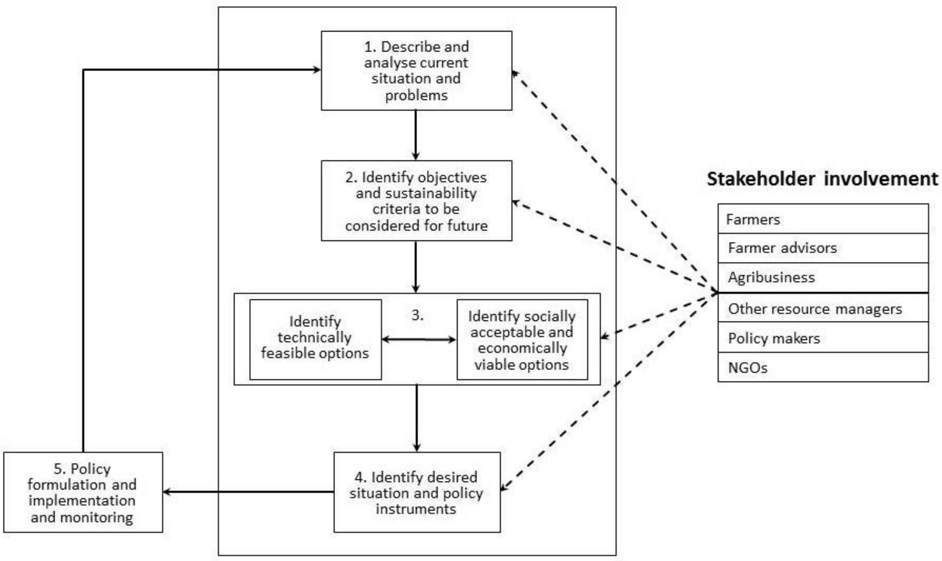

Fig. 9 Schematic of analyzing land use management and policy scenarios based on interactive modelling and synthesis jointly with stakeholders (modified from: Rötter et al., 2016)

The WP-task 7.3 will be performed by the Postdoctoral researcher (hired by UGOE-tropags) in close collaboration with Dr. Koch, Prof. Erasmus, and PI RP Rötter and in consultation with all other PIs.

WP-task 7.4: Development and testing a geospatial information system with a web frontend for interactive analyses of land use management and policy scenarios (LUIS – land use information system): The aim of LUIS is to support integrated, iterative and transdisciplinary land-use systems analysis with feed-backs to groundwork (WPs 1, 2, 3), modelling/scaling (WPs 4, 5, 6) and stakeholder discussions (Fig. 3).

This WP-task aims at the development and testing of a (prototype) information system with user interface for the quantitative exploration of the consequences of different land use management and policy scenarios for the three major land use types on selected sustainability indicator groups (water use, carbon budget, nitrogen balance, biodiversity, productivity, profitability). It will incorporate feed-backs from stakeholders on the adequacy and short-comings of empirical data from ground-work as well as the modelling results. It comprises the following duties:

7.4.1 Identification of required functionality of the system including visualization techniques in close consultation with key stakeholders

7.4.2 Operationalization: implementation and testing of technical functionality

7.4.3 Evaluation of functionality jointly with key stakeholders

WP-task 7.4 will be performed by the postdoctoral researcher in close collaboration with Dr. Koch, Prof. Erasmus and PIs JH Feil and RP Rötter, and in close consultation with key stakeholders.

WP-task 7.5: Capacity building for utilizing and improving LUIS for decision making: This WP aims to instruct and exchange with key stakeholders on the construction and analysis of land use management and policy scenarios and the interpretation and synthesis of the integrative modelling outcomes for the different scales (grid, farm type, region). Post-model analysis comprises formulation of risk management strategies, recommendations for supportive policy interventions as well as feed-back to field/farm level and modelling/scaling research. PIs Rötter, Erasmus and Dr. Koch supported by the postdoctoral researcher and the other PIs and South African Partners will provide support in interpreting and synthesizing.

This WP-task includes the following duties:

7.5.1: Produce training materials (description of LUIS, its functionality, examples of scenario analysis output and instructions on how to interprete charts, tables, etc).

7.5.2: Organize and conduct stakeholder workshops on interactive scenario analysis and interpretation

7.5.3: Produce syntheses of analysed scenarios and their interpretation in various forms utilizing different media

Tab. 8 Timing of activities in WP 7 Integration & Synthesis [SP 1 – UGOE]

WP		2018				2019				2020				2021			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
7.1	Development of integrative framework		■	■	■	■											
7.1.1	Integrative framework		■	■	■												
7.1.2	Sustainability indicators		■	■	■	■											
7.1.2	Data requirements				■	■											
7.2	Development of stakeholder platform		■	■	■	■	■	■	■								
7.2.1	Inventory & initial selection stakeholders		■	■													
7.2.2	Establish mechanisms		■	■	■	■											
7.2.3	Expand stakeholder platform			■	■	■	■	■	■	■	■	■	■				
7.3	Large area assessment of multiple risks																
7.3.1.	Inventory available data		■	■	■												
7.3.2	Stratification		■	■													
7.3.3	Identification Risks				■	■	■										
7.4	Development/evaluation of a land use information system (LUIS)						■	■	■	■	■	■					
7.4.1	Define functionality						■	■	■	■							
7.4.2	Operationalization							■	■	■	■						
7.4.3	Evaluation with stakeholders								■	■	■	■					
7.5	Capacity building and exchange on LUIS									■	■	■	■	■			
7.5.1	Training materials									■	■	■					
7.5.2	Stakeholder workshops									■			■				
7.5.3	Syntheses											■	■	■			

3.7.2 Major milestones for WP 7: Integration & Synthesis

M7.1 Integrative framework for integration of results from all SPs documented [project month 9; 12/2018]

M7.2 Sustainability indicators selected, data requirements determined and mechanisms for stakeholder dialogue developed (Report) [project month 12; 03/2019]

M7.3 Quantification of potential climate-induced risks for Limpopo Region documented (Report and paper draft) [project month 15; 06/2019]

M7.4 Journal article on integrative framework for analysing land use management und policy scenarios submitted (e.g. to Global Environmental Change) [project month 18; 09/2019]

M7.5 Prototype of LUIS developed and its functionality tested jointly with stakeholders [project month 23; 02/2020]

M7.6 Multi-stakeholder workshop held on applying and improving LUIS [project month 23; 02/2020]

M7.7 At least one journal article on the operationalization and applicability of LUIS submitted (e.g. to: Ecological Modelling) [project month 26; 05/2020]

M7.8 At least two journal articles on LUIS with different specific applications / land use issues (effects climate change; ecosystem resilience etc) (e.g. in (i) Nature Climate Change or (ii). Global Change Biology) [project month 30; 09/2020]

M7.9 Final multi-stakeholder workshop held with presentations of scenario analyses and possible expansions of LUIS held and documented [project month 31; 10/2020].

4. Exploitation plan & data management

SALLnet partners from Germany and South Africa will utilize the data and results to write high quality research papers, to present at international conferences, and deliver to existing databases/networks like SASSCAL, to produce dissemination material such as policy briefs, and to promote the development of services according to the needs expressed by local stakeholders.

The research data strategy of SALLnet follows the best practices from the European Horizon 2020 Open Research Data Pilot in which it is stated that data that “underpins published research findings and/or has longer-term value“ is published and that neither IPR should be breached nor business-critical data should be shared. SALLnet will classify data in different categories based on criteria like IPR, data protection level, or publication status, and it will provide data management plans for each category. The plans will contain information about the data sets, list institutional and national policies applied, describe the standards and metadata used, define data sharing policies, and ensure that the respective data is archived and preserved beyond the lifetime of the project itself. SALLnet will be supported by the Göttingen eResearch Alliance, which supports research projects planning data management. With respect to the execution of the data management plans, data publication will be either made available through community-specific repositories or through public ones like OpenAIRE. South African partners applying for ACCESS support, need to provide a Data Management Plan (DMP), specifically using the DMP protocol for NRF funds.

4.1 Economic prospects of results

WP 1: The research within WP 1 is not intended to bring about direct economic benefits to the partners and the involved farmers. There is, however, considerable potential of research results and new insights on how to options to close feed gaps on farm being utilised by extension services and the farming community. As farmers are closely involved in our research through the farm survey and the ecosystem service assessment on sites managed by the farms we expect visible high adoption of mitigating strategies.

WP 2: We currently do not plan any economic utilization of our results. However there might be substantial economic benefits of adopting more sustainable management practices. We particularly anticipate that farmers might profit from adopting our recommendations for rangeland management in drought and post-drought years, based on the findings of our DroughtAct experiment. Results from the assessment of ecosystem multifunctionality (with WP 1 & 3) will be incorporated into model-based evaluations of land-use and policy scenarios and thus indirectly contribute to improved livelihood security in the face of climate-related risks.

WP 3: We currently do not plan any economic utilization of our results. However, farmers might adopt their management based on the findings of our cost-benefit analysis to reduce costs for pesticide inputs.

WP 4: The research within WP 4 is not intended to bring about direct economic benefits to the partners and the involved farmers. However, based on our findings with regard to the development of risk management options and the agent based modelling, farmers might adopt their management and politicians might improve their decision making. This could lead to a higher productivity and a more sustainable development of the entire sector.

WP 5: In the short term no economic exploitation is planned during the project period, but it is at least not excluded that the macadamia model could be used for the optimization of management practices in plantations in the long term.

WP 6: We currently do not plan an economic utilization of our model developments and simulation results. We do not anticipate any direct economic exploitation success.

WP 7: During the life time of the project, no economic exploitation is planned – neither of the system developed nor of its applications; however, the resulting economic benefit could be considerable through propagating more sustainable land use management practices than the current ones, and by stimulating policy decisions in support of enhanced ecosystem resilience and sustainable land use and development pathways (in the short and long run) – some effects may even be visible during the project's lifetime.

4.2 Scientific and/or technical prospects of results

WP 1: The on-farm analysis of feed shortages and their development will provide insight into the factors that are mainly responsible for the feed gaps. Together with the results from the on-station cover crop experimentation this will give scope for mitigation strategies. It is expected that this research will contribute to our scientific knowledge of sustainable arable-livestock husbandry in the semi-arid region southern Africa and will be published in international peer review journals. At the same time the research has potential to become relevant for the farming practice in the region and will be disseminated among the relevant stakeholders.

WP2: The scientific approaches in SALLnet build on previous work in LLL and on the in-depth expertise of participating scientists. We expect that our experimental evaluation of ecosystem resistance and resilience in the face of severe drought will substantially advance scientific understanding of the determinants of terrestrial ecosystem sensitivity to combined effects of grazing and drought. Likewise, suitable intervention strategies will be identified; these are urgently needed to avoid shifts to undesirable, degraded states of Africa's savanna ecosystems. An integrated assessment of multiple ecosystem services is currently lacking for Sub-Saharan Africa, but prerequisite for predicting multifunctionality of diverse landscapes under climate and land use change scenarios. Results will be published in scientific journals and presented at national and international conferences.

WP3: We expect that our results will guide the macadamia farmers towards more biodiversity-friendly management options through the optimization of two regulating ecosystem services. Both biological control and pollination services have the potential to increase fruit quantity and quality, but their interactions along a land use intensity and climatic gradient are yet not well understood. WP 3 will provide novel insights in the effects of interacting ecosystem services and incorporate these findings into cost-benefit analysis, APSIM models and risk assessments to predict the implications of future climate change and land use scenarios on long term-efficiency and resilience of macadamia farms. Moreover, WP 3 will contribute to the assessments of multiple ecosystem services functions in the major land use types to predict multifunctionality of diverse landscapes under climate and land use change scenarios.

WP4: This work package will provide new insights into the potential of, partially novel, risk management options with regard to improving the efficiency and/or resilience of different farm types. To the best knowledges of the PIs, this is the first comprehensive and integrated investigation of agricultural risk management in a transition country that is and will exposed to climate change and other agri-relevant risks to such an extent like South Africa. Furthermore, the integration of these concrete risk management options into the agent-based modelling approach represents a novelty. It will deliver new findings of the effects of on-farm risk management options at a regional level and the efficiency of policy options to support these. Therefore, the research has the potential to become relevant for farming practices in the region and will be disseminated among the relevant stakeholders. At the same time, the results will published in scientific journals and presented at national and international conferences.

WP5: In this WP, a new model for Macadamia is being developed. Crop modelling of tropical perennial crops is still lacking to a large extent. Hence, a contribution to this field is highly needed. Based on this we will provide management recommendation for adapting to climate change. For the annual crops, the models APSIM, WOFOST, DSSAT should deliver concrete management improvements. However, no economic benefit should be drawn from this for the subproject. Rather, this is seen as part of capacity building. At policy-level, we will provide information on productivity, carbon storage and other ecosystem services on the two types of land use in the context of climate change. In particular, we will consider scenarios that meet the 1.5 or 2.0° C target.

As in the other WP, results will be published in scientific journals and brochures and presented at scientific conferences. We will conduct training courses on crop modelling to present our results and teach young researchers in this field. These courses contribute to capacity building in South Africa.

WP 6: SALLnet is a substantial improvement with added value compared to the first phase of LLL. In WP 6, the aDGVM2 will be coupled with a nitrogen cycle. Nitrogen has an important impact on plant growth and vegetation dynamics. It is often argued that nitrogen limitation may mitigate growth at elevated CO_2 concentrations and thereby influence future ecosystem functions such as carbon sequestration, productivity, diversity and vegetation patterns. The proposed model developments will allow us to study these factors.

We will generate an ensemble of climate and land use scenarios to systematically investigate the impacts on vegetation, ecosystem functions and ecosystem services. These simulations will be conducted with and without nitrogen cycling. We will specifically consider the 1.5° and 2°C targets in our simulations.

Results will be published in scientific journals and brochures and presented at scientific conferences. We will conduct training courses on vegetation modelling to present our results and teach young researchers in this field. These courses contribute to capacity building in South Africa.

In **WP7** a new **L**and **U**se **I**nformation **S**ystem (LUIS) will be developed for state-of-the-art inter- and transdiciplinary research on the climate resilience of ecoystems and sustainable land use. As such, this constitutes a substantial scientific innovation that is also of big importance for practical applications and the avoidance of potential land use conflicts in the target region that could trigger social unrest or other unsustainable developments.

To provide decision-support for meeting international policy goals like the UN Sustainable Development Goals (SDGs), in particular those related to poverty elimination, zero hunger , good health and climate protection (e.g. SDGs 1,2,3 und 13) , the data generated by the project (on e.g. carbon sequestration, ecosystem productivity, profitability and other ecosystem services) and synthesized in WP 7 for the different land use management and policy scenarios considered will also deliver important information in the context of climate impact research. In particular, project outputs will show the quantitative consequences of alternative land use scenarios of realizing the 1.5 respectively 2.0°C climate targets.

4.3 Scientific and economic connectivity

WP 1: will be based on existing strong linkages among the German and South African partners. The on-farm as well as the on-station research will be jointly performed through the South African Universities of Limpopo and Venda and the University of Göttingen. The PhD student applied for in this proposal will enroll at Göttingen University but will be jointly supervised by the partners from ULIM, UVEN-soil and UGOE-grass. It is intended to strengthen the research effort by obtaining a second PhD student to be funded by DAAD. He/she will also be jointly supervised and will enroll at ULIM. In addition we will call for African and German master students to be involved in the research.

WP 2: The assessment of ecosystem multifunctionality requires a joint effort of South African and German partners from WP 1-3, thus strengthening existing collaboration. Not only the assessment of multiple ESs, but also the effort of calibrating rapid field methods with elaborate methods will be shared among participating scientists. We plan for a tandem of a South African and a German PhD student, supported by German and South African MSc students, and coordinated by a German PostDoc. The analysis of ES demand will be done with WP 4 to jointly design and analyze interviews on ES valuation. Results will also provide essential information for the analysis of land-use scenarios in WP 7. We envisage an iterative approach with an early, transdisciplinary integration of stakeholders. The better understanding of environmental constraints for tree establishment will facilitate an upscaling and risk evaluation (in WP 6) and synthesis (in WP 7) to explore feasible management options for bush control.

UBonn, UWITS-gci and ULIM will also conduct a joint capacity building workshop on the estimation of soil- and vegetation-mediated ESs (forage quantity and quality, tree biomass, etc.), including allometric approaches and field spectroscopy.

WP 3: WP 3 will strengthen the existing collaborations between South African and German partners. Using a transdisciplinary approach, stakeholders will be involved in the research and development of management strategies. UGOE-ecol and UVEN-biodiv will conduct a training workshop on field ecology methods and quantification of biodiversity-mediated ecosystem functions and services.

WPs 4, 5, 6 and 7: SALLnet will deepen and expand the collaboration between German and South African project partners, both within the SALLnet consortium and between other SPACES projects (e. g. synergies in modelling activities and training with EMSAfrica) and SASSCAL (e. g. data storage). These collaborations will facilitate future projects in further phases of the SPACES initiative and beyond.

5. Division of work / cooperation with third parties

Coordination will be managed by Prof. Rötter supported by a 75% ‘project manager’ position located at UGOE-tropags. Financial management and reporting systems are in place to provide transparent accounting processes, and UGOE has ample experience in the auditing and reporting requirements of BMBF. WPs 1-7 are jointly led by South African and German PIs. While WPs are individually responsible for meeting their respective objectives, there is a need to jointly coordinate activities, e.g. the proposed training workshops or thematic sessions/side events at conferences. In most cases, co-located field experiments and research will necessitate the coordination of farmer visits, transportation and extension activities. A communication strategy will be developed to maintain effective communication within the project team and with relevant stakeholders. A publication plan will be established with emphasis on joint authorships of German and South African scientists and wide accessibility, especially of the integrative and synthesis publications of the collaborative work. A kick-off meeting and annual workshops will be platforms for presenting project findings and networking amongst the project teams and with local stakeholders. Additional public outreach will be maintained via a project website and regular press releases.

SALLnet aims for a major impact on regional capacity to undertake research in the future. All subprojects incorporate PhD and MSc projects under tandem supervision at German and South

African universities. The interactions of researchers and academics amongst the partners – as well as with local stakeholders – will also enhance regional cooperation and stimulate citizen science delivering important complementary information from monitoring (e.g. from a denser rainfall recording network in support of WPs 5-6; recording species diversity on farm in support of WPs 1-3). Provision of travel funds will allow African researchers to attend scientific conferences, stakeholder dialogues and connect with partners in Germany. Conversely, travel to field sites allows German partners to collect field data and gain understanding of the local context that will inform existing modelling and engagement frameworks. There is special need to build more local capacity in the assessment of multiple ESs, as well as in systems modelling and scenario construction to support integrated regional assessment of climate change impacts and response strategies. Therefore, several week-long training courses are planned in cooperation with African partner universities, which will be open for other terrestrial SPACES II initiatives (i.e. OPTIMASS-ORYCS or EMSAfrica). UVEN-biodiv and UGOE-ecol will conduct an intensive training course on field ecology methods and quantification of ecosystem functions and services (5 days).

Students from South Africa and Germany will also be integrated into jointly developed E-learning courses for agro-ecosystems modelling using APSIM. The Limpopo region is critically important for RSA, due to the universities involved, but also because of its natural capital in form of biodiversity hotspots, iconic species and unique earth system phenomena; Limpopo is also of strategic socio-economic importance for subsistence farming, commercial farming, forestry, mining and tourism.

In WP 6, we will collaborate within the SALLnet consortium for model parameterization (WP 2, 4), for aggregating environmental input data for models and joint modeling studies (WP 5, WP 7). In addition, we will collaborate with the SPACES EMSAfrica project. This project also conducts modelling studies with aDGVM and the LPJ-GUESS DGVM (Thomas Hickler, Simon Scheiter, Goethe University Frankfurt). Synergy effects will be achieved by aggregation and utilization of environmental forcing data and model parameterization at different regions and spatial scales. We also plan joint training courses on socio-ecological and dynamic vegetation models with project partners in the EMSAfrica project (Thomas Clemen, HAW Hamburg, Germany and Karen Bradshaw, Rhodes University, South Africa). This course will be designed for young researchers and it will be open for all SPACES projects and other interested students.

In WPs 5 and 7, there will be very close collaboration in terms of (a) crop simulation model, development, intercomparison, improvement and evaluation and (b) integrated regional assessment – with both the MACSUR (www.macsur.eu) and AgMIP (www.agmip.org) systems modelling networks – in particular with partners specialized in relevant fields. UGOE-tropags is a very active partner in these networks, and UGOE researchers have made distinct contributions among others, to the advancement of crop modelling (see, e.g. Rötter et al. 2015; see, https://www.impactsworld2017.org/program-speakers/plenaries/#state-art-climate-impacts-research), as well as to approaches for integrated regional assessment of agricultural systems in the context of climate change adaptation (Ewert et al., 2015). These are currently further being developed together with, a.o. the Potsdam Institute of Climate Impacts Research (PIK) and the University of Bonn, Germany in the framework of the SUSTAg project.

6. Necessity of the grant

Please see declarations submitted by each applicant individually together with AZA(P) documents.

7. References

Addo-Danso SD, Prescott CE, Smith AR (2016) Methods for estimating root biomass and production in forest and woodland ecosystem carbon studies: a review. For Ecol Manag 359:332–351

Aggarwal PK, Rötter RP, Kalra N, et al (2001) Land use analysis and planning for sustainable food security: with an illustration for the state of Haryana, India. IRRI

Asseng S, Ewert F, Rosenzweig C, et al (2013) Uncertainty in simulating wheat yields under climate change. Nat Clim Change 3:827–832 . doi: 10.1038/nclimate1916

Balmann A (1997) Farm-based modelling of regional structural change: A cellular automata approach. Eur Rev Agric Econ 24:85–108

Balmann A, Happe K (2001) Agentenbasierte politik-und sektoranalyse-perspektiven und herausforderungen

Barreteau O, Bousquet F (2000) SHADOC: a multi-agent model to tackle viability of irrigated systems. Ann Oper Res 94:139–162

Berger T (2001) Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. Agric Econ 25:245–260

Berger T, Troost C (2014) Agent-based Modelling of Climate Adaptation and Mitigation Options in Agriculture. J Agric Econ 65:323–348

Bond WJ (2008) What limits trees in C4 grasslands and savannas? Annu Rev Ecol Evol Syst 39:641–659

Bradford JB, D’Amato AW (2012) Recognizing trade-offs in multi-objective land management. Front Ecol Environ 10:210–216

Buitenwerf R, Bond WJ, Stevens N, Trollope WSW (2012) Increased tree densities in South African savannas:> 50 years of data suggests CO2 as a driver. Glob Change Biol 18:675–684

Cardinale BJ, Duffy JE, Gonzalez A, et al (2012) Biodiversity loss and its impact on humanity. Nature 486:59–67

Castella J-C, Kam SP, Quang DD, et al (2007) Combining top-down and bottom-up modelling approaches of land use/cover change to support public policies: Application to sustainable management of natural resources in northern Vietnam. Land Use Policy 24:531–545

Chave J, Réjou-Méchain M, Búrquez A, et al (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Change Biol 20:3177–3190

Claessens L, Antle JM, Stoorvogel JJ, et al (2012) A method for evaluating climate change adaptation strategies for small-scale farmers using survey, experimental and modeled data. Agric Syst 111:85–95

Coelli TJ, Rao DSP, O’Donnell CJ, Battese GE (2005) An introduction to efficiency and productivity analysis. Springer Science & Business Media

Coetzer KL, Witkowski ET, Erasmus BF (2014) Reviewing Biosphere Reserves globally: effective conservation action or bureaucratic label? Biol Rev 89:82–104

Cunningham SA, Fournier A, Neave MJ, Le Feuvre D (2016) Improving spatial arrangement of honeybee colonies to avoid pollination shortfall and depressed fruit set. J Appl Ecol 53:350–359

Dai A (2013) Increasing drought under global warming in observations and models. Nat Clim Change 3:52–58

Di Falco S, Chavas J-P, Smale M (2007) Farmer management of production risk on degraded lands: the role of wheat variety diversity in the Tigray region, Ethiopia. Agric Econ 36:147–156

Díaz S, Kattge J, Cornelissen JHC, et al (2016) The global spectrum of plant form and function. Nature 529:167–171 . doi: 10.1038/nature16489

D'Odorico P, Bhattachan A, Davis KF, et al (2013) Global desertification: drivers and feedbacks. Adv Water Resour 51:326–344

Duffy JE, Godwin CM, Cardinale BJ (2017) Biodiversity effects in the wild are common and as strong as key drivers of productivity. Nature 549:261–264

Evans TP, Kelley H (2004) Multi-scale analysis of a household level agent-based model of landcover change. J Environ Manage 72:57–72

Ewert F, van Ittersum MK, Heckelei T, et al (2011) Scale changes and model linking methods for integrated assessment of agri-environmental systems. Agric Ecosyst Environ 142:6–17

Feil J-H, Musshoff O (2013) Modelling investment and disinvestment decisions under competition, uncertainty and different market interventions. Econ Model 35:443–452

Feil J-H, Musshoff O (2017a) Analysing investment and disinvestment decisions under uncertainty, firm heterogeneity and tradable output permits. Schriften Ges Für Wirtsch- Sozialwissenschaften Landbaus 52:191–205

Feil J-H, Musshoff O (2017b) Modelling investments in short rotation coppice: a value chain perspective. Biomass Bioenergy in press:

Feng Q, Zhao W, Fu B, et al (2017) Ecosystem service trade-offs and their influencing factors: A case study in the Loess Plateau of China. Sci Total Environ 607:1250

Ferner J, Linstädter A, Südekum K-H, Schmidtlein S (2015) Spectral indicators of forage quality in West Africa's tropical savannas. Int J Appl Earth Obs Geoinformation 41:99–106

Fisher JB, Sitch S, Malhi Y, et al (2010) Carbon cost of plant nitrogen acquisition: A mechanistic, globally applicable model of plant nitrogen uptake, retranslocation, and fixation. Glob Biogeochem Cycles 24:

Fredrickson EL, Estell RE, Laliberte A, Anderson DM (2006) Mesquite recruitment in the Chihuahuan Desert: historic and prehistoric patterns with long-term impacts. J Arid Environ 65:285–295

Gasparatos A, Stromberg P, Takeuchi K (2011) Biofuels, ecosystem services and human wellbeing: Putting biofuels in the ecosystem services narrative. Agric Ecosyst Environ 142:111–128

Godfray HCJ, Beddington JR, Crute IR, et al (2010) Food security: the challenge of feeding 9 billion people. science 327:812–818

Greene WH (2008) The econometric approach to efficiency analysis. Meas Product Effic Product Growth 1:92–250

Griscom BW, Adams J, Ellis PW, et al (2017) Natural climate solutions. Proc Natl Acad Sci 114:11645–11650

Guuroh RT, Ruppert JC, Ferner J, et al (2018) Drivers of forage provision and erosion control in West African savannas—A macroecological perspective. Agric Ecosyst Environ 251:257–267

Happe K, Balmann A, Kellermann K, Sahrbacher C (2008) Does structure matter? The impact of switching the agricultural policy regime on farm structures. J Econ Behav Organ 67:431–444

Hardaker JB (2004) Coping with risk in agriculture. Cabi

Heard TA (1994) Behaviour and pollinator efficiency of stingless bees and honey bees on macadamia flowers. J Apic Res 33:191–198

Hengl T, Jesus JM de, MacMillan RA, et al (2014) SoilGrids1km — Global Soil Information Based on Automated Mapping. PLOS ONE 9:e105992 . doi: 10.1371/journal.pone.0105992

Higgins SI, Bond WJ, Trollope WS (2000) Fire, resprouting and variability: a recipe for grass–tree coexistence in savanna. J Ecol 88:213–229

Hoffmann MP, Castaneda Vera A, van Wijk MT, et al (2014) Simulating potential growth and yield of oil palm (Elaeis guineensis) with PALMSIM: Model description, evaluation and application. Agric Syst 131:1–10 . doi: 10.1016/j.agsy.2014.07.006

Holzworth DP, Huth NI, Zurcher EJ, et al (2014) APSIM–evolution towards a new generation of agricultural systems simulation. Environ Model Softw 62:327–350

Howlett BG, Nelson WR, Pattemore DE, Gee M (2015) Pollination of macadamia: Review and opportunities for improving yields. Sci Hortic 197:411–419

Huth NI, Banabas M, Nelson PN, Webb M (2014) Development of an oil palm cropping systems model: Lessons learned and future directions. Environ Model Softw 62:411–419

Jones JW, Hoogenboom G, Porter CH, et al (2003) The DSSAT cropping system model. Eur J Agron 18:235–265

Joubert DF, Rothauge A, Smit GN (2008) A conceptual model of vegetation dynamics in the semiarid Highland savanna of Namibia, with particular reference to bush thickening by Acacia mellifera. J Arid Environ 72:2201–2210

Kattge J, Knorr W, Raddatz T, Wirth C (2009) Quantifying photosynthetic capacity and its relationship to leaf nitrogen content for global-scale terrestrial biosphere models. Glob Change Biol 15:976–991

Laborte AG, Nuñez B, Dreiser C, Rötter RP (2001) SysNet tools II: The MGLP user interface for interactive land use scenario analysis. IRRI Tech Bull

Laborte AG, Van Ittersum MK, Van den Berg MM (2007) Multi-scale analysis of agricultural development: A modelling approach for Ilocos Norte, Philippines. Agric Syst 94:862–873

Langan L, Higgins SI, Scheiter S (2017) Climate-biomes, pedo-biomes or pyro-biomes: which world view explains the tropical forest–savanna boundary in South America? J Biogeogr 44:2319–2330

Le Provost G, Gross N, Börger L, et al (2017) Trait-matching and mass effect determine the functional response of herbivore communities to land-use intensification. Funct Ecol

Lee E, Felzer BS, Kothavala Z (2013) Effects of nitrogen limitation on hydrological processes in CLM4-CN. J Adv Model Earth Syst 5:741–754

Leenaars JGB, Hengl T, Gonzalez MR, et al (2015) Root zone plant-available water holding capacity of the Sub-Saharan Africa soil, version 1.0. ISRIC - World Soil Information, Wageningen

Lefcheck JS, Byrnes JE, Isbell F, et al (2015) Biodiversity enhances ecosystem multifunctionality across trophic levels and habitats. Nat Commun 6:

Lehtonen HS, Rötter RP, Palosuo TI, et al (2010) A modelling framework for assessing adaptive management options of Finnish agrifood systems to climate change. J Agric Sci 2:3

Lu N, Fu B, Jin T, Chang R (2014) Trade-off analyses of multiple ecosystem services by plantations along a precipitation gradient across Loess Plateau landscapes. Landsc Ecol 29:1697–1708

Luedeling E, Smethurst PJ, Baudron F, et al (2016) Field-scale modeling of tree–crop interactions: Challenges and development needs. Agric Syst 142:51–69

Maestre FT, Quero JL, Gotelli NJ, et al (2012) Plant species richness and ecosystem multifunctionality in global drylands. Science 335:214–218

Martin AR, Isaac ME (2015) Plant functional traits in agroecosystems: a blueprint for research. J Appl Ecol 52:1425–1435

Martín-López B, Iniesta-Arandia I, García-Llorente M, et al (2012) Uncovering ecosystem service bundles through social preferences. PLoS One 7:e38970

Mbatha KR, Ward D (2010) The effects of grazing, fire, nitrogen and water availability on nutritional quality of grass in semi-arid savanna, South Africa. J Arid Environ 74:1294–1301

McSweeney CF, Jones RG (2016) How representative is the spread of climate projections from the 5 CMIP5 GCMs used in ISI-MIP? Clim Serv 1:24–29

Meyer ST, Koch C, Weisser WW (2015) Towards a standardized rapid ecosystem function assessment (REFA). Trends Ecol Evol 30:390–397

Morandin LA, Long RF, Kremen C (2016) Pest control and pollination cost–benefit analysis of hedgerow restoration in a simplified agricultural landscape. J Econ Entomol 109:1020–1027

Moretti M, Dias AT, Bello F, et al (2017) Handbook of protocols for standardized measurement of terrestrial invertebrate functional traits. Funct Ecol 31:558–567

Ne'eman G, Jürgens A, Newstrom-Lloyd L, et al (2010) A framework for comparing pollinator performance: effectiveness and efficiency. Biol Rev 85:435–451

O'Connor TG, Puttick JR, Hoffman MT (2014) Bush encroachment in southern Africa: changes and causes. Afr J Range Forage Sci 31:67–88

Palosuo T, Kersebaum KC, Angulo C, et al (2011) Simulation of winter wheat yield and its variability in different climates of Europe: a comparison of eight crop growth models. Eur J Agron 35:103–114

Perez-Harguindeguy N, Diaz S, Garnier E, et al (2013) New handbook for standardised measurement of plant functional traits worldwide. Aust J Bot 61:167–234

Popp A, Calvin K, Fujimori S, et al (2017) Land-use futures in the shared socio-economic pathways. Glob Environ Change 42:331–345

Prentice IC (2008) Terrestrial nitrogen cycle simulation with a dynamic global vegetation model. Glob Change Biol 14:1745–1764

Prentice IC, Bondeau A, Cramer W, et al (2007) Dynamic global vegetation modeling: quantifying terrestrial ecosystem responses to large-scale environmental change. In: Terrestrial ecosystems in a changing world. Springer, pp 175–192

Rader R, Bartomeus I, Garibaldi LA, et al (2016) Non-bee insects are important contributors to global crop pollination. Proc Natl Acad Sci 113:146–151

Raudsepp-Hearne C, Peterson GD, Bennett EM (2010) Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc Natl Acad Sci 107:5242–5247

Reed J, Van Vianen J, Deakin EL, et al (2016) Integrated landscape approaches to managing social and environmental issues in the tropics: learning from the past to guide the future. Glob Change Biol 22:2540–2554

Reidsma P, Wolf J, Kanellopoulos A, et al (2015) Climate change impact and adaptation research requires integrated assessment and farming systems analysis: a case study in the Netherlands. Environ Res Lett 10:045004

Rietkerk M, Ketner P, Burger J, et al (2000) Multiscale soil and vegetation patchiness along a gradient of herbivore impact in a semi-arid grazing system in West Africa. Plant Ecol 148:207–224

Rötter RP, Carter TR, Olesen JE, Porter JR (2011) Crop-climate models need an overhaul. Nat Clim Change 1:175–177 . doi: 10.1038/nclimate1152
Rötter RP, Hoanh CT, Laborte AG, et al (2005) Integration of Systems Network (SysNet) tools for regional land use scenario analysis in Asia. Environ Model Softw 20:291–307
Rötter RP, Van den Berg M, Laborte AG, et al (2007) Combining farm and regional level modelling for Integrated Resource Management in East and South-east Asia. Environ Model Softw 22:149–157
Ruane AC, Goldberg R, Chryssanthacopoulos J (2015) Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. Agric For Meteorol 200:233–248 . doi: 10.1016/j.agrformet.2014.09.016
Ruppert JC, Harmoney K, Henkin Z, et al (2015) Quantifying drylands' drought resistance and recovery: the importance of drought intensity, dominant life history and grazing regime. Glob Change Biol 21:1258–1270
Russell SJ, Norvig P (1995) Artificial intelligence: a modern approach (International Edition)
Sankaran M, Ratnam J, Hanan N (2008) Woody cover in African savannas: the role of resources, fire and herbivory. Glob Ecol Biogeogr 17:236–245
Sankaran M, Ratnam J, Hanan NP (2004) Tree–grass coexistence in savannas revisited–insights from an examination of assumptions and mechanisms invoked in existing models. Ecol Lett 7:480–490
Scheiter S, Higgins SI (2009) Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach. Glob Change Biol 15:2224–2246
Scheiter S, Langan L, Higgins SI (2013) Next-generation dynamic global vegetation models: learning from community ecology. New Phytol 198:957–969
Schleussner C-F, Rogelj J, Schaeffer M, et al (2016) Science and policy characteristics of the Paris Agreement temperature goal. Nat Clim Change
Schlüter M, Hinkel J, Bots P, Arlinghaus R (2014) Application of the SES framework for model-based analysis of the dynamics of social-ecological systems. Ecol Soc 19:
Sheffield J, Goteti G, Wood EF (2006) Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. J Clim 19:3088–3111
Soliveres S, Van Der Plas F, Manning P, et al (2016) Biodiversity at multiple trophic levels is needed for ecosystem multifunctionality. Nature 536:456–459
Stevens N, Lehmann CE, Murphy BP, Durigan G (2017) Savanna woody encroachment is widespread across three continents. Glob Change Biol 23:235–244
Thornley JH, Parsons AJ (2014) Allocation of new growth between shoot, root and mycorrhiza in relation to carbon, nitrogen and phosphate supply: teleonomy with maximum growth rate. J Theor Biol 342:1–14
Thuiller W, Albert C, Araújo MB, et al (2008) Predicting global change impacts on plant species' distributions: Future challenges. Perspect Plant Ecol Evol Syst 9:137–152 . doi: 10.1016/j.ppees.2007.09.004
Van den Berg MM, Hengsdijk H, Wolf J, et al (2007) The impact of increasing farm size and mechanization on rural income and rice production in Zhejiang province, China. Agric Syst 94:841–850
Van Ittersum MK, Ewert F, Heckelei T, et al (2008) Integrated assessment of agricultural systems–A component-based framework for the European Union (SEAMLESS). Agric Syst 96:150–165
van Ittersum MK, Leffelaar PA, Van Keulen H, et al (2003) On approaches and applications of the Wageningen crop models. Eur J Agron 18:201–234
Van Ittersum MK, Rötter RP, Van Keulen H, et al (2004) A systems network (SysNet) approach for interactively evaluating strategic land use options at sub-national scale in South and South-east Asia. Land Use Policy 21:101–113
Van Paassen A, Rötter RP, Van Keulen H, Hoanh CT (2007) Can computer models stimulate learning about sustainable land use? Experience with LUPAS in the humid (sub-) tropics of Asia. Agric Syst 94:874–887
van Vliet J, Bregt AK, Brown DG, et al (2016) A review of current calibration and validation practices in land-change modeling. Environ Model Softw 82:174–182
Verburg PH, Dearing JA, Dyke JG, et al (2016) Methods and approaches to modelling the Anthropocene. Glob Environ Change 39:328–340 . doi: 10.1016/j.gloenvcha.2015.08.007
Verburg PH, Van De Steeg J, Veldkamp A, Willemen L (2009) From land cover change to land function dynamics: a major challenge to improve land characterization. J Environ Manage 90:1327–1335
Vuuren DP van, Edmonds J, Kainuma M, et al (2011) The representative concentration pathways: an overview. Clim Change 109:5 . doi: 10.1007/s10584-011-0148-z
Ward D (2005) Do we understand the causes of bush encroachment in African savannas? Afr J Range Forage Sci 22:101–105
Warszawski L, Frieler K, Huber V, et al (2014) The inter-sectoral impact model intercomparison project (ISI–MIP): project framework. Proc Natl Acad Sci 111:3228–3232
Whitebread AM, Pengelly BC (2004) Tropical legumes for sustainable farming systems in southern Africa and Australia

Wiegand K, Saltz D, Ward D (2006) A patch-dynamics approach to savanna dynamics and woody plant encroachment–insights from an arid savanna. Perspect Plant Ecol Evol Syst 7:229–242

Wood SA, Karp DS, DeClerck F, et al (2015) Functional traits in agriculture: agrobiodiversity and ecosystem services. Trends Ecol Evol 30:531–539

Zaehle S, Friend AD (2010) Carbon and nitrogen cycle dynamics in the O-CN land surface model: 1. Model description, site-scale evaluation, and sensitivity to parameter estimates. Glob Biogeochem Cycles 24:

Zimmermann J, Higgins SI, Grimm V, et al (2010) Grass mortality in semi-arid savanna: the role of fire, competition and self-shading. Perspect Plant Ecol Evol Syst 12:1–8

Zimmermann J, Higgins SI, Grimm V, et al (2015) Local density effects on individual production are dynamic: insights from natural stands of a perennial savanna grass. Oecologia 178:1125–1135

Unpublished (in prep./submitted/in revision)

Grass I, Meyer S, Taylor PJ, Foord SH, Hajek P, Tscharke T (in review) Pollination limitation despite managed honeybees in South African macadamia orchards.

Hoffmann MP et al. (in revision) Exploring adaptations of groundnut cropping to prevailing climate variability and extremes in Limpopo Province, South Africa, (submitted to Field Crops Research 10. September 2017).

Mudongo EI, Ruppert JC, Linstädter A (in prep.) Adding realism and management options to global change experiments: the DroughtAct approach. Manuscript (V1.2).

Rapholo et al. (2017) Maize-lablab intercropping: a promising option for ecological intensification in southern Africa. Accepted as poster at the Global Food Security Conference 3-6 December 2017 Cape Town.

Rötter, RP et al. (in review) Linking modelling and experimentation to better capture crop impacts of agroclimatic extremes – a review. Field Crops Research, Special Issue.