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Disentangling effects of climate and land-use change on West African drylands' forage supply

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ABSTRACT

Livestock rearing is the most important agricultural activity in global drylands, making forage supply an essential ecosystem service (ES). Most drylands are expected to experience increasing levels of climatic aridity and land-use pressure in the future. As few studies account for combined effects of these global change drivers, we still have a limited understanding of how these drivers jointly shape forage supply. Here, the concept of social-ecological systems (SESs) is useful, as it helps to formalize the complex interrelationships of drivers. Taking advantage of steep gradients of climatic aridity and land-use pressure in West Africa, a crossed space-for-time substitution was applied to capture combined effects of climate and land-use change on forage supply. We have operationalized the SES concept via structural equation modelling, and analysed how drivers directly or indirectly affected forage quantity, quality and their integrated proxy (metabolisable energy yield). Results demonstrate that contemporary dryland SESs are mainly controlled by land-use, which has often been used as a proxy for other variables, such as climatic aridity. Aridity was also directly linked to a higher risk of vegetation degradation, indicating that future drylands will be less resilient to grazing pressures. The importance of land-use drivers for ES provision implies that sustainable grazing management could potentially mitigate detrimental climate change effects. However, model effects mediated by intermediate variables, such as aridity, short-term vegetation dynamics, and weather fluctuations, make it extremely difficult to predict climate change effects on ESs. Integrating structural equation modelling into the well-defined SES concept is thus highly useful to disentangle complex interdependencies of global change drivers in dryland rangelands, and to analyze drivers' direct and indirect effects on ESs. Our novel approach can thus foster a deeper understanding of patterns and mechanisms driving ecosystem service supply in drylands, which is essential for establishing sustainable management under conditions of global change.

1. Introduction

Livestock rearing is the dominant land-use sector on earth and plays a critical role in human nutrition and food security (Godber and Wall, 2014; Herrero and Thornton, 2013). Approximately 40% of global agricultural gross domestic product is derived from livestock rearing, providing income for more than 1.3 billion people and nourishment for at least 800 million of the world's poor in the developing world (Herrero and Thornton, 2013). Livestock rearing is also the primary type of land-use in drylands, which comprise arid, semi-arid and dry-subhumid ecosystems (Adeel et al., 2005). As drylands support many socially disadvantaged groups that rely heavily on grazing and farming (Godber and Wall, 2014), livelihood security in drylands is highly dependent on the 'forage' ecosystem service that is provided by rangeland vegetation (Adeel et al., 2005; Phelps and Kaplan, 2017). Including livestock production into agricultural activities often compensates for negative effects of climatic, market and disease shocks on livelihood security by diversifying risk and increasing income (Martin et al., 2016;

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Thornton et al., 2007).

In many dryland regions such as those in Sub-Saharan Africa, increasing local demands for livestock products will also increase demands for forage (Herrero and Thornton, 2013). The expected grazing land expansion and intensification of livestock rearing practices may exert detrimental feedbacks on ecosystem functions and on the supply of ecosystem services (ESs), including forage supply, which implies the quantity as well as quality of forage resources (Guuroh et al., 2018; Reynolds et al., 2007; Vandandorj et al., 2017). Various abiotic and biotic factors may interactively contribute to this 'feedback spiral' towards degradation (King and Hobbs, 2006).

Besides changing land-use, climate change constitutes another severe threat to dryland rangelands worldwide (Maestre et al., 2012; Ruppert et al., 2015). Climate change effects on drylands will be particularly strong, with most drylands projected to experience an increase in precipitation variability, including more extreme rainfall events and intense droughts, and temperature (Maestre et al., 2012). Although it is widely acknowledged that global drivers of change interact, we still have a limited understanding how they shape ES supply through their various interdependencies (Oliver and Morecroft, 2014). In this regard, Guuroh et al. (2018) recently contributed to a better understanding of the relative importance of global change drivers on ES supply, including forage provision, in Sub-Saharan Africa. However, this study was not designed to investigate direct and indirect effects of land-use and climate change on ESs and this remains a critical knowledge gap.

To formalize and disentangle the joint effects of global change drivers on ES provision from dryland rangelands, the concept of social-ecological systems (SESs) is particularly useful (Huber-Sannwald et al., 2012; Linstädter et al., 2016). Within an SES, a dynamic co-adaptation exists between human decision-making and ES provision. Hence, human and ecological subsystems are coupled and interlinked by diverse drivers operating across multiple spatial and temporal scales (Stafford Smith et al., 2007).

Another characteristic of dryland rangelands is the high inter- and intra-seasonal variability in forage supply. Firstly, forage provision in seasonal climates is always subject to periodic fluctuations due to the phenological development of plants (Butt et al., 2011). Secondly, variable weather conditions can trigger substantial short-term vegetation responses, especially at the beginning of the growing season (Brüser et al., 2014). Finally, disturbances such as grazing and fire may cause an immediate loss of plant biomass (Augustine and McNaughton, 2006; Oesterheld et al., 1999). Due to a variety of anthropogenic disturbances overlaying other sources of spatio-temporal variability, spatio-temporal patterns in forage provision are particularly complex in sub-Saharan Africa (Brottem et al., 2014).

Besides the inherent complexity of dryland SESs and the importance of intra-seasonal and short-term variation, there is a third reason for our limited understanding of how global environmental changes modulate ES provision on a regional scale: global change implies changes in multiple biotic and abiotic factors. This hampers the disentanglement of their direct and indirect effects on ecosystem services. In this context, structural equation modelling (SEM) is increasingly applied, as it allows direct and indirect drivers (i.e. the effect that a variable A exerts over a variable B by a mediator variable C), as well as combined effects on target variables to be separated (Eldridge and Delgado-Baquerizo, 2017; Gaitan et al., 2014; Ochoa-Hueso et al., 2018). These effects are usually shown via path diagrams with linkages or pathways between variables.

Identifying such effect pathways and the variables that mediate these effects (via indirect linkages) would support monitoring and early-warning systems to foster adaptive livestock management strategies (Stuth et al., 2005). Furthermore, knowing direct and indirect effects of climate and land-use change on forage supply at a regional level would enhance our ability to understand and predict impacts of global change on this critical ecosystem service (Martin et al., 2014).

To achieve such an understanding, one of the most efficient study approaches is to exploit natural gradients in climate and land-use (Oliver and Morecroft, 2014). Here we take advantage of the fact that in West Africa's Sudanian savannas, a steep regional gradient of climatic aridity is overlain by sharp local gradients of land-use pressure (Ferner et al., 2015; Guuroh et al., 2018; Ouédraogo et al., 2015). Hence, a crossed space-for-time substitution can be used for both climate and land-use change, while previous ES studies typically focussed either on climate change (Valencia et al., 2016; Yuan et al., 2017) or land-use change (Allan et al., 2015) and assessed only a limited set of drivers (Oliver and Morecroft, 2014).

The aim of our study is to assess the simultaneous effects of climate change and land-use change on the quality and quantity of the African drylands' forage supply. Uniquely, our study *formalizes* the direct and indirect effects of global drivers of change through a SES approach, and *quantifies* direct and indirect effects via structural equation modelling (SEM). Three hypotheses were tested: (H1) Combining the SES framework with SEM helps to disentangle causal relationships underlying land-use and climate change effects on forage supply; (H2) SEM also helps to detect feedback pathways of long-term and short-term drivers; and (H3) global environmental change has strong indirect effects on forage supply that can either strengthen or counteract its direct effects.

2. Materials and methods

2.1. Study area

The study area spans northern Ghana to central Burkina Faso, and covers ca. 106 000 km^2 in West Africa's Sudanian savannas (Fig. 1). The climate is characterized by a rainy season from May to August in the north, and April to October in the southeast. The area includes a steep gradient of climatic aridity, ranging from a mean annual precipitation (MAP) of 600 mm in the north to 1200 mm in the southeast (Fig. 1). This corresponds to aridity indices (UNEP, 1997) of 0.31 (semi-arid) to 0.69 (humid) and a precipitation seasonality (coefficient of variation) ranging from 79 to 124 (Hijmans et al., 2005). The main geological units are migmatite in the north and sandstone in the south (Ferner et al., 2015), corresponding to plinthosols and lixisols as the main soil types (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). The Sudanian savannas in the study area are used as low-input rangeland sites (Fig. 1) and constitute a belt of farmed parkland savanna (Maranz, 2009) with > 3000 years of livestock farming (Ballouche and Neumann, 1995). Apart from adjusting the timing and intensity of grazing to forage provision, no rangeland management techniques (such as sowing of legumes or fertilization) are applied. Outside protected areas, recent land-use consists of a mosaic of fallows, non-arable land, forest fragments and fields (Friedl et al., 2010).

2.2. Study design

2.2.1. Social-ecological systems

We used a social-ecological system (SES) perspective (Huber-Sannwald et al., 2012; Linstädter et al., 2016) to asses the dynamic coadaptation between human decision-making and the environment's