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Integrating spatio-temporal variation in resource availability and herbivore movements into rangeland management: RaMDry—An agent-based model on livestock feeding ecology in a dynamic, heterogeneous, semi-arid environment

Pascal Fust*, Eva Schlecht

Section Animal Husbandry in the Tropics and Subtropics, University of Kassel and Georg-August-Universität Göttingen, Steinstrasse 19, 37213 Witzenhausen, Germany

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ABSTRACT

Fast growth of the human population puts high pressure on pasture habitats due to increasingly high grazing intensities on shrinking grazing land. Adapted herbivore management is needed to maintain the long term productivity of the rangeland ecosystem, especially in dry climates where precipitation is highly erratic and where forage yield and quality of the pasture are highly dynamic. We used an agent-based approach to develop a spatially explicit model for a case study region in Madagascar. Our model "RaMDry" integrates the movements and feeding metabolism of domesticated ruminants in order to assess the potential of adaptive livestock production in a highly dynamic, heterogeneous, semi-arid rangeland system. It evaluates the additional metabolic energy costs due to pastoral herd movements in search of forage, incorporates seasonal dynamics in forage quality in terms of feed digestibility and relates forage availability and quality to climatic conditions. In the presented study, we focused on describing the processes simulated in RaMDry in detail, simplifying model conditions by implying free-ranging conditions. We verified the results of the model through global and local sensitivity analysis and pattern-oriented modeling and compared findings with observed patterns and existing data from literature. Our model provides a useful tool to assess strategies and effects of locally adapted herd and rangeland utilization for sustained food security and household economy of livestock keepers in the semi-arid tropics and sub-tropics. Subject for further analysis of the model is its capability to simulate different management strategies and climatic conditions as well as the development of the models' capacity to predict accumulative effects of environmental degradation.

1. Introduction

More than 25% of the terrestrial surface is currently utilized as grazing grounds for livestock (Allen-Diaz, 1996; UNEP, 2004). However, human intervention in form of agricultural expansion, urbanization and overgrazing has resulted in alarmingly high levels of fragmentation and degradation of the natural rangelands, particularly in arid and semi-arid environments (UNEP, 2004; Steinfeld et al., 2006). Important (mostly anthropogenic) drivers for degradation of pasture habitats are change of climatic conditions and, particularly in less developed countries, the fast growth of the human population that puts high pressure on these ecosystems due to an increased demand for natural resources (Reynolds et al., 2007). Yet, the most frequently mentioned cause of degradation of rangelands is their unadapted management by land users, such as increasingly high grazing pressure (e.g. Ward and Esler, 2011). Mismanagement of livestock density in relation to the forage yield and quality of the pasture is most likely to occur in dry climates, where production of primary biomass is highly erratic (Steinfeld et al., 2006) as a result of high variability in precipitation. Due to their high temporal and spatial heterogeneity, the complex behavior of the herbivore-rangeland system in such landscapes is challenging when it comes to the prediction of effects of changes in management and/or environmental conditions (McCollum et al., 2011; Lohmann, 2012), which is a precondition for the sustainable utilization of natural resources in these zones.

The effects of unadapted herbivory on rangelands can have dramatic, long-term impacts on the functions of the whole rangeland ecosystem (Laca, 2009), leading to a reduction of primary productivity in general and palatable plant species in particular (Illius and

* Corresponding author.
E-mail address: tropanimals@uni-kassel.de (P. Fust).

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O'Connor, 1999; Czegledi and Radacsi, 2005), which in consequence results in dissatisfying performance of the herbivores. In traditional animal husbandry, mitigation of these effects has been accomplished by the implementation of different grazing strategies, such as rotational grazing (Stafford Smith, 1996), adaptive herd management or nomadic pastoralism, where continuously controlled herd movements allow exploiting grazing resources in a very sustainable way by tracking the temporal and spatial dynamics in resource availability. Particularly in arid regions, where high fluctuations in quantity and quality of feed and water resources require a high level of mobility, the recent boost in human population combined with restricted access to rangelands as a result of lack of land ownership or clearly defined and respected use rights has increased the pressure on the currently available foraging grounds and the risks of an unsustainable utilization of these natural resources (e.g. Hobbs et al., 2008). Thereby, these additional challenges for the utilization of rangelands demand a further increase in herd mobility involving extra energy expense for movements in search of feed or alternatively an increase in productivity at reduced space and new, adaptive strategies in grazing management. While extensive knowledge on grazing management is available for regions with temperate climate, expertise in management and ecology of rangelands in arid environments is still relatively poor (Boval and Dixon, 2012). A major reason for this scientific shortcoming is the high level of unpredictability involved, which complicates the conclusive definition of the relevant ecosystem processes, the involved drivers and the respective interactions. The high spatial and temporal variability in forage quality and availability in dryland pastures has been claimed to furthermore limit the advances in our understanding of the processes in these ecosystems (O'Reagain, 2001; Beukes et al., 2002; McIvor, 2011; Jakoby et al., 2015).

In tropical and subtropical countries, pastures and crop residues constitute the main nutrient resource for ruminants (Lazzarini et al., 2009). As a result of the short growth period for vegetation, tropical grasses usually embed increased amounts of cell wall compounds, e.g. lignin, thereby – in combination with low protein contents – providing feed of restricted digestibility (Leng, 1990; Brown, 1999). The marked decline in feed quality as a result of fast maturation of such grasses has been identified as one of the main limiting factors to animal production in the tropics (Van Soest, 1982; Leng, 1984; Fernandez-Rivera et al., 2005), but has been ignored in many rangeland models so far (e.g. Martin et al., 2014; Accatino et al., 2017, but see Rasch et al., 2016).

Traditionally, focus factors considered in rangeland and grazing management are stocking density, animal species, as well as the spatial and temporal distribution of forage offer. However, only few attempts have yet been made to integrate spatial heterogeneity (e.g. Derner et al., 2012) and non-linear scaling (e.g. Laca, 2009), although landscape ecology studies have revealed many years ago the potential effects of landscape patch configuration on individual animal's movement and the reciprocal effects of herbivores on landscape heterogeneity (e.g. Moen et al., 1998; With et al., 1999; Marion et al., 2005). High resource heterogeneity, one of the characteristic factors of rangelands and the according grazing systems in arid and semi-arid environments, is a key factor determining the dynamics of large herbivores and the landscape (Laca, 2009). As the spatial distribution of resources and selective feeding behavior of herbivores strongly affect their movement from grazing bout to landscape scale (Carvalho et al., 2011), it has proved to represent an important factor for grazing efficiency and therefore also foraging productivity (Wallis De Vries, 1996; Dijkman and Lawrence, 1997; Jung et al., 2002). Yet, the impact of spatial forage heterogeneity on herbivore nutrient intake and thereby productivity is still poorly understood (Marion et al., 2005).

The application of ecological modeling has been proved to be a valuable tool to study complex processes (Weisberg et al., 2006), especially regarding its potential to predict reactions of systems on altered environmental conditions. Since 1970, numerous models have been developed focusing on various ecological and economic aspects of rangelands and grazing management with a broad range of approaches and purposes (e.g. Coughenour, 1993; Beecham and Farnsworth, 1998; Derry, 1998; Diaz-Solis et al., 2003; Adler and Hall, 2005; MacOpiyo, 2005; Rufino et al., 2009; Kuckertz et al., 2011). As Tietjen and Jeltsch (2007) stated in their review on models for semi-arid grazing systems, basically all models lacked the consideration of climatic variability, e.g. the ability to resolve changes in intra-annual precipitation (Jakoby et al., 2015). This issue is particularly challenging when aiming at assessing the effect of future climate changes on livestock production systems in sub-Saharan countries. Predictions for these countries not only indicate a general decrease in precipitation and therefore in length of the growth period of vegetation, but also an increase in temporal variability and change in precipitation distribution (Thornton et al., 2006; Thornton et al., 2007; Rust and Rust, 2013). It is furthermore remarkable that the integration of the climate-dependent dynamics of resources' quantity, their nutritive quality and their spatial arrangement in a rangeland model for analysis of their effects on grazing herbivores has to our knowledge never been accomplished.

Deterministic, mechanical models often over-simplify spatial variability and fall short of being fully spatially explicit (Nonaka and Holme, 2007). These models are furthermore hardly able to embody complex event-driven dynamics and non-equilibrium ecosystem dynamics, two further characteristics of ecological processes in arid and semi-arid environments (Cipriotti et al., 2012). Agent-based models (ABMs) currently represent the most promising possibility to overcome these limitations by supporting dynamic, adaptive relations between individual mobile entities and the integration of stochastic events in a spatially-explicit context (Wiegand et al., 1995; Grimm and Railsback, 2005; Grimm et al., 2005). While some ABMs have been developed to simulate different specific aspects of rangeland ecology (MacOpiyo 2005; Müller et al., 2007; Kuckertz et al., 2011; Rasch et al., 2016), the dynamics of climate, vegetation and foraging herbivores have rarely been integrated within a habitat and rangeland management model. Modeling approaches to combine vegetation characteristics with animal behavior and movement and metabolic productivity in a spatially-explicit manner to incorporate important dryland aspects such as spatial heterogeneity are missing so far.

This paper therefore aims to broaden the understanding of ecological aspects in rangeland and herd management in semi-arid environments. Using an agent-based approach, we developed a spatially explicit model integrating energetic implications of animal movements to assess the potential of highly dynamic, heterogeneous semi-arid rangeland for adaptive livestock production. Main focus of the model is to account for the specific processes in rangeland-based livestock production systems in dry zones and to assess the dynamics in system performance. As such, we incorporated a) seasonal forage quality, b) spatially heterogeneous forage distribution, and c) the effect of climatic variability on forage resources. For the development of RaMDry (Rangeland Model in Drylands), data from a semi-arid region in southwestern Madagascar has been integrated. However, RaMDry uses a modular data structure, which explicitly promotes its applicability for any other arid or semi-arid rangeland area. Due to the complexity of the model, this publication provides a description of the model considering free-ranging conditions, excluding any active influences on animal movements by herders. Nevertheless, we would like to note that the model has – by its agents-based concept – been specifically developed to integrate active herding strategies and interactive behavior between herders, animals and the vegetation. In this paper, we first give a short introduction to the exemplary study region in Madagascar, followed by the general description of our