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Landscape-scale interactions between pastures, crops, trees and cattle in savanna grassland systems

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Abstract: Conversion of rangelands into cropland has been promoted for agricultural intensification of up to 400 million ha land in the Guinea Savannah. Realistic assessment of potential environmental and socio-economic side-effects is difficult as large areas, changing climate, soil, hydrological, plant, animal and human aspects need to be considered. The predominant cattle grazing systems on pasture under Acacias are complex including herd mobility in the landscape. Interactions between soils, plants and animals include plant reactions to grazing (resprouting, resource allocation), effects of pasture quality on animal nutrition and subsequently of manure quality on soil fertility. Herders design management strategies to cope with drought, expanding cropping areas (constraining herd mobility), and labour constraints. We present a recently developed coupled integrated model (MLL), of an agent-based economic model (**M**PMAS), a soil-plant model (**L**UCIA) and a herd model (**L**IVSIM). Lucia is spatially distributed, operates at landscape scale, and provides daily water, soil, soil organic matter and plant (including grasslands) dynamics. An extended LIVSIM simulates herd nutrition and reproduction, milk and meat production of multiple herds in the landscape. MPMAS simulates monthly agent decisions on land use, grazing locations and household economics. We show results from coupled model runs of rangelands in transition to crop-livestock systems at the Borana plateau, South Ethiopia, under scenarios of climate change, pasture accessibility and cattle selling strategies, and discuss applications of MLL in context with environmental impacts of agricultural intensification. Scenario runs demonstrate the added value of the high temporal and spatial resolution, feedbacks on animal performance during stress periods (dry season feed quality; fodder availability under climate change), pasture degradation risks under current or adaptive herd management strategies. The ability of the coupled models to dynamically simulate feedback processes makes it a valuable tool for assessing LUC impacts on systems performance, ecosystem functions and livelihood impacts.

***Keywords**:* Coupled social-ecological model framework; crop-livestock integration; agricultural intensification; agent-based model

1 INTRODUCTION

Dynamics and dimension of land use change in Subsaharan Africa have been unprecedented in the last decades (Herrero et al., 2012; Kibret et al., 2016). Fragile savanna ecosystems are under threat from different sides (Herrero 2010): Agricultural intensification through conversion of rangelands into agriculture has been proposed for some time (World Bank 2009) and is now increasingly taking place. At the same time, livestock numbers have been increasing world-wide (Herrero et al., 2012), raising concerns about ecological side effects in ecosystems with low carrying capacity and traditionally low livestock densities like Subsaharan savannas (FAO, 2006). Both trends are linked, as shrinking and fragmented areas for traditional rangeland herding, reduced herd mobility and less access to communal grazing lands lead to increasing livestock densities in the remaining grazing areas. Potential ecological consequences are overgrazing and soil compaction, erosion and degradation, loss of tree cover, bush encroachment, decrease in soil carbon and clean water, loss of biodiversity (FAO, 2006), which can be aggravated by climate change. Societal consequences include reduced production and household income and land conflicts between farmers and herders (Rohwerder 2015). As potential alternative route to sustainable agricultural intensification, a range of integrated crop-livestock systems has been proposed (e.g. Duncan et al., 2013).

Both, the risk assessment of imminent large-scale land use change as well as the search for alternative pathways require an understanding of interactions between humans, herds, plants and their physical environment (e.g. soil, hydrology, weather, topography). The necessity of new assessment tools for pastoral – agricultural transitions including crop-livestock integration has been highlighted by Romney et al. (2003), Herrero et al. (2012) and Rufino et al. (2014). An integrated simulation model that aims to capture the inherent complexity of these socio-ecological systems needs to be dynamic, spatially distributed at the landscape-scale and representing individual household decisions. Existing models are either not biophysically process-based or spatially explicit (Rasch et al. 2017; Rotz et al. 2005), lack detailed representation of plant physiology (Oomen et al. 2016), of agricultural systems (Boone et al., 2011), tropical smallholder conditions (Johnson et al. 2008) or herd management decisions (Rotz et al. 2005). In a review on integrated grazing models Snow et al. (2014) identified lack of detailed process-based plant-animal interactions, full economic accounting of animal products, selective grazing, herd mobility and consideration of a whole farm instead of single paddocks as main constraints of existing models.

In the following we present three originally independent models coupled into an integrated framework that simulates interactions between soils, plants, animal herds and household decisions in an Ethiopian watershed. The presented framework can represent impacts of savanna land use conversion, but is sufficiently generic for applications in other contexts.

2 DESCRIPTION OF THE COUPLED MODEL

The integrated model system introduced here consists of three dynamically coupled individual models. a) MPMAS (Mathematical Programming Multi Agent Systems) is an agent-based bioeconomic model for the simulation of agricultural decisions that represents agent-agent and agent-environment interactions (Schreinemachers & Berger 2011; Troost & Berger 2016), which has been applied in numerous case studies around the world to analyze, for example, agricultural yield gaps (Hampf et al. 2018), adaptation to climate change and variability (Troost & Berger 2015; Berger et al. 2017), agricultural policy (Troost et al. 2015), among others. Additions to MPMAS for this study were a switch from seasonal to monthly decision interval and shared access to communal grazing areas. b) LUCIA (Land Use Change Impact Assessment tool) was designed to assess landscape-scale plant productivity, soil fertility and degradation (Marohn & Cadisch 2011). It has been amended for perennial and intercropping systems and contains numerous management options (e.g. Liu et al. 2019). Soil organic matter dynamics and detailed erosion routines are also included (Lippe et al. 2014). For this study we added a grassland module that improves simulation of resprouting after grazing and introduces dormancy of grasses in drylands. c) The Livestock Simulator LIVSIM (Rufino et al. 2009), simulates effects of feed management strategies on ruminant livestock herd performance on the individual animal base. The version used here contains modified equations for metabolizable energy and crude protein demand as well as for animal energy partitioning (Bateki & Dickhöfer 2020. Details on the models are summarised in Table 1.

Table 1. Characteristics of the Mathematical Programming Multi-agent systems (MPMAS), Land Use Change Impact Assessment tool (LUCIA) and Livestock Simulator (LIVSIM)

	MPMAS	LUCIA	LIVSIM
Domain	Farm households	Soil, plants	Animal herds
Processes	Production / consumption decisions	Hydrological, plant growth, soil (organic matter) dynamics	Build-up of body mass, reproduction, lactation
Applications	Farm economics and resilience	Effects of land use and management on ecosystems	Herd status, milk and meat production
Spatial representation	Explicit	Distributed	Point model
Temporal resolution	Monthly	Daily	Monthly
Reference	https://mpmas.uni-hohenheim.de	https://lucia.uni-hohenheim.de	https://models.pps.wur.nl/livsim

To technically link the three models, a specific coupling engine was built, called MLL after the models' initials. MPMAS and LUCIA run in separate processes and communicate via the TCP/IP protocol, so that the coupled model could theoretically be run on different machines on a network. Both are written in different programming languages and only share well-defined interfaces to exchange few variables. On the other hand, LUCIA and LIVSIM are both written in Python 2.7 and multiple instances of LIVSIM (one per herd) are directly called from the running PCRasterPython (4.2.1) script in LUCIA. Thus, all communication in MLL runs through LUCIA at a monthly interval. Historically, an MPMAS-LUCIA coupling already existed (Marohn et el. 2013), which was conceptually extended, reimplemented and amended with LIVSIM.

Conceptually, MPMAS receives crop yield and, for grazing, edible aboveground biomass data from LUCIA for every pixel in the landscape (Figure 1). In turn, LUCIA gets spatially explicit land use and grazing zones from MPMAS. MPMAS receives livestock information like body weight, age, pregnancies, births, deaths for each individual animal from the LIVSIM instances, which receive information on management-induced changes in herd composition (slaughtering, selling and buying) from MPMAS. At the beginning of each month, LUCIA receives projected average daily feed consumption from LIVSIM. Based on this information LUCIA calculates grazing impact, simulates vegetation regrowth and, in case of pasture depletion, moves the herd to another pixel. Due to LUCIA's daily time step, this may happen between two model communication events. The pixel with the highest quantity of crude protein in the aboveground biomass available for grazing within the zone predefined by MPMAS, is selected as next grazing location. Apart from pasture consumption, LIVSIM informs LUCIA about quantity and quality of faeces and urine excreted. The quality of excreta depends on the vegetation quality provided by LUCIA in the previous timestep.

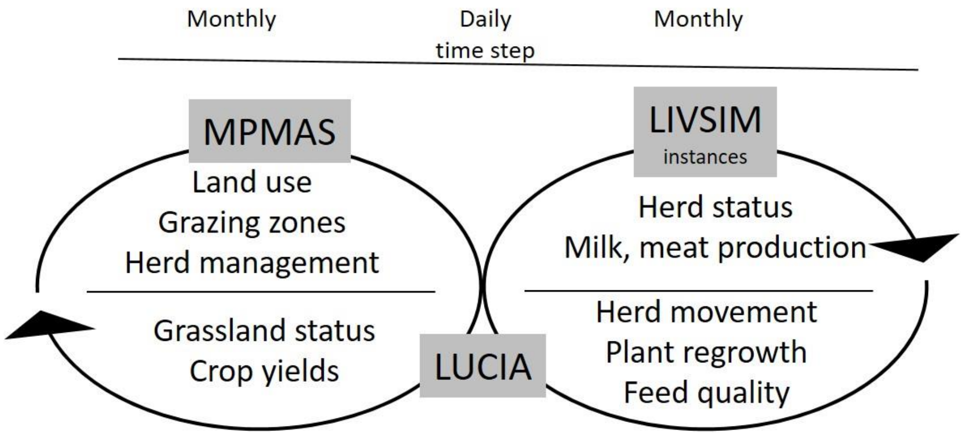


Figure 1. Coupled model structure and exchanged variables

Agents in our study sell animals to obtain cash to buy cereals, when animals are getting too old or too weak or – in selected scenarios - due to expected shortcoming in feed. Feed shortage is expected, when grass biomass in the accessible grazing zones at the beginning of a month plus grass regrowth expected for the coming month (based on historical experience) would not suffice to cover the herd's calculated demand. When assigning grazing zones, agents respect access restrictions due to tenure and collective pasture management arrangements by traditional herder communities, provided as scenario input. The combination of monthly zonal decisions and daily herd movement options based on pasture quantity and quality allows for a continuum of grazing strategies between free ranging and managed grazing, where zones are grazed sequentially by priority. In LUCIA, feed quality is determined by N, P, K and lignin contents and changes with plant phenological development. Animals preferentially graze leaves, and leaf regrowth is stimulated by grazing. Plant biomass of high nutrient content and digestibility produces high quality dung, which is easily decomposable in soil organic matter pools and vice versa.

3 CASE STUDY

As a case study we chose an area of approximately 60,000 ha on the Southern Ethiopian Borana plateau. Rainfall is bimodal and was about 550 mm annual in average years, and 330 mm in drought years according to Seckinger (2014) and daily data for Yabelo and Mega by the National Meteorological Agency of Ethiopia.

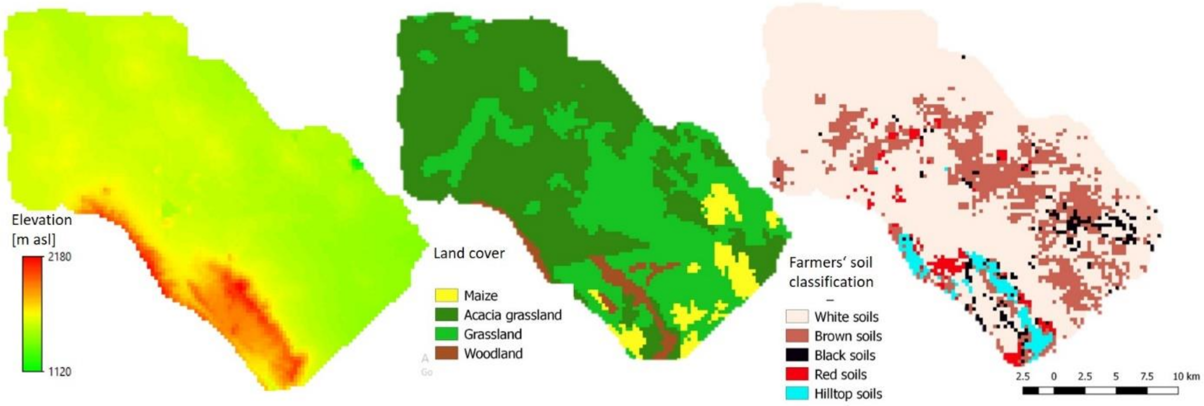


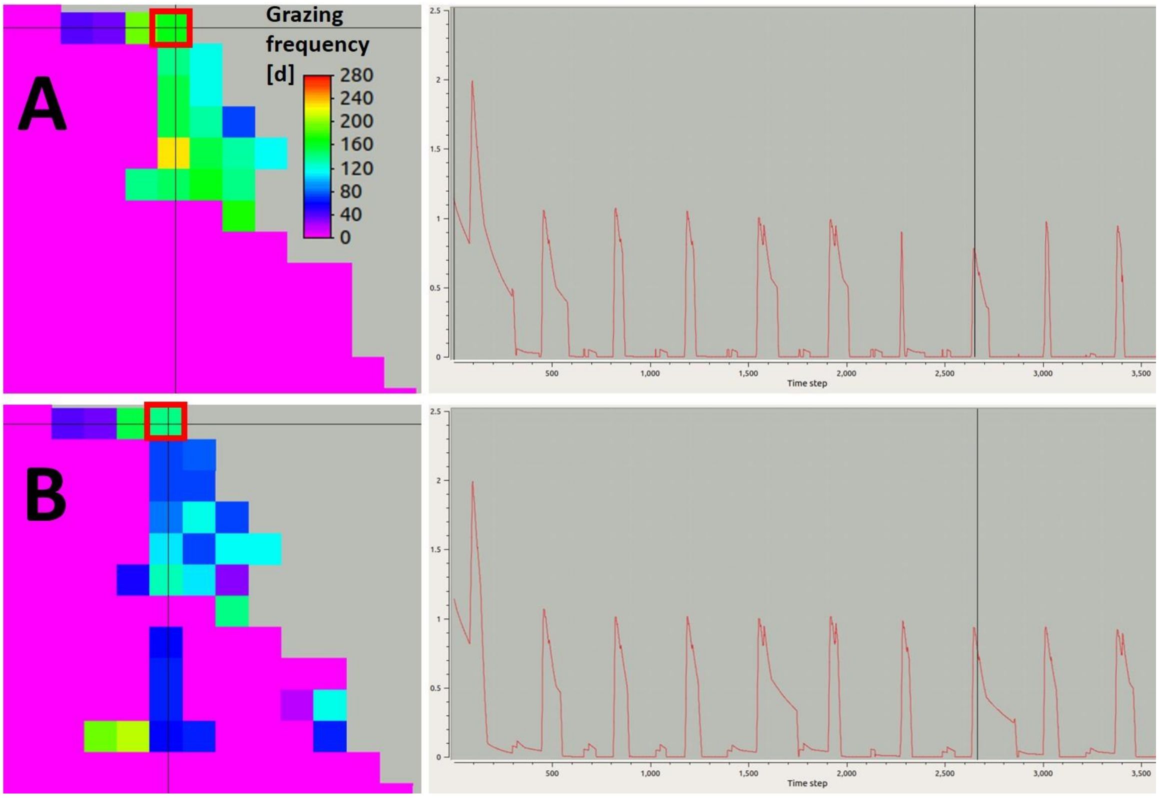
Figure 2. Topography, land use and soil of the study area (sources USGS 2004; Glatzle 2012 (local farmers' classification))

For model parameterisation and calibration, soil data from Glatzle (2012), pasture biomass data from Hasen-Yusuf et al. (2013) and a survey on grazing areas by Wario (2015) were employed. Measured rainfall of Yabelo and Mega sites (both in the Borana region) from 2012-2017 were used to generate a 5-year loop of gap-filled rain data, which was repeated twice as representation of typical weather. Agent characteristics such as herd and household size, monthly consumption demand, cereal, milk and animal prices were calculated based on ILRI (2014).

In the following we present scenarios to highlight the major interactions between vegetation growth, grazing, regrowth after grazing and management decisions. To reduce complexity, we abstract from the coordinated, but competitive grazing situation in Borana, where multiple herds share access to the same areas. We assess herd movement within a confined area simulated to be exclusive to the herder agent. Scenarios were run for 10 years. Out of many, twelve simulated scenarios are presented in this study, which varied in 3 factors: Area access: Herds had access to a) 20 pixels á 9 ha in both dry and wet seasons, respectively; b) 30 pixels in dry and wet seasons; c) 30 pixels in the dry and 16 in the wet seasons. This reflects typical community rules to set aside certain part of the area (here 14 pixels) during the wet season, when pasture was (expected to be) unlimited, to have more biomass reserves in the dry seasons. Agent strategy for selling cattle: A pre-emptive selling strategy was implemented, where cattle were sold when the agent anticipated lack of feed for the coming month. This was contrasted with scenarios in which the agent keeps all animals even if they run the risk of dying due to fodder shortage in the next month. Rainfall regime: A typical weather scenario and a drought scenario with more pronounced dry seasons and less annual rainfall in years 3 and 4 per 5-year loop were constructed based on the above-mentioned measured data.

4 RESULTS

Maps of cumulative grazing days in Figure 2 show that pixels were not grazed uniformly, owed to the spatial variability of soil hydrology and of resprouting behaviour of the vegetation after grazing. These lead to different pasture build-up and quality and preferential grazing determined by LUCIA. Figure 2A represents a scenario of limited grazing area (20 / 20 pixels per wet / dry season), no pre-emptive reduction of cattle stocks; 2C shows an ungrazed pixel on the heat map with the respective AGB on the right for the same scenario in comparison. In the scenario shown in Figure 2B herd size is reduced under imminent pasture shortage (pre-emptive sales) and pixels are set aside during wet seasons (only 16 pixels accessible) to have more reserves available (30 pixels) in dry seasons. Compared to 2A this scenario shows a prolongation of grazing periods on the selected pixel until pasture depletion and herd movement occur. Particularly in the dry seasons, pixels were depleted after a few days and the herd moved on. Figure 2D shows degrading vegetation even under the pre-emptive and setting-aside herd management scenario, where pasture biomass declined from wet season to wet season and did not recover after year 7. Aboveground pasture biomass was further affected by drought conditions under all selling strategies (data not shown).



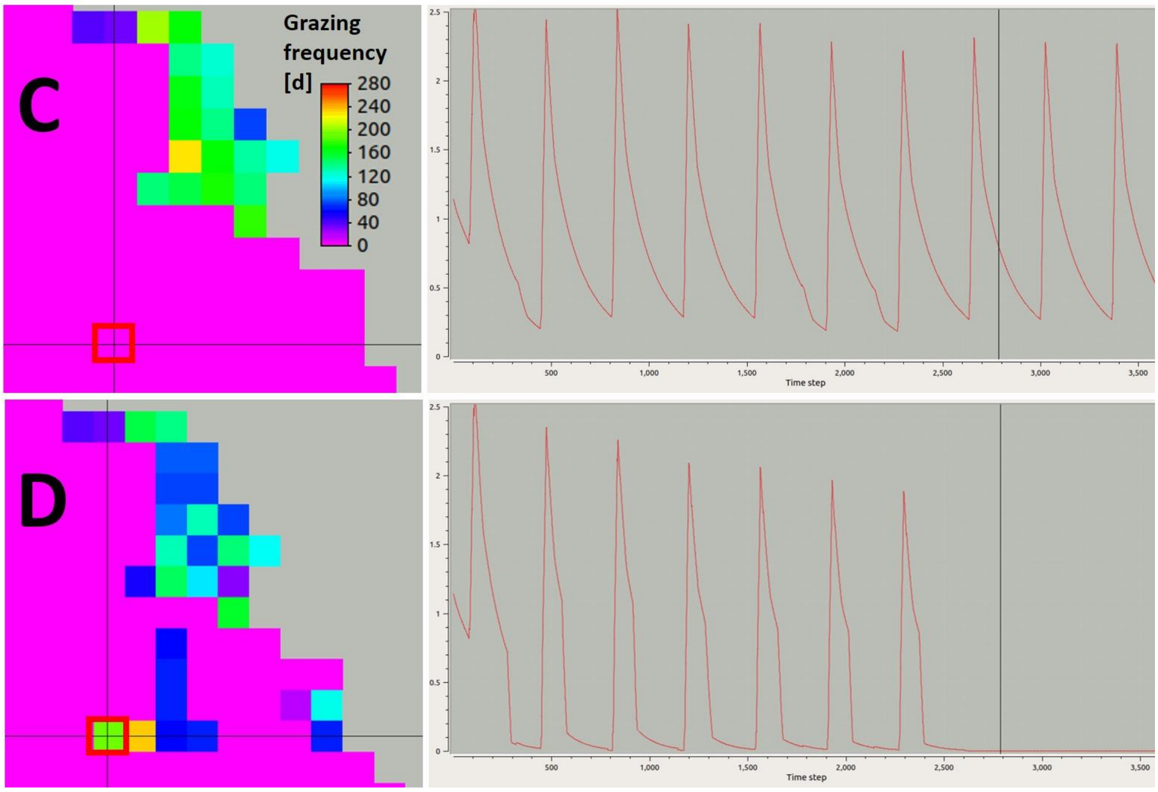


Figure 2. Selected grazing area in the Borana simulations. Cumulative grazing time maps on day 2664 and pasture aboveground biomass time series for two different pixels (2A and B vs. 2C and D). Zero stands for pixels that were not grazed in the scenarios. 2A and 2C: 20/20 pixels accessible in wet/dry season, no pre-emptive animal selling strategy under foreseen feed shortage; 2B and 2D with 16 / 30 pixels accessible and pre-emptive selling.

Figure 3 shows on a monthly basis that the accessible grazing area had a clear effect on herd size and composition. Where only 20 pixels of 9 ha each were accessible in dry and wet season, large part of the herds was sold around month 40 under the pre-emptive selling strategy, and even earlier under typical than under drought conditions. Under drought conditions herds were sold under the pre-emptive strategy even if they had access to larger grazing areas (second row in Fig. 2). Without pre-emptive selling herd numbers built up to > 75 heads (compared with around 50 under pre-emptive selling), but decreased later when grass reserves were depleted. Herd size and status both responded positively, i.e. more animals and a higher proportion of animals in the higher body weight classes, to setting aside areas for the dry season under typical weather conditions. This means that access was allowed to only 16 pixels (right column) and the strategy was successful for both herd size management strategies.

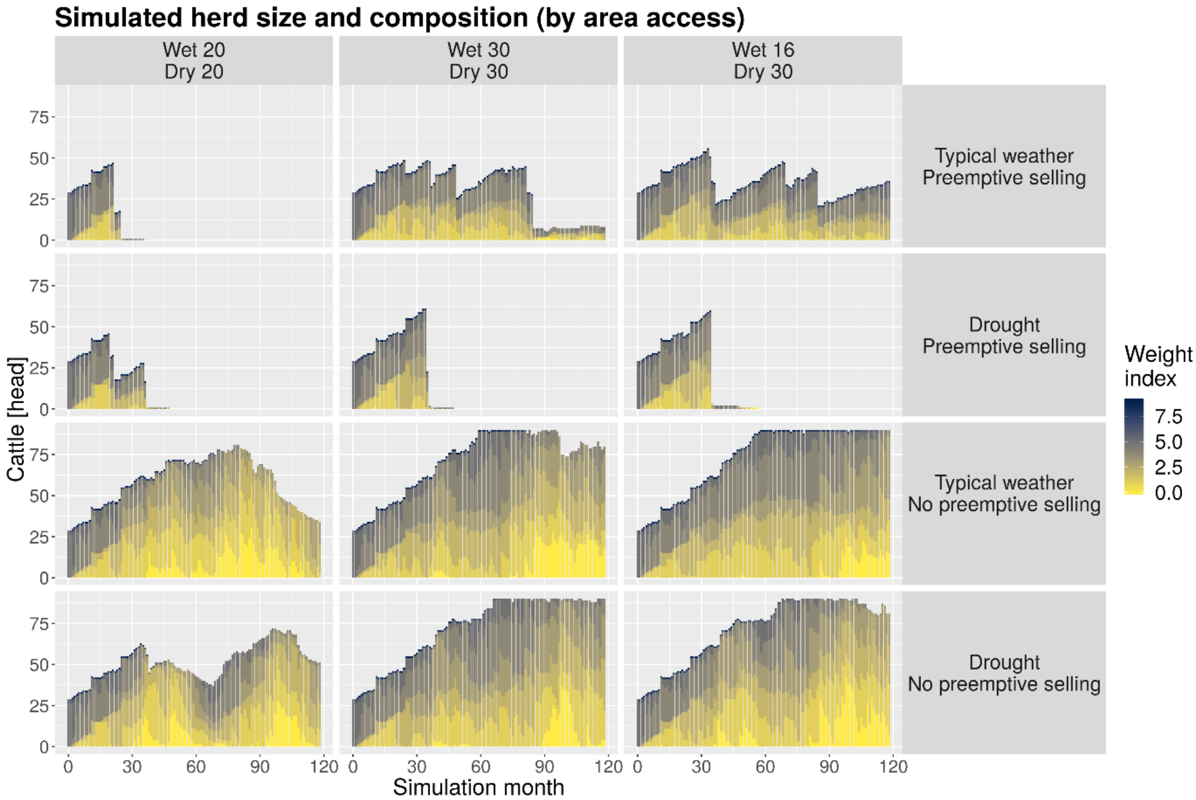


Figure 3. Herd size and status (weight classes) under 12 scenarios varying a) access to grazing area in dry and wet season, b) cattle selling strategy (pre-emptive referring to agents selling animals when anticipating feed shortage) and c) rainfall regime. Scenarios were run for 120 months. Column header shows the number of 9 ha pixels available in the wet and dry seasons.

Sustainability of the selling strategy is also reflected by the balance between births and deaths animals, which was always positive under pre-emptive selling conditions (data not shown). Pasture was degraded more severely if no pre-emptive selling strategy was chosen (data not shown).

5 DISCUSSION

This study aimed to demonstrate the capabilities of our integrated human-plant-animal model MLL to represent interactions between the biophysical environment and pastoral management of Subsaharan savannas. Our simulations realistically show the feedback loop between biophysical conditions (here rainfall), accessibility of grazing areas, agent herd management decisions, herd performance and environmental impact (pasture degradation). Herd composition and body weight clearly responded to the access to grazing areas, particularly under drought conditions when plant growth was limited. In this case grasslands tended to be degraded through overgrazing. Although it is too early to evaluate herders' land management and cattle selling strategies regarding sustainable resource use (preventing pasture degradation) and resilience to feed shortage (setting aside pasture areas), our case study shows that the integrated model captured the interactions between plant growth, herd nutrition and agent decisions.

This study has been conceptualised as a proof of concept and complexity of the scenarios was deliberately limited. Scenarios that reflect herders' strategy to split herds into younger and older animals have been run, but are not presented as they are beyond the scope of this study. Future scenarios will include multiple agents and the option to switch from pastoral to various agricultural land uses, as land use conversion was one of the starting points of our study. Initialisation effects affecting AGB (Fig. 2) that have been neglected here, because they appeared equally in all scenarios, will be addressed in future runs. Among the next steps in model development will be a) more mechanistic representation of feed quality influence on livestock nutritional status; b) accounting for spatial aspects of herd migration such as walking distances, fragmentation of landscapes and maximum distances from water holes.

6 CONCLUSIONS

MLL, the integrated MPMAS-LUCIA-LIVSIM model framework, has been developed from its individual models by adding monthly decisions on herd management and movement on communal grazing land in MPMAS, a daily decision mechanism for herd movement and paddock selection and improved pasture physiology in LUCIA, and the implementation of multiple LIVSIM instances adapted to tropical nutrition. A specific coupling mechanism allows to dynamically couple the three models and exchange variables on a monthly basis. A first case study conducted on data from the Ethiopian Borana plateau shows the capability of the integrated model to capture feedback between landscape-scale biophysical dynamics and household decision-making. This makes MLL a promising tool for the assessment of imminent trends in the research area but also in other savanna areas, including land conversion and limited access to grazing grounds, intensification of herding activities with related overgrazing, and climate change effects on grassland productivity.

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