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Coupled biophysical and decision-making processes in grassland systems in East African savannahs – A modelling framework

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ABSTRACT

Increasing livestock densities on limited grazing areas in African savannahs lead to resource degradation through overgrazing, aggravated by drought. Assessing herd management strategies over longer periods at landscape scale is important to propose options for sustainable land use. This requires an understanding of processes related to hydrology, nutrient cycling, herd movement, pasture degradation, and animal resilience that involve dynamic soil-plant-animal interactions and human decisions about stocking rates, livestock purchases and sales.

We present the coupled model system MPMAS-LUCIA-LIVSIM (MLL), the combination of a spatially explicit agent-based model for human decision-making (MPMAS), a spatially distributed landscape model for water flows, nutrient cycles and plant growth (LUCIA), and a herd model (LIVSIM) representing grazing, body weight, nutrition and excreta of individual animals. MLL represents daily vegetation growth in response to grazing and organic inputs, monthly animal performance influenced by forage availability and quality, and herders' management in response to resource status. New modules for selective grazing, resprouting of pasture, herd movement and model coupling were developed for MLL.

The test case of a pastoral system in the Ethiopian Borana region demonstrates the capabilities of MLL to simulate key soil-plant-animal-human interactions under climate-related management scenarios with varying access to grazing land, changing cattle prices and different spending / saving behaviour of herders. 20-year simulations showed the negative impact of consecutive drought years on vegetation biomass, on herd development and movement and how reserving grazing areas for dry seasons could mitigate overgrazing and improve income. Seasonality and drought response of vegetation growth, selective grazing of different plant parts, resprouting after grazing, calving intervals, milk yields and lactation in response to forage supply and quality as well as herder reactions to shocks were plausibly represented.

Building upon this successful proof-of-concept, MLL can be used to identify robust management options for improved grazing systems in savannahs in follow-up research.

1. Introduction

1.1. Recent trends in pastoral systems of Subsaharan Africa

Savannahs cover 50% of the land surface in Africa (Osborne et al., 2018) and are among the areas with highest densities of cattle, goat, and sheep worldwide (Gilbert et al., 2018). Savannahs in Subsaharan Africa (SSA) have seen drastic land use and management changes during the last decades (Hill and Guerschman, 2020; Kibret et al., 2016), driven by demographic transition (Tabutin and Schoumaker, 2020), large-scale investment (Shankland and Gonçalves, 2016) and institutional influence (Ollenburger et al., 2016).

Savannahs in SSA are ecosystems with low carrying capacity (FAO, 2006). Additionally, pressure on these pasture resources has increased

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Table 1
Overview of coupled models in the MLL (MPMAS-LUCIA-LIVSIM) approach.

Model	MPMAS: Mathematical Programming-based Multi Agent Systems	LUCIA: Land use change impact assessment tool	LIVSIM: Livestock Simulator
Domain	Agents	Soil, plants, landscape	Animal herds
Processes	Production, investment, consumption decisions, accounting	Plant growth and competition, nutrient cycling, hydrology, erosion	Feed-manure conversion, meat /milk production, reproduction
Applications	Adoption of innovations, land use, herd management, economic impacts	Resource base sustainability, environmental impacts of land use	Herd performance
Space	Explicit	Distributed	Non-spatial
Time step	1 month	1 day	1 month
Language	C++	PCRaster-Python	Python
Reference	mpmas.uni-hohenheim.de	lucia.uni-hohenheim.de	models.pps.wur.nl/livsim

due to expanding crop lands and shrinking grazing areas, restricted herd mobility (Gonin, 2016), and increasing livestock populations (Herrero et al., 2012). Drought years like 2006, 2009, and 2015 in large parts of Ethiopia (Kibret et al., 2020) led to acute shortages of animal feed and as a result to resource overuse; thus, profound changes in ecosystem functions and biome shifts are expected (Martens et al., 2021). The combination of climatic extremes and resource overuse threaten herd populations as economic base of herders. Limited access to grazing land has already led to violent conflicts in the border region of Northern Kenya, South Sudan, and Southern Ethiopia (e.g. Human Rights Watch, 2015).

Strategies to overcome the overuse of natural resources in pastoral systems and related management options at system level require the understanding of underlying biophysical processes. To date, resource use and recycling between animals, plants and soil; vegetation regrowth after grazing, and drought stress effects on plants are only partially understood in their spatio-temporal context. Complexity increases further as herder decisions interact with biophysical processes. As Herrero et al. (2012) pointed out, the agricultural and pastoral sectors "*are changing at unprecedented rates and are becoming more difficult to project. Integrated assessments are becoming a key step towards understanding change but [...] increasing in complexity and [...] difficult to put together comprehensively across sectors*".

Computer simulation models are increasingly used for the integrated assessment of social-ecological systems (Kolosz et al., 2018), because identifying sustainable land use options implies assessing their long-term impacts on farm economy and ecosystem functions. At the same time, shortcomings in existing simulation models have been identified, particularly for savannah systems. Rufino et al. (2014) stressed the necessity of developing models that better account for feedback mechanisms between crop and livestock components in integrated systems to facilitate *systems thinking*, whereas Rötter et al. (2021) identified the need for better integration of economic modelling and mechanistic vegetation modelling at landscape scale to attain more practical relevance.

1.2. State of the art of plant-animal-human savannah models

Several herd models exist that account for animals' nutrient and energy requirements, their growth and milk production. Rotz et al. (2005), in their beef submodel of the Integrated Farm System Model IFSM, included plant growth and simulated feed requirement, quality, and intake as well as performance of animals, excreta, and environmental impacts on single farms. Johnson et al. (2008) described a combination of biophysical pasture simulation models (SGS pasture model, DairyMod, and EcoMod) that cover plant physiology, nutrient balances, soil organic matter (SOM) dynamics, and environmental processes in the soil. A simplified point-scale water balance for infiltration and soil moisture as well as management strategies (rotations, cutting, hay, silage, concentrate feeding; cattle movement according to pasture biomass) were part of this model system. Plant-animal interactions from an ecological (in contrast to agronomic) perspective in savannah ecosystems are covered in SAVANNA and its extension for SOM-related processes, G-range (Boone et al. 2011). Scheiter and Higgins (2012) presented a dynamic and spatially explicit coupled vegetation-herbivore model in a case study on savannah carrying capacity for elephants. A comprehensive review on process-based models that represent plant-plant and plant-animal interactions by Snow et al. (2014) identified detailed process-based plant-animal interactions, full economic accounting of animal products, selective grazing, and herd mobility as main tasks for future model development. Bateki and Dickhoefer (2019) addressed feeding behaviour and adaptive capacity of animals to changing environmental conditions as gaps in grassland ruminant models. Warth et al. (2020) compared 12 physiological and ecological plant-animal models for savannah ecosystems and found that plant-plant competition effects on tree seedling recruitment, trampling and seed dispersal by animals, herd movement, land use change (LUC) and management effects on herd mobility and grazing pressure were under-represented.

Regarding human decisions, SAVANNA has been dynamically coupled to the agent-based DECUMA model (Boone et al., 2011) for the purpose of assessing adaptive capacity of herders under stress caused by drought, policy, and limited access to land. Households decide on animal buying and selling, and on herd movement driven by forage availability and accessibility, herd composition, as well as water reservoir and household location. Scenarios on drought, blocked access to grazing land, and lease of grazing lands for wheat production have been run using the coupled system. Regarding crop production, however, the ensemble is non-spatial. Scheiter et al. (2019) coupled a dynamic global vegetation model to an economic model optimizing management options for economic value. A social-ecological savannah model system focusing on the resilience of rangeland systems under shocks, stressors, and policy interventions was presented by Rasch et al. (2016). It combines the animal component of an agent-based model accounting for forage consumption, body weight gain, deaths, and births (Gross et al., 2006) with the plant model Linrange (Oomen et al., 2016).

1.3. Models used for the present study

The Livestock Simulator (LIVSIM) is a non-spatial dynamic herd model, developed to assess the effect of different feed management strategies on cattle performance based on availability and nutritional quality of feed resources (Descheemaeker et al., 2018) (Table 1). LIVSIM simulates energy and protein requirements, monthly changes in body weight, milk yield, reproductive rate, and mortality, amounts and concentrations of nitrogen, phosphorus, and potassium in animal excreta (Rufino et al., 2011, 2009). The model has been used to evaluate the impact of different feeding strategies on the life time productivity of dairy cattle in the central highlands of Kenya (Rufino et al., 2009) and Southern Mali (de Ridder et al., 2015). However, LIVSIM was developed using feeding recommendations for livestock production systems in temperate regions and a feed intake model from highly productive dairy cattle in the United States. Thus, utilizing available data characterizing tropical livestock production systems, Bateki and Dickhoefer (2020) modified the growth and lactation curves, the metabolizable energy and protein requirement estimations, and implemented a semi-mechanistic statistical feed intake model.

The Land Use Change Impact Assessment tool LUCIA is a dynamic and spatially distributed model designed to assess impacts of land use and management on soil fertility, biomass production, watershed functions, and environmental services (Marohn et al., 2013a). It combines daily time step and landscape scale, physiological and ecological processes, water balance and flows, soil nutrient and organic matter cycling, plant growth and competition as well as land use and management strategies. Applications include climate change and management impact on agroforestry systems (Yang et al., 2019); erosion in rubber plantations under different weed management (Liu et al., 2020, 2019), participatory modelling of soil rehabilitation strategies in Kenyan smallholder systems (Marohn et al., 2017). Warth et al. (2021) amended LUCIA with a specific grassland module to simulate grazing impact on forage availability and nutritional quality as well as pasture degradation under severe stress conditions. Allocation of plant growth reserves in response to grazing and spatial animal excreta effects determined by user-defined herd movement were included in this model version. The present study introduces further improvements regarding selective grazing, dynamic nutrient cycling between soil, plants, SOM and excreta, and dynamic demand-driven herd movement.

The Mathematical Programming-based Multi Agent Systems MPMAS (Schreinemachers and Berger, 2011) is a bioeconomic multi-agent simulation model for human decision-making that has been applied to a large variety of crop and crop-livestock systems (e.g. Berger et al., 2017; Carauta et al., 2021; Mössinger et al., 2022; Schreinemachers et al., 2009, 2010; Troost et al., 2015; Troost and Berger, 2015; Wossen et al., 2018). In particular, the MPMAS application of Schreinemachers et al. (2007) combined household decision-making, soil productivity change and a herd model to endogenize livestock feeding and stocking rates in poverty analyses for Uganda. MPMAS and LUCIA have previously been dynamically coupled (Marohn et al., 2013b) to simulate the impact of soil conservation measures in cropping systems on household economy, crop yields, and environment. The coupling of MPMAS-LUCIA forms the basis for the newly developed model system MLL (MPMAS--LUCIA-LIVSIM) presented in this study.

1.4. Rationale and study aim

Sustainability assessment of land use options in savannah ecosystems needs to dynamically and spatially explicitly account for water and matter flows, and herd movement; plant and animal performance; and herders' cropping and grazing, buying and selling decisions.

The aim of the present study was to develop a tool capable of simulating a) grazing management options for sustainable use of forage resources, b) herd composition and herders' household economy, c) options for preventing resource overuse and environmental degradation in savannah ecosystems, and d) resilience against shocks. Such a tool would represent, in a process-based manner, i) plant growth depending on climatic and edaphic conditions influenced by grazing and human management; ii) herd composition, performance and mortality in response to pasture availability and quality, as well as herd management; and iii) human decisions taking plant development, animal performance and herd status into account when buying or selling animals or moving herds between paddocks.

For this purpose, we coupled the abovementioned **M**PMAS, **L**UCIA and **L**IVSIM models into the dynamic and spatially explicit soil-plant-animal-human model system MLL to assess pastoral systems over longer time spans at the landscape level. The present study focused on the methodological aspects of model coupling and highlights the interactions between plants, animals, and humans as represented by the three coupled models.

Our working hypotheses were that a) the coupled models produce added value in their respective domains compared to simulations with the standalone models; i.e. the interactions produce outputs (ideally: explain processes) that cannot be produced by the individual models; b) the outputs plausibly reflect observed trends; and c) the coupled models are sensitive to inputs and interactions, and sensible in terms of biophysical processes. The following requirements for the coupled model system were defined:

1 Dynamic, process-based, spatially explicit simulation of soil, plant, and livestock components in grazing and farming systems accounting for impacts of land use and animal grazing on system-level nutrient and water balances.
2 A plant module combining agronomic management options and ecological processes such as competition for resources in tree and shrub savannahs, adequate representation of seasonal dynamics of forage quantity and quality under grazing and plant stress induced by climatic extremes.
3 A herd model suited for (sub)tropical farming and pastoral systems.
4 Socio-economic decision-making processes on herd composition (buying and selling of animals), herd movement, and trade-offs with crop production accounting for agent behaviour, learning, and technology adoption.
5 A framework to dynamically couple the individual models integrating their time steps and spatial scales.

Developing highly complex integrated modelling systems to capture multiple biophysical and socioeconomic processes is not a trivial task; the attempt often leads to “integronsters” (Voinov and Shugart, 2013). Given the many interactions in agricultural and pastoral systems, especially model testing, calibrating, and validating a complex integrated model poses a challenge. Arnold et al. (2015) argued for a step-wise procedure, initially testing individual components, subsequently moving to larger, partly integrated units before finally assessing the full model system. Following this suggestion, our study focused on a single herd and household system to keep model interactions traceable and demonstrate the mechanisms of model coupling and system interactions. Interactions between several hundred human agents have been simulated in a coupled MPMAS-LUCIA framework (Marohn et al., 2013b). Herd-herd and plant-plant competition have been tested in standalone and coupled model runs; they will be addressed in a follow up study.

2. Materials and methods

In the first part of this section we will describe the full logic and capability of MLL in general following the ODD protocol (Overview, Design Concepts and Details) for describing individual- and agent-based models (Grimm et al., 2020, 2006).

In the second part, we explain model parameterization and initialization for a proof-of-concept study to analyse the plausibility of simulated agent-environment feedbacks. To ensure a thorough evaluation and discussion of the specific feedback loops in focus, this parameterization limits complexity for the test case by abstracting from cultivation of crops, agent-agent and herd-herd interactions. It focuses on the feedback between a confined rangeland area, a cattle herd and the decisions of one single pastoralist household in managing the herd under perceived open-access conditions.

2.1. Overview of the coupled model system

2.1.1. Purpose and patterns

MLL was constructed to simulate the feedback processes between humans, herds, and land management decisions, vegetation growth, nutrient cycling and water flows, animal performance as well as human livelihoods in pastoral savannah land use systems as influenced by the biophysical and economic environment. The overall aim is to enable the analysis of vulnerability and resilience of the savannah land use system and herders' livelihoods to external drivers, including climatic extremes, reduced land access, uptake of new economic activities, land conversion, and population pressure. The rationale for building the model was to explore and identify patterns of system behavior that result from

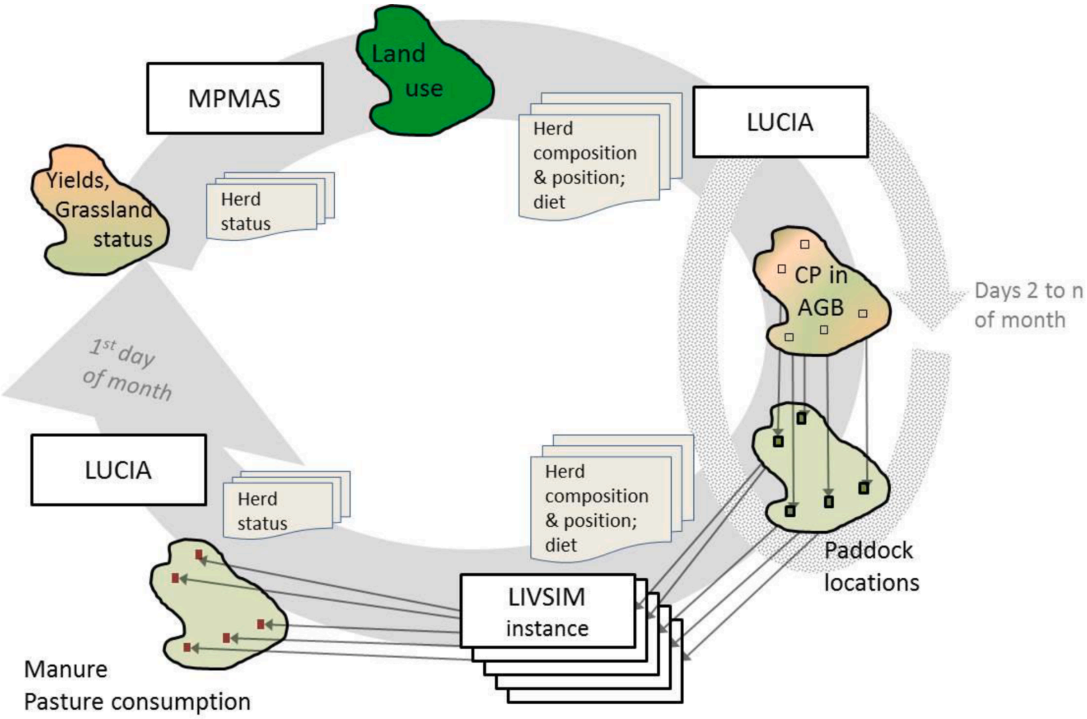

Fig. 1. Data exchange between multi-agent MPMAS, land use change LUCIA and livestock LIVSIM models (square boxes); spatial PCRaster maps (irregular shape), multiple documents are semicolon delimited text files. Multiple non-spatial LIVSIM herds (instances) are run in parallel. AGB = aboveground biomass; CP = crude protein.

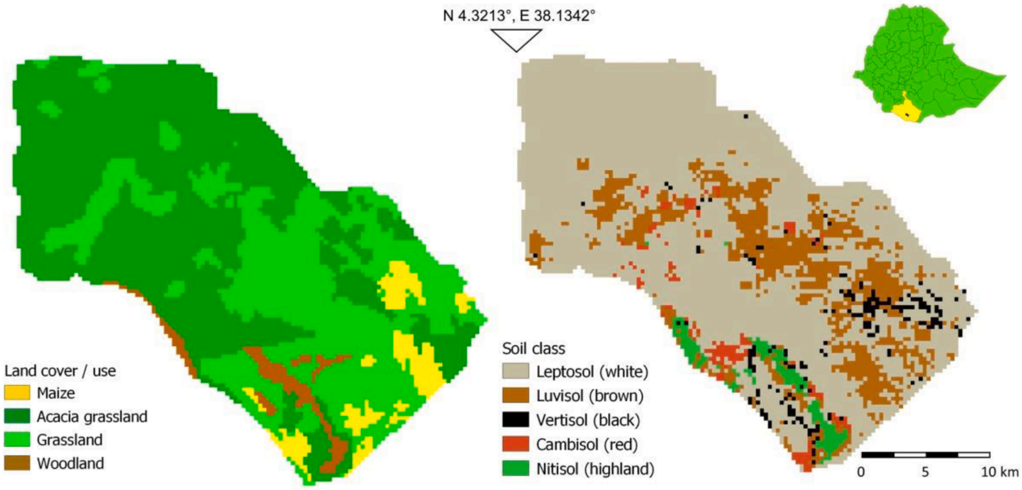

Fig. 2. (left) Land use according to Warth et al. (2021) and (right) soil types (SoilGrids system, v0.5.1; extracted by Glatzle (2012) (Elias et al., 2015; Google, 2018); WRB and local classification. Map upper left corner: N 4.3213°, E 38.1342°. Inlay in soil map: Borana region in Ethiopia (from https://gadm.org accessed Feb 2022).

combining process knowledge, including under counterfactual situations. Model development was not primarily pattern-driven, but rather process knowledge-driven. Nevertheless, we expect the model to be able to reproduce observed and plausible patterns in system behavior, namely quantitative relationships and feedback dynamics between herd size, grazing area, rainfall, grass regrowth / depletion and soil nutrient dynamics that correspond to local knowledge, empirical observation or generic scientific experience. Specific quantities and even dynamic patterns that can be used for evaluation are not necessarily universal, but may depend on local circumstances and are hence discussed for our case study specifically (results section), not in this general model description.

2.1.2. *Entities, state variables and scales*

MLL comprises the following entities: a) human agents (herder households), characterized by the state variables: livestock owned, herds managed, land access, cash reserves, household composition, and observed landscape state as well as behavioural parameters governing decisions and expectations; b) animals (here: cattle) characterized by breed, sex, age, body weight, condition, gestation status, lactation stage, feed intake, nutritional requirements, and nutrient excretion; c) herds, collectives of animals, characterized by their position in the landscape and parameters governing their potential movement and feed intake; d) landscape cells characterized by location, topography, local drain direction, land use and sub-entities vegetation (with plant growth state

Table 2
Scenarios implemented in the coupled MPMAS-LUCIA-LIVSIM.

External driver	Scenario	Factor description
Rainfall regime	Typical rain	5-year loop of two measured years (2016-2014-2014-2014-2016)
	Drought	Rain events reduced to 60% in years 3 and 4 of the 5-year loop
Cattle prices	Typical cattle price	Typical live cattle prices
	Low cattle price	Decreased live cattle prices by 50%.
Community pasture management	Full area access	54 ha of grazing land, no area reserved for dry seasons
	Reserved area	54 ha of grazing land, but 27 ha accessible only during dry seasons
Low access	Reduced area	Reduced grazing area access to 27 ha during all seasons
Emergency selling	None	No animals are sold because of low body weight
	Default	Male and older female animals are sold when reaching lowest body weight class; females before and in reproductive age are not sold
	Full	All animals in lowest age-specific body weight class are sold
Spending/saving	Limited spending	Discretionary non-food expenditure between a defined minimum and maximum (equal to twice the minimum). Spending beyond minimum only if cash reserves equivalent to 6 months of minimum food expenditure have been accumulated.
	Minimal saving	Only minimal cash reserves (i.e. equivalent monthly expenses for cereals), the remainder is spent

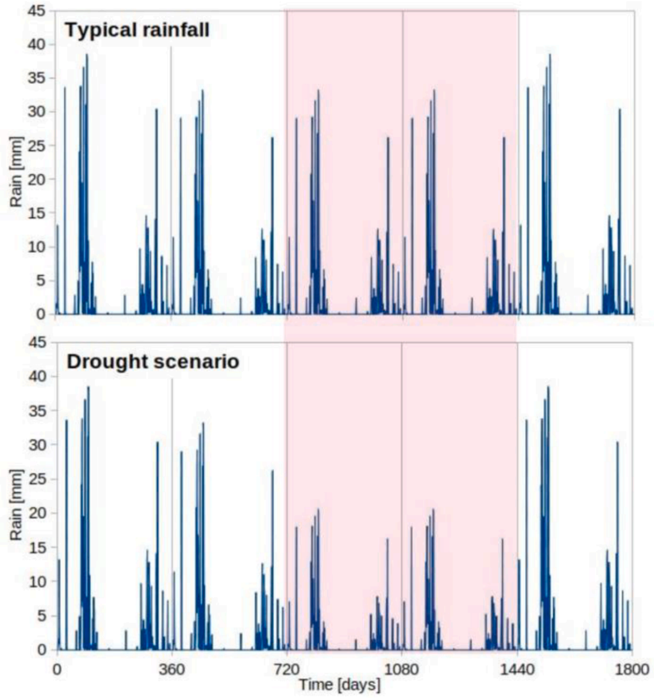

Fig. 3. 5-Year rainfall data looped for model scenarios: (a) typical rainfall based on combined measurements at Madhecho, Yabelo and Mega; (b) hypothetical drought scenario with dry years in years 3 and 4 per 5-year loop.

variables and parameters), and soil (with state variables and parameters describing water flows, carbon and nutrient cycling); and e) grazing units, at which access rights of agents and monthly herd movement are defined. A grazing unit typically consists of various map cells (pixels) in the model.

Scales: Raster-based spatial resolution, i.e. pixel size, is flexible and chosen to be 9 ha for the simulations in the present study. Temporal resolution for plant growth, soil processes, grazing, and herd movement is one day. Animal states are updated and herd management and livelihood decisions are taken on a monthly basis.

2.1.3. Process overview and scheduling

Fig. 1 provides an overview of the feedbacks in the model system, how they are distributed over the three coupled models and which state variables are communicating between components.

In MLL, a herder agent makes **land, herd and household management decisions** at the beginning of each month. The agent decides which animals to sell or slaughter, how to subdivide the remaining animals into herds, and within which grazing units it will let these herds roam. In addition, it decides on milk sales, grain purchases for human consumption, food consumption, non-food expenditure, and cash savings. These decisions occur simultaneously as part of one agent optimization problem, which is solved by MPMAS per herder household. For each herd, **pasture biomass demand and excreta deposition are then projected** for the upcoming month by LIVSIM.

On each day of the month, LUCIA first simulates **plant growth and soil processes** for each cell. Based on biomass quantity and quality at the current location, herds move autonomously between cells within the grazing units selected by the herder agent for the current month. The **herd grazes** and the quantity and quality of excreta is determined by pasture quantity and quality and affects vegetation and soil state at its location. Once all days of a month have been simulated, LIVSIM **updates the state of all animals** in the herds as a result of actual forage quality and consumption during the month. The **updated herd and grassland states are observed** by the herder agents and form the basis for their individual management decisions at the beginning of the following month.

2.2. Design concepts

Basic principles, emergence, and observation: MLL combines process-based plant physiology and growth, soil and SOM-related processes, and nutrient and energy metabolism of the animals and their reproduction with a conceptualization of human behaviour that is rooted in bounded rationality and considers multiple objectives of herder activities. It is designed to simulate grassland and soil state including temporal pasture degradation, herd size and composition, and herder food security, income, and wealth as emergent properties of the system.

Adaptation and objectives: A herder agent uses constrained optimization to adapt its monthly decisions on herd management to the states of herd, grassland, cash reserves, household demands, and prices in order to satisfy multiple objectives, which partly reflect immediate utility criteria and partly precautionary rules to ensure long-term viability. These objectives are: i) meeting the household minimum cereal (for human consumption), milk, meat, and non-food expenditure demands; ii) keeping a minimum reproductive herd size; iii) keeping a minimum reserve of cash savings; iv) selling cattle not used for breeding at a well-marketable age; v) keeping as many animals as possible (for reproductive purposes, as in-kind savings, and for social status); and vi) maximize discretionary spending and/or saving (i. e. spending beyond the minimum household demands and saving beyond minimum cash reserve). Objectives are associated with utility weights to allow for prioritisation if they cannot be fulfilled at the same time.

Herd movement within an assigned grazing unit follows fixed rules based on observed standing biomass and herd biomass demand in the current grazing paddock (pixel), while target pixels depend on standing biomass quality.

Sensing, Prediction, Learning: A herder observes the state of pasture, herd, household, and prices at the moment he or she takes the monthly decisions. To decide which animals to sell or keep, the herder agent

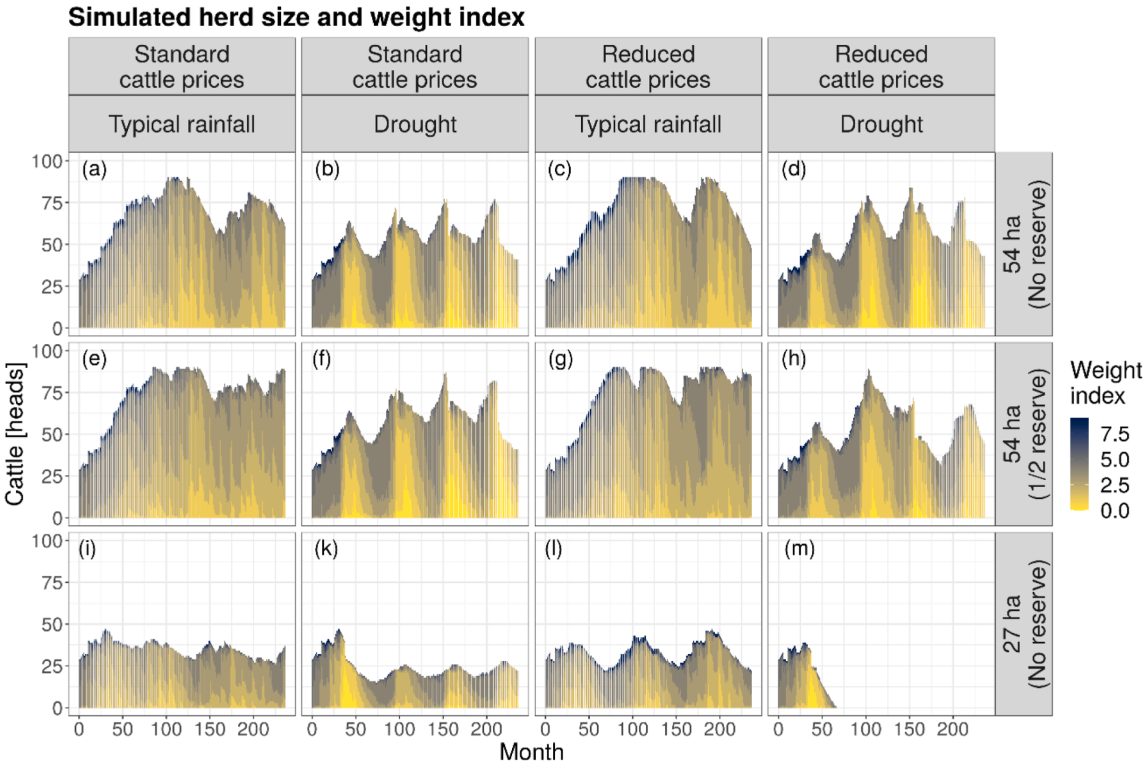

Fig. 4. Simulated herd size and composition (weight index) under different rainfall, cattle price and grassland area allocation scenarios, all for Default emergency selling and Limited spending (Table 1) over 20 years. The weight index relates actual weight to expected age- and sex-specific minimum and maximum weight: From 0 (severely undernourished, close to survival threshold) to 9 (extremely well-fed, close to maximum expected body weight).

predicts the utility value of the animal in the following month based on the current state of the animal and current prices.

Interaction: Herds and animals compete for pasture if grazing on the same paddock, i.e. pixel. The available pasture is divided proportionally to feed demand (estimated based on the intake module of LIVSIM) between herds and between animals within one herd. In principle, herder agents compete for grazing grounds, but they try to avoid competition by keeping herds apart, if enough free paddocks are available within their accessible area.

Collectives: Herds, as collectives of animals, are endogenously formed by the herder agent considering restrictions in movement for specific animal types (e.g. calves, lactating animals), accompanying herders, and pasture availability.

In reality, pastoralist communities take collective resource management decisions, e. g. by defining exclosures for dry season grazing or for keeping young animals. These decisions are currently not endogenously modelled but imposed as exogenous access rules.

Stochasticity: Both LIVSIM and MPMAS allow stochastic simulation of mortality, fertility and newborns' sex of animals, resp. household members. For the present study, these variables were simulated deterministically in LIVSIM, while household composition in MPMAS was kept constant.

2.3. Details

2.3.1. Initialization

At the start of the model simulation, household composition, cash reserves and herd composition are initialised based on existing information on the study area. Vegetation and soil state are initialized based on field and literature data.

2.3.2. Input

External boundary conditions considered in the model system are daily weather, monthly prices, and seasonal grazing unit access rules defined by herder communities.

2.3.3. Submodel: herder decisions (MPMAS)

To simulate pastoralist systems, we extended the newest version of MPMAS (Troost et al., 2022; Mössinger et al., 2022) to allow for monthly (rather than yearly) decision intervals, communal land ownership, community-based access rights to land, and competitive use of pastoral areas. Also, we added decision components for individual animal states, herd formation and movement and interfaces to exchange herd and grassland state as well as herd movement rules with LUCIA and LIVSIM.

Monthly, each herder agent solves a multi-objective mixed-integer programming (MO-MIP) problem. Piecewise-linear penalty functions weigh different degrees of not meeting the six individual objectives (mentioned in Design Concepts) against each other and establish a priority order. For example, the agent might be willing to reduce non-food-expenditure by 70% before starting to reduce cereal consumption. If that does not suffice, the agent might prefer to first reduce cereal consumption by up to 10%, before further reducing non-food expenditure. Generally, the agent gives priority to the minimum objectives (i-iii). Milk and meat are provided by the herd, while cereals have to be bought. Cash for cereal purchase and non-food expenditure has to be obtained by selling live cattle or milk. To be able to reflect animal state in the MIP model, animals are categorized into discrete state classes. For example, the continuous body weight from LIVSIM is categorized into a ten-level weight index representing age-specific weight classes equally spaced between age-specific minimum and maximum weight: From 0 (severely undernourished, close to survival threshold) to 9 (extremely well-fed, close to maximum expected body weight.)

The agent prioritises herd size (i.e. keeping animals) as soon as minimum household consumption and cash reserve demands have been met. This reflects pastoralist culture, in which wealth and status are projected by herd size and mutual solidarity rules discourage unnecessary sales (Hurst et al., 2012), but potentially also economic

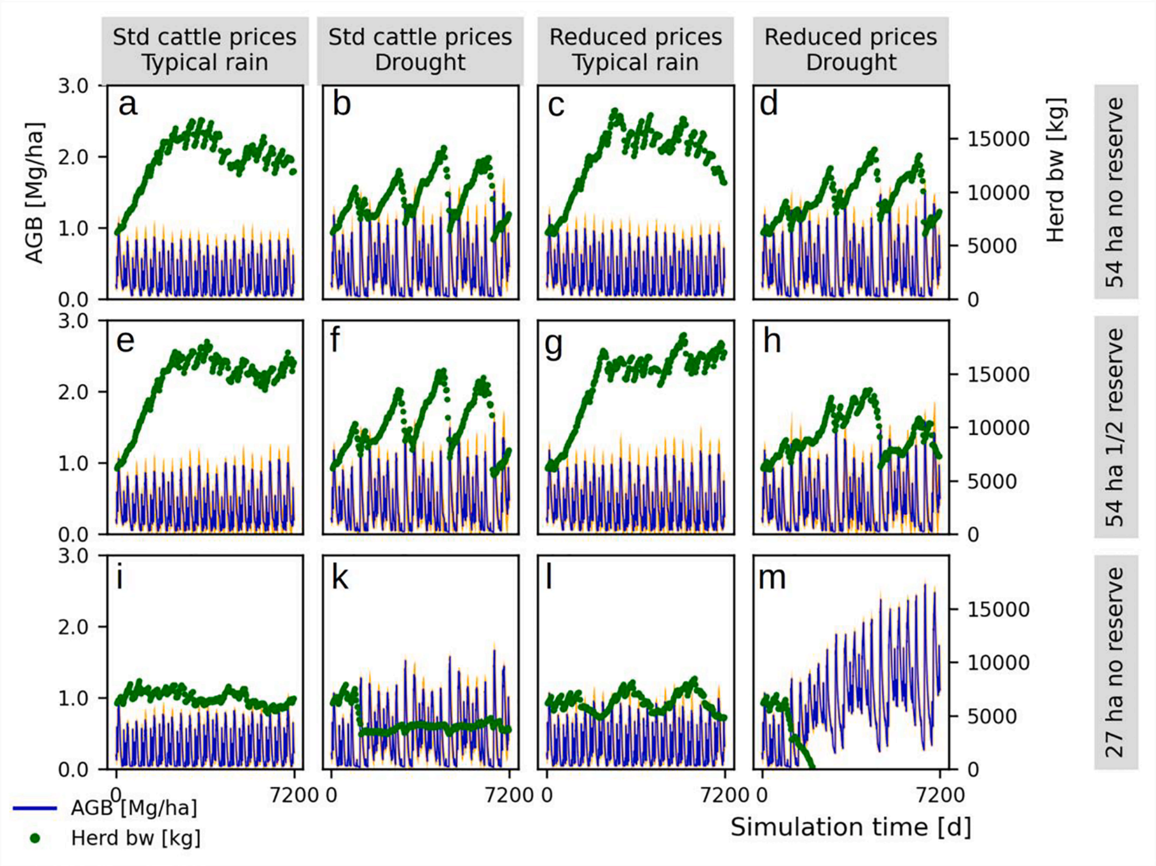

Fig. 5. Daily pasture above-ground biomass (AGB) of the grazed pixels (blue lines represent averages and orange standard deviations) and monthly herd body weight (green dots) under different rainfall regime, meat price and grassland area allocation scenarios over 20 years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

rationality given that high inflation rates and limited access to a bank account complicate monetary savings and may make in-cattle savings attractive. Nevertheless, even without immediate need for cash, the herder agent will sell male animals not used for breeding before they get too old to obtain a good price, or old cows no longer expected to reproduce. Depending on scenario settings, also very weak animals that are close to the age-specific minimum weight are sold (obj. iv). Cash obtained in this way is not always immediately needed to cover agent minimum objectives and hence available for discretionary spending or saving. In different scenarios, we explore different rules to prioritise either agent spending or saving in these cases.

Agents can assign and prioritise the grazing units for their herd for the following month, considering observed or expected standing pasture biomass, distance between grazing units, and expected grazing by other herders.

2.3.4. *Submodel: animal status (LIVSIM)*

For the present study, the modified LIVSIM version from Bateki and Dickhoefer (2020) was used. N, P, K and lignin concentrations in forage biomass are converted to crude protein, P, and K concentrations per kg of feeds for further metabolization by animals. Using multiple linear regression models presented in Warth et al. (in prep.), we estimated metabolizable and gross energy, dry matter digestibility, and neutral detergent fibre concentrations in the feed at the start of each month. Animal fertility, live weight changes and milk yield are influenced by feed availability (i.e., quantity) and quality. Feed dry matter intake is estimated based on the nutritional status and performance of each animal. Based on feed intake and digestibility, the total amount of fecal dry matter and its N, P, K contents are simulated as nutrients returned to the soil and, indirectly, to the vegetation. Thus LIVSIM simulates (nutritional and reproductive) status of the herd, and MPMAS provides herd composition as far as affected by the herder's decisions (e.g. selling, slaughtering).

2.3.5. *Submodel: plant, soil, and landscape processes (LUCIA)*

In LUCIA, plant growth is determined by species-specific physiology of annual and perennial herbaceous and woody plants, soil properties, weather data, nutrient supply, management actions, and grazing. For the present study, LUCIA was extended with a grassland module that reflects plant dormancy by determining onset and length of the growing period depending on plant available water. Plants react to grazing by a dynamic shift in assimilate allocation. Allocation of assimilates to plant organs was amended with a source-sink approach that allows preferential resprouting of leaves after defoliation and storage of surplus assimilates in a reserve pool. Heavy grazing and low net assimilation rates deplete the reserve pool and limit resprouting. This may cause plant degradation and eventually plant death once reserves and leaf area are depleted. A standing litter pool was introduced, so that dry leaf and stem necromass are not directly transferred into the soil litter pools, but are available for grazing. Further details can be found in Warth et al. (2021).

2.3.6. *Submodel: herd movement and grazing*

The model system was completed by introducing a herd movement and grazing module. Within the grazing units assigned by MPMAS agents on a *monthly* basis and which typically entail multiple pixels, herds can autonomously take *daily* movement decisions: Whenever the forage reserve on the currently grazed pixel does not meet herd demand for the next two days, the herd moves to the pixel with highest amount of *edible crude protein in the above-ground biomass* (edCPAGB), a

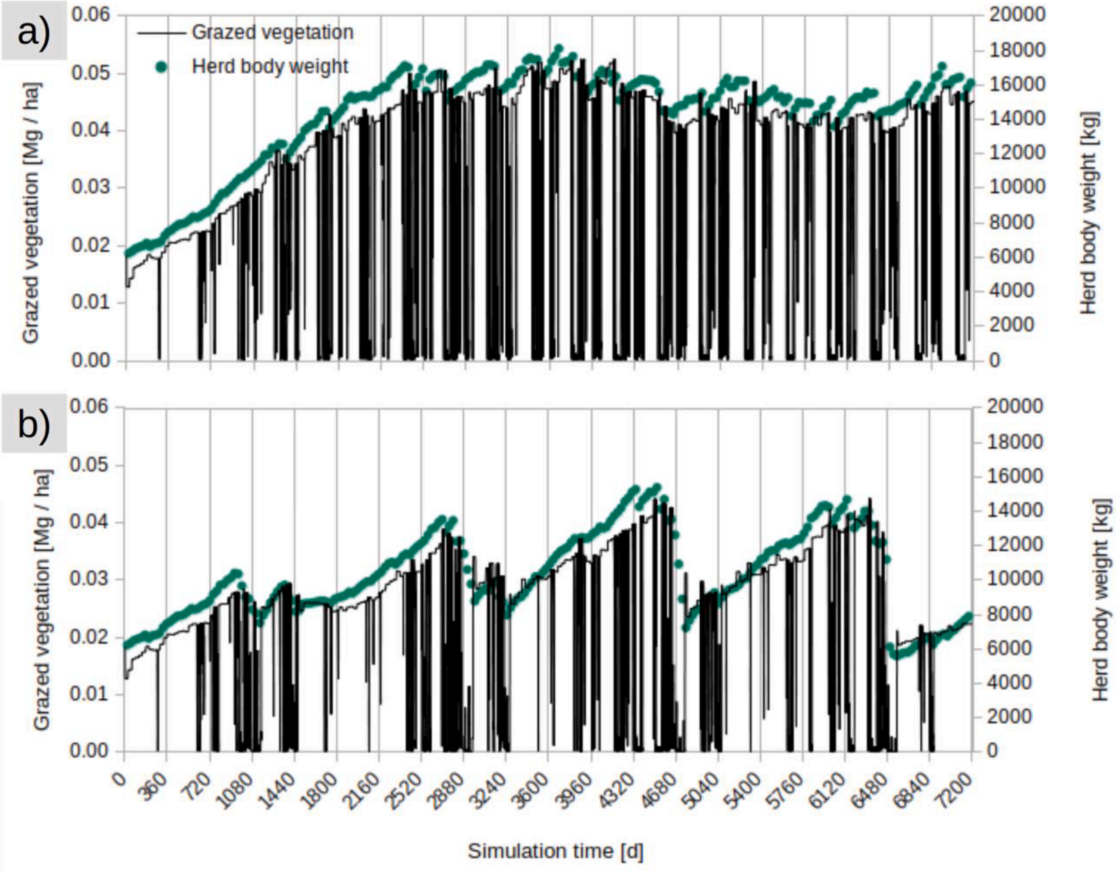

Fig. 6. Comparative dynamics of herd body weight and available pasture AGB under (a) typical rainfall and (b) drought scenario (both for 54 ha with reserve and standard meat prices).

combination of forage quantity and quality, within the assigned grazing unit. Should all pixels determined by the herder be depleted below the demand for two days, the herd can enter a second round of autonomous paddock selection by edCPAGB. This mechanism reflects grazing below a threshold that may hamper pasture regeneration, which real-world herders would avoid if possible.

Simulated animals prefer leaves over fruits, stems, and dead standing biomass, which change in proportion during plant development; this herbivore selectivity depends on animal species and grazing preference. Forage nutritional quality (crude protein, lignin, and P concentrations) varies with plant development stage. Up to two plant species (e.g. grass under *Acacia sp.*) can grow on a pixel and are grazed proportionally according to their crude protein concentrations and relative palatability / accessibility.

2.3.7. *Technical implementation of coupling and model availability*

Both LUCIA and LIVSIM are implemented in Python, which allows the LIVSIM component to be used directly by LUCIA in-process. Multiple non-spatial LIVSIM instances are run simultaneously, each representing a single herd. In contrast, MPMAS, written in C++, runs as a separate process. LUCIA and MPMAS processes communicate via TCP/IP connection using a custom protocol for data exchange. An overview of the scheduling and data exchange between components is given in Fig. 1. The MLL model used for our study, i.e. software and data, is provided for download at http://projekte.uni-hohenheim.de/mas/software/supplement_MPMAS_LUCIA_LIVSIM_a1.zip. The latest stable LUCIA code can be requested from C. Marohn; LIVSIM from C. Bateki. Model documentation for LUCIA can be found under https://lucia.uni-hohenheim.de and for MPMAS under https://mp-mas.uni-hohenheim.de.

2.4. *Case study and scenarios*

Our case study was located on the Borana plateau, a region in Southern Ethiopia dominated by cattle herding, but under beginning land use change to cropping.

2.4.1. *Study site, model parameterization and calibration*

We modelled a watershed of approximately 600 km^2, at an altitude between 1100 and 2200 m above sea level. Cambisols, Leptosols, Luvisols, and Vertisols are dominant soils (Glatzle, 2012; Hengl et al., 2017) in the study area (Fig. 2). Average annual rainfall between 2004 and 2013 was 645 mm/a (ranging from 327 to 1343 mm/a) and the mean temperature was 20°C (Tuffa and Treydte, 2017).

The landscape for modelling was generated based on elevation, soil, and land cover maps from primary and secondary data as described by Warth et al. (2021) and with a pixel length of 300 m (i.e. pixel area 9 ha). This resolution was chosen as representative for extensive grazing and produced reasonable herd movement intervals. The abovementioned area allowed us to incorporate biophysical data from a previous project and corresponded to Dirre site in Wario et al. (2016), where typical herd movements have been recorded. Maximum herd distance from a homestead can be set in MPMAS, but this was not done for this study. The selected area and resolution resulted in reasonable model run times. We distinguished four vegetation types: *Acacia spp.* with grassland in the Northern Leptosol areas, pure grassland on Lepto- and Luvisols, woodlands in the SW mountain ranges on Nitisol, and maize in the SE Vertisol areas, (see Warth et al. (2021) for topography map); in our simulations animals were allowed to access only the grasslands.

LUCIA and LIVSIM were calibrated and tested individually before the coupled simulations were run. To calibrate LUCIA, including the newly developed grassland module, we used aboveground vegetation data for

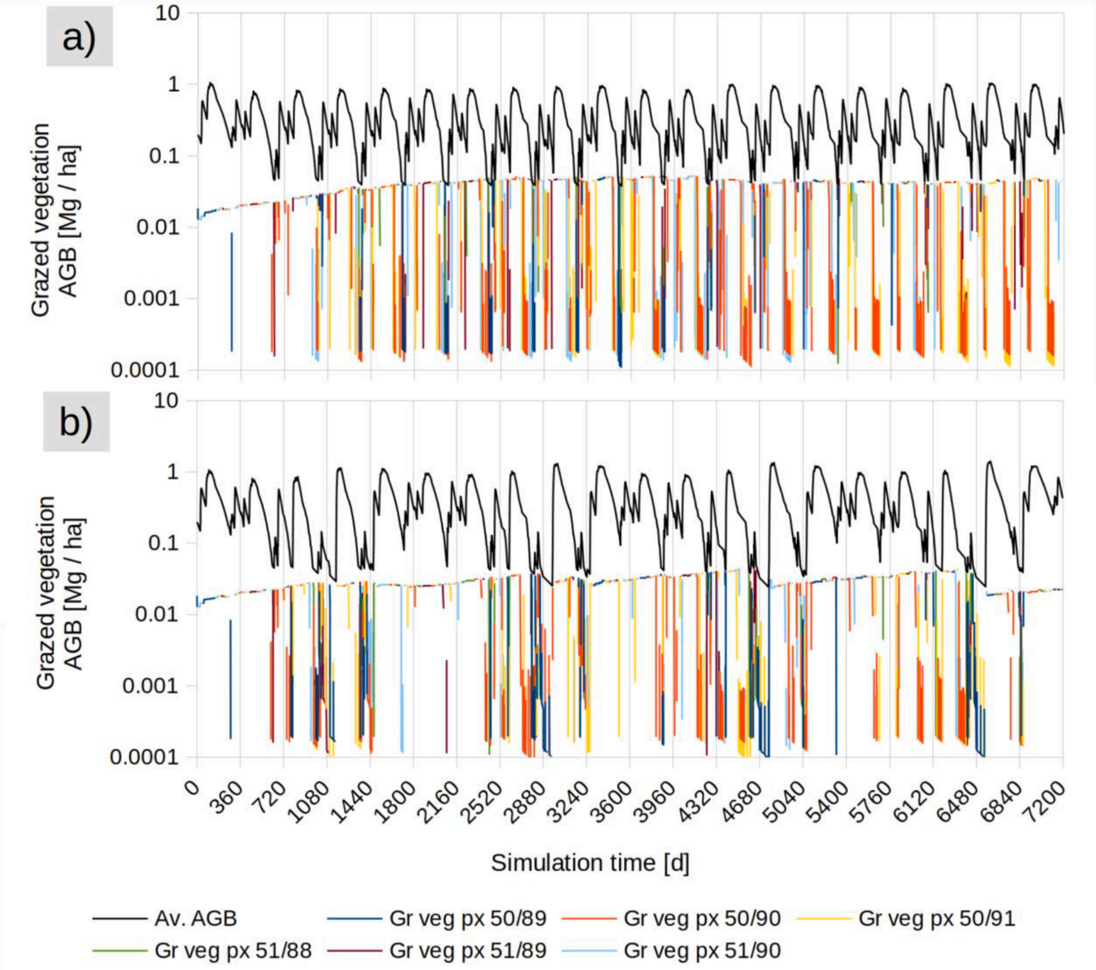

Fig. 7. Pasture biomass (black line) and grazed aboveground vegetation (multi-coloured lines) under corresponding a) typical rainfall and b) drought scenarios (both for 54 ha with reserve and standard meat prices). Each colour represents a specific grazed pixel, hence frequently changing colours stand for frequent herd movement due to pasture depletion. Grazed vegetation may exceed pasture biomass when cattle consume standing litter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

grassland and *Acacia spp*. as described by Warth et al. (2021).

Within the modelled landscape, we focused, as described above, on a single herder household by assigning the agent an area of exclusive access to the agent, undisturbed by the influence of other herders. However, we let the agent act as in a community-managed open access situation assuming economic rationality that perceives that it cannot exclude others from access beyond access rules specified by the herder community[1]. The size of the exclusive access area (54 ha) was chosen, such that we expected it to allow for maintenance of a self-reproducing herd providing for reliable incomes in a semi-arid rangeland region in East Africa. Meshesha et al. (2019) report carrying capacities for the Borana research area between 0 - 1 Tropical Livestock Units (TLU) per hectare (ha) and year. Tache and Sjaastad (2010) found that pastoralist households considered as rich by the Borana owned about 60 TLU on average, while “self-reliant” households own 30 TLU, “thin-handed” 12 TLU, and “poor” 7 TLU on average. Thus, an initial herd size of 29 heads of cattle on the 54-ha grazing land was chosen allowing herd growth up to a rich level from an initially low stocking rate. The LIVSIM version used in the present study already contained breed-specific information for Boran cattle in the study region (Rufino, 2008). MPMAS household composition, consumption demands and prices were estimated from the IBLI household survey (IBLI yearbook).

2.4.2. *Scenarios*

To explore model feedbacks and system stability under a variety of external stress and behavioural assumptions, we ran a combination of scenarios (Table 2) representing climate change (i.e. increased frequency of dry years), access to different extent of grazing areas and varying cattle prices relative to grain prices as well as potential herders mitigation strategies (dry season reserves, emergency selling, saving behaviour) in response to cattle conditions or meat/milk shortages during fodder limitations.

Simulations were run for 20 years. While only six selected map cells were made accessible to our simulated herder, all map cells of the watershed were simulated.

Two weather scenarios were created, one representing typical rainfall regime and the other prolonged periodic drought conditions as observed in the area. The typical rain scenario was built from recordings by the

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[1] In situations where exclusive access is perceived, economic theory would expect herders to maximize benefit by (possibly) not grazing as much pasture as possible at a certain time (e.g. by keeping a lower herd size) in order to reap the benefits of better grown pasture at later points of time. In open-access situations, the herder cannot be sure to reap those benefits him/herself, because other herders might have their herds graze it. Effects of own grazing on pasture regrowth are hence considered as a potential benefit in the perceived exclusive access situation, but not in the perceived open-access situation. In the latter case, only collective action can set boundaries on access. Optimization of grazing for pasture regrowth has to occur at the collective level, e.g. through reserve areas.

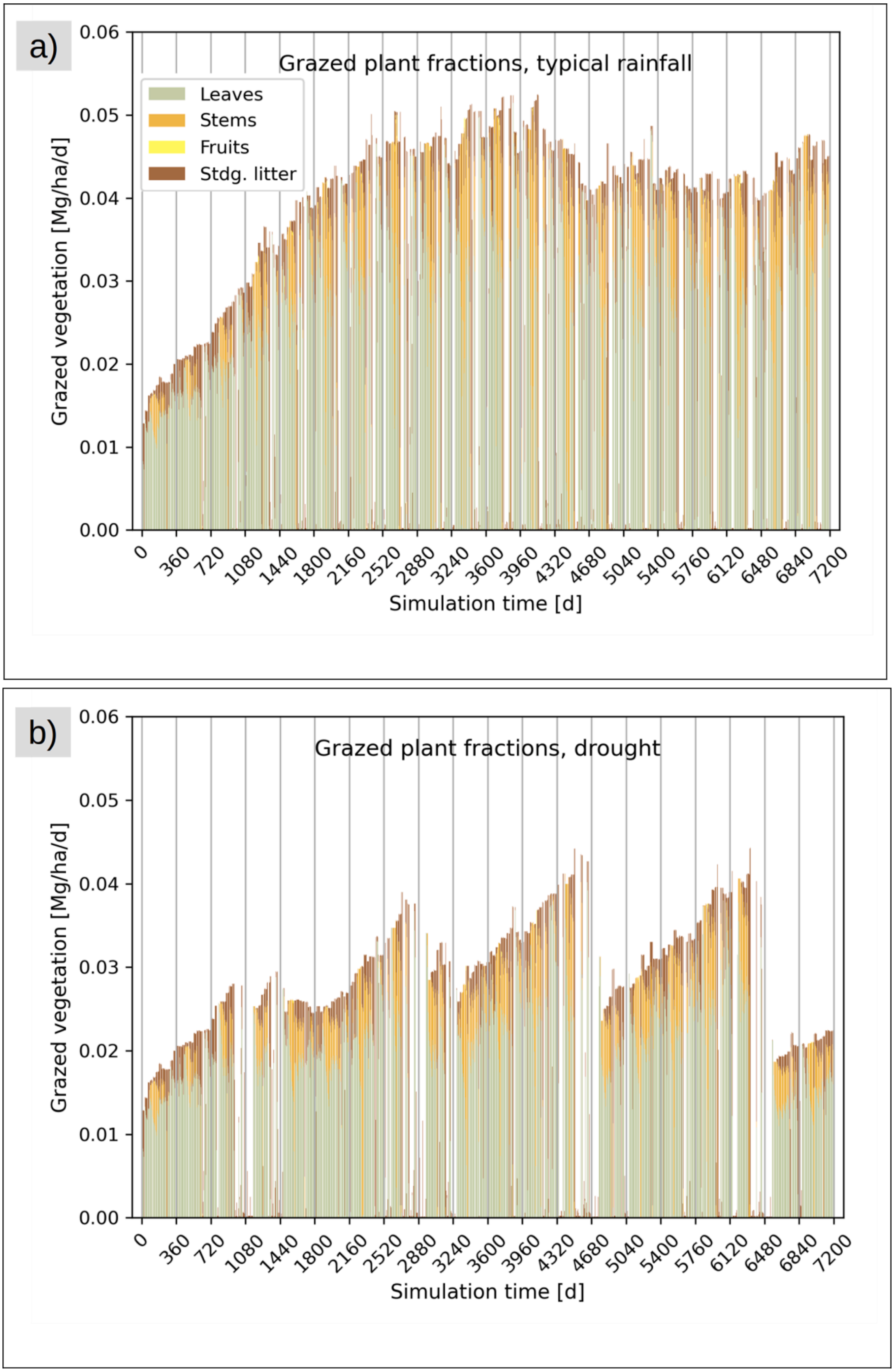

Fig. 8. Cumulative amounts of grazed biomass components (leaves, stems, fruits, standing (stdg) litter) in response to varied rainfall regime; (a) typical rainfall scenario (scenario corresponding to Fig. 5e); (b) drought scenario (scenario 5f); both for 54 ha with reserve and standard cattle prices.

National Meteorological Agency of Ethiopia for nearby stations Yabelo (see Tuffa and Treydte, 2017) in 2014 (total 526 mm) and Mega (Lat 4.07, Lon 38.32) in 2016 (gap-filled, total 463 mm), combined into a 5-year sequence (2016-2014-2014-2014-2016). These years represented a drier and a wetter year derived from nearly complete measurement data. This 5-year period was looped four times. For the drought scenario, all

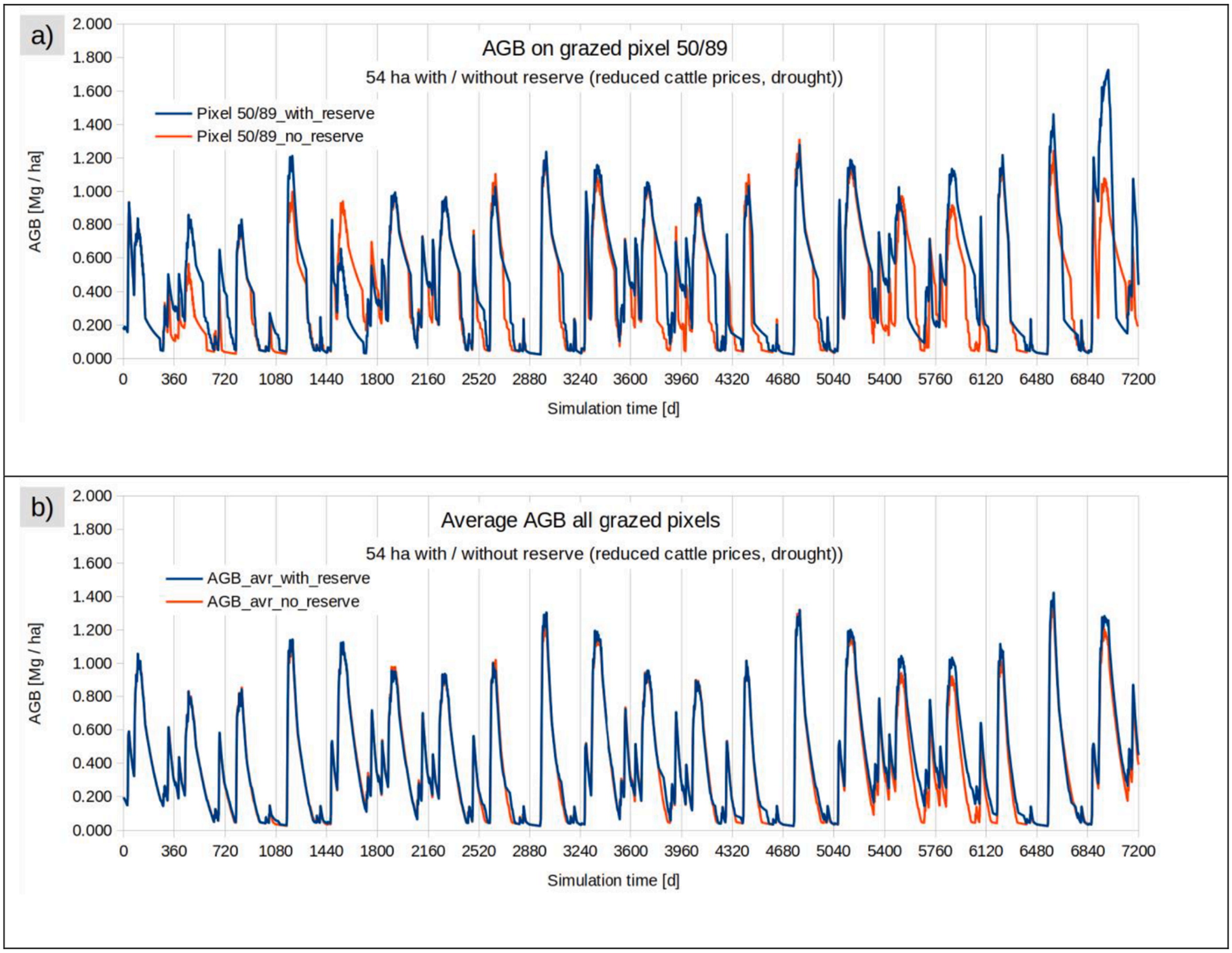

Fig. 9. (a) Above-ground biomass (AGB) recovery on one specific set aside pixel; (b) average AGB on all six observed pixels. Red lines represent year-round full access, i.e. no areas reserved for dry seasons (see Fig. 5d) and blue ones limited access, i.e. reserves set aside during wet seasons (see Fig. 5h); both under the same scenario of reduced meat price. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

rain events in years 3 and 4 of every 5-year period were reduced to 60% (Fig. 3, bottom). This resulted in an artificial drought dataset that excluded effects of changes in rainfall distribution. Air temperature and reference evapotranspiration (ET0) were obtained from weather station recordings in Madhecho, starting in August 2012 (raw data by Seckinger (2014), and radiation from satellite data (Pfeifroth et al., 2019)). These data were available for one year and looped 20 times for our scenario runtime.

We explored two different management responses to drought: As a community response, we considered the declaration of reserve areas that are not grazed during the rainy season and opened only during the dry season (Reserved area) (Wario et al., 2016). As an individual agent response, we distinguished three Emergency selling assumptions that control whether the agent pre-emptively sells animals in the lowest age-specific weight class or keeps them even if they might die of hunger soon. Drought resilience theoretically also depends on an agent’s propensity to save income and keep cash reserves, which depends on unobserved individual preferences. While we originally compared many different prioritization schemes for discretionary spending/saving behaviour, differences in simulation results between most schemes were small and we focused our discussion in this article on two extreme schemes only: Limited spending, in which non-food spending is governed by a monthly minimum and maximum and all remaining cash is saved; and Minimal saving, with all money except for a cash reserve equivalent to one month of grain expenditure being immediately spent.

3. Results

3.1. Herd size development

In a first step of analysis of the simulation results, we focus on climate, size of accessible grazing area, and different meat price scenarios, because these had a strong impact on herd dynamics and demonstrate well the range of outputs achieved. In the typical rainfall scenario, after an initial herd growth, herd size in the examples with 54 ha of accessible grazing area remained close to 90 heads, the upper limit set by the agent’s household labour capacity, with a fairly stable composition of decently fed animals (body weight index >4 out of 9) (Fig. 4a and c). In the middle of the 20-year simulation, relative body weight modestly deteriorated and subsequently, herd size dropped to 55 heads, thereafter relative body weight and herd size recovered.

With more intensive droughts, herd size oscillated between 45 and 75 heads in approximately 4-year intervals associated with a shift between a very poorly fed herd (body weight index <2) and a quite well-fed herd (Fig. 4b and d).

Dry-season reserves softened the intermediate drop in herd sizes and maintained a higher, more stable relative herd body weight in the standard prices scenarios (Fig. 4e and g). Their effect in the drought scenario, however, was ambiguous (Fig. 4f and h).

The cattle meat price scenarios (50% price reduction) did not alter the general pattern of herd development in the 54-ha scenarios, just somewhat shifting herd size peaks. When the grazing area was reduced

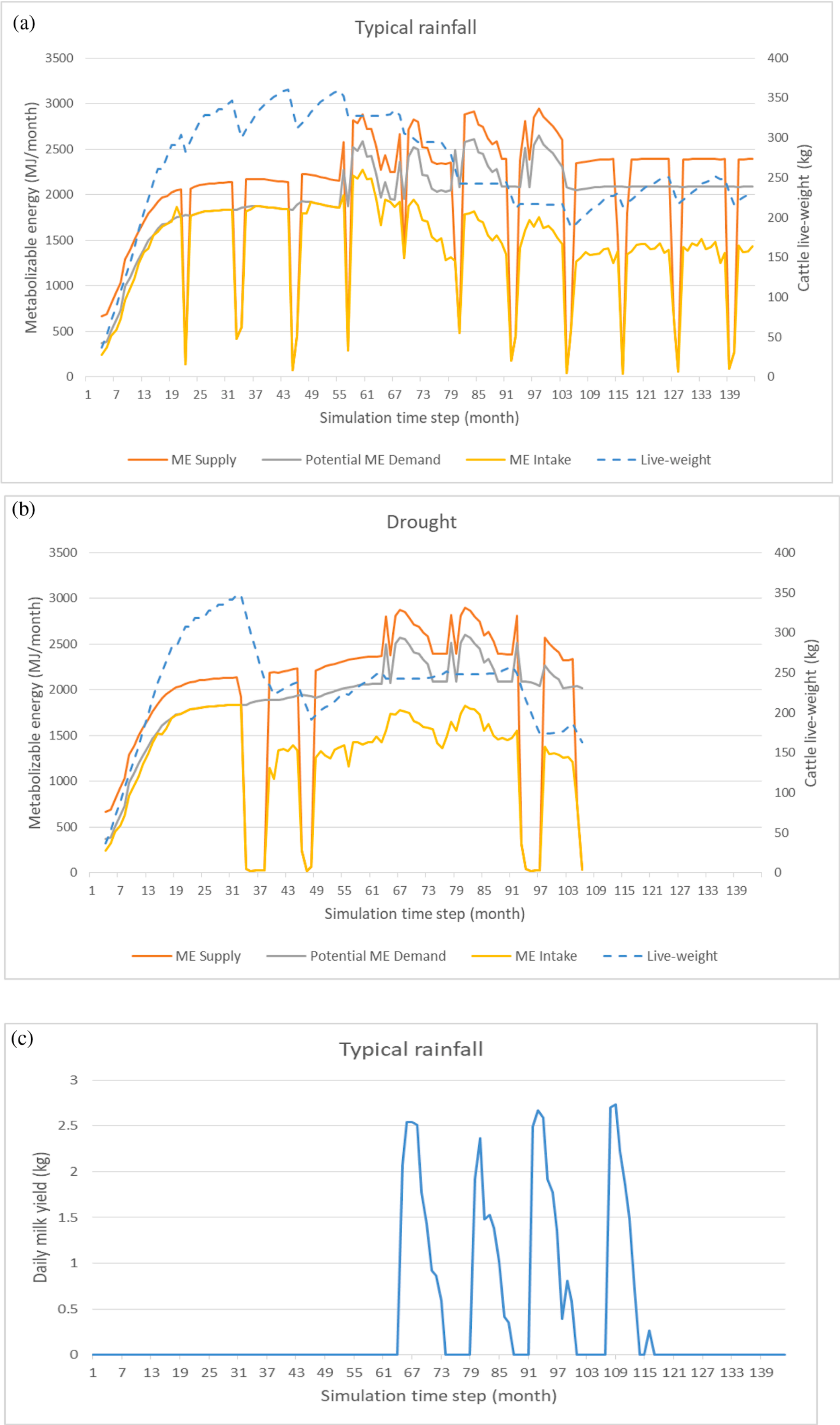

Fig. 10. Changes in cattle body weights and milk yields under typical rainfall (a and c) and drought (b and d) scenarios based on supply and intake of metabolizable energy (ME) during a representative animal’s lifetime in the given herd.

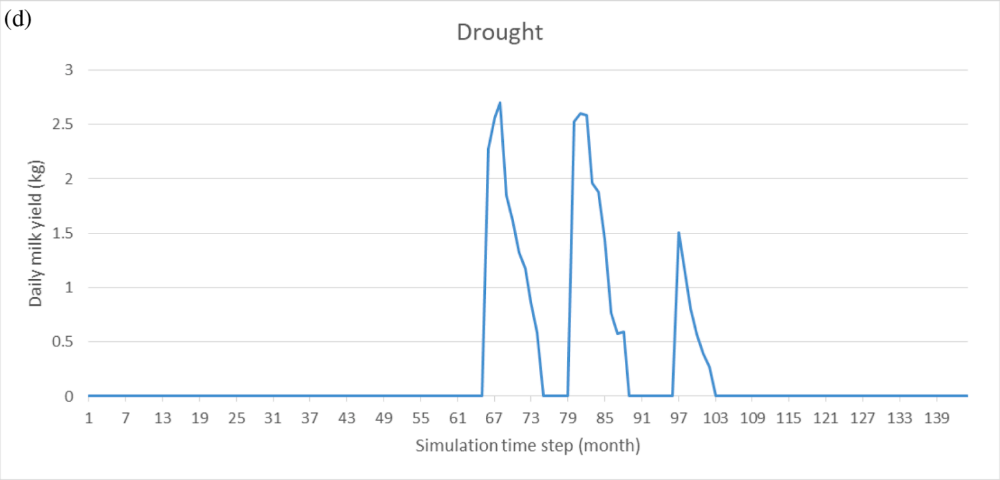

Fig. 10. (*continued*).

Table 3
Simulated reproductive and productive performance (incl. standard deviation) of cattle herds at full area access (54 ha of land all year round) under typical rainfall and drought scenarios in the Borana region of Ethiopia.

Parameter	Scenarios Typical rain	Drought
Mean age at first calving for females* born in herd (years)	5.2 ± 0.2	5.3 ± 0.5
Mean number of calves for females born in herd (n)	1.4 ± 0.6	1.3 ± 0.5
Total number of calves born in the whole herd (n)	100	85
Total number of female calves born (n)	64	53
Total number of females born in the herd that calved (n)	28	24
Mean calving interval for females born in herd (years)	1.8 ± 0.5	1.5 ± 0.6
Mean milk yield per lactation for females born in herd (kg)	369 ± 43	287 ± 130

[*] Females born in herd were used as indicator to factor out the initialisation effect of the herd defined in each run.

to only 27 ha, the herd size was reduced to around 30 animals under typical rainfall and less than 27 heads under drought conditions (Fig. 4i, k and l). When increased drought stress and extended low cattle sales prices occurred simultaneously the herd and herder agent family could not be sustained on 27 ha (Fig. 4m).

The observed trends in herd development resulted from multiple feedback loops between pasture, herd, and herder. To disentangle the individual effects, we will describe the responses of each subsystem to the development in the other subsystems in detail in the following sections.

3.2. Grassland dynamics

3.2.1. Above-ground biomass related to herd body weight

Above-ground biomass (AGB) under grazing oscillated seasonally between 0.01 and 1.5 Mg dry matter / ha. When herders had access to the full area, the AGB long-term trend remained stable (full recovery after grazing) over the 20-year simulation period (Fig. 5a–h). In the drought scenarios, AGB declined for extended periods to near zero in drought years with corresponding reductions in herd body weight (Fig. 5b, d, f and h). Peak AGB was higher in the drought scenarios compared to the respective corresponding typical rainfall regime, particularly during times of reduced grazing pressure; this may be explained with reduced stocking rates (as indicated by reduced herd size in Fig. 4 and body weight Fig. 5) due to sales or starvation.

Under the scenarios of limited grazing area (27 ha or 3 pixels) combined with drought (Fig. 5k and m) the herd did not fully recover after the first drought in year 3. For example, depletion of the pasture resource on all three pixels under drought between days 900 and 1100 led to a drop of herd body weight from > 8000 to < 5000 Mg (Fig. 5k) or even complete loss of the herd (Fig. 5m) when drought was combined with low meat price and hence increased selling of animals. The loss of herd body weight was also reflected in the individual animals' body weight (light colour in Fig. 4k and m). After herd collapse, pasture AGB recovered beyond its initial grazed levels (Fig. 5m) as plant growth at the beginning of the rainy seasons (rising limbs) was undisturbed by grazing.

3.2.2. Feedback between herd body weight, grazing and vegetation

During most periods, the quantity of grazed vegetation was determined by the demand rather than the supply side, i.e. more pasture was available than could be consumed. Hence, dynamics of grazed AGB closely matched those of herd body weight (which was linearly related to potential uptake of pasture) rather than seasonal patterns (Fig. 6).

Periods with very low amounts of grazed pasture occurred more frequently in the typical rainfall scenario (Fig. 6a), where herd body weight continuously rose to 16-18 Mg combined with normal seasonal low rainfall periods. Under severe drought conditions (Fig. 6b), herd body weight abruptly dropped during dry years, and so did pasture consumption. The fact that reductions in herd weight preceded reductions in consumption may be an indicator of herders' foresight to sell part of the herd before pasture would become limiting.

When pasture AGB became limiting, grazed vegetation (live and dead material) was larger than AGB (i.e. only living material), meaning that herds resorted exclusively to consuming available standing litter. These situations occurred regularly under the typical rainfall scenario once herd body weight had built up (Fig. 7a), but only during few extremely dry years in the corresponding drought scenario (Fig. 7b).

Situations with very low quantities of grazed biomass, i.e. a high proportion of standing litter, occurred more frequently during the typical rainfall scenario. This is reflected by frequent herd movement (changing graph colours in Fig. 7).

3.2.3. Nutritional quality and selective grazing of pasture

Although AGB is quantitatively limiting during dry seasons, tropical pastures are often additionally of low quality. Cattle grazed selectively, preferring leaves over stems, seeds, and standing litter. Compared to the typical rainfall scenario (Fig. 8a), the drought scenario regularly caused break-down of biomass consumption (Fig. 8b). Periods when cattle fed mainly on stems and standing litter were more frequent in the typical rainfall scenario. Additionally, seasonally a shift from leaf to stem biomass occurred in both scenarios during rainy seasons. A fraction of stems and standing litter was always consumed as part of our scenario

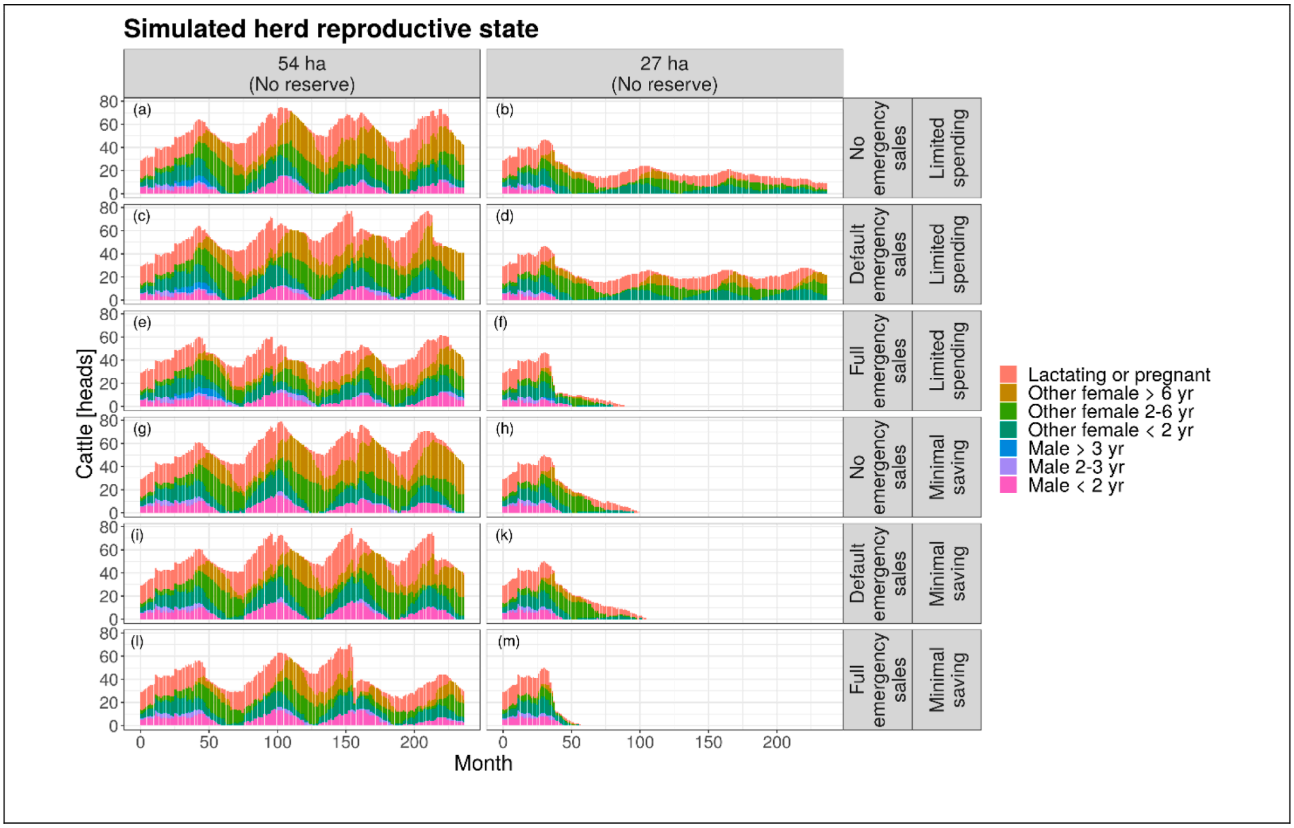

Fig. 11. Simulated herd composition by age and reproductive state under different area access, emergency selling and saving scenarios, all under drought and standard cattle price conditions (Table 1) over 20 years.

settings, reflecting imperfect discrimination of cattle between leaves and stems.

The simulated changes in grazed plant composition resulted consequently in altered forage quality due to different nutritional qualities of different plant fractions. The resulting average crude protein concentration of the grazed biomass oscillated between 10 to 19%, while neutral detergent fibre (NDF) concentration varied between 50-67%, impacting sensitive on animal performance (data not shown).

3.2.4. The effect of access to grazing areas on AGB regrowth

We analysed the effect of different paddock access rules on regrowth of AGB (resilience to grazing) comparing scenarios of year-round full access vs. seasonally limited access to dry reserves, both under reduced meat prices and drought ('stress' conditions shown in Fig. 5d and h).

On pixel 50/89, where part of the land was set aside from grazing during rainy seasons, AGB was in most years preserved for a longer time into the dry season (Fig. 9a).

In contrast to pixel 50/89, average available AGB across all six grazed pixels (Fig. 9b) hardly differed between both access scenarios indicating that animals could partly compensate for limited access. However, during periods of increasing stocking rates during the last five years, AGB in the scenario with set-aside land appeared to be more resilient to overgrazing.

3.3. Animal performance

The cattle productive performance (i.e., body weight gain and milk yield) was influenced by the changes in quantity of forage biomass available over time in all scenarios. For example, under full area access (54 ha), a higher individual animal productive performance was observed under the typical rainfall (Fig. 10a) compared to the drought (Fig. 10b) scenario. Animal performance was most strongly influenced by limitations in metabolizable energy (ME) supply. While under typical rainfall a seasonally short period of low ME supply and hence ME intake only moderately reduced growth performance, ME intake was lower than maintenance requirements (though never zero) over prolonged periods (up to three months) in the drought scenario, which lead to losses in body weight. Even though directly after the severe drought, ME supply to and ME intake of individual animals were seasonally less limited than in the typical rainfall scenario (due to a lower stocking rate and thus reduced inter-animal competition), animal reproductive performance was limited due to overall insufficient body condition.

Reduced ME intake during periods of forage shortage not only affected body condition and animal body weight gain, but also cattle reproductive performance. Mean age at calving or mean number of calves born in the herd were on average only slightly reduced by drought scenarios. It must be considered that the differences in total number of calves in a herd (Table 3) are the combined result of altered reproductive performance and herders' management, i.e. sale of animals, under the two climate scenarios, as discussed below. In addition, animals produced more milk under the typical rainfall than the drought scenario.

3.4. Herd management and herder income

Fig. 11 compares the different Emergency selling and Spending/ savings strategies under extended drought conditions, illustrating the development of the herd composition in terms of age, sex, and pregnancy or lactation state. We can observe cycles in the number of both pregnant and lactating animals (subsumed in one class in the graph) in the herd and, with a slight lag, in the presence of young animals. This cyclic behaviour is a consequence of the reduction or delay in reproduction of cows due to the above shown recurrent drought induced fodder stress situations in these scenarios that led to a lack of young animals (up to two years of age) once previous generations have been sold (males) or matured (females).

The agent's Default emergency selling strategy (male and older female animals only, Fig. 11c and i) led to more abrupt herd size reductions than not selling weak animals at all (Fig. 11a and g), since more animals were sold than would eventually die of weakness before being sold at conventional timing (Fig. A1 in the appendix).

We also observe that selling all low weight animals (Full emergency selling) led to lower average herd sizes (Fig. 11e and l) in earlier cycles and to complete herd breakdown when only 27 ha were accessible (Fig. 11f). As Table 4 shows, in the drought scenario the Default emergency selling strategy increased the herder's overall income, measured as the accumulated expenditure and final savings of the agent, due to a somewhat faster replacement of older female animals and periodically reduced stocking rates. Reserving half the area for grazing in the dry season increased overall income under drought conditions or in combination with a Minimal saving strategy.

In the same way, the agent's Minimal savings strategy generated higher overall incomes due to faster replacement of older female animals. However, it led to a highly variable spending pattern with considerably more months without any non-food expenditure compared with a more evenly distributed spending under the Limited spending scenario (see Table 4 and Fig. B1 in the appendix). The Minimal savings strategy led to herd breakdown at 27 ha (Fig. 11h, k and m). Cereal shortages were negligible except in those scenarios that showed herd breakdown.

4. Discussion

Our working hypotheses were that we can construct an integrated model system that (a) simulates coupled key dynamics of herd size and composition, grassland depletion and recovery, and herder livelihoods as emergent endogenous outcomes from process-based system knowledge, (b) achieves plausible orders of magnitude and (c) is not over-constrained, but shows plausible reactions to external drivers.

4.1. Plausibility of simulation outcomes

Given access to land that allows for a herd size characterized as 'rich and resilient' by local herders at typical local stocking rates, the herder was able to sustain a corresponding herd size in the long run under economic or climatic pressure. At peak herd size, a stocking density of about 1.3 TLU/ha was reached, which is considered the upper carrying capacity under common grazing conditions in the area (Meshesha et al., 2019). At the same time, MLL could reproduce herd breakdown when extended external pressure such as frequent severe droughts (as expected under future climate change conditions) was combined with a Minimal saving strategy and reduced area access corresponding to herd sizes considered vulnerable by local herders. Area access could generally reduce by increasing population pressure, or conversion of grassland to cropping areas. In reality, herd recovery is then often supported by gifts from other herders (Tache and Sjaastad, 2010). Simulated herd size and dynamics under the different scenarios can hence be considered plausible. Simulated AGB under grazing (0 – 1.4 Mg/ha) varied within expected ranges (Warth et al., 2020) and increased when grazing ceased. Nutritional quality of available forage was mostly within the upper range of values reported for the area (e.g. CP 60-200 g kg^{-1} DM, NDF 170-750 g kg^{-1} DM of individual available forage plants; Abebe et al., 2012) and predictions could be improved in the future by better considering plant physiological effects (e.g. age, nutrient remobilization). As shown in Fig. 5, pastures reacted sensitive to drought stress and high stocking rates and regenerated when the latter were reduced (e.g. by selling or death of cattle). As expected, grazing intervals on individual paddocks (pixels) decreased during stress periods (dry seasons, droughts, high stocking rate; Fig. 6). Simulated vegetation performance and feedbacks can thus be considered plausible.

Cattle growth and reproductive performance were mostly in close agreement to literature values. For example, mean age at first calving was 5.2 years in our simulations under typical rainfall compared to 4.9 years reported by Takele Gebissa (2014). Our simulated mean milk yield per lactation was – with 369 kg per cow and lactation – lower compared with the 473 kg reported by Duguma et al. (2012), but it was still within the surveyed range by Takele Gebissa (2014). On the other hand, milk yields predicted by MLL were clearly sensitive to drought with an average reduction of 22% per lactation and cow compared to the typical rainfall scenario, reflecting the interplay between availability and nutritional quality of forage (e.g. increased proportion of consumed standing litter under drought conditions) and consequently the reduced forage intake and use in cows.

The detailed coverage of biophysical processes and behavioural rules enables MLL to capture how agent herd management decisions may have subtle, not directly obvious feedbacks. Selling very weak animals before they die ensures that the herder agent receives at least some income to cover consumption demands, but may also slow down or even endanger herd recovery if female animals are sold that might have recovered and then contributed to reproduction. During good times, when mostly well-nourished animals are sold, each animal receives a better price and can cover consumption demands for a longer time, so animals can be sold at a slower rate. This creates an economic feedback which accelerates simulated herd growth in times of favourable climatic conditions and also accelerates herd size decline during times of water

Table 4

Economic indicators under different area access, emergency selling, and saving scenarios under drought and typical rainfall conditions (Table 1) accumulated over 20 simulation years. Note: prices are from 2012, when 1 ETB (Ethiopian Birr) = 0.056 USD (World Bank, 2022).

			Animals sold/ slaughtered		Cash spent during simulation / held at simulation end		Grain expenditure deficit		Months with no extra expenditure	
Area access	Spending behaviour	Emergency selling	Typical #	Drought #	Typical '000 ETB	Drought '000 ETB	Typical ETB	Drought ETB	Typical #	Drought #
54 ha	Limited spending	No	163	162	270	230	11	11	6	24
		Default	165	173	272	264	11	11	6	19
		Full	172	181	276	258	11	11	6	12
	Minimal saving	No	194	169	364	245	11	12	55	59
		Default	194	186	364	304	11	18	55	78
		Full	194	189	364	271	11	16	55	69
54 ha (half reserved for dry season)	Limited spending	No	154	159	281	255	11	11	6	17
		Default	154	180	281	283	11	11	6	14
		Full	162	190	292	265	11	11	6	6
	Minimal saving	No	222	173	464	299	11	11	44	52
		Default	222	203	464	357	11	15	44	70
		Full	224	188	474	395	11	18	46	73
27 ha	Limited spending	No	132	114	85	45	20	96	112	176
		Default	132	115	85	51	20	39	112	148
		Full	132	69	80	58	28	7700	104	186
	Minimal saving	No	139	60	127	59	29	7191	104	189
		Default	139	66	127	66	29	6915	104	187
		Full	141	64	128	76	29	9436	104	207

stress. Thus, the coupled MLL shows good potential to contribute valuable evidence to the current debate on herders' mitigation strategies to cope with ongoing and future climate change.

Setting aside grazing land during rainy seasons to create reserves for dry seasons appears to be an effective strategy for more severe droughts. In Borana, dry reserves are often located close to reliable dry season freshwater sources to minimize walking distances; they form an integral part of management (Wario et al., 2016, 2015). Our simulations do currently not consider drinking water access for animals, potentially underestimating the effect of dry conditions as well as the benefits of dry reserves close to water sources.

Care has to be taken, however, when interpreting income effects of agent management strategies, such as the Minimal savings and Emergency selling strategies discussed here, that rely on feedbacks of earlier extraction of animals and consequently, reduced stocking rates on the nutritional status of the remaining herd. Our simulations used an artificial exclusive access scenario, in which the herder alone is able to reap the benefits of reduced herd sizes. In open access situations, this is not guaranteed as other herders might not have reduced their herd size, thus reducing or even reversing potential benefits. This is also the reason why we did not simulate the herder to anticipate and optimize grassland recovery. As in an open access situation, the agent only reacts to developments with a time lag.

4.2. Niche of the MLL framework, added value and necessary amendments

The integration of LUCIA and LIVSIM provides dynamic feedback between vegetation biomass and quality (N, P, K, lignin contents), animal nutrition, quantity and quality of excreta, as well as soil fertility status. This feedback loop is an achievement compared with models with uni-directional information flows as e.g. in the set-up used by Descheemaeker et al., (2018). Variables are updated daily, and LUCIA accounts for position and lateral water, matter and nutrient flows in the landscape. Local accumulation of plant nutrients in the landscape, depletion of vegetation biomass and degradation of soils can thus be captured using MLL. On the other hand, degradation of soils by trampling and compaction still need to be included in LUCIA. The capability to account for plant quality in response to seasons and grazing requires specific field data for model calibration, which are not frequently measured. Lignification as an effect of plant aging is not yet included in LUCIA.

Compared with many ecological models, LUCIA – due to its origin from a crop model – is relatively detailed regarding plant physiology (e.g. plant nutrition, water stress and response to meteorological inputs). It also includes detailed hydrological and soil processes at landscape level. Trophic mechanisms are simulated in more detail in MLL than in other coupled plant-animal-human models (e.g. Scheiter et al., 2019; Scheiter and Higgins, 2012), allowing to specifically account for grazing effects on water, nutrient and carbon cycling in the landscape. On the other hand, successional dynamics like bush encroachment, endogenous changes in abundance or plants of different age on one pixel are not simulated. While two different plant types on one pixel can compete for light, water and nutrients, plant density and species composition cannot change dynamically (instead, these would need to be introduced as exogenous land cover change).

Defined grazing positions provide the interface to landscape scale soil processes. Herd movement is represented in MLL by a two-level decision mechanism (daily response to depletion of fodder availability through LUCIA, and tactical monthly decision by MPMAS), which a coupling of LUCIA-LIVSIM alone does not provide. MPMAS further provides a strategic level that can capture dynamic land tenure, community-level seasonal access rules, preferred watering locations, post-harvest use of croplands and transhumance decisions into distant grazing grounds at monthly resolution. The daily movement decisions implemented in LUCIA ensure operational reaction at the relevant time scale of pasture grazing (analogous to the separation of decision levels for crop management in Troost et al. (2022)). They may have to be extended to reflect locations of drinking water sources and maximum daily walking distances.

The available decision mechanism and the dynamic feedback between models allow MLL to flexibly capture many different herd management strategies, which are characteristic for pastoralists, and reacting to land access, soil fertility and vegetation dynamics. Such strategies include exclosures, setting aside grassland reserves for dry seasons, stimulating resprouting and avoiding moribund plants by grazing, or moving herds to stubble fields after crop harvesting, and exploitation of spatio-temporal niches, among others.

5. Conclusions

This study demonstrated the capability of the coupled MPMAS-LUCIA-LIVSIM (MLL) to realistically represent complex interactions between a herder agent, cattle, pasture and the soil in savannah landscapes. MLL produced plausible outputs for plant growth, animal performance and herd dynamics under various selling and land access strategies, exogenous cattle prices and rainfall scenarios. Spatio-temporal interactions between grazing animals and plant growth, nutrient cycling between plant biomass, litter, soil, animal and faeces, as well as pasture depletion and regeneration in response to grazing pressure were plausibly captured by the model as were animal nutritional status, body weight, milk yield and household income. In particular, the MLL approach demonstrated a unique capacity to realistically capture the impact of different herd and household resource management strategies through accounting for the dynamic feedbacks between the coupled models under climate change conditions.

Our study had been conceptualised as a proof of concept under simplified settings with only one herder agent and one herd. In order to address current relevant issues and opportunities in East African savannahs – e.g. conversion of larger pasture areas to cropping systems at various levels of intensification / mechanisation, or limited herd access to grazing grounds near village areas and during periods of transhumance, as well as integrated crop-livestock and rotational systems to mention but a few – MLL and its future model scenarios will be adapted to simulate more complex settings. This requires additional model evaluation at higher levels of integration (Arnold et al., 2015; Voinov and Shugart, 2013). The coupled models will further be amended to deal with more sophisticated mutualistic behaviour between herders (cooperation vs. competition, particularly on communal lands) and herd movement rules in the landscape. Our coupling mechanism is based on a previous custom-made approach (Marohn et al., 2013b) that used a wrapper to couple MPMAS and LUCIA. With more models being added to the framework, standardised open source approaches like the BMI (Peckham et al., 2013), that support multiple languages and OS as well as spatial grid representation, will become more and more interesting options for future studies.

Future scenarios will include interactions between several herders and herds on the same land, integrated crop-shrub-livestock systems, dynamic agent-defined change of land use between farming and pastoral systems. These improvements will allow analysing impacts of the changing systems on the environment (soil organic matter, landscape carbon, water and nutrient budgets), crop yields and food security in more detail.

CRediT authorship contribution statement

Carsten Marohn: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Christian Troost:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Benjamin Warth:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft. **Christian Bateki:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft. **Mink Zijlstra:** Methodology, Software. **Faizan**

Anwar: Software. **Benjamin Williams:** Software. **Katrien Descheemaeker:** Methodology, Writing – review & editing. **Thomas Berger:** Conceptualization, Methodology, Software, Resources, Writing – review & editing. **Folkard Asch:** Conceptualization, Investigation, Resources, Writing – review & editing. **Uta Dickhoefer:** Conceptualization, Writing – review & editing. **Regina Birner:** Conceptualization, Writing – review & editing. **Georg Cadisch:** Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The manuscript contains a download link to the model softwares and input data used.

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Appendices

Herd balances

Fig. A1

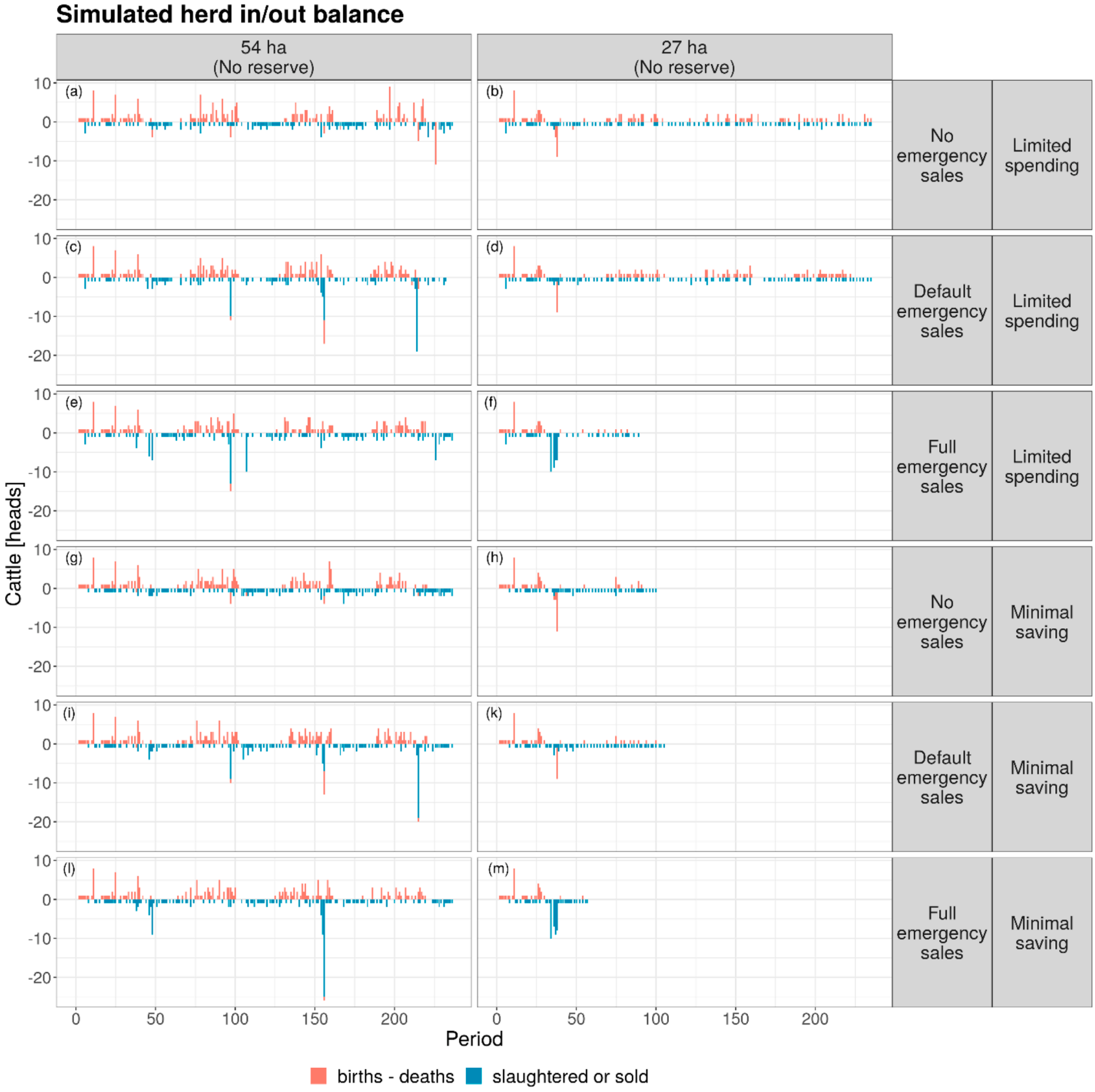

Fig. A1. Sales, births, and deaths of animals with different management strategies under drought and standard cattle price conditions.

Cash utilisation

Fig. B1

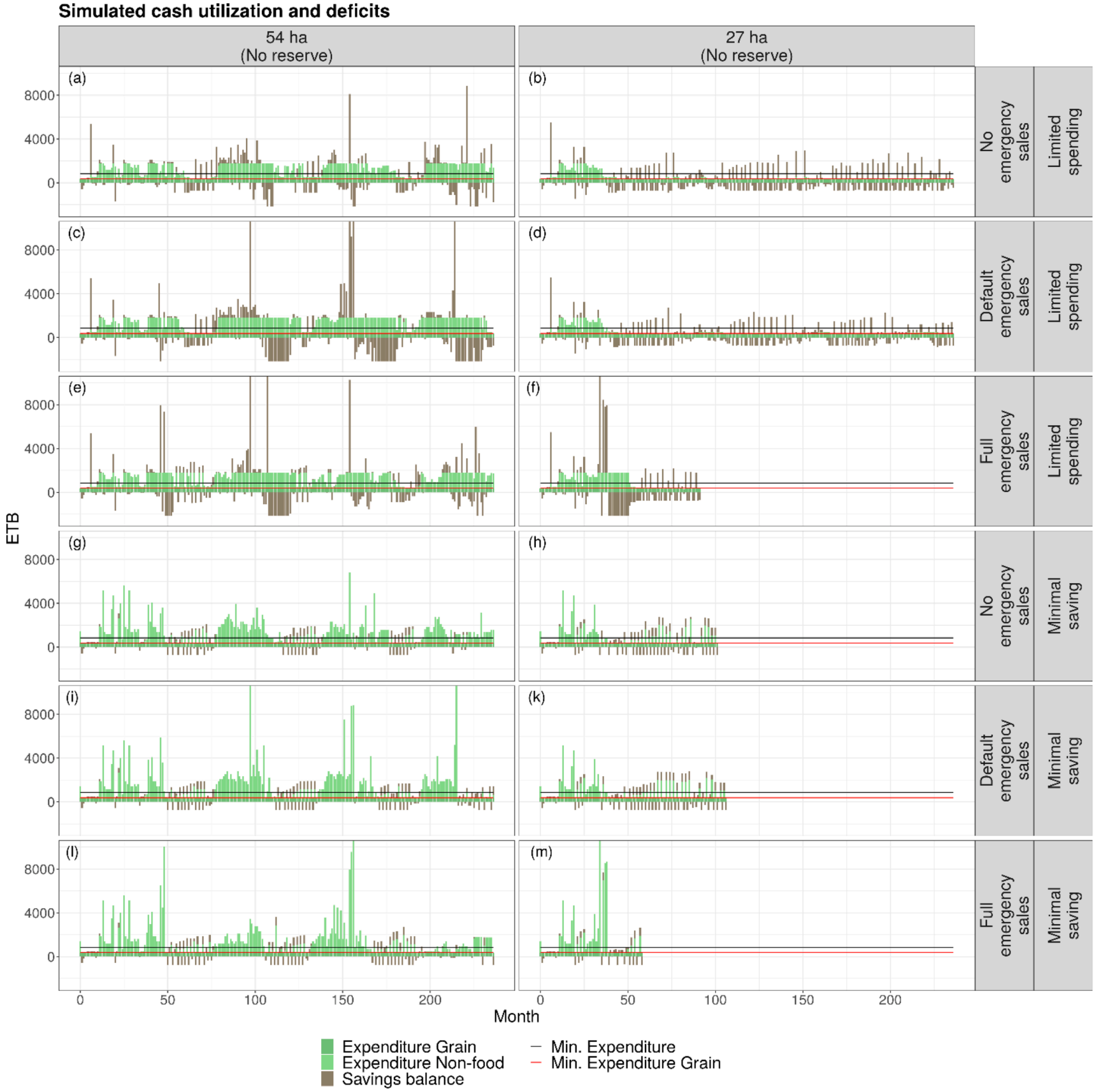

Fig. B1. Simulated cash utilisation for food and non-food expenditure, and savings under different management scenarios; all for drought and standard cattle price conditions.

State variables exchanged between models

Table A1

Table A1
State variables exchanged between models and their units (communication from MPMAS to LIVSIM is routed via LUCIA).

Exchange direction	State variables	Unit	Data type
MPMAS to LUCIA	Herd grazing areas Herd composition Herd management Supplementary feed	Coordinates / priorities Various variables Various variables kg $month^{-1}$ $herd^{-1}$	Tables
	Land use	Class	ASCII maps
LUCIA to LIVSIM	Potential biomass available for grazing Crude protein, P, K, lignin in plant organs	Mg $pixel^{-1}$ g kg^{-1} DM	Dynamic scalar point data
LIVSIM to LUCIA	Potential pasture demand, faeces and urine N, P, K deposition	Mg day^{-1}	Scalar data allocated to grazed pixel
LIVSIM to MPMAS	Herd composition per age class Herd state Milk yield	Animal number kg bw $animal^{-1}$ kg	csv table
LUCIA to MPMAS	AGB (above-ground biomass)	Mg ha^{-1}	ASCII maps

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