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ORIGINAL ARTICLE

Assessing impacts of crop area expansion and crop-livestock integration on ecosystem functions in African savannas using the coupled LUCIA and LIVSIM models

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Abstract

Large-scale land use change (LUC) of African Guinea savannas to crop fields is expected to cause negative impacts on ecosystem functions (ESF) and long term land productivity. The complex interactions of key processes in savannas evoked by LUC calls for a process-based modelling approach. We employed the dynamically coupled Land Use Change Impact Assessment (LUCIA) model and the Livestock Simulator (LIVSIM) which represent LUC impacts on soil processes, landscape-scale matter fluxes, seasonal grass and crop growth, and livestock nutrition, production and reproduction, depending on seasonal feed availability and quality on accessible pastures. For a rangeland in Borana, Ethiopia, two different LUC scenarios were evaluated in comparison to the baseline of traditional pasture-based land use. In the intensive LUC scenario 52% of grassland was converted into unfertilized maize fields, inaccessible for livestock. The integrated LUC scenario of the same grassland conversion rate allowed feeding maize straw and provided high-quality feed reserves from seasonally managed pastures. LUC in the intensive LUC scenario led to declining yields in the second year after conversion. Feed production on the remaining rangeland patches was insufficient for livestock nutrition, causing drops of herd body weight and herd size particularly in drought years. Resilience of herd performance to LUC was enhanced in the integrated LUC scenario when feeding maize straw and high-quality feed reserves. In both LUC scenarios, topsoil organic carbon storage decreased after ploughing shrub grassland for cultivation, and so did soil water storage capacity due to soil pore destruction. Soil erosion of less than one cm after 10 years occurred under cultivation. The simulation results indicated that the well validated model framework could predict impacts of LUC and simple crop-livestock integration on savanna ESFs, grass growth dynamics and livestock production during seasonal and inter-annual rainfall variation. This study lays the foundation for further land use scenario simulations to improve the understanding of benefits and risks caused by savanna grassland conversion.

Keywords Land use change, Soil degradation, Livestock nutrition, Overgrazing, Process-based modelling, Model coupling

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Introduction

The Guinea Savanna zone covers about 30% of Sub-Saharan Africa (SSA), extending from Guinea in the West to Ethiopia in the East, and southward to Mozambique (Morris et al. 2009). The main land use in these grasslands is pastoralism, which involves moving animal herds. Traditional management controls the number of livestock per area and time in order to keep the seasonally water-limited grassland system in a dynamic equilibrium. This management aims to nearly close nutrient cycles (via urine, dung, and litter) and provide high-quality biomass of valuable forage species that grows back over the alternation of grazing and rest periods, wet and dry seasons, and rainy and drought years (British Geological and Survey 2019; FAO 2017).

While only about 14% of the Guinea Savanna zone, based on the definition of Morris et al. (2009), is currently under cultivation (ESA 2016), large-scale conversion of grasslands to crop fields (grassland conversion) is gaining momentum (Assede et al. 2023; Hill and Guerschman 2020; Kibret et al. 2020). Grassland conversion is suggested to increase land productivity and income of small-scale farmers, especially when herd sizes exceed grassland carrying capacity (e.g. due to population growth, herd mobility restrictions, drought) and when achievable selling prices for animals are low (Morris et al. 2009). However, benefits and food security for smallholders through cropping compared to pastoralism are discussed controversially (Danso et al. 2018; Müller et al. 2018; Searchinger et al. 2015; Tilahun et al. 2017).

Yet, the impacts of described land use change (LUC) at landscape-scale on livestock production, savanna ecosystem functions (ESF), and the sustainability of crop production within different systems and over longer periods are mostly unknown.

More specifically regarding LUC impacts on soil-related ESFs, cropping, particularly with plowing, accelerates mineralization of soil organic matter (SOM) reducing soil organic carbon (SOC) storage (Babalola and Opara-Nadi 1993). Nutrient mining and depletion, which often occur within the first years after grassland conversion, result in reduced soil fertility, especially when crop residues are removed, nutrients are not recycled via manure, and other organic inputs are low (Braimoh and Vlek 2004; Jaiyeoba 2003). This may result in reduced crop yields in the medium and long term (Braimoh and Vlek 2004).

Decomposition of organic matter reduces pore volume and thus increases soil bulk density, which leads to reduced soil water storage capacity and increased runoff (Oliveira et al. 2015; Trabaquini et al. 2015). Crop fields also have a higher evapotranspiration during the growing season than permanent grassland (Odongo et al. 2019), which results in reduced water availability. This constrains crop growth and reduces yield stability, and, thus, decreases food security under rain-fed, seasonally water-limited growth conditions.

At landscape-scale, converting grassland to crop fields reduces available pasture for livestock, which increases grazing pressure on remaining pasture areas. This potentially leads to grassland degradation due to overgrazing, thus reducing feed available on remaining pastures and, therefore, deteriorating animal nutrition (Mekasha et al. 2014; Tefera et al. 2007; Wario et al. 2016). This is particularly the case where enclosed crop fields are established (Angassa and Oba 2008).

Integrated crop-livestock systems can be a sustainable alternative, where herds get access to fields after cropping, providing crop residues as additional feed resource in the off-season (Mekasha et al. 2014; Rusinamhodzi et al. 2015). Additionally, intensively managed grazing of remaining pastures with appropriate stocking densities can enhance feed availability and quality, particularly in the dry season, without causing grassland degradation. Intensively managed grazing systems are characterized by seasonal grazing of animals at high stocking densities in wet season pastures, while other pastures are set aside during this period to save forage for the dry season (Crawford et al. 2019; Kurtz et al. 2016).

Understanding the complex interactions of the major processes in savannas evoked by land use change (LUC) described above calls for a process-based modelling approach. This approach should combine functions from crop, grassland, livestock, and LUC modelling for comparing land use scenarios (Ma et al. 2019; Warth et al. 2020).

The objective of this study was to assess trade-offs of grassland conversion to crop fields regarding crop yields, livestock production, and the following ESFs: carbon (C) storage in soil and vegetation, retention of plant available nitrogen (N_{min}) in the soil, soil water contents and reduced erodibility. Furthermore, we assessed options to optimize ESFs, and biomass- and livestock production in the landscape under the expansion of crop fields and different stocking densities, via intensively managed grazing and crop-livestock integration.

We used a process-based modelling approach and data from an approx. 600 km² watershed in Borana, Southern Ethiopia, an area where traditional pasture-based savanna land use predominates, but where cropping is also practiced and which has the potential for increasing agricultural use (Mekasha et al. 2014; Tefera et al. 2007; Tilahun et al. 2017). In this regard, we compared the (1) traditional pasture-based land use system of livestock moving across the grassland with the following two LUC scenarios to test the corresponding hypotheses.

(2) Intensive LUC scenario representing the expansion of small-scale crop production into parts of the grassland.

We hypothesize that livestock production as well as the provision of the ESFs SOC- and N_{min} content (as long- and short-term indicators of soil fertility), plant biomass C, water storage and protection of soil from erosion decrease when grassland is converted to maize fields.

(3) Integrated LUC scenario representing intensively managed grazing, integrated with small-scale cropping, where crop residues can be grazed in the dry season and resulting excrements are recycled to crop fields (crop-livestock system).

We hypothesize that the integrated crop-livestock system, allows the grassland conversion mentioned under (2) to be managed more sustainably through higher and more stable livestock and crop production with less negative effects on ESFs as compared to separate pastoralism and cultivation.

Methods

Model description

In the following two sub-sections, we describe the Land Use Change Impact Assessment (LUCIA) and Livestock Simulator (LIVSIM) models that were coupled for the present study.

LUCIA model

The LUCIA model is a spatially explicit and distributed grid-based landscape model that runs on a daily time step. It can represent different land use, soils, vegetation types in changing topography. LUCIA was developed to simulate trade-offs and potentials of LUC, regarding agricultural production and ecosystem functions (ESFs), (e.g., soil fertility, water retention, and soil C storage). In the model, land use and management (e.g., tillage, mulching, fertilizer application) affect soil surface cover, water balance, erosion, nutrient cycles, soil organic matter (SOM) fluxes, and plant growth (Marohn et al. 2013, 2022; Marohn and Cadisch 2011).

To reflect pasture-based savanna systems, we implemented plant physiological routines that allow resprouting of perennials after drought or grazing, conceptually based on the Linrange model (Oomen et al. 2016). Resprouting depends on the fill level of a growth reserve pool which is on the one hand replenished during plant growth that is not resource limited, usually in the rainy season, and on the other hand is used by the plant for regrowth after grazing and at the beginning of the rainy season. The reserve pool can get depleted through overgrazing, causing plant death and consequently grassland degradation. Flexible biomass partitioning, where leaves are given priority during regrowth, influences growth rate and herbage quality. Plant dormancy in response to drought determines the onset and length of the growing period, following seasonal rainfall patterns. A detailed description of the routines can be found in Warth et al. (2021). Parameter sensitivity, limitations and uncertainties are discussed in Section “Model limitations and further improvements”.

Standing hay of perennial grasses and standing crop residues (summarized under the term standing litter) are relevant as additional feed resources in pasture-based and agro-pastoral savanna systems, particularly in the dry season (Gilo and Kelkay 2017; Mekasha et al. 2014). We implemented model functions that reflect standing litter dynamics by inserting an additional biomass pool for standing litter. Senescent leaves and stems are first shifted into the standing litter pool, instead of the ungrazable surface litter pool. In a second process, standing litter is reduced via steady turnover into the surface litter pool, via grazing offtake and / or via plowing (Eq. 1). When grassland is converted or fields are tilled, standing litter is completely plowed under and therefore transferred into the soil litter pool, together with surface litter and grass above-ground biomass (AGB).

$$W_{standLit} = W_{standLit} + \frac{W_{lv}}{turn_{lv}} + \frac{W_{st}}{turn_{st}} - \frac{dGrz_{standLit}}{dt} \tag{1}$$

when $simD \neq plowD$

$$W_{standLit} = 0$$

when $simD = plowD$.

with:

$W_{standLit}$ (tons/ha) standing litter

W_{lv}; W_{st} (tons/ha) leaf; stem biomass

$turn_{lv}$; $turn_{st}$ (d) leaf; stem biomass turnover time

$\frac{dGrz_{standLit}}{dt}$ (tons/ha/d) grazing offtake standing litter

$simD$; $plowD$ (d) day of simulation; plowing date

In contrast to growing biomass with phenologically changing N, P, K concentrations, the qualities of standing dead leaves and stems are both constant species-specific values. Total standing litter quality thus depends on the fractions of standing dead leaves and stems, which change dynamically due to different senescence rates.

Maize fields and therefore standing litter consisting of crop residues were only accessible to cattle for grazing during off-seasons, supplementing livestock nutrition in the coupled LIVSIM.

LIVSIM model

LIVSIM is a non-spatial, dynamic herd model running on a monthly time step (Rufino 2008). The model was developed to assess how different feeding strategies affect productive and reproductive performance of ruminant livestock herds, depending on the genetic potential of the animals, and the quantity and nutritional quality of available feed resources. A comprehensive description of the LIVSIM model can be found in Rufino (2008).

The LIVSIM version used for this study has been modified to more accurately simulate feed intake and productive performance for cattle production systems in the (Sub-) Tropics (Bateki and Dickhoefer 2020).

Feed can be represented under three categories in the stand-alone LIVSIM, namely concentrates, forages, and pastures, defining their quantities and nutritional characteristics. For model coupling (Section "Model coupling"), nutritional characteristics and digestibility of feeds in LIVSIM were predicted based on dynamic nutrient concentrations of grassland AGB and standing litter from LUCIA, using linear regressions (Online Appendix 1) developed for this study. Equations were derived using own data that summarize nutrient composition of pasture samples from the Guinea Savanna in Ethiopia, Ghana, and Kenya (Bateki 2015; Onyango et al. 2019). The linear regressions were employed for exchanging variables regarding nutritional quality of grazed fodder between both models in the coupling process, as described in the following section.

Model coupling

AGB and standing litter offtake via grazing as well as the deposition of nutrients from faeces and urine are external variables in the standalone LUCIA. Similarly, the quantity of fodder and its nutritional quality are external variables in LIVSIM. In the coupled version, those variables are received from the respective counterpart model. Thus, dynamic feedbacks between plant biomass production and quality under changing seasonal and land use patterns, livestock nutrition and performance, as well as faecal production and soil fertility are accounted for. To couple both models, a specific coupling module was built in Python (Marohn et al. 2022). The coupling module accounts for the different time steps of both models, in one direction by breaking down monthly updated amounts from LIVSIM (e.g. herd fodder demand) into daily amounts during that month for LUCIA (e.g. grazing offtake). In the opposite direction of variable exchange, the module accumulates daily amounts from LUCIA (e.g. grazed fodder) during one month for the variable update of one time step in LIVSIM (e.g. herd body weight).

Variable exchange between the models

Initialization: A simulation run is initialized in LIVSIM by sending the initial herd body weight (BW) to the coupling module. Based on the assumption that cattle consume 2.5% of their BW daily, the module estimates daily herd fodder demand for the first month and sends it to LUCIA. At the same time, first approximations of amounts and qualities of faeces and urine are converted into daily organic and mineral soil nutrient inputs and sent to LUCIA.

Step 1 in Fig. 1: After the initial month, variable exchange starts with actual herd fodder demand, and faeces and urine produced for the month started, depending on animal status and ingested fodder, calculated by LIVSIM (Bateki and Dickhoefer 2020). The values are sent to the coupling module.

Step 2 in Fig. 1: The coupling module breaks down monthly fodder demand and produced faeces from LIVSIM into daily quantities for the month started in LUCIA.

Step 3 in Fig. 1: Grazed AGB and standing litter based on daily fodder demand and limited by daily fodder availability on the grazed pixels in LUCIA is sent to the coupling module, together with average N, P, K, and lignin concentrations in the AGB (derived from plant organ specific concentrations) and standing litter. The coupling module accumulates grazed AGB and macronutrients for one month.

Step 4 in Fig. 1: The coupling module converts the cumulatively grazed AGB and macronutrients of the past month into available fodder amount and quality (employing equations described in Online Appendix 1), respectively, and communicates them to LIVSIM.

Herbivore selectivity

For daily grazing of grass AGB and standing litter in LUCIA (step 3 in the variable exchange), leaves are preferred by grazing animals over fruits, stems, and standing litter (see Section "LUCIA model"). Proportions of different plant organs and standing litter of grazed biomass depend on availability of the plant organs and standing litter on the grazed pixel, as well as user-defined herbivore selectivity (Fig. 1) (Warth et al. 2021). Accordingly, quality and amount of urine and faeces are estimated in LIVSIM based on the ingested fodder nutrient composition (Bateki and Dickhoefer 2020; Marohn et al. 2022).

Herd movement

The location of grazing in LUCIA is controlled by the herd movement sub-module, built in PCRaster (Fig. 1). For this, the user defines a specific grazing area accessible to a livestock herd (Fig. 2). This grazing area can be changed on a monthly basis using a monthly raster map input to LUCIA, defining the accessible pixels, e.g. for managed seasonal grazing. Within the grazing area, the LIVSIM herd is moved to the pixel with the highest AGB crude protein quantity by the herd movement sub-module. Movement happens as soon as fodder on the currently grazed pixel drops below a

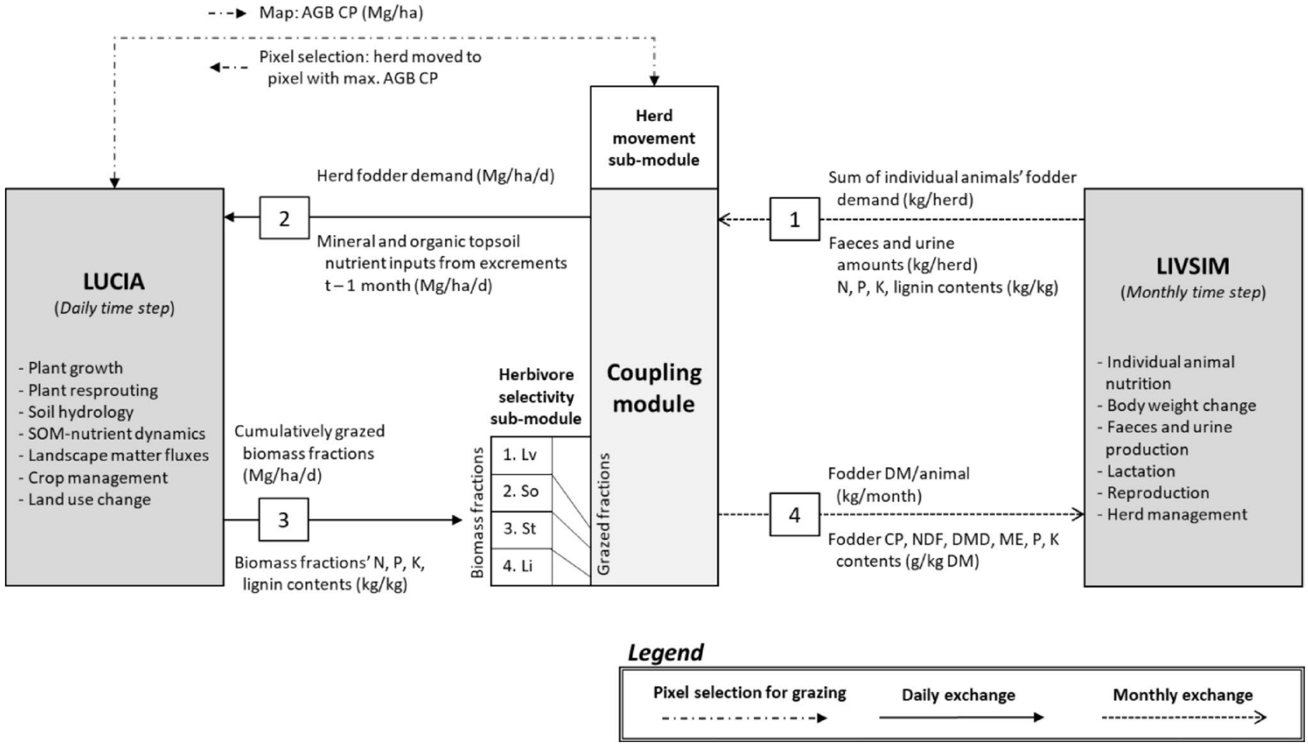


Fig. 1 Overview of variables exchanged via the coupling module between the coupled LUCIA and LIVSIM models. Scheduling of variable exchange steps is indicated by the numbers in boxes. Different arrow types indicate exchange at different temporal scales (daily, monthly). *AGB CP* crude protein in above-ground biomass, *SOM* soil organic matter, *BW* livestock body weight, *DM* dry matter, *NDF* neutral detergent fiber, *DMD* digestibility of dry matter, and *ME* metabolizable energy, *Lv* leaf biomass fraction (1 = highest priority for grazing), *So* fruit biomass fraction, *St* stem/stalk biomass fraction, *Li* standing litter fraction (4 = lowest priority for grazing)

user-defined AGB threshold, which for this study was calibrated to reflect herd movement frequency observed in the field (Wario et al. 2016). In a second step, when AGB on all accessible pixels of the grazing area is below a user-defined threshold, the herd moves as soon as available AGB on the current pixel is grazed down to a minimum amount (Marohn et al. 2022).

Case study site and field data

Our case study was located in a watershed of approx. 600 km² in the Borana region of Southern Ethiopia (Fig. 2). Elevation, soil, and land cover / land use maps were created based on secondary data (Warth et al. 2021). Vegetation types defined and parameterized have been described by Warth et al. (2021): *Acacia spp.* trees and shrubs with grassland (shrub grassland), open *Pennisetum mezianum*-dominated grassland without trees or shrubs, woodlands, and maize.

One year of daily air temperature, solar radiation, and evapotranspiration (ETo) obtained from weather station recordings in Madhecho 2012/13 were looped for long term simulations (ETo calculated based on air temperature, solar radiation, relative air humidity and wind speed via FAO-56) (Seckinger 2014). We used rainfall data for 2011 to 2017 (Warth et al. 2021).

Breed-specific parameters (e.g. growth and lactation rates) for Borana cattle defined in LIVSIM by Bateki and Dickhoefer (2020) were retained for simulating the herd in the present study.

Model validation

The grassland parameterization used in this study has been validated before by Warth et al. (2021), using time-series of plot-specific grass AGB records for open and shrub grassland, measured in 2012/13 in the study watershed (Kidake 2014).

The *Acacia spp.*-dominated woody vegetation component of shrub grassland simulated in this study has also been calibrated by Warth et al. (2021) against site-specific measurements of tree canopy dimensions, AGB, and plant cover. Along with this, the model fit for seasonal tree leaf flush and shedding was validated by Warth et al. (2021) against field data (Breuer 2012; Kisambo et al. 2016; Seckinger 2014).

Additionally for this land use change (LUC) study, we calibrated maize grain yield of a common variety in Borana (Melkassa 1) for rainfall, soil conditions and management

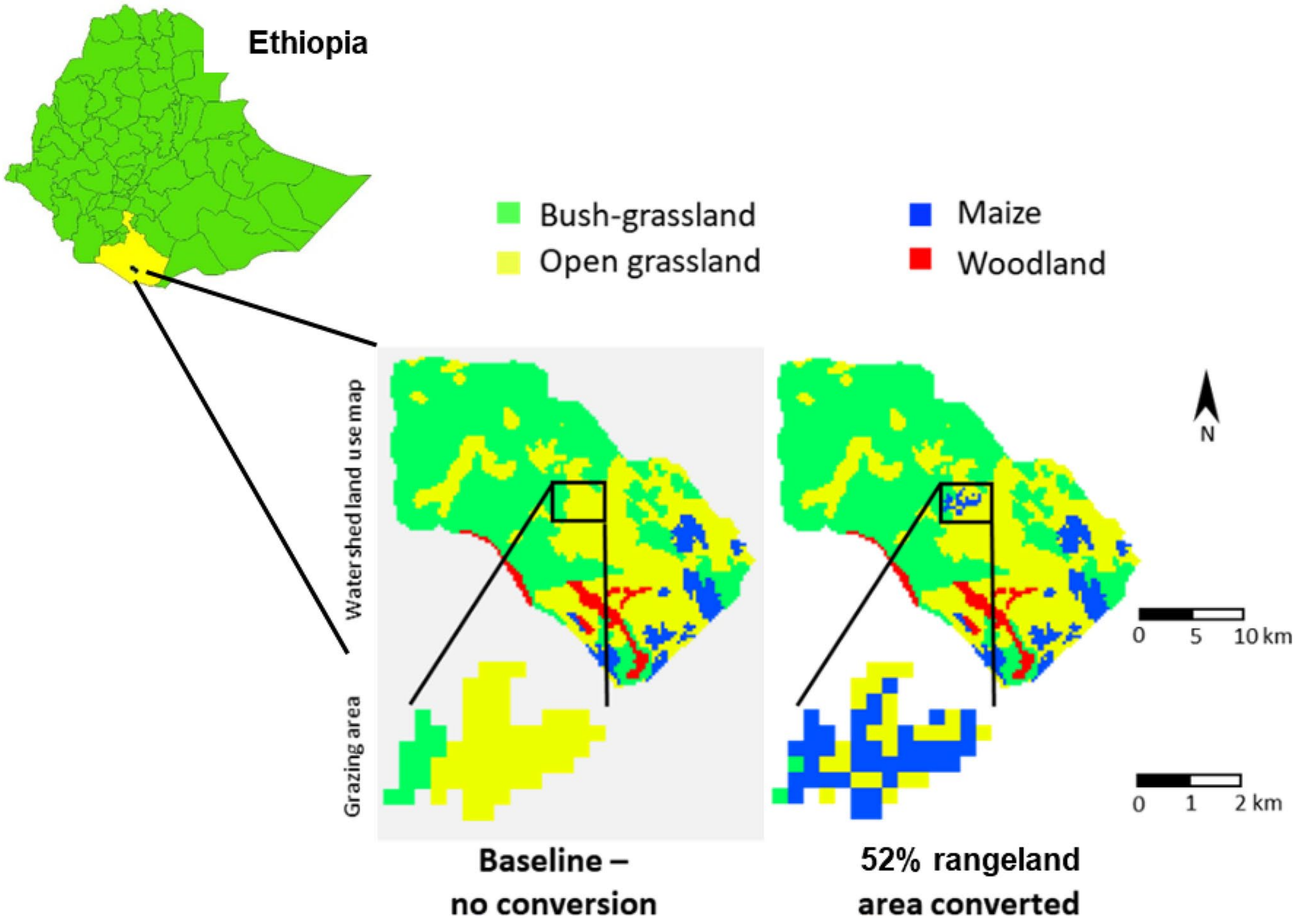


Fig. 2 Land use maps used for scenario simulations representing the traditional herd management (baseline) without land use change (LUC) (left) and the final extent of LUC in the defined grazing area within the study watershed in year 10 of the simulation (right)

of the Yabello Research Station against secondary data for 2012 (Natol Bakala and Yonas Shimalis 2017). Maize straw biomass was calibrated based on the harvest index of 0.47 for the same variety according to Alemseged et al. 1996. Model accuracy of predicting maize grain yield and corresponding straw production was evaluated based on RMSE (Loague and Green 1991).

Prediction accuracy for the livestock component of the model was evaluated using the mean relative error, based on averages of predicted age at first calving, calving interval, number of calves per cow, and milk yield per lactation, against observed literature values by Duguma et al. (2012) and Wario et al. (2017).

Based on the validation, in order to set up a balanced system as baseline for different LUC scenarios, we checked the plausibility of 10-year model predictions under traditional pasture management for topsoil organic carbon (SOC), N_{min} stocks, topsoil water stocks, and grass and shrub AGB, along with the dynamics of herd BW, herd size and the number of animals born, died, and removed from the herd (Gedam 2019).

Land use and management scenarios

Scenario simulations were run for 10 years at a daily time step. Spatial resolution of the simulated landscape was 300 × 300 m per pixel, deemed representative for extensive grazing as it produced reasonable herd movement intervals. We focused on 600 ha grazing area, a sub-landscape of 67 pixels defined according to observations by Wario et al. (2016) in the same area. The entire watershed was simulated to represent lateral matter fluxes according to watershed borders, that influence matter intake into and through the grazing area.

Based on common management practices for livestock and crop production systems in African savannas, we tested the baseline of traditional pasture-based land use and scenarios of partial grassland conversion to small-scale cropping systems, and of the integration of intensively managed grazing with cropping by running the scenarios summarized in Table 1.

(1) Traditional herd management (baseline) – Trad_Grz: For this study, two cattle herds of 80 heads each as

Table 1 Overview of the key settings in each scenario simulated by the coupled models

Setting	Trad_Grz[a]	LUC_Intensive[b]	LUC_Integrated[c]
Maize fields (LUC) after 10 years (% study area)	0	52	52
Pasture reserved for dry season grazing	No	No	Yes
Crop residues removed (%)	-	40	40
Crop residue grazing (left over after 40% removal)	-	No	Yes

[a] Traditional herd management (baseline): herd of initially 160 heads rotating across 600 ha pasture, 300 m spatial resolution, daily time step, 10-year simulation run

[b] Land use change (LUC) scenario, smallholder cropping: similar to Trad_Grz, but maize expansion from year 3 until 9, at a constant rate of 7.5% (5 pixels) per year, maize grown from March to July, 40% of straw removed after harvest

[c] Crop-livestock integration scenario: similar to LUC_Intensive, but herd has access to maize straw as additional feed (straw left over after 40% removal at harvest), intensively managed grazing system: non-grazed pixels in wet season (April-May) as pasture reserve for dry season

Table 2 Analyzed model outputs between scenarios

Model output	Indicated ESF, plant and livestock production
Topsoil SOC stocks (topsoil thickness: 24–38 cm, depending on soil type)	ESF: carbon storage, influence on soil water storage capacity and therefore on grass and crop productivity
Topsoil N_{min} stocks (topsoil thickness: 24–38 cm, depending on soil type)	ESF: soil fertility, influence on grass and crop productivity (sustainability of the cropping system)
Topsoil water content (topsoil thickness: 24–38 cm, depending on soil type)	ESF: plant water availability, influence on plant growth under strongly seasonal rainfall
Erosion and sediment deposition	ESF: prevention of soil loss and translocation, influence on spatial pattern of soil carbon storage, soil fertility and soil water storage capacity
Above- and belowground vegetation biomass-C stocks	ESF: carbon storage
Sum of grassland AGB and standing litter	Pasture production and productivity, preservation or degradation of feed resources, influence on animal nutrition
Maize straw biomass	Production of an additional feed resource, influence on animal nutrition
Maize grain yield	Good for consumption and sale, influenced by the various ESF
Number of animals in the herd	Livestock reproduction and herd stability, depending on animals born, died and removed, influenced by animal nutrition
Total herd body weight	Livestock production for consumption and sale, influenced by animal nutrition

described by Wario et al. (2016) were merged into one herd. Consequently, the herd size was initialized with 160 heads of cattle of different sex, age and reproductive status according to Takele Gebissa (2014) and Wario et al. (2017), and was limited to a maximum herd size of 250 heads assuming labor limitation (Gedam 2019). Animals were removed from the herd in the model once the user-defined maximum age was reached (bulls 6 years, cows 15 years) and calves were removed when maximum herd size was reached. The total initial animal BWs, divided by the grazing area resulted in an initial stocking rate of 0.23 TLU / ha, which is in accordance with Yusuf (2013). Representing the status quo land use and management, the herd was moved within the 600 ha grazing area of shrub- and open grassland vegetation.

(2) LUC scenario with common smallholder cropping – LUC_Intensive: The herd was initialized as in Trad_Grz. The conversion of the most productive 52% of the grassland area to maize fields (Angassa and Oba 2008; Morris et al. 2009) (Fig. 2), started in year three of the simulation, assuming a constant conversion rate of 7.5% or 5 pixels per year for 7 years. Successive LUC started in year three of the simulation, after two spin-up years as in Trad_Grz. For this scenario which was intended to represent increasing conversion pressure on savannas, the conversion rate was set higher than recently reported by Elias et al. (2015) and Habtamu et al. (2018). Before field preparation, shrubs and trees were cleared and 80% of their biomass was removed. Maize was sown in the last week of March after tillage, grown without fertilizer application as usual for capital-limited smallholders in the area, and harvested mid/end of July (Alemseged et al. 1996). For fuel or construction uses, 40% of the straw was removed from maize fields (Jaleta et al. 2015). The remaining residues were plowed under. Livestock was not allowed to access maize fields, but all remaining grassland within the grazing area.

(3) Crop-livestock integration scenario – LUC_Integrated: herd was initialized as in Trad_Grz. The expansion start and rate of crops into grassland was as for scenario LUC_Intensive, but the herd could access maize fields during the off-season. Residue grazing is thus integrated into a system of intensively managed grazing of remaining grasslands. Intensively managed grazing in this context means that during the main grass growing period in April and May, herd access is restricted to few grassland pixels, while the rest of the grassland is kept as reserve for the dry season.

We compared the following model outputs (Table 2), to test the hypotheses formulated in Section "Introduction".

Results

Model evaluation

Grass growth and crop yields

LUCIA's simulation of seasonally changing grassland above-ground biomass (AGB) under regular grazing was compared with measured grassland AGB time series of five plots from two years field data, showing a mean correlation coefficient (R^2) and root mean square error (RMSE) of 0.49 and 0.29 tons/ha, respectively (Warth et al. 2021).

Additionally, a plausibility check for a 10 years simulation run of the baseline scenario Trad_Grz showed that simulated topsoil water stocks (Fig. 4c) and consequently simulated grass AGB (Fig. 3a) and shrub AGB (Fig. 3b) responded visibly to observed rainfall seasonality and inter-annual rainfall variability. So did the maximum and minimum values of grass and shrub AGB, indicating similar recovery patterns after dry seasons and drought years, as well as grass after grazing, under various soil conditions in the grazing area (Fig. 3). Only in year 10, the minimum value of grass AGB showed hampered regrowth, indicating grassland degradation on some pixels of the grazing area (Fig. 3a).

Predicted maize yield was lower (4.42 tons/ha) than yields observed (4.51 tons/ha) by Natol Bakala and Yonas Shimalis (2017), whereas predicted straw production (5.16 tons/ha) was higher than observed (5.00 tons/ha) by Alemseged et al. (1996), resulting in an RMSE = 0.13 tons/ha for both parameters.

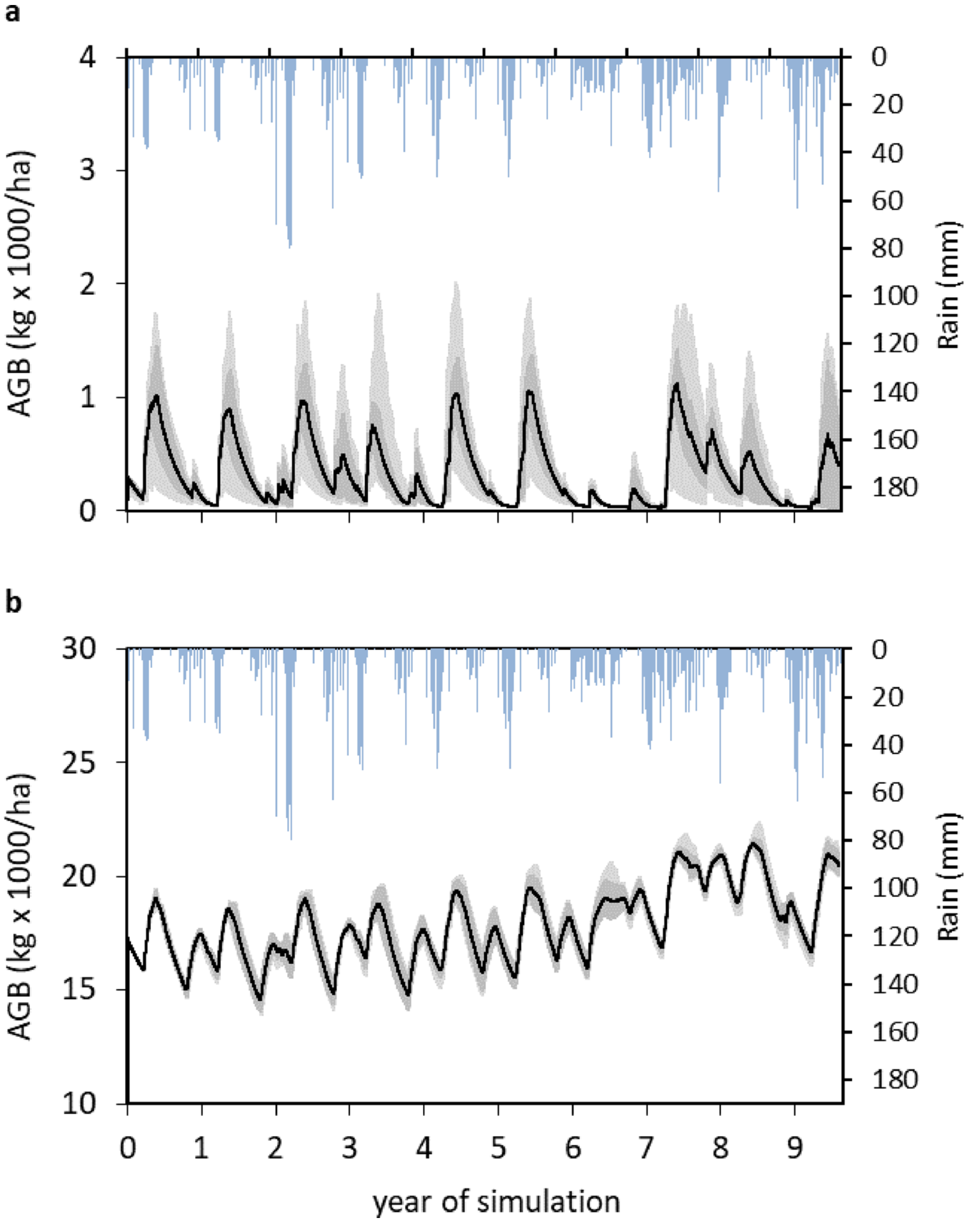


Fig. 3 Grass above-ground biomass (AGB) (**a**) and shrub (*Acacia spp.*) AGB (**b**) during 10-year simulation runs (daily time step). Averages of 67 pixels of the grazing area ($n = 67$, shrub AGB $n = 12$), (solid black line), standard deviation (dark grey shading), and maximum and minimum values (light grey shading)

Ecosystem functions

The following ecosystem functions were checked for plausible dynamics in the Trad_Grz scenario run for 10 years.

Simulated topsoil water stocks followed seasonal and inter-annual patterns of measured rainfall, whereas the base level of average topsoil water stock increased over 10 years to 1.26 of the initial value at day 1 (Fig. 4c).

Simulated topsoil plant available nitrogen (N_{min}) decreased (Fig. 4b), when simulated grass AGB increased (Fig. 3a), showing a plausible relationship between the two variables.

Predicted average topsoil organic carbon (SOC) stock decreased over 10 years to 0.98 of the initial value at day 1 (Fig. 4a). Pixel values within the grazing area varied between a maximum of 1.03 and a minimum of 0.94 in year 10 compared to the initial value. This is comparable to results of (Ritchie et al. 2024).

Average topsoil SOC on maize-covered pixels outside the grazing area, during 10 years in Trad_Grz, visibly followed seasonal patterns of maize growing seasons (Online Appendix 2).

Livestock production.

Compared to reference values from literature (Table 3), the model predicted lower average milk yield per lactation, higher age at first calving and a lower number of calves per cow, while the calving interval was shorter. This resulted in mean relative errors (MRE) for the four different parameters between 0.04 and 0.32 (Table 3).

Additionally, the simulated timeseries of herd body weight (herd BW) and herd size over 10 years under Trad_Grz were checked for plausibility via comparison to related simulation outputs. Simulated herd BW followed seasonal and inter-annual variability of simulated standing grass AGB (Fig. 5a): Herd BW increased to 1.61 of the initial value until year 4, with seasonal fluctuations, visible e.g. between years 1 and 2, and in year 4. Thereafter, herd BW decreased by 24%, corresponding to lower grass AGB in the dry seasons at the beginning of years 5 and 6 (grass biomass below grazable level during one to two months), compared to the years before (zero to half a month). A loss of 54% of herd BW was observed in the severe drought year 7, corresponding to a grass biomass peak of only 20% of that in the years before. In year 8, herd BW increased again, corresponding to higher above-average grass AGB production. Herd size (number of animals) showed a similar but less fluctuating trend compared to herd BW (Fig. 5b), with animals being removed from the herd on a regular basis due to aging and maximum herd size (e.g. reached in years 4 and 5). Death of animals only occurred in the severe drought year 7 and shortly thereafter.

Scenario simulations

Pasture, livestock, and crop production

The sum of grass AGB and standing litter within the grazing area decreased gradually as maize fields expanded into the grassland from year 3 onwards in the LUC_Intensive and LUC_Integrated scenarios compared to Trad_Grz (Fig. 6a).

The sum of grass AGB and standing litter showed no substantial difference between LUC_Intensive and LUC_Integrated, due to identical LUC patterns, indicating that dry season reserves in LUC_Integrated did not increase the amount of feed available (Fig. 6a). Regarding total feed biomass, comprising grass AGB, grass standing litter and crop residues, maize straw in LUC_Integrated could increase feed resources in the grazing area by 39 to 163 tons in dry seasons compared to LUC_Intensive (Fig. 6b). This was particularly important in drought year 7, when grass AGB was below-average in all three scenarios (0.17 to 0.23 of 10-year average grass AGB). Maize straw accounted for 63% of total feed biomass of year 7 in LUC_Integrated and therefore provided feed resources in the dry season that were not available in LUC_Intensive or even in Trad_Grz (Fig. 6b).

Corresponding to decreasing grass AGB and total feed biomass under LUC (Fig. 6), herd BW and herd size decreased over the 10-year simulation period in the LUC_Intensive (0.14 of initial BW, 0.18 of initial herd size) and LUC_Integrated scenarios (0.33 of initial BW, 0.44 of initial herd size) compared to the Trad_Grz (0.94 of initial BW, 1.18 of initial herd size) (Fig. 7). Number of calves born and milk produced by the herd during the 10-years simulation period were 332 calves and 103 tons of milk in Trad_Grz, followed by 246 calves and 83 tons in LUC_Intensive, and 232 calves and 78 tons in LUC_Integrated.

Looking at certain events, in year 3 (start of LUC) there was a loss in 7.5% of pasture area in the LUC scenarios, compared to Trad_Grz but no substantial differences in herd BW and herd size between the three scenarios were visible (Fig. 7a). At the end of year 4, total herd body weight started to decrease in the LUC scenarios compared to Trad_Grz, along with herd size that declined from year 5 (Fig. 7). In drought year 7, herd body weight dropped to 0.80, 0.39, and 0.44 of the initial value in Trad_Grz, LUC_Intensive, and LUC_Integrated, respectively, corresponding to below-average feed resources. Along with herd BW, herd size dropped to 0.78 and 0.76 of the initial value in LUC_Intensive and LUC_Integrated, respectively. In Trad_Grz, herd size remained stable in drought year 7. Herd BW recovered only slowly after drought in Trad_Grz, followed by LUC_Integrated and LUC_Intensive, where pasture area and feed resources were reduced. However, in LUC_Integrated, the

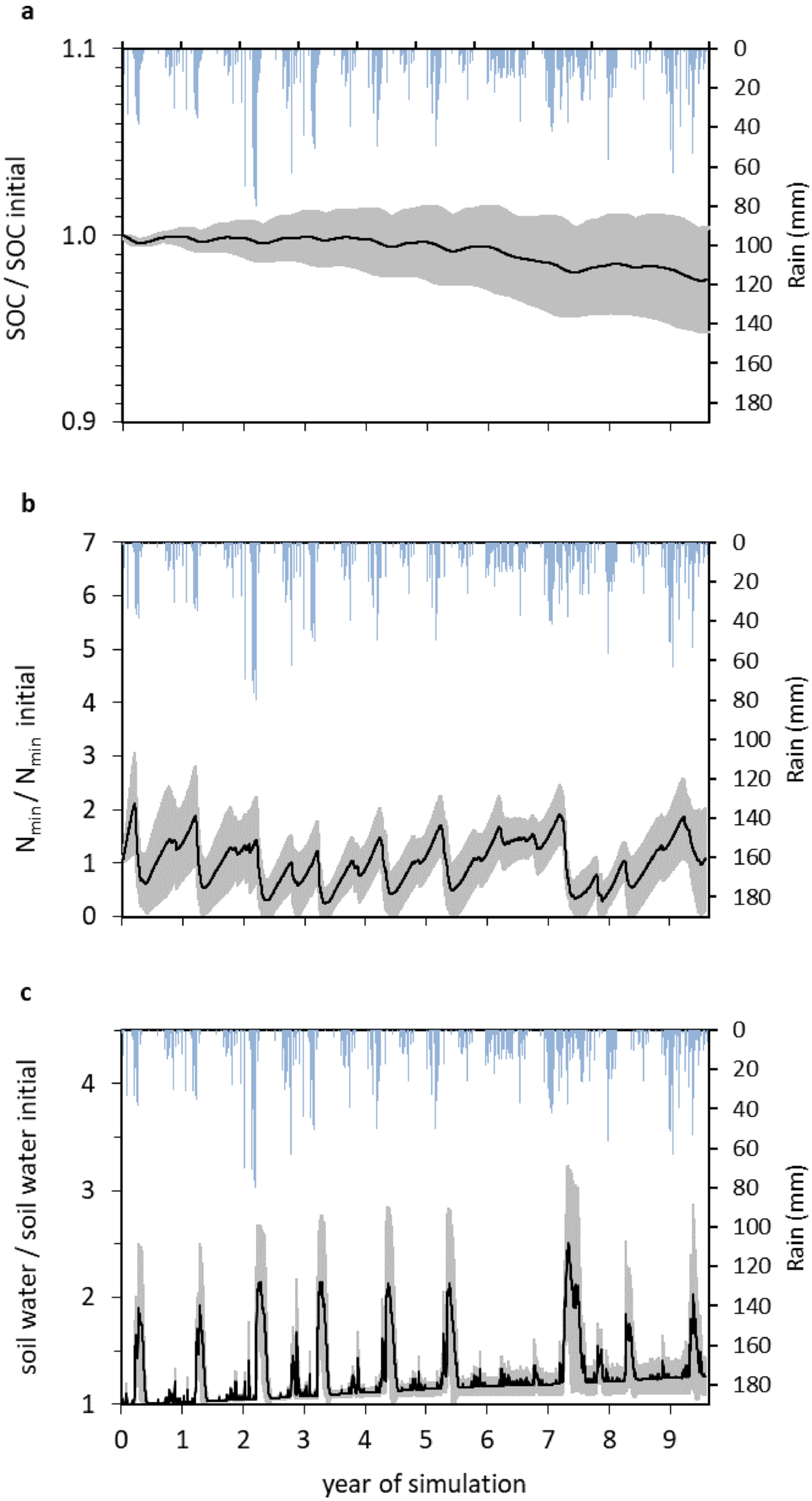


Fig. 4 Soil organic carbon (SOC) stock in topsoil (24 to 38 cm thickness depending on soil type) (**a**), topsoil mineral nitrogen (N_{min}) stock (**b**), and topsoil water stock (**c**) during 10-year simulation. Values of the three parameters are normalized over respective initial stocks to account for different initial soil conditions of the soil types. Averages of 67 pixels of the grazing area (*n* = 67), (solid black line), standard deviation (dark grey shading)

Table 3 Simulated vs. observed reference values of herd average age at first calving, calving interval, calves per cow, and milk yield per lactation (average ± standard error)

	Unit	Simulated value	Observed reference value	References	Mean relative error
Age at first calving	months	58 ± 0	56 ± 1	Wario et al. (2017)	0.04
Calving interval	months	17 ± 0	19 ± 0	Wario et al. (2017)	0.26
Calves per cow	animals	2.5 ± 0.13	3.2 ± 0.12	Wario et al. (2017)	0.32
Milk yield per lactation	kg	339 ± 8	473 ± n.a.	Duguma et al. (2012)	0.28

herd appeared more resilient to pasture loss by LUC than in LUC_Intensive, due to available maize straw as additional feed in dry seasons avoiding a drastic drop in herd BW and size (Fig. 7).

The differences in maize grain yield per ha crop field between the scenarios LUC_Intensive and LUC_Integrated were small over the simulation period (maximum difference of 60 kg per ha in year 3), indicating negligible effects of grazed straw and recycled faeces on soil fertility for maize growth.

The average annual maize grain yield on converted grassland within the grazing area varied between 130 and 3130 kg per ha depending on the year during the simulation period, decreased from the first cropping in year 3 until the low-rainfall-year 7 and increased slowly thereafter (Online Appendix 3). Yields fluctuated on different pixels by a maximum range of 2.45 tons per ha between years and 2.56 tons

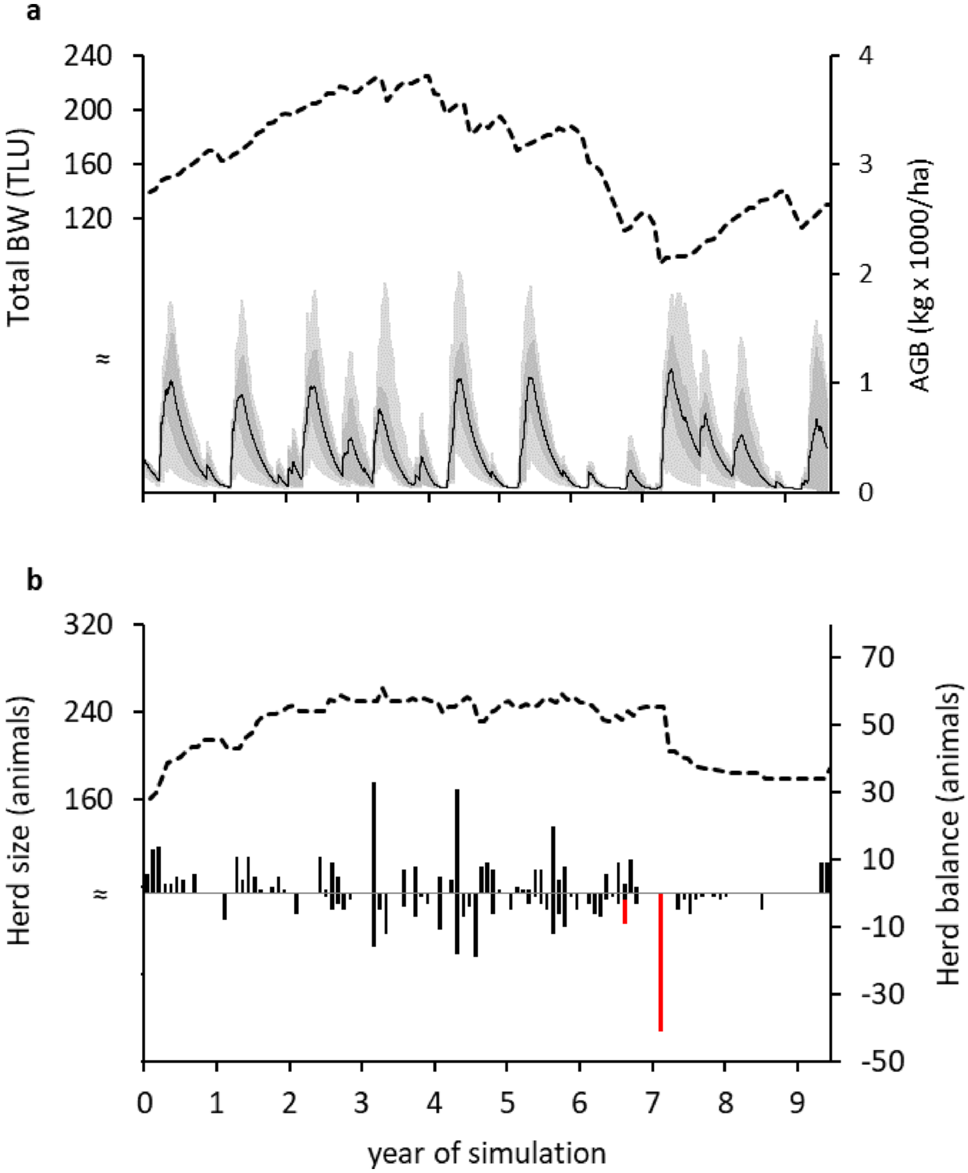


Fig. 5 **(a)** Herd body weight in tropical livestock units (TLU = 250 kg), (dashed line, left y-axis) combined with standing grass above-ground biomass (AGB) (solid line, same as in Fig. 3a, right y-axis). **(b)** Herd size (dashed line, left y-axis), combined with herd balance (right y-axis, positive bars = animals born, negative black bars = animals removed or sold, and negative red bars = animals died)

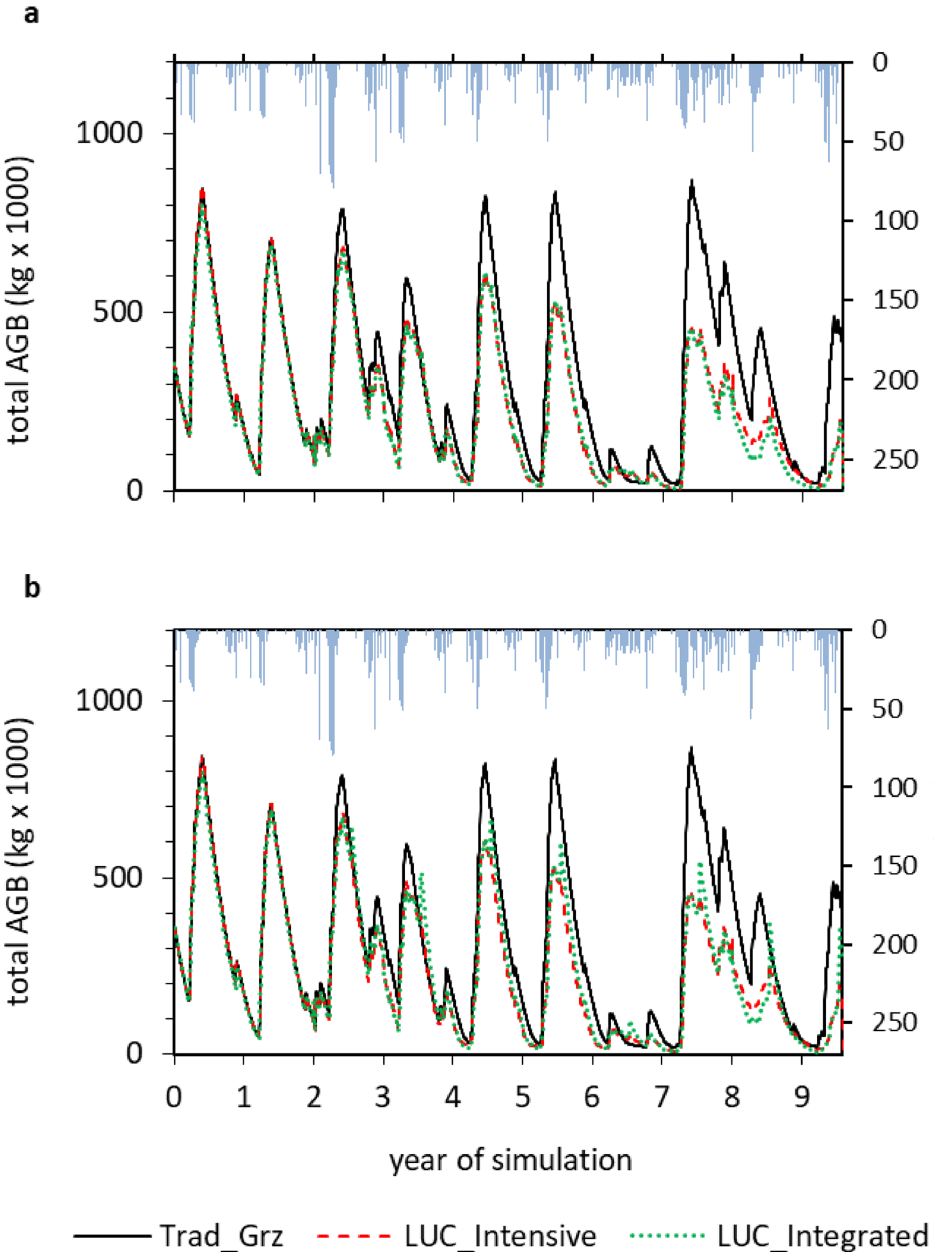


Fig. 6 **(a)** Sum of grass aboveground biomass (AGB) and grass standing litter and **(b)** total feed biomass comprising grass AGB, grass standing litter and crop residues of the total grazing area for the traditional herd management scenario Trad_Grz and two land use change (LUC) scenarios

per ha between pixels within a year (Online Appendix 6). Maize yields did not consequently follow the inter-annual rainfall pattern. Predicted yields correlated well with the simulated annual average of nitrogen limitation for maize growth, indicated by $R^2=0.64$ (drought year 7 excluded). Low nitrogen limitation allowed a high maize yield level on pixels where shrub grassland was converted, but yields declined over time (Online Appendix 6).

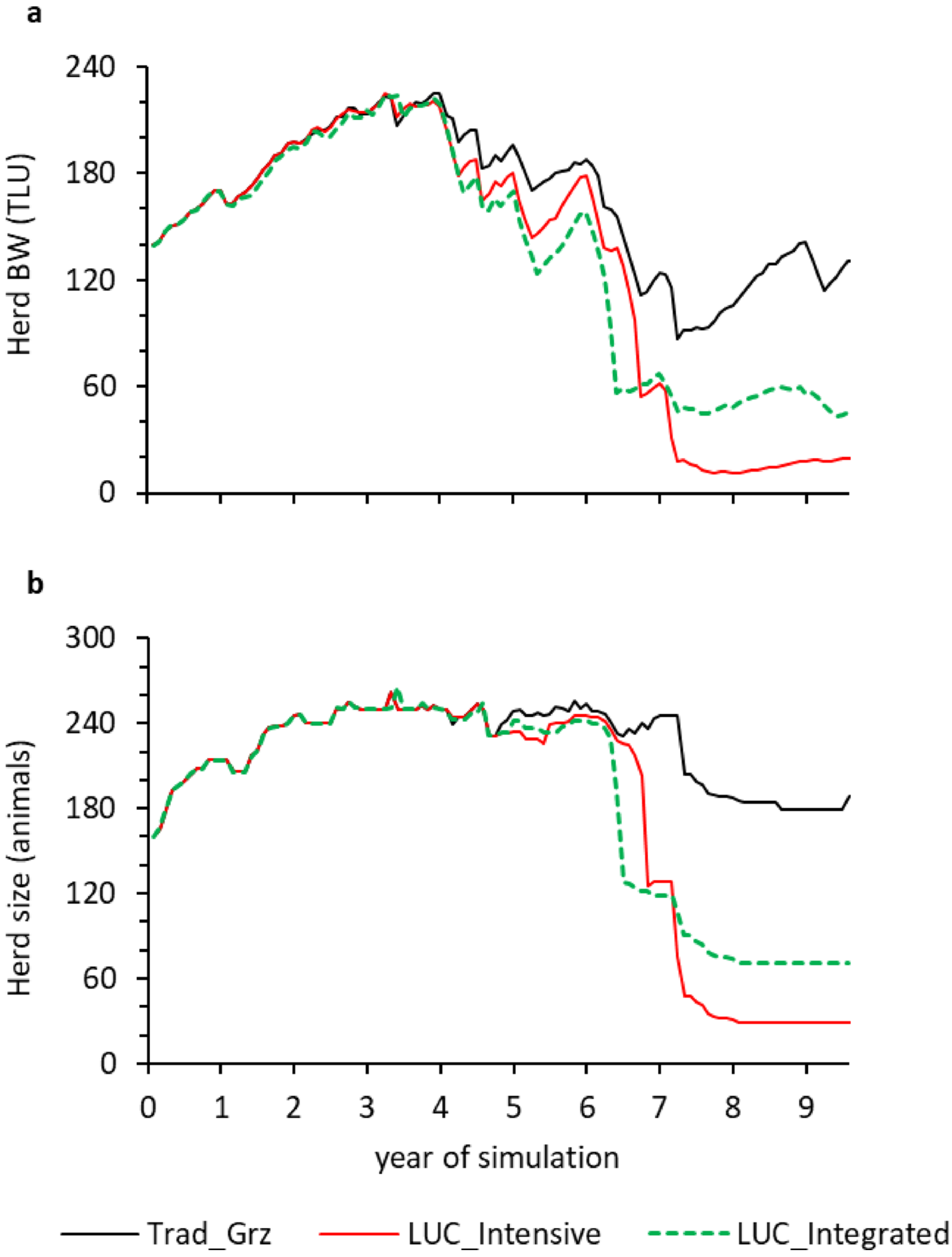
Ecosystem functions

No differences in SOC and biomass C stocks between the two LUC scenarios were predicted by the model. Topsoil SOC stocks of the total grazing area decreased in the LUC scenarios, compared to Trad_Grz, resulting in a difference of 0.66 tons of C per ha in year 10. Also, biomass-C stocks after 10 years had declined to about 0.23 of the initial value in the LUC scenarios, constituting a loss of 2.20 tons of C, compared to Trad_Grz (Fig. 8b).

Topsoil N_{min} and water stocks did not differ substantially between Trad_Grz and the LUC scenarios (Online Appendix 4).

Soil erosion in the study watershed under Trad_Grz accounted for less than one cm after 10 years occurring on few pixels outside the grazing area in the Southern hills and consequently deposition distributed over the Southern plains (Fig. 9). Erosion events in these zones of the watershed were

Fig. 7 **(a)** Herd body weight in tropical livestock units (TLU = 250 kg) and **(b)** herd size for the traditional herd management scenario Trad_Grz and two land use change (LUC) scenarios



mainly predicted for already established maize fields under heavy rainfall.

Within the grazing area, there was no erosion in Trad_Grz. Despite runoff and runon being similar to Trad_Grz, in scenario LUC_Intensive, erosion and deposition were predicted by the model (Fig. 9). Erosion events occurred mainly on LUC pixels of years 3 to 7, during heavy rains right after the grassland had been converted and plowed before maize cultivation or shortly after sowing. The soil lost from these LUC pixels accounted for less than one cm after 10 years, similar to erosion from already established maize pixels outside the grazing area. The eroded soil was distributed within the grazing area and beyond, following stream flows (Fig. 9).

Discussion

For this study, we employed the mechanistic landscape model LUCIA, amended by grassland functions and coupled to the livestock herd model LIVSIM. Stable levels of topsoil organic carbon (SOC), plant available nitrogen (N_{min}) stocks, topsoil water stocks, and grass and shrub above-ground biomass (AGB) over 10 years, following seasonal and inter-annual variation of rainfall proved a reliable

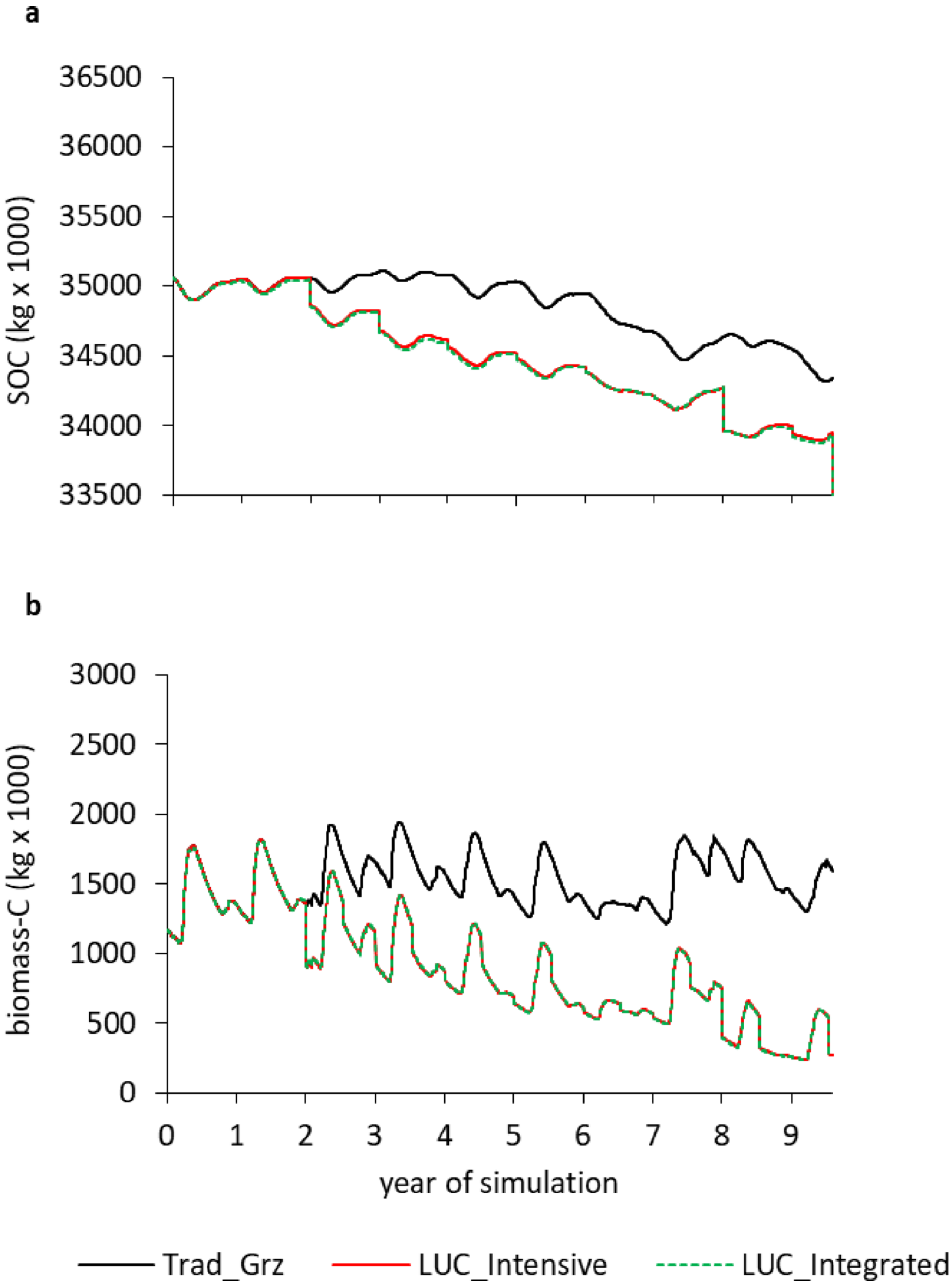


Fig. 8 **(a)** Soil organic carbon (SOC) stock in topsoil of 24 to 38 cm thickness (depending on soil type) and **(b)** above- and below-ground vegetation biomass-C stock of the total grazing area for the traditional herd management scenario Trad_Grz and two LUC scenarios

simulation setup for long term scenario runs for an African savanna. This together with the dynamics of herd BW and herd size responding to the dynamics of feed biomass availability proved functioning model coupling (Worku et al. 2022; Yusuf 2013).

The scope of this work was to use the model as a tool to assess the impact of savanna grassland conversion to maize fields on various ecosystem functions (ESFs) and livestock and crop production. Secondly, we aimed to test whether integrated crop-livestock systems with intensively managed grazing allow the ongoing grassland conversion and intensification to be managed more sustainably as compared to separate pastoralism and cultivation.

Ecosystem functions

Grassland conversion to unfertilized crop fields reduced the system's C storage, represented by the sum of SOC and biomass-C stocks by 4.8% after 10 years, enhanced N_{min} content as proxy for soil fertility by 16% (average of 10 years), reduced soil water storage capacity by 4.2% after 10 years (base level), represented by topsoil water stock, and enhanced erosion by less than one cm (approx. 140 tons/ha)

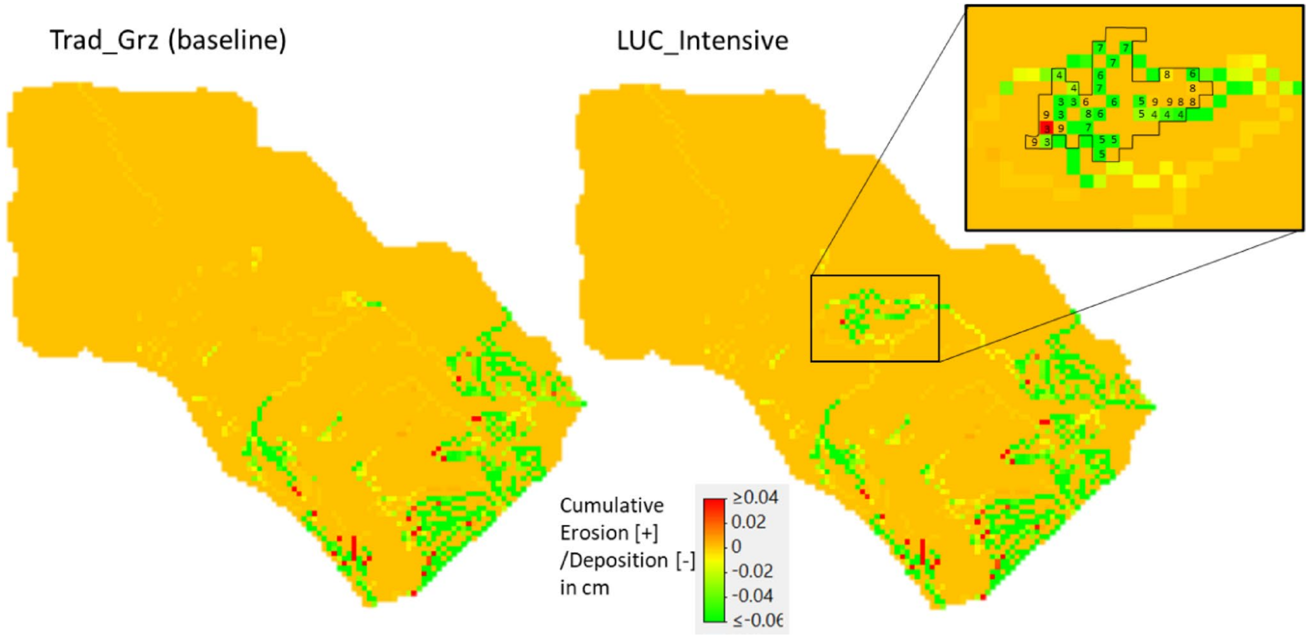


Fig. 9 Cumulative erosion (positive values) and deposition (negative values) as topsoil loss and gain (cm), respectively, after 10 years for scenarios Trad_Grz (left) and LUC_Intensive (right). The grazing area is marked by a frame in the map zoom. Pixel numbers indicate year of LUC

accumulated over 10 years, as proxy for the system's capacity to prevent soil loss.

Topsoil SOC of the grazing area under the LUC scenarios diverged from Trad_Grz over 10 years, mainly due to SOC drops at the beginning of years 3, 4, and 9, when shrub grassland with above-average SOC content was converted to maize fields, along with plowing, which accelerates soil organic matter (SOM) turnover (Babalola and Opara-Nadi 1993). Therefore, the conversion of shrub grasslands to crop fields is less favorable than converting open grasslands in terms of soil C storage as well as regarding C stored in the vegetation, mainly in woody plants, which are slashed and their wood mostly removed (Batlle-Bayer et al. 2010; Siraj and Abdella 2018). These trends confirm hypothesis 1, which states that SOC content decreases when grassland is converted to maize fields. A higher SOC concentration and higher plant biomass per ha in shrub grasslands than open grasslands has also been reported by Amara et al. (2020) and Mogashoa et al. (2021). Consequently, the loss of C is greater when shrub grassland is converted.

The increase of the base level of topsoil water stock was 4.2% smaller under the LUC scenarios than under Trad_Grz, due to regular plowing of maize fields, which loosens the soil and thereby destroys soil pores, resulting in a subsequent increase in bulk density, comparable to findings by Kalhoro et al. (2018).

Since runoff and its erosive force as well as maximum particle transport capacity were similar for Trad_Grz and both LUC scenarios, erosion under LUC was most likely enabled by increased erodibility, via the loss of grassland surface cover through LUC, plowing shortly before the start of the rainy season and slowly developing maize canopy cover in the early rainy season, in accordance with results of Lippe et al. (2014) and Liu et al. (2019). This could be confirmed by the timing of the main erosion events, that occurred after grassland conversion during the first rains of the season. The impact of less than one cm of erosion on topsoil SOC on the remaining grassland pixels in the LUC scenarios was small (Online Appendix 5a). Consequently, the impact of erosion and deposition on grass AGB on remaining grassland pixels in the LUC scenarios was also small (Online Appendix 5b). The small extent of erosion differs from results of Tadele et al. (2022) who identified gully erosion being the major form of soil movement in a Borana savanna. LUCIA simulates sheet erosion but not yet gully erosion.

Comparing LUC_Intensive with LUC_Integrated, the effect of additional removal of crop residues via grazing on SOC replenishment under LUC_Integrated was small, because only 78 tons of dry matter or 32 tons of biomass C within the grazing area were grazed cumulatively until year 10 (Rufino et al. 2011; Valbuena et al. 2012).

Changes in ESF caused by LUC mainly affected maize production on converted shrub grasslands, as discussed in the following section.

Grass growth and crop yields

Compared to Trad_Grz, in the LUC scenarios, the level of total grass AGB decreased constantly with the number of pixels converted to maize fields but still following rainfall seasonality and inter-annual variability. This indicated that grasslands were resilient to increasing grazing pressure without degrading, regarding AGB. Grassland degradation in terms of species shifts to less valuable forage species and bush encroachment, reported by Angassa (2002); Kraaij and Milton (2006); and Yassin (2019) could not be represented by the model yet as discussed in Section "Model limitations and further improvements". In year 10 seasonal pasture regrowth in the LUC scenarios was only 0.07 tons per ha, compared to 0.61 tons per ha in Trad_Grz. The impeded regrowth did not indicate grassland degradation due to overgrazing because grass plants were still alive on all grassland pixels. It could rather be explained by the selection of the last 3 of 10 most productive shrub grassland pixels within the grazing area for LUC in year 9 and consequently only less productive open grassland pixels remaining (Online Appendix 5b), (Angassa and Oba 2008). Therefore, the remaining pastures as a whole could be considered degraded, because of low grass regeneration potential left on open grasslands.

Predicted maize yields in the different years were similar under LUC_Intensive and LUC_Integrated (maximum difference of 60 kg per ha), probably because animals grazed straw on maize fields only for few days a year in LUC_Integrated, when all the other feed resources on pastures were used up (discussed under Ecosystem functions), corresponding with small amounts of faeces and urine fertilizing the maize fields.

The following analysis, which applies to both LUC scenarios, discusses factors that influenced yield fluctuations on different pixels from year to year and within years, which is relevant for land use planning and decision-making of smallholders. Rainfall amount (best visible in drought year 7) and soil nutrient depletion (indicated by the correlation between yield and nitrogen limitation of $R^2 = 0.64$) appeared to influence maize production, in accordance with findings by Jaiyeoba (2003) and Tilahun et al. (2017). As discussed in Section "Ecosystem functions", shrub grassland pixels were characterized by higher topsoil SOC contents than open grassland pixels and consequently a drop in SOC was observed after conversion, indicating SOM mineralization. With mineralization of SOM caused by grassland conversion, organically bound nitrogen was released, indicated by 1.16 times higher N_{min} stocks as average over the simulation period under the LUC scenarios compared to Trad_Grz. Released N most likely boosted maize growth in the first years of cropping, before N depletion started to constrain maize growth in subsequent years, comparable to findings by Jaiyeoba (2003). In contrast, low soil fertility after conversion of open grassland sites without shrubs most likely limited maize growth from the first year of cropping, explaining the constantly low yield level (Online Appendix 6). This predicted difference in yield, depending on the converted grassland type is comparable to findings by Kwari et al. (2011).

On one hand, we observed nitrogen limitation for maize growth within the grazing area. On the other hand, topsoil N_{min} stock in the LUC scenarios was higher compared to Trad_Grz. This contradiction can be explained by simulated maize roots that need to grow from nearly zero, limiting N_{min} uptake in the early stage, whereas simulated grass roots are still present at the beginning of the rainy season, which is in accordance with findings by Weih et al. (2018). Additionally, lower plant density and a shallower root system restrict N_{min} uptake by the simulated maize to a smaller rooted topsoil volume compared to the grass, in accordance with results of Franzluebbers et al. (2014).

No trend was evident that would explain an effect of soil erosion and deposition on yields, because less than 1% of the topsoil was lost over 10 years with negligible effects on soil fertility.

The LUC patterns, preferentially converting fertile shrub grassland for high maize yields, reduced feed availability under climate variability. The consequences for livestock production in intensive cropping and integrated crop-livestock systems are discussed in the following section.

Livestock production

Grassland conversion caused a decline in livestock production, represented by herd BW and herd size. Within 10 years, calves born were more than 25% and milk produced around 20% lower in LUC scenarios than in Trad_Grz. Particularly the resistance and resilience of the herd in drought periods was reduced. In drought year 7, when feed supply per ha was below average across scenarios, the herd was more sensitive in the LUC scenarios because available pasture was reduced, resulting in a severe feed deficit and a drop in BW, compared to Trad_Grz (Online Appendix 7a).

Comparing LUC_Intensive with LUC_Integrated, livestock production was less vulnerable to drought in the integrated system under LUC, despite grass AGB being similar to LUC_Intensive throughout the 10-years simulation period, in accordance with results of Peterson et al. (2020). This effect was best visible in drought year 7 of the simulation when only two small peaks of less than 100 tons of pasture biomass within the grazing area were insufficient to cover the feed requirement of the total herd in both LUC scenarios (Fig. 6a, Online Appendix 7a). However, pasture quality expressed as biomass ME content for these two peaks was about 4 to 8 times higher under LUC_Integrated than under LUC_Intensive (Online Appendix 4b), due to setting aside higher quality pastures during the growing period, as reserve for the subsequent dry season (Wario et al. 2015). Similar results have been found by Müller et al. (2019), comparing free ranging versus herded livestock feed quality. Feed quality of the managed pastures could therefore partly compensate for low pasture production in drought year 7. Additionally, under LUC_Integrated, 60% of maize residues were available as feed and more than half of it was grazed in the dry season of drought year 7 between the two pasture biomass peaks (Fig. 6b). This importance of additional feed from crop residues has also been identified by Mekasha et al. (2014) and Rusinamhodzi et al. (2015). Higher pasture quality and additional crop residues as feed under LUC_Integrated than under LUC_Intensive resulted in less animals dying shortly after drought in year 7 (28 vs. 80 animals lost) (Online Appendix 8).

For policy makers developing incentives for cropping in the savanna, as well as for smallholders' land use planning and decision-making, the results of the study indicate that the conversion of savanna grassland is not recommended, regarding the ESFs C storage and soil water storage capacity. Additionally, grassland is converted at the cost of sustainable feed supply and therefore livestock production.

If there are incentives for large scale LUC, reasonable crop yields can only be achieved by converting fertile shrub grasslands. This should be balanced with maintaining some of the productive shrub grassland as the main source of feed for livestock and as a C stock. These remaining grasslands should be managed as seasonal pastures, enhancing nutritional feed quality, partly compensating pasture lost to LUC. Crop-livestock integration is suggested to provide crop residues as additional fodder in dry seasons. Additionally, SOM and soil fertility must be conserved in the crop fields to stabilize yields over the years and to store SOC.

Such comprehensive land use planning is challenging, as it involves private and community land with diverse property rights and stakeholder interests (Kamara et al. 2005; Mcpeak and and Little 2019).

Model limitations and further improvements

Savanna vegetation

Regarding the implemented plant physiological routines for savanna system simulations in LUCIA, grass growth was most sensitive to dormancy parameters that determine start and length of the growing period, as well as to biomass allocation to leaves and stems that influenced growth rate and assimilation. Dormancy parameters were calibrated, because they were challenging to obtain from field data or literature. Employing the model for a different savanna environment would therefore need recalibration of those parameters. A detailed description of the sensitivity analysis can be found in Warth et al. (2021).

Model validation showed that simulated grass AGB peaks did not correspond to measured values for some plots (Warth et al. 2021). Possible reasons proposed by Warth et al. (2021) could be dung and urine patches creating local soil fertility hotspots (Jeltsch et al. 1998), a diverse structure of woody overstory across plots influencing grass growth (Scholes and Archer 1997), or unrecorded differences in grazing intensity prior to grass AGB sampling. Obtaining field data under controlled conditions, excluding such influences in extensive and diverse savanna grasslands is challenging.

On plant community scale, LUCIA simulated one dominant grass and one shrub species, representing the herbaceous and the woody savanna vegetation layer, respectively, with static plant densities. To improve the representation of pasture degradation in terms of feed amount and quality, ecological routines could be integrated into LUCIA. These routines should represent shifts in grassland plant communities resulting from changes in grazing regimes by incorporating selective grazing functions and various plant functional types, that respond differently to grazing and to interactions with other plant functional types (Belsky 1992; Lohmann et al. 2018; Snow et al. 2014). Equally, routines representing a seedbank and tree recruitment mechanisms need to be implemented into the model to allow simulating bush encroachment or re-colonization of degraded pasture areas by shrubs (Coughenour 1993; Jeltsch et al. 2000; Sankaran et al. 2013; Tessema et al. 2016).

Livestock production.

Herd BW recovered after drought year 7 in different rates across the LUC scenarios, but herd size did not follow, probably because of underestimated livestock reproduction, indicating the need for more careful calibration of LIVSIM. Additionally, pastoralists re-stock their herds buying animals after severe losses due to drought (Boone et al. 2011). This could be represented by employing a threshold-dependent routine in LIVSIM which adds a defined number of animals of different sex and age to the herd, as soon as herd size drops below a certain threshold.

Herd management under LUC pressure, including selling and buying livestock could be simulated in a more realistic way, by dynamically coupling LUCIA-LIVSIM to an agent-based socio-economic decision-making model, such as described by Marohn et al. (2022).

Ecosystem functions

The base level of topsoil water content increased constantly over 10 simulated years in all three scenarios (Online Appendix 4b), likely due to decreasing soil bulk density and consequently enhanced total pore volume by continuous root growth and death on grasslands. Prediction accuracy of the topsoil water stock could be improved by implementing trampling functions including impacts on topsoil bulk density and therefore pore volume (Cumming and Cumming

2003; Greenwood and McKenzie 2001; Savadogo et al. 2007).

This research focused on the biophysical components of LUC in savanna grasslands, but the economic outcomes and food security from certain land use decisions are equally important to savanna pastoralists. The economic trade-off between reduced herd performance due to lost pasture and additional maize yield from those converted pastures in different livestock-, crop- and mixed systems could be assessed by employing an agent-based, coupled socio-ecological model such as described by Marohn et al. (2022). This type of model allows to simulate the farmer's decision on land use, management, and crop-livestock integration practices, influenced by variable rainfall conditions and the provision of ESFs, as well as driven by different market prices for livestock products and grain (Marohn et al. 2013, 2022).

Conclusions

The large-scale conversion (52%) of savanna grassland to maize fields is not recommended as it caused C losses from soil and vegetation of 2.86 tons per ha in 10 years compared to the traditional pasture-based system. The loss of pasture through LUC reduced fodder availability and consequently decreased herd BW and herd size by more than 80%. Livestock production was more resilient to LUC and drought with crop-livestock integration and intensively managed grazing, providing maize straw as additional feed and high-quality pasture from dry season reserves, respectively. Without external fertilizer input, reasonable maize yields could only be achieved on fertile shrub grassland sites in the first years after conversion, whereas resource-poor open grassland sites were not suitable for maize production.

Crop-livestock integrated systems therefore potentially allow sustainable intensification of crop and livestock production under climate variability in African savannas, given that limited resources are used in a smart and efficient way. Soil fertility conservation and reduced organic matter export are needed to stabilize crop yields and C-storage over time on converted grasslands. Reduced soil disturbance, dung translocation to crop fields, legume intercropping, and agroforestry are management options that could conserve plant available water, and ease the competition between organic matter utilization (feed, fuel, and construction material) and the conservation of C-stocks and soil fertility (Adam et al. 2025; Duncan et al. 2013; Muoni et al. 2020; Valbuena et al. 2012).

Such management practices can be assessed by further scenario simulations using the LUCIA-LIVSIM model that provides many functions needed regarding plant-plant and plant-animal interactions, livestock mobility, and LUC and management effects on soil and vegetation. Amending the model with additional functions of dung management, feed conservation (e.g. intercropped legumes), trampling impacts on soil and vegetation under high stock densities, and dynamics of savanna vegetation composition (e.g. bush encroachment) would complement process representation for more realistic management scenarios.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40808-025-02600-y.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Benjamin Warth, Carsten Marohn and Christian Adjogo Bateki. The first draft of the manuscript was written by Benjamin Warth and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability All data supporting the findings of this study are available within the paper and its Supplementary Information containing Appendices, as well as in the models' raw input and output data. Supplementary appendices containing equations and related descriptions, as well as supplementary results' figures, referenced in the manuscript/paper are available in Figshare with the identifier https://doi.org/10.6084/m9.figshare.28692506.v1.The zipped folder "Raw_Data_Warth_2025" available in Figshare with the identifier https://doi.org/10.6084/m9.figshare.28692470.v1 contains model inputs and raw output files for the coupled LUCIA and LIVSIM models. The data are organized in 3 sub-folders, according to the baseline and the two scenario simulations, described in the manuscript/paper. Each of the scenario sub-folders contains a "maps" folder providing LUCIA model inputs in the form of text files and map files, as well as LIVSIM model inputs in the form of spreadsheets. Each "maps" folder contains an "Outputs" sub-folder, providing raw model outputs of LUCIA (text files) and of LIVSIM (spreadsheets).For further information about the LUCIA model, please refer to https://lucia.uni-hohenheim.de/en.For further information about the used LIVSIM model, please refer to the co-author Dr. Christian Adjogo Bateki.

Declarations

Conflict of interest The authors declare no competing interests.

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