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Sustainable intensification of fodder crop production can mitigate feed shortage and seasonality in East Africa

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ABSTRACT

The growing demand for livestock products from growing populations and economies will require additional forage to meet livestock feed requirements. Employing a novel, globally applicable seasonal demand and supply assessment methodology, we investigate the seasonal availability of fodder for ruminants and the potential for growing fodder crops to mitigate current and future demand shortfalls while preserving key conservation and wetland areas in East Africa. Our results indicate that grazing, which respects land for environmental conservation, will not provide sufficient fodder to meet demand throughout the year in many areas. Fodder crops from improved pastures, some conserved as hay, and new crops such as dual-purpose sorghum for food and feed production have a significant potential to provide fodder biomass, especially for maintaining sufficient fodder in the dry season. Forage production in East Africa needs to be intensified in a sustainable way while carrying capacity and stocking rates must be closely monitored.

1. Introduction

The supply of fodder for livestock production in Sub-Saharan Africa is becoming an increasingly urgent problem due to projected population and income growth and a shift in demand patterns towards a greater supply of protein from animal-based foods (Herrero et al., 2023). Per capita demand for animal products in Sub-Saharan Africa is expected to be 55% higher in 2050 compared to 2020 (Komarek et al., 2021) with populations almost doubling (Jones and O'Neill, 2016). Moderate increases in the consumption and production of livestock products in these regions can contribute to healthy diets and sustained livelihoods of livestock farmers (Parlasca and Qaim, 2022). Thus, many countries aim to increase local production of animal products.

It is crucial for regions to have a steady supply of fodder for ruminant livestock throughout the year to achieve self-sufficient livestock production. In particular, the densely populated Lake Victoria region of East Africa needs to increase fodder production to meet the rising demand. A significant challenge for many farmers in developing countries is the seasonal availability of forages, which is expected to become even more critical due to projected climate and land use changes. Climate change is anticipated to have a negative impact on livestock food and feed supply chains, particularly in vulnerable regions like East Africa, where there are already limitations in socioeconomic and institutional capacities (Godde et al., 2021). As a result of this pressure, a shift toward more intensive livestock production with reduced grazing and higher requirements for fodder crops is likely (FAO, 2019). Additionally, areas where

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pastoralists supply a significant portion of livestock products often experience conflicts between livestock keepers and other stakeholders, especially related to contested land use, land ownership, access to water, and conflicts leading to changes in livestock production systems (Caravani, 2019). By carefully planning and producing fodder crops, they can serve as a vital supplement to grazing in supplying livestock feed, even outside of the growing season.

Here, we show the potentials for meeting future fodder demands in East Africa through grazing, conservation of pasture, and production of additional fodder crops while respecting environmental boundaries. We analyze the demand for livestock products and resulting fodder demands to meet the demand for products from cattle, sheep, and goats. The extended Lake Victoria Basin (eLVB) in East Africa is a representative example of areas facing increasing supply-side pressures from changing climate and land use while simultaneously having to meet substantially growing demand. Sustainable intensification of livestock production systems can help reduce the land footprint of increasing production of livestock products (Bosire et al., 2016) and has the potential to meet both food demand and environmental targets (McDermott et al., 2010). The cultivation of fodder crops is a particularly promising strategy for meeting nutritional requirements in the dry season when pasture availability is limited.

The methodological contribution of this analysis is the combination of potential feed from grazing and fodder production simulated using a customized variant of the Global Agro-Ecological Zones (GAEZ) model at high spatial resolution (Fischer, 2021) with demand projections using the Shared Socioeconomic Pathways (SSP) version 1 (Lutz and Butz, 2017; Riahi et al., 2017) toward the year 2050. Considering the seasonality of fodder and pasture biomass, this approach demonstrates how and where pasture and fodder crops can meet the growing demand for ruminant livestock feed within the constraints of conserving wetlands and key environmental areas. This paper thus extends limited data available on the quantity of pasture-derived grazing biomass separate for dry and wet seasons in East Africa, as well as potential seasonal gaps in biomass supply for raising ruminants. The seasonal availability of fodder crops has not been studied on a larger scale, and we contribute by the novel inclusion of various fodder crops, including dual-purpose sorghum. Additionally, we expand the scope of previous studies by calculating fodder balances at the level of administrative units in contrast to previous studies (Fetzel et al., 2017a; Piipponen et al., 2022) which calculated raster-level grazing intensities. This approach has the advantage of taking into account the trade of both fodder and livestock within a specific region. This especially pertains to pastoralists in the eLVB region, who frequently relocate their livestock to areas where forage is abundant.

We analyze the potential for growing additional fodder production in the eLVB to help maintain socially and environmentally sustainable grassland uses. Strong integration with local stakeholders, including policymakers, benefited the co-creation of transdisciplinary knowledge within the project, leading to this article. The international coordination of countries around Lake Victoria is indicative of an integrated strategy for transboundary ecosystems and agroecological zones to jointly plan supply and implement policies for meeting future demand. Agricultural production and trade planning can be helpful when implemented at the basin level because water resources are essential for livestock water needs and agricultural production systems.

2. Methods and data

The empirical part of this research consists of five steps. We discuss the methods and data used in these steps in this section and present the results in section 3. First, the feed demand to sustain current livestock units is determined according to gridded data on the current livestock in the eLVB (Section 2.1). Next, we use GAEZ to assess the potential forage available and accessible through grazing under current environmental and agronomic constraints (Section 2.2). Based on available modeling outcomes for the future demand for livestock products, we estimate related future feed demand and show how this compares to fodder available through grazing (Sections 2.4 and 2.3). Section 2.5 explains the methodology used to assess the region's production potential of fodder crops. A simplified schematic overview of the modeling framework employed in this study is provided in Figure A 1 in appendix.

2.1. Current demand for fodder

To prime the analysis of future fodder demand, we first assess how and where current livestock grazing systems are already exceeding grazing capacity. To do so, we compute fodder demand for current livestock units and relate it to the potential production of dry matter (DM) from pasture. This method differs slightly from the projection method for assessing fodder balances in 2050. The projection approach which constitutes the majority of this paper and is explained in section 2.2 onwards, uses projected livestock product demand to estimate fodder demand.

For estimating current fodder demand, we use the distribution of cattle, sheep, and goats from the Gridded Livestock of the World (GLW3) dataset (Gilbert et al., 2018a, 2018b, 2018c). These distributions are transformed into animal units (AU) using conversion factors of 0.5 AU per cow and 0.1 AU per goat or sheep. Feed demand per AU is calculated as 2% of a liveweight of 455 kg per AU per day. [1] We base the percentage used here on the lower bound cited in (Cottrill, 2012). The lower bound represents current livestock systems with partially limited productivity and feed intake. We compute demand at the grid-cell level and then aggregate to administrative units captured in the Food and Agriculture Organization's (FAO) Global Administrative Unit Layer (GAUL). While previous research showed that seasonal demand in pastoral systems could be lower due to lower digestibility in the dry season (Assouma et al., 2018), here we use the generalized demands since we are interested in the demand necessary to fulfill the needs of a system that mitigates these seasonal effects.

[1] Many methods for calculating livestock or animal units are available. An overview of the animal unit and other methodologies is for example available in (Benoit and Veysset, 2021). The daily intake is also described by the authors.

The scale of the administrative unit chosen to analyze current and future feed balances two goals of modeling livestock systems. On the one hand, systems can be subject to trade across wider spatial entities than a region. Here, aggregated analysis at the national or sub-national level examining trade potentials is well suited. On the other hand, systems can be restricted by physically moving livestock, especially those in intensive systems, and by highly local grazing intensities. Gridded analysis at a fine spatial resolution is most applicable for these cases. Since the analysis we present here combines the two approaches, we choose the administrative unit as an intermediate level of detail, balancing the advantages of both approaches.

2.2. Potential fodder supply from grass and forages

The potential supply of livestock fodder is calculated using GAEZ potential production. Variations in land quality combined with agronomic management determine the production potential of various fodder crops. The GAEZv4[2] methodology (Fischer, 2021) assesses the agronomically possible upper limit to produce grasses and fodder crops under given agro-climatic, soil and terrain conditions for specific levels of agricultural inputs and management conditions. GAEZ uses spatially explicit land use, soil quality, and climate data to calculate suitability classes and potential and actual yields for a wide array of crops. We applied the GAEZ methodology to the eLVB at a finer spatial resolution and with parameters adapted to additional fodder crops compared to its global version.

Grid-cell level biomass supply from grass and fodder is aggregated to administrative units and tabulated by land use class, environmental protection status, and land quality. We assume livestock grazing and forage production from current (year 2016) land use classes 'shrubland' and 'grassland or regularly flooded herbaceous vegetation'. Further, we exclude all protected areas (IUCN and non-IUCN) reported by the World Database on Protected Areas (WDPA) 2017, key biodiversity areas, and permanent and seasonal wetlands as recorded by the Center for International Forestry Research (CIFOR). Because yields differ depending on biophysical and climatic conditions, GAEZ reports area extents and production potential by suitability classes. To safeguard very marginal (less than 20% of regionally maximum achievable biomass yields) shrub- and grassland, we only consider livestock feed from very suitable (VS, 80–100% of maximum production), suitable (S, 60–80%), moderately suitable (MS, 40–60%) and marginally suitable (mS, 20–40%) areas. Henceforth, we will call these areas' unprotected pastures', assuming that roaming livestock may use them for feed. The extent to which animals can obtain calories from grazing is regionally different and depends, for example, on the height and the mix of plants growing in a grazing area. For the net available fodder considered in the analysis, we assume a pasture utilization rate of 66.7 %, hence excluding one-third of the potential yields calculated by GAEZ. Such consideration of potential fodder available from grazing is an advancement over most previously used net primary production data, which can lead to overestimation of production potentials (Fetzel et al., 2017b). Next to feed from grazing, we include additional fodder crops in the second step in the analysis. In this step, if fodder crop production is also analyzed on grass- and shrub-land, the pasture production is discounted by the share of land used for producing the fodder crop.

We complement the analysis of pasture DM production by analyzing temporal pasture variability. We do so using time series for the potential production of pasture S_{pst} in each year between 1961 and 2010. Since we are only interested in the effects of changing climate on pasture production potential, the only varying inputs to the GAEZ model are climate data. At the same time, we hold land use and other input data, such as productivity constant. To compare across years, we compute yearly deviations from mean production potential in an area as a share of the mean over the whole time period.

2.3. Projected demand

The total demand for livestock fodder in 2050 is derived from the projected demand for livestock products. Livestock product demand projections for ruminant meat and dairy products are obtained from the IMPACT model (Komarek et al., 2021) to determine livestock numbers and associated feed requirements. We utilize demand and population projection scenarios to account for uncertainty in future socio-economic development. In the results section, we focus on the "middle of the road" Shared Socio-Economic Pathway (SSP 2) but also discuss human population projections in line with other SSPs and the resulting demands (Table 1). We use the IMPACT model's reference scenario for income elasticities but discuss how results depend on this assumption below. National-level demand data are downscaled to a 1 × 1 km grid according to gridded human population data consistent with the SSPs (Jones and O'Neill, 2016). Livestock product demand for each product x in grid cell i at time t in country j is given by L_{xit}. It is calculated as the total population of the grid cell p_{itj} divided by the total population of the country P_{tj} times total projected demand for product x in the country L_{xtj}.

$$L_{xit} = \frac{p_{itj}}{P_{tj}} L_{xtj} \tag{1}$$

This procedure applies to multiple livestock products and all available scenarios.

We introduce three simple efficiency gain scenarios to account for changes in production systems and general efficiency improvements. The scenarios are built on stakeholder-informed specific studies for Uganda (FAO, 2019). Scenario development is

[2] The Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) have cooperated over several decades to develop and implement the Agro-Ecological Zones (AEZ) modelling framework and databases. GAEZ v4 is the most ambitious global assessment to date and a Data Portal has been developed (see https://gaez.fao.org/) to make the database widely and easily accessible for users.

Table 1
Scenarios for livestock product demand projections and feed efficiency. Spatially explicit human population Shared Socioeconomic Pathways (SSP) scenarios are used to derive livestock product demand. Production systems and herd characteristics projections from FAO were used to derive feed efficiency gain scenarios. A detailed description of the process of deriving feed efficiency gain scenarios from all aspects of herd characteristics is provided in the supplementary information.

Scenario	Long name	Scenario description				
Socio-economic scenarios *applied to human population projections for livestock product demand*						
SSP 1	Sustainability	Low human population growth				
SSP 2	Middle of the road	Medium human population growth				
SSP 3	Regional rivalry	High human population growth				
Efficiency gain scenarios *applied to feed demand*						
		Feed efficiency (θ)	*Production system shares in 2050 in %*		*Herd characteristics examples (agro-) pastoral/(semi-) intensified systems*	
		Gains in %	*(agro-) pastoral*	*(semi-) intensive*	*off-take (%)*	*Slaughter age (years)*
BAU	Business as usual	no gains	90% (49% + 41%)	10% (2% + 8%)	12.5/16.7	8/6
PAS	Majorly remaining (agro-) pastoral	20%	60% (25% + 35%)	40% (15% + 25%)	14.3/22.2	7/4.5
INT	Substantially (semi-) intensified	45%	45% (20% + 25%)	55% (25% + 30%)	14.3/25.0	7/4

outlined in detail in the Supplementary Material. First, we use a business-as-usual (BAU) scenario with feed demand according to the earlier suggested conversion ratios (Alexander et al., 2016). We then scale these to a scenario where farmers continue to produce livestock in mostly (agro-)pastoral systems (PAS) but with a gradual efficiency increase to 20% in 2050. For example, by 2050, we assume a reduced DM demand of 20 kg DM per kg of beef. In a third scenario, we analyze demands under a 45% efficiency increase caused by a shift to primarily sedentary semi-intensive or intensive production systems (INT).

Total DM feed demand in each region, which can be supplied by either pasture or fodder crops, is obtained by multiplying the quantities of livestock product demand L_{xit} with feed conversion ratios γ and feed efficiency scaling factor θ. Summarizing over all livestock product types x gives us the total feed quantities required to meet the demand for feed to produce livestock products in region i. θ is equal to 1 in the BAU scenario, equal to $1 - 0.2 = 0.8$ in the PAS scenario and equal to $1 - 0.45 = 0.55$ in the INT scenario with the highest efficiency increases. For the calculation of DM feed demand (1000 t), we use feed conversion ratios γ_x for each livestock product type x which we obtain from Alexander et al. (2016); i.e., 25 kg of DM per kg of beef, 700 g of DM per kg of whole milk, used as a proxy for dairy products, and 15 kg of DM per kg of goat or sheep meat. In the feed demand specification, we keep requirements for livestock constant within the year. Constant feeding is chosen to ensure that the feed availability throughout the year is suitable for mitigating constraints imposed by seasonality as set out in the objectives of this study.

$$D_{it} = \sum_{x} \gamma_x {}^* \theta^* L_{xit} \tag{2}$$

Efficiency gains in the PAS and INT scenarios are driven by a gradual shift from pastoral and agro-pastoral production systems in BAU to semi-intensive and intensive production, as well as changes in herd structure (Table 1). When comparing the INT demand scenario to feed availability, we do not include pasture available for grazing as feed consumable by animals as in the first two scenarios. However, conserved pasture DM is available for animals to consume up to a maximum of 50% of total demand in the INT efficiency scenario in both the growing and the dry seasons. While these feed efficiency gain scenarios are discussed below to address inherent changes in livestock systems, we separately analyze how external socio-economic changes impact demand through SSP scenario analysis.

2.4. *Projected future seasonal demand for fodder crops*

We derive fodder crop demand by analyzing the seasonal gap between pasture supply and fodder demand to meet projected livestock product demand. Although integration of additional tropical forages and optimization of feed composition can reduce fodder crop demand (Baltenweck et al., 2020; Paul et al., 2020c) and increasing the productivity of livestock production systems is likely (Bosire et al., 2022), here we first evaluate the maximum need without assuming any productivity gains. We are also introducing scenarios for improving efficiency in livestock feed, which are outlined below. In case of additional productivity gains, more pastures may be used for environmental protection. We specifically evaluate the potential production of fodder crops on shrub and grasslands in low input regimes as defined in the GAEZ methodology. This ensures that intensification is environmentally sustainable by limiting fertilizer and pesticide use and is aligned with current smallholder practices.

To account for seasonally adjusted demand for fodder crops beyond grazing, we compute the length of the wet season under local climatic conditions using GAEZ estimated crop calendars. We thus obtain the length of the wet (growing) season in days for each crop in each grid cell. Dry season fodder crop demand is calculated as demand during the dry period days minus the surplus (if any) production of unprotected pasture that was not needed for grazing in the wet season, e.g., conserved as hay.

In the wet/growing season, demand for additional fodder crops is determined by the gap between demand for fodder dry matter (DM) and supply of DM by pasture if this gap exists and zero if otherwise. This approach is derived from the analysis of current use and pressures on grasslands for grazing, for which we present results in section 3. The current patterns combined with literature on future projections show that a) currently extensive grazing-based production systems are by far the prevailing systems in the region, b) livelihoods and culture based on grazing are unlikely to disappear in the future entirely, and importantly, c) the exclusion of unproductive land for pasture production we use in determining its DM production potentials will ensure that in the theoretical model setup, first less capital-intensive grazing will be used before fodder crops. In addition, in the results section, we separately display the production potentials of all fodder crops without imposing this sequential use assumption.

The total demand for fodder crops in each region is the sum of demand in the dry season and demand in the wet season:

$$D_{fc} = max\left[(365 - t_{pst})^* \frac{D}{365} - \alpha\left(S_{pst} - \frac{t_{pst}D}{365}\right), 0\right] + max\left[t_{pst}{}^*\frac{D}{365} - S_{pst}, 0\right] \tag{3}$$

where we use D as shorthand for total fodder demand D_{it} from equation (2) and omit the *it* indices for better readability. The total fodder demand is $D = D_{fc} + D_{pst}$. This total demand is the sum of demand for fodder dry matter from fodder crops (*fc*) and pasture (*pst*), $\frac{D}{365}$ is the daily demand for fodder, t_{pst} is the length of the wet season for fodder in days, S_{pst} is the yearly production of DM by pasture, α is a discount factor of 0.8 for discounting DM available from fresh to conserved fodder. While ideally, discounting would be handled through modeling ruminant digestion explicitly, this goes beyond the scope of this study. Instead, we use an assumption of 0.8 for a discounting factor, which is in-between the lower end of around 2–3% losses in the nutritional value of alfalfa through processing and up to almost half for some types of sorghum (Heuzé et al., 2015a, 2015b). Thus, our assumption is a reasonable middle ground that also accounts for potential post-harvest losses during processing and storage.

For t_{pst} time series are available for the years 1981–2010. In the results presented here, the analysis of D_{fc} is implemented for the average length of the wet season over these years. For further sensitivity analysis, this could be changed to reflect different percentiles to determine the potential of fodder crops to mitigate the low supply of fodder from forages in particularly dry years.

2.5. Supply of fodder crops and pasture balance

We compute the future potential supply of fodder crops other than pasture using GAEZ potential production but using different areas than for pasture in section 2.2. Economically suitable areas for fodder crop production at the farm level are determined using only prime land qualities, i.e., very suitable and suitable extents. Additional fodder crops include Alfalfa, Brachiaria grass, and Napier grass from unprotected pastures, as well as dual-purpose sorghum cultivated on cropland. While the results are available in a gridded data set at a resolution of 30 arcseconds, we aggregate the main results of this study at the sub-region level for a better overview.

Land conservation is critical for the environmental sustainability of grazing and fodder crop production. We consider sustainability in two main dimensions. First, environmental sustainability is captured through land protection measures. Second, social sustainability is partly covered by selecting only grass- and shrublands for feed production so that conflicts between pastoralists and crop farmers are mitigated. By excluding protected areas and wetlands from land considered for fodder production, we show that grass- and shrublands are only sufficient for meeting local fodder demand when production is intensified. For ease of reading, we will refer to 'grass- and shrublands' as 'pastures', as the focus here is on grazing livestock.

Excluding areas of lower suitability ensures that crop production is economically feasible and environmentally sustainable. The exclusion of less suitable areas in fodder production negates the need to use substantially higher amounts of farm inputs, including fertilizer, on less suitable land to achieve similar or slightly lower yields than on more suitable land. Hence, this choice of land suitability limits costs, pollution, and other detrimental environmental effects.

Seasonal production potential from these unprotected suitable pastures is sequentially combined with demand projections. This novel approach evaluates the supply gap from grazing as a sole source of feed for ruminants feeds and relates it to the production and conservation potentials of fodder crops. In sequential order, first, we assess the most common system of grazing animals on natural pastures. Local stakeholders stressed the importance of the seasonal aspect of pasture productivity as a significant component of sustainable grassland management. Fodder during the dry season can be supplied as hay conserved and not needed during the wet season or from intentional fodder crop production, either using improved pastures or cropland. Although hay production is not common in East Africa today, it represents a transition to a second, more intensive livestock production system.

We analyze the current forage balance in each administrative unit to identify where grazing demand intensity is likely to be at its maximum and where additional fodder crops are most urgently needed. In the current situation, the region relies on pastoral and agro-pastoral systems prevailing, for example, in Uganda, with 90% of cattle held in these extensive systems (FAO, 2019). We align our future scenarios to the current situation and a likely shift toward more intensified production systems in the future. These will need less scarce grazing areas but are likely to increase the demand for fodder crops further, as discussed below. Previous modeling studies (Fetzel et al., 2017a) suggest that regions with either surpluses or deficits of forages and grasses from grasslands exist in our study area. Field research found that grazing demand intensities are significantly higher than those estimated in previous modeling studies (Irisarri et al., 2017). We seasonally adjust the resulting pasture production potential because non-seasonally adjusted production can not account for the losses in nutritional values from conservation (Onyango et al., 2019).

Third, well-managed improved pastures can boost pasture yields and improve soil health. We select promising crops well suited for the local context. In addition to the already cultivated Napier and Brachiaria grasses, we also assess alfalfa as a possible alternative. As a fourth option, we explore dual-purpose sorghum cultivated for food and animal feed on current cropland. Although yields are lower than their sustainable potential, which is common in many parts of sub-Saharan Africa, cropland accounts for more than one-third of the study area. We do not consider the use of cropland solely for animal feed, as this would compete directly with food-crop production, which could further reduce traditional pastoral grazing land (Nakalembe et al., 2017) and may not be economically viable at the farm level (Baltenweck et al., 2020).

3. Results

3.1. Land sustainability

In addition to restricting our analysis to pastures, we exclude all wetlands and pastures designated as protected areas or key biodiversity areas, totaling 76,310 km^2 in the eLVB (Fig. 2). From the remaining unprotected pastures (148,221 km^2), some 62,576 km^2 could be used directly by grazing animals to sustain current ruminant livestock herds (as reported in the Gridded Livestock of the World (GLW)(Gilbert et al., 2018a, 2018b, 2018c) during the growing season. Another 24,111 km^2 unprotected pastures provide biomass conservable as hay for feed during dry seasons. The remaining 61,534 km^2 of unprotected pastures have very marginal land quality (very marginally suitable or not suitable categories in GAEZ) or are not needed for current levels of livestock herds.

3.2. Current seasonal balance of forages from grass- and shrub-lands

We summarize the potential quantities of feed dry matter (DM) from pasture grasses and legumes from GAEZ modeling after excluding protected areas and wetlands. Since land use categories for conservation and wetlands are assumed constant over time, only the utilized pasture- and cropland vary between the analysis of the current state and projected potentials (Fig. 1).

The seasonally adjusted total amount of fodder DM supply is compared to the demand per region (Fig. 3). Our model simulations suggest that in most regions in Uganda, the seasonally adjusted forages are insufficient to meet current demand. The average surplus from an administrative region's supply from natural forages exceeding its demand corresponds to 22.25% of the region's forage production potential. However, more regions are experiencing a shortfall rather than a surplus (median at −22.26%), as indicated in yellow-red in Fig. 4. The most extreme differences between forage demand and supply occur in Western Kenya and Acholi, Uganda. While the Acholi region has a production potential almost five times its current demand, Western Kenya has a shortfall of −80.22%. The extreme case of Western Kenya, where the fodder supply or production potential is only 34,017 t to meet a demand of 1,933,891 t of DM, is an excellent example of possible interpretations of a significant feed deficit. The large gap between the supply and demand suggests that either a) additional fodder biomass is imported into the region to meet the demand for the high population of ruminant livestock, or less likely, b) the animals found here are already primarily fed by additional fodder crops, or c) the GLW methodology allocates too many livestock in this densely populated region.

Total fodder demand in the eLVB region is projected to rise significantly in the coming decades from a range of between 99,828,557 t (SSP1) and 101,282,581 (SSP3) in 2020 up to 177,393,156 t (SSP3) by 2050 when assuming current feed efficiency. These numbers could reduce by 20% when assuming our PAS scenario and 45% under the intensified (INT) livestock – not fodder crop – production

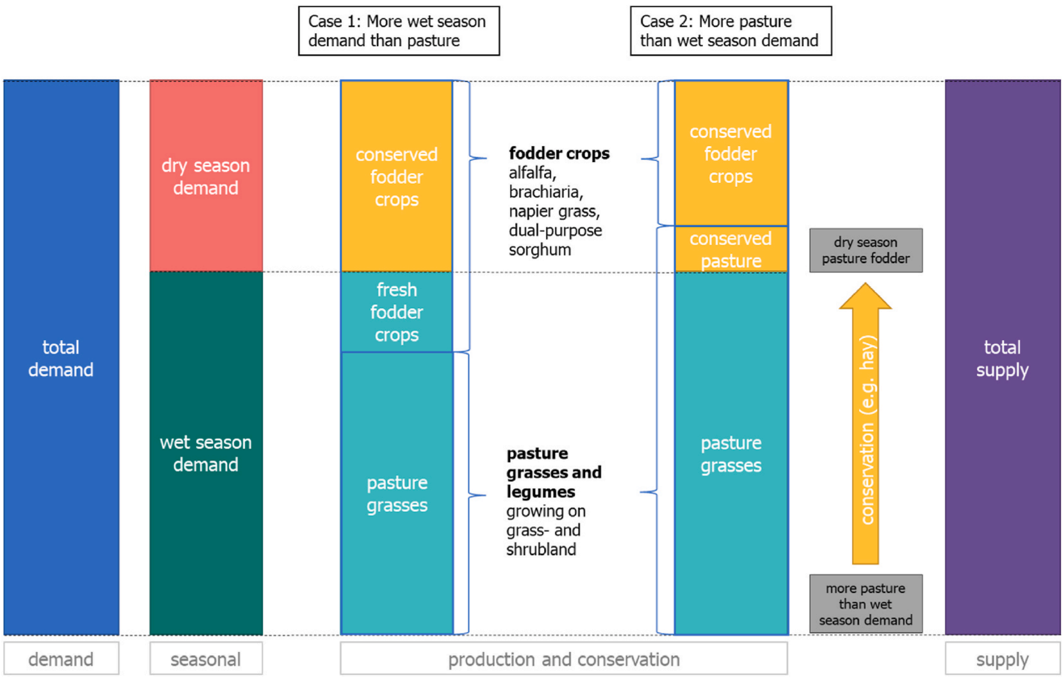

Fig. 1. Schematic representation of seasonality equilibrium analysis. Note that this sketch is only representative of a theoretical equilibrium situation where supply is equal to demand. In the empirical analysis, excess demand or supply can occur.

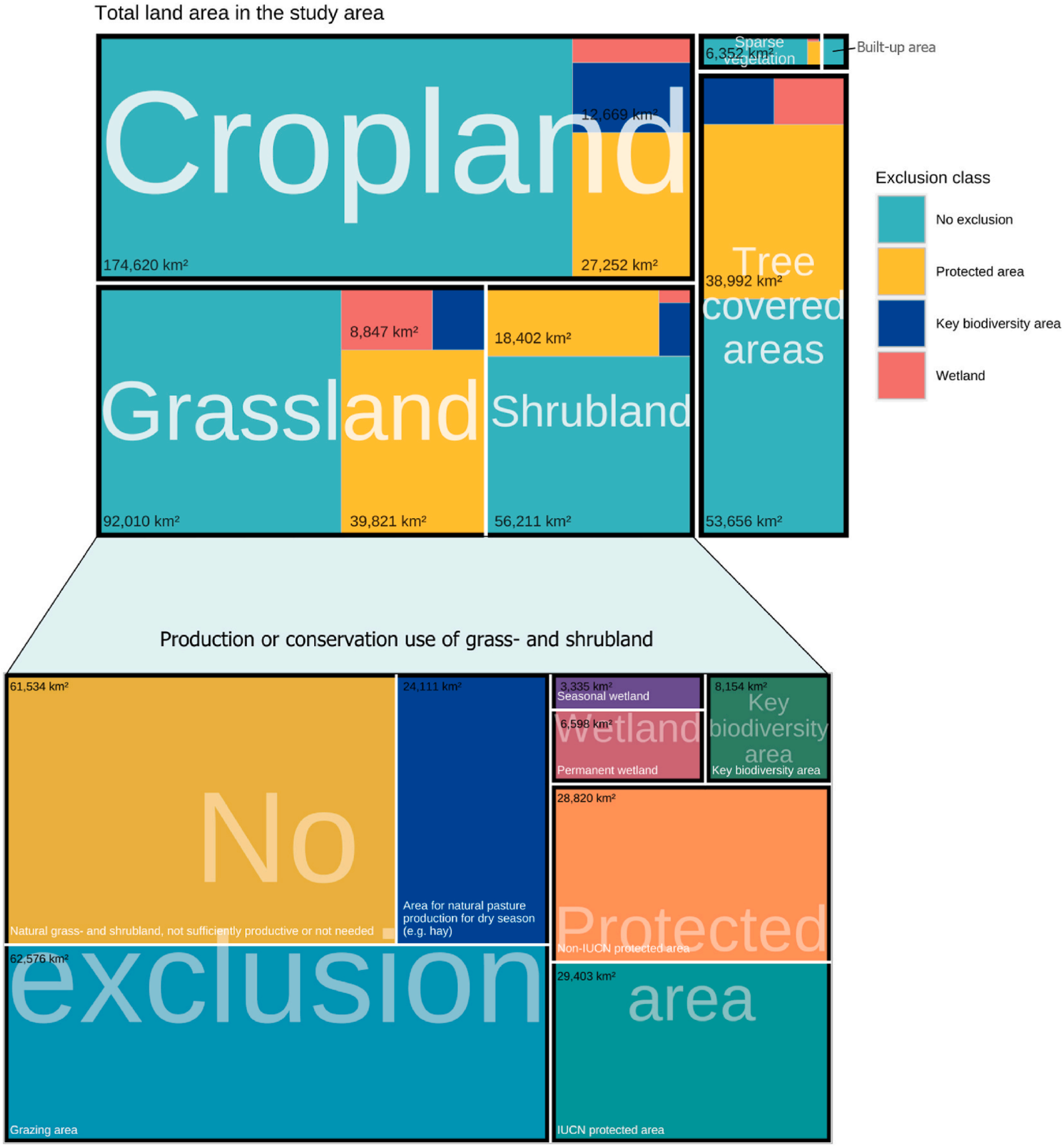

Fig. 2. Top: Disaggregation of total land area in the study area at baseline. Bottom: Disaggregation of current (2010) grass- and shrub-land in the study area into exclusion classes and use for livestock production. Note the land balance shown differs across the regions analyzed in this study.

scenario. The disaggregation of total demand shows increased pressure on grazing land and diminishing opportunities for dry season feeding with conserved DM from pasture. This leads to growing demand for fodder crops and possible negative environmental impact due to denudation. In the 'Middle of the Road' scenario (SSP2), the proportion of demand that dry matter available from livestock grazing pastures (turquoise in Fig. 4) can meet rises from 34% in 2020 to 54% in 2050. This increase is equivalent to more than doubling the net amounts of dry matter, given the substantial simultaneous increase in demand. Thus, by 2050, the demand for livestock feed during the growing season will be so high that any potential for preserving feed (hay) for the dry season will have disappeared. While in 2020, conserving pasture could cover 44% (SSP2) of total demand, the quantities will not be sufficient for future feed demand. As there are spatial variations, conserving pasture dry matter and other natural fodder may be possible in some selected regions where pasture productivity is exceptionally high. However, in large parts of the eLVB, fodder crops will arguably play an increasingly important role. Demand for fodder crops in the wet season will rise from 12% to 22% of total demand between 2020 and 2050 and 11%–27% in the dry season. The main driver is increasing overall demand, leading to demands above pasture production potential. In absolute terms, the aggregate total for the eLVB amounts to 21,853,270 t (SSP1) – 22,992,410 t (SSP3) in 2020 and is projected to quadruple to 82,790,942 t (SSP2) – 87,234,559 t (SSP3) by 2050. In the increased efficiency scenario with significant shares of agro-pastoral and pastoral production, a reduced overall feed demand leads to higher shares, which can be a supply of pasture DM. When efficiency in pastoral systems increases, we observe higher shares of total demand covered by pasture supply. While in the reference case under BAU, we find that all DM from pasture is consumed in the growing season, leaving no potential for conservation,

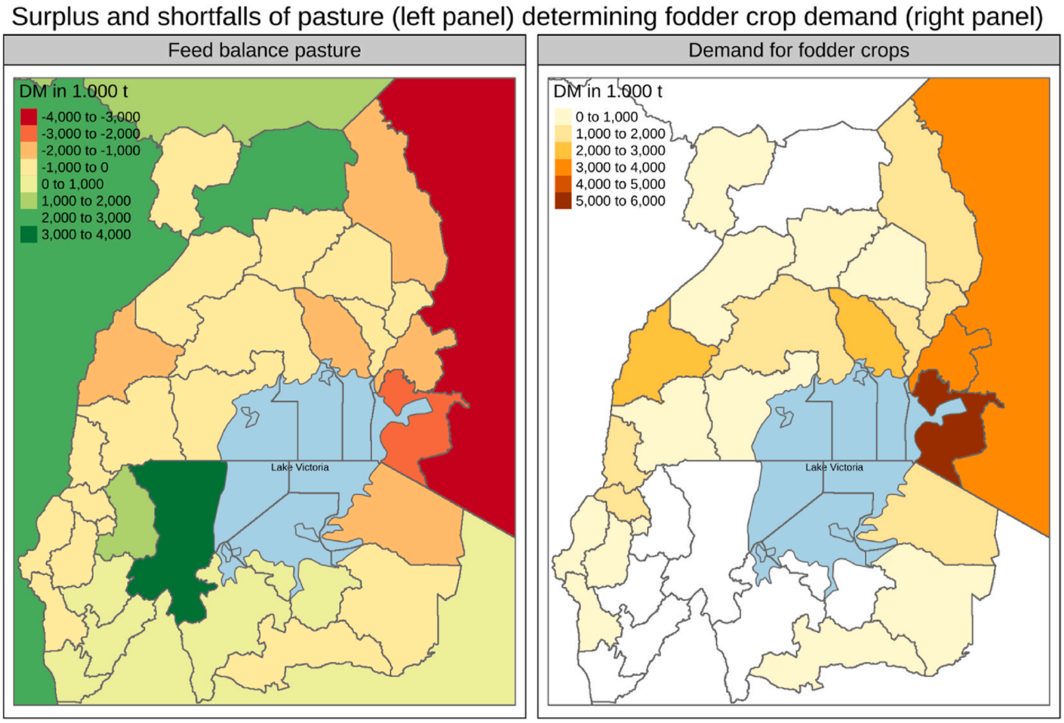

Fig. 3. Left panel: Feed balance is the surplus/shortfall of seasonally adjusted grazing area supplied by pasture forages and grass legumes minus demand by current animal units in the extended Lake Victoria Basin's administrative units. In the left panel green areas do not exhibit a gap in pasture supply to feed demand, while there is a gap between demand and supply covered by pasture in all areas with yellow, orange or red fill. Demand for fodder crops in the right panel is the excess demand in the BAU efficiency scenario after accounting for seasonally adjusted pasture supply. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

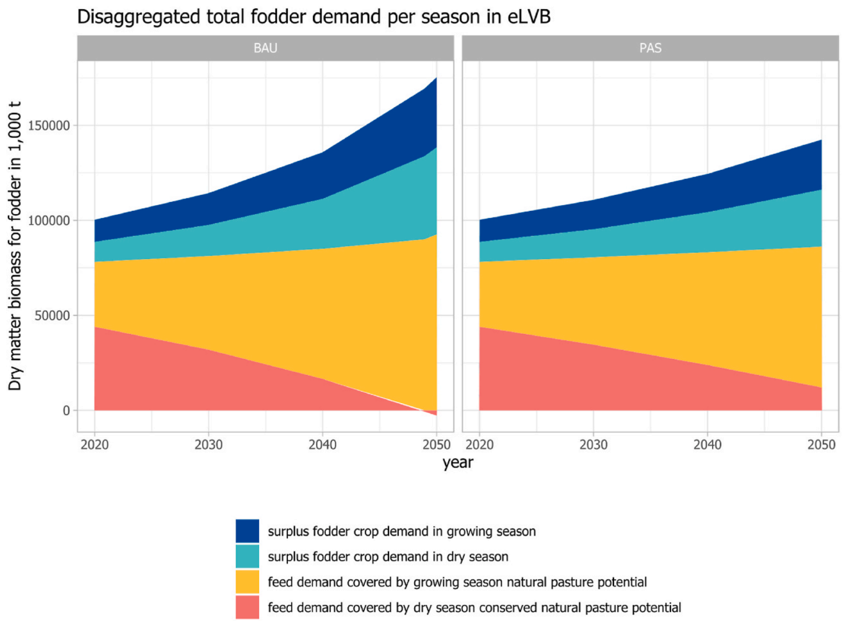

Fig. 4. Disaggregation of fodder requirements for meeting projected animal product demand in eLVB in middle-of-the-road scenario SSP2. Left panel shows the business-as-usual (BAU) feed efficiency scenario. Right panel shows an efficiency gain scenario of 20% reduction of feed requirments. resulting from increased agro-pastoral systems (PAS). Quantities are obtained by comparing wet/growing season net primary production of pasture derived from GAEZ to projected livestock fodder demand derived from IMPACT and population projections.

efficiency increases can mitigate this issue. A fraction of total pasture DM production can be conserved in the PAS scenario for the next dry season.

Climate variability increases the importance of conserving pasture grass. Variability in pasture production has increased over the past decades (Fig. 5, details in Appendix). The latest climate data for 2001–2020 suggest a trend towards slightly increasing production potentials. However, climate variability is likely to be even more pronounced in the future, thereby reducing the degree to which farmers can rely on fodder from grazing natural pastures only (Sloat et al., 2018).

3.3. Potential production of fodder crops

Supplementary fodder crops can fill the gap left by natural forage production and provide sufficient feed to meet the demand for animal-based foods. We estimate technical production potentials of different fodder crops complying with land and environment constraints (only unprotected pastures), food security (only dual-purpose sorghum, i.e., for food and feed), and farm economics (only use of prime land growing fodder crops). Pasture and dual-purpose sorghum production potentials far exceed the potential of Napier grass, Alfalfa, and Brachiaria (Table 2). The main reason is that we impose stricter land constraints for fodder crops, assuming only prime land for production, compared to livestock grazing on pasture. This strategy avoids food-feed competition, which can support the efficient allocation of resources to livestock or crops while limiting detrimental environmental and other undesired impacts (Röös et al., 2017; Schader et al., 2015). Although we show the technical potential of dual-purpose sorghum varieties on all cropland, economic production is only viable when farmers can access markets to sell sorghum grain to take full advantage of the dual-purpose property.

If farmers develop natural pastures by growing alfalfa, brachiaria, or Napier grass on the corresponding very suitable and suitable (VS + S) areas, the production potential from pastures alone is 15–24% lower compared to the maximum of 89 million tons. This preliminary analysis hints toward emphasizing the general benefits of fodder crops, especially their potential to limit seasonal constraints over their productivity. Local optimization of the mix of forage crops could lead to further increases in fodder production potentials. When choosing a single crop, alfalfa production reduces pasture production the most. Brachiaria and Napier grass production reduce pasture areas less and thus also reduce pasture DM production less.

3.4. The potential of fodder crops to meet future demand

The total demand for feed to produce the quantities of livestock products demanded by the increasing population in the area will more than double by 2050 under all SSPs considered (1, 2, and 3). The uncertainty of global demand depending on population figures from SSPs is low. Therefore, we focus on the representative "middle of the road" SSP 2 (analysis details in Appendix). However, the demand depends on future local economic, demographic, and governance developments. In the future, experts commonly assume a substantial shift from pastoral systems toward more intensive sedentary systems. Estimates informed by local stakeholders see a reduction of the share of pastoral systems in Uganda from 41% today to 16–35% in the future, depending on economic and governance scenarios (FAO, 2019). The shift will have a more significant impact in regions where pastoralism is the primary production system, compared to peri-urban and urban areas, where pastoralist production is less frequent. We analyze three demand scenarios dependent on efficiency linked to production system changes: the BAU, PAS, and INT scenarios described in section 2.3 (Table 1). The scenarios

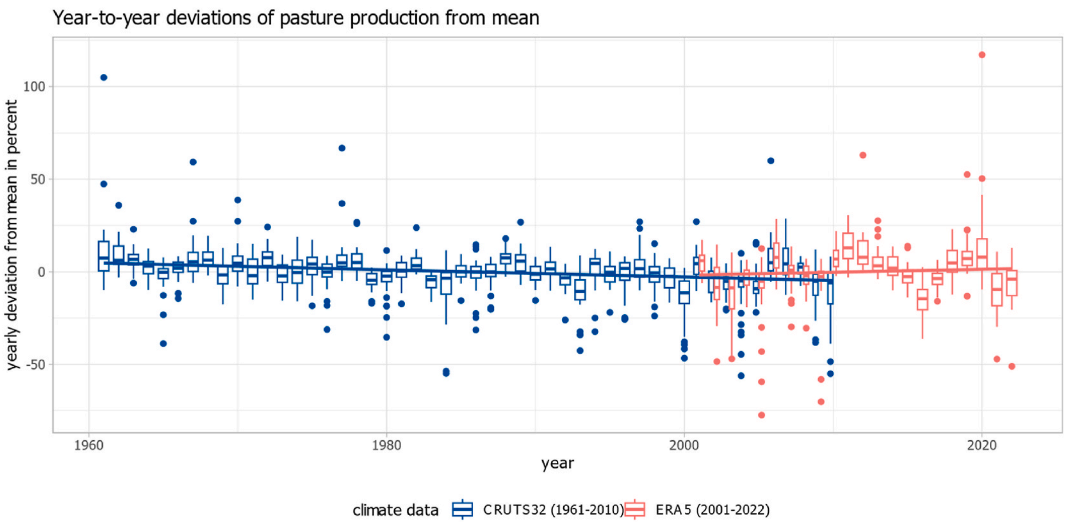

Fig. 5. Boxplot and linear trend (blue line) of deviations of pasture production per year from average (1961–2010) in percent for administrative units in eLVB. GAEZ was forced with observed historic climate data CRUTS32 and ERA5. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Rainfed low input production potentials of fodder crops and pasture in 1000 t DM in the shares of Uganda, Rwanda, Burundi, Kenya, and Tanzania rectangular study area. Sorghum potential is analyzed on current cropland as opposed to all other crops for which production is only summarized on non-protected current grass- and shrubland. Cultivation of fodder crops (dual-purpose sorghum, alfalfa, brachiaria, Napier grass) assumes farm economics by using only prime land (VS + S land quality, see Methods). For pasture, we assume free livestock roaming will also use less productive land (VS + S + MS + mS land quality). The last three rows display the production potential of pasture after accounting for land needed for the specified fodder crop.

Crop	*Grown on*	*Potential DM production in 1000 t*
dual-purpose sorghum	Current cropland	**134,657**
alfalfa	Current unprotected shrub- and grassland	**16,015**
brachiaria	Current unprotected shrub- and grassland	**11,945**
Napier grass	Current unprotected shrub- and grassland	**25,193**
Pasture	Current unprotected shrub- and grassland which is at least marginally suitable	**89,108**
Pasture	As pasture but excluding prime land (VS + S) for potential alfalfa production	**66,880**
Pasture	As pasture but excluding prime land for potential brachiaria production	**74,215**
Pasture	As pasture but excluding prime land for potential Napier grass production	**75,170**

include a pastoral scenario (BAU) where 90% of livestock production depend on extensive grazing of grassland savannah with little or no additional inputs and management; a medium scenario (PAS) in which 40% of livestock are kept under more efficient (semi-) intensive systems, and where crops are at least partially integrated with livestock; and an intensified scenario where 55% of livestock are kept under the most efficient and more sedentary intensively managed systems (INT). The scenarios assume that higher shares of intensive and semi-intensive systems result in the most efficient utilization of feed resources with a concomitant significant livestock

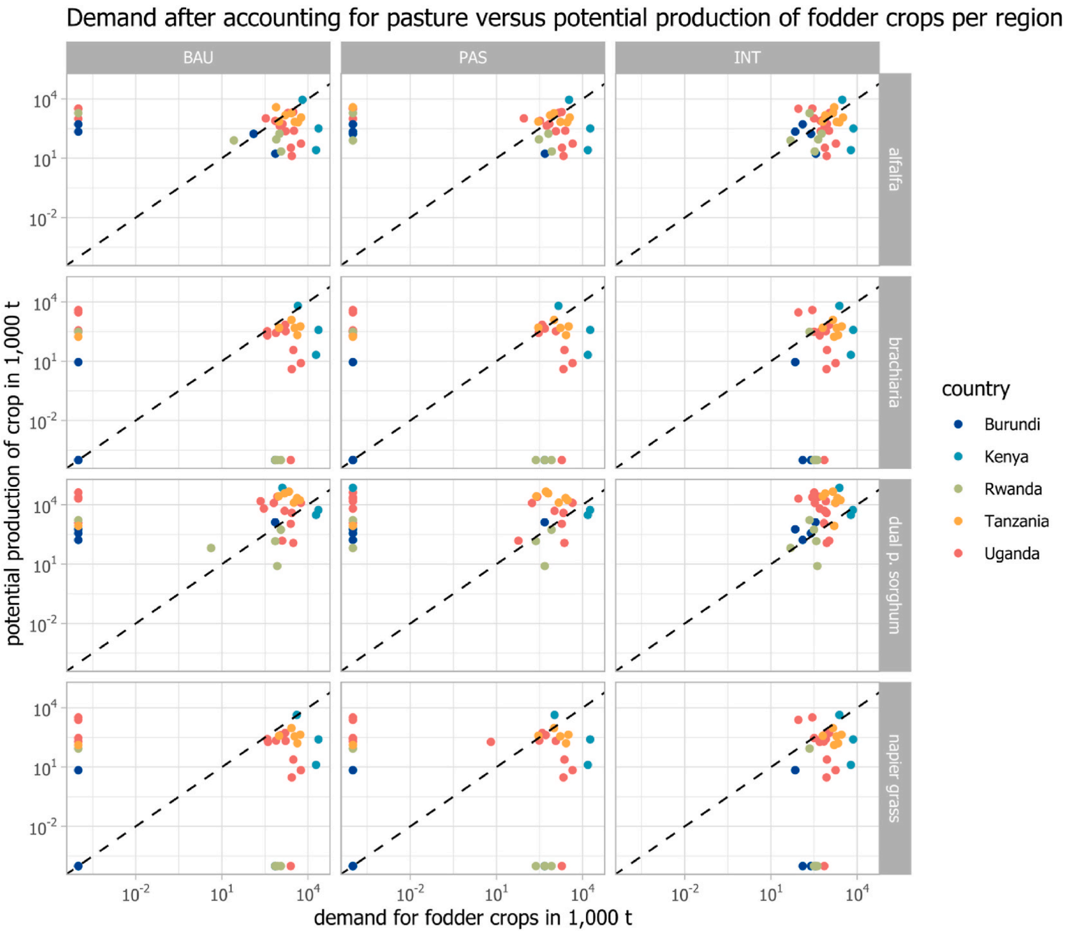

Fig. 6. Demand vs. supply of fodder crops in 2050 under three feed efficiency scenarios (BAU, PAS, INT) in administrative units of eLVB after accounting for demand met by pasture on land not allocated to selected fodder crops in the region. Points for administrative units above the 45°-line represent regions where potential production exceeds the demand in the region. In regions on the graph below the 45°- line, the additional fodder crop in each panel is insufficient to meet the additional demand. Note the logarithmic scales on both axes.

productivity increase.

As the demand for feed from all sources steadily increases, the potential of grasslands to supply DM quantities might not be sufficient if at least partly pastoralist production systems keep playing a role in the future. A comparison of potential production and fodder crop demand (BAU and PAS scenarios in Fig. 6) shows that several regions do not require additional fodder beyond grazing. These offer the most significant potential for growing fodder crops such as alfalfa, brachiaria, or Napier grass and expanding grazing livestock numbers. With time, the number of regions where sufficient quantities of fodder crops can be harvested increases. In addition to the optimal mix of fodder crops adapted to local conditions, the trade of either livestock products or fodder from regions with excess production potential can help reallocate surplus production to suitable areas (details of trade analysis in section 4.1). The reduced fodder requirements in the PAS scenario with a 20% efficiency gain in pastoralist and agro-pastoralist systems show that fewer regions will require additional fodder crops. However, the number of regions with deficient fodder DM supply will remain significant. Thus, even under improved production systems relying partly on pastoralist systems, they will need planning, production, and trade of fodder crops to mitigate seasonal grazing DM shortages.

The analysis presented in the INT scenario in Fig. 6 shows that shifting to majorly intensified livestock production systems with a maximum of 50% conserved pasture DM in a region's overall feed composition does not solve the issue of local fodder crop shortages entirely. While efficiency increases are assumed to lower the overall gap between DM supply and demand by 45%, fodder crop demand rises as the share supplied by pasture drops. Therefore, in this setting, the number of regions that do not provide sufficient quantities of fodder crop DM to meet local fodder crop demand remains substantial. Overall, the INT scenario balances suggest that the fodder crop demand after accounting for grazing will not be met in the intensified scenarios in many regions.

4. Discussion

We highlight that seasonality and increasing demand will likely increase pressure on pasture fodder availability in East Africa. Conservation of pasture forages, i.e., hay production, can only partially mitigate this challenge. Our estimates for the eLVB show that by 2050, if all ruminants are fed only by grazing, all biomass from available pastures will be needed in the wet season, leaving little to nothing for conservation in the dry season. The modeling results show that conserving fodder crops for livestock for the dry season can largely mitigate the increasingly important aspect of seasonality. Policies aiming to meet future demand for livestock products should be regionally integrated, carefully considering grazing potentials and planning fodder production accordingly. Well-managed livestock production systems, including improved pastures and some dual-purpose food-feed crops cultivated on cropland, can provide a sufficient local supply of fodder while respecting environmental boundaries, such as preserving protected areas, key biodiversity areas, and wetlands. The data thus support the hypothesis that sustainable intensification has a possible sparing effect on the most crucial land needed for conservation. The analysis we present here focuses on production potentials and simplifies future demand projections by using estimates from a global model. Incorporating local experts' knowledge will be necessary for detailed local planning projections.

An integrated farming approach considering the livelihoods of livestock and crop farmers, consumers, and the political economy is needed to develop fodder supplies further, mitigate seasonality effects exacerbated by climate change, and reduce negative environmental impacts such as pollution or soil erosion (Wynants et al., 2019). This includes sustainable intensification through improvements in livestock productivity, crop residue use, and feed composition (Paul et al., 2020a; Sandström et al., 2022), and addressing socioeconomic factors like gender disparities between female- and male-headed households (McKune et al., 2015). Efficiency gains through improved feeding and animal health are much needed and can substantially reduce feed DM requirements. However, analysis of our efficiency gain scenarios shows that a mix of pastoral and intensive livestock production is likely to leverage the advantages of both types of systems.

At the level of smallholder farmers, incentives may not always be aligned with societal needs. Growing fodder crops requires high upfront investments, often non-affordable for smallholder farmers. Budgetary constraints are among the main hindrances to the intensification of regional livestock systems (Mlote et al., 2013). Overcoming these trade-offs will be essential for implementing sustainable intensification of livestock fodder production (Paul et al., 2020b; Salmon et al., 2018). Integration of pastoralists into markets and guidance to prevent overgrazing are essential measures to improve the sustainability of food and feed systems and maintain a certain degree of culturally desired pastoralist lifestyles (Ayantunde et al., 2011), particularly in the drier parts of the eLVB.

Intensification of livestock production, as assumed in the INT scenario based on substantial economic development projections in eLVB, cannot provide sufficient fodder under all circumstances. The reduction of pasture fed to animals increases fodder crop demand in these cases beyond locally sustainable supply potentials. This constraint in supplying fodder crops under intensified conditions emphasizes the need to carefully consider locally adapted livestock supply options, such as pasture, locally produced fodder crops, and traded fodder crops and livestock products. We discuss trade explicitly in section 4.1.

The productivity of livestock systems could further increase, and subsequently, more animals can be kept per unit area when livestock health and mortality are better managed in the future. However, overuse of grasslands could be a consequence (Gutierrez et al., 2009). Regular monitoring of carrying capacities is a potential solution that can, at the same time, identify productivity increases and potential over-stocking. This will also help pastoralists identify sustainable livelihoods and reduce vulnerability (López-i-Gelats et al., 2016). In this study, we show that the eLVB region as a whole has the potential to supply sufficient fodder crops by sustainably intensifying existing pasture or cropland in the case of dual-purpose sorghum without over-utilizing these areas.

Finding crops best suited for local conditions is essential to optimize fodder DM yields and land use for the livestock product value chain. Locally adapted mixes reduce the land used for fodder crops compared with grazing-only (Thornton and Herrero, 2015) or growing a single crop. Suitable crops from this analysis can guide farmers and local governments. To achieve an optimal balance of productivity and ecological consequences such as emissions, biodiversity loss or pollution, and economic feasibility, decisions should be made at the farm and plot level depending on local conditions and needs (Bosire et al., 2019). Monitoring stocking rates and carrying capacities is recommendable to assess seasonal needs for fodder crops and maintain grazing at ecologically and economically sustainable levels.

Additional co-benefits and disadvantages of proposed fodder crops beyond their nutritional content for animals should be carefully considered. For instance, alfalfa can improve soil fertility in crop rotation as a leguminous crop because of its nitrogen fixation property. However, farmers in the region would need substantive investments to shift toward legumes (Snapp et al., 2019). Sorghum can contribute to food security because grains are edible for humans. Thus, food security can remain at similar levels when replacing other food crops with dual-purpose sorghum. In addition, grains are available even in drought years but at lower yields and fodder quality (Somegowda et al., 2021). As we showed above, fodder crops can help mitigate the increasing seasonal variability in DM availability from natural pastures. Still, if its cutting regime is well managed, it can also provide a permanent soil cover to maintain soil fertility and soil organic matter while eliminating risks of soil denudation and erosion.

Production of fodder crops is not widely adopted in East Africa currently. This is despite their often productivity-enhancing effects on agricultural production systems by filling seasonal gaps in feed supply. Beyond productivity, studies have shown that livestock can increase the incomes of smallholder households (Nilsson et al., 2019). A limiting factor for fodder production is the availability of extension and training services (Omollo et al., 2018). Locally adapted strategies for sustainable intensification are needed and will be most successful if integrated with well-suited political and development programs (Jayne et al., 2019). Ideally, the integration of fodder crops to mitigate seasonality will be bundled with other innovations in agri-food systems, as this is among the most promising ways of reaching broad adoption and triggering the transformation of agricultural production systems (Barrett et al., 2020). Potential components for such a bundle could be animal health services, extension services, or market development. It is essential to include formal and informal institutions, which are critical for delivering extension services for implementing the intensification of (fodder) crops in the region (Yami and van Asten, 2018).

Projected future climate change and increasing variability are likely to lead to low ruminant productivity due to variations in pasture DM production, high carbon footprint, and heat stress for livestock (Carvajal et al., 2021; Godde et al., 2020; Rahimi et al., 2021). Adaptation will thus be required (Thornton et al., 2022). Crops such as drought-tolerant dual-purpose sorghum grown for food and feed can be more adapted to climate change by complementing natural pastures during drought.

Beyond adaption to climate change, mitigation is also an essential factor in livestock systems responsible for substantial shares of greenhouse gas emissions. In addition, the sustainability of livestock production can only be ensured when respecting a multitude of essential sustainability criteria. Next to climate change adaptation and mitigation, sustainability concerns water consumption and water pollution during livestock rearing and fodder production, biodiversity impacts of land use change, and the consequences of fodder crop and ruminant livestock production on nitrogen cycling. Because of space limitations, we discuss how this study implicitly addresses several of these issues in more detail in the appendix.

4.1. Trade for meeting demands for livestock products or fodder

International trade of livestock products in the countries of the eLVB region is currently at deficient levels. The import of livestock products in the three categories built for this analysis, beef, dairy, and small ruminant products, recorded by FAOSTAT is below 1% of local demand in 2020 (FAO, 2022) except for goats and sheep in Kenya, where imports correspond to 1.76%. Export quantities are slightly more important. Exports account for less than 1% of local demand for most commodities in most countries. In four exceptional cases, the exports to demand ratio is higher, namely Kenyan (5.97%) and Tanzanian (1.43%) small ruminant product exports and Rwandan (1.27%) and Ugandan (2.97%) dairy product exports. Within-country trade from one region to another, for example, trade from rural to urban areas, is likely to be higher. A conducive environment for the trade of livestock products that provides infrastructure and reduces legal and other barriers can be an enabling factor for increasing the production of livestock products for export in areas with sufficient livestock feed without the necessity of trading fodder.

The trade of fodder crops included in this analysis is more complex to capture using official statistics. For Alfalfa meal and pellets, statistics are available (FAOSTAT), ranging from import quantities of 0 t in Uganda in 2020 to 49 t in Kenya, which is still a negligible fraction of demand. Trading fodder crops would require fewer adaptions of livelihoods and production systems in producing countries because animals could remain in currently overgrazed regions when enough fodder is imported to feed them. A trade-off, however, exists between this goal and minimizing emissions and costs of trade. When fodder is traded, the weight of traded products is a multiple of the weight of potentially traded livestock products, given feed conversion ratios significantly smaller than 1.0. Hence, if the main objective in optimizing fodder production is reducing costs and emissions from trade, producing animal products close to feed sources and trade of meat and dairy products is superior to the trade of fodder.

The foreseen economic development and population growth of urban areas on the sub-continent are projected to significantly increase meat demand and livestock density in and around cities (Latino et al., 2020). Enabling within-country and international trade of feed and livestock products can aid in efficiently allocating livestock and fodder production to the most suitable areas and reduce the need for land use change associated with production needed to meet urban demand. Hence, increased continental trade can help achieve food security at moderate environmental costs (Janssens et al., 2022). The need for international or intercontinental trade could be limited by increased productivity, allowing for higher local production. For example, external projections show that while net imports of livestock products can grow up to sixfold between 2010 and 2050, implementing several productivity-enhancing measures in the livestock sector could lead to 41.7% lower net imports compared to a reference scenario without these enhancements (Enahoro et al., 2019).

Two significant restrictions currently limit the trade of livestock products in the region. First, the trade of fresh animal products requires a cold chain. Hence, sufficiently processed food products can not be traded in cases where a continuous cooling chain cannot be guaranteed. The second limitation is the issue of common standards in the East African Community (EAC). This was emphasized by local stakeholders engaging in the project work underlying this research. If these issues around standards and tariffs prevail and individual assessments of business cases are positive, increasing and supporting the regional trade of livestock feed is advisable. Regional trade of livestock products would still ensure feed production in areas found to be most productive but somewhat less efficient given the higher weight of feed compared to the weight of livestock products it can support.

4.2. Limitations and future research

The potentials for fodder crops presented here are an essential subset of an integrated strategy for meeting future demand for livestock fodder. Many other components are needed in addition. We discuss here different strategies for assessing and managing livestock supply that go beyond the modeling in this article. These include monitoring and efficient use of grasslands, using crop residues, feeding goats browses that are not seasonally limited (Muwanika et al., 2019), and other feed sources. Integration of these fodder sources into a strategy for producing sufficient fodder is a vital addition to grazing and cultivation of fodder crops to meet the demand for livestock products.

While crop residues and other by-products have the potential to increase global food supply by up to 13% (Sandström et al., 2022) and lower land use for livestock in East Africa by up to 25% (Govoni et al., 2023), we do not include crop residues in this analysis. Doing so ensures that the related uncertainty on the share of by-products used in animal diets does not influence our estimates of fodder crop potentials. Similarly, the quantities consumed by browsing are not included here. Consequently, the results presented here are upper bounds for fodder crop demand. They suggest that while increasing productivity from using by-products and browsing is necessary, the region could even achieve a local fodder supply with zero utilization of crop residues and other alternatives.

This study focuses more on fodder production potentials than scenarios of future feed demand compositions. Future studies can improve our simplified estimation of future feed demand, which is based on an assumption of preferential use of pasture. Therefore, developing stakeholder-driven scenarios for future feed use across livestock production systems is an important avenue for future research to inform livestock fodder production planning.

5. Conclusion

Analysis of feed requirements and fodder crop potentials in East Africa shows that highly seasonal pasture supply is insufficient to meet projected future demands under several scenarios. We show that fodder crop production has substantial potential to mitigate the seasonality of fodder DM deficits. The analysis shows that the gap between fodder DM demand and supply can be closed by partly practicing sustainable intensification and sustainable pastoralism through growing alfalfa, brachiaria, or Napier grass and dual-purpose sweet sorghum in existing grazing and suitable pasture areas that respect environmental protection. The GAEZ model can help identify the most productive regions where this is possible.

Our results indicate that neither a business-as-usual approach with substantial shares of pastoralist and agro-pastoralist livestock production systems nor a complete shift to sedentary intensive systems is likely to be able to produce sufficient livestock products for future demand. In some regions, grazing remains the optimal choice, while others have significant potential for growing, feeding, and exporting livestock fodder crops such as alfalfa. When carefully selecting fodder crops to be produced at the farm level, additional co-benefits such as the grain for human consumption from dual-purpose sorghum can be leveraged best. An important avenue for future research remains to identify sets of optimal mixes of fodder crops and livestock production systems and analyze trade patterns at a regional level in East Africa and beyond. Combining crop production potentials and demand projections, as we have done in this article, can be a good starting point for this type of analysis.

CRediT authorship contribution statement

Julian Joseph: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Sylvia Tramberend:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Fred Kabi:** Writing – review & editing, Validation. **Günther Fischer:** Resources, Methodology, Formal analysis, Data curation. **Taher Kahil:** Writing – review & editing, Supervision, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2025.101158.

Appendix

7.1 Schematic overview of modeling framework

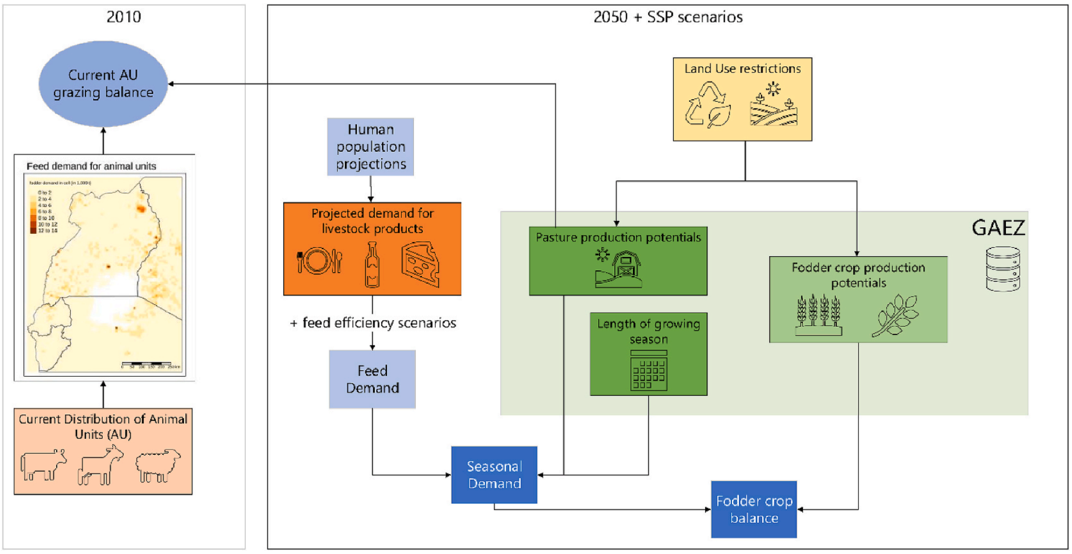

Fig. A 1. Simplified schematic overview of modeling framework

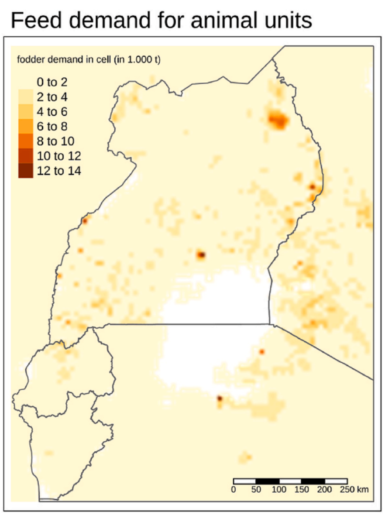

Fig. A 2. Fodder demand for current animal units in the extended Lake Victoria Basin

7.2 Demand under SSP and efficiency improvement scenarios

Fig. A 3. Feed demand projections under different SSP and feed efficiency improvement scenarios

7.3 Variability of forage availability

Running the AEZ model for 1981 to 2022 allows for identifying temporal trends of natural pasture production. We compare the average quantities of pasture and forage legumes potential production of dry matter over this time with yearly amounts. The deviation from the mean in percent in each year is displayed in Fig. 5 in the main text.

The percentage changes show a slight tendency for lower production and more frequent adverse shocks of up to half of the potential production of an area. The frequency of outliers with strong increases in production potential decreases after 1980. For example, in the more recent data, we see a period of four years of considerably below-average production from 2001 to 2004 with particularly pronounced outliers where several regions experienced reductions in the availability of more than 20% of dry matter. These decreases in availability could be at least partly mitigated by producing and storing fodder crops. The variability found in pasture production is primarily due to increases in climate and precipitation variability, which is likely to increase further in the future, thereby reducing fodder availability (Sloat et al., 2018).

7.4 Additional aspects influencing sustainability of fodder production

By far, the largest share of greenhouse gas (GHG) emissions emitted on the farm level in beef production systems arises from methane emissions from enteric fermentation (Poore and Nemecek, 2018). While optimizing feed for cattle in meat production systems is essential to limiting GHG emissions, we concentrate on the contributor causing the second largest share, land use change. This is especially relevant since methane emissions in the region could have been overestimated in the past (Ndung'U et al., 2019). Land use change is almost as relevant as livestock level emissions in dairy and small ruminant systems as in beef production. At least in parts of the study area, GHG emissions are higher in production systems relying on grazing only than in those implementing fodder crops or zero-grazing (Brandt et al., 2020; Wilkes et al., 2020). Productivity gains from integrating suitable high-productivity feed crops and concentrates can have a land-sparing effect, thereby significantly reducing emissions (Havlík et al., 2014). Alongside zero-grazing strategies or regulations promoting reduced grazing recently adopted in study countries, fodder crops can hence play a significant role in limiting the emissions from meat and dairy production (Kiggundu et al., 2019). A primary driver is the improved productivity of livestock. In Uganda, livestock was found to be more productive, requiring less DM when feedlots were introduced as opposed to pure grazing (Asizua et al., 2017). To maintain the ecologically favorable results of this type of livestock production, we analyzed only the production of fodder crops on current grass and shrubland. This explicitly excludes the conversion of other types of lands into cropland, which could lead to the release of GHG or other undesired environmental effects.

Water is an essential requirement for growing fodder crops and, to a far lesser extent, for drinking water for animals. Water requirements for growing crops are already implicitly included in the crop model. Because drinking water accumulates to such comparably small quantities, we neglect these amounts in this analysis. However, an area for future study is the limitations imposed on the usability of grassland for grazing by the availability of drinking water nearby. Currently, this issue in selected pastoralist areas could increase with climate change. Still, it can also be mitigated in the future by the construction of wells and a partial move away from pastoralism to more sedentary systems. Water pollution and other related environmental impacts of increased livestock production should be assessed in addition to limiting these adverse effects on ecosystems (Enahoro et al., 2023).

We do not include irrigation water in our analysis. If fodder crops were irrigated, the water footprint of the livestock production systems would increase. Excluding irrigated crops is a deliberate choice to leave this critical resource for the production of crops for human consumption in a region that, in some areas, is likely to see increases in water scarcity (Tramberend et al., 2021). Water requirements for growing fodder crops are often higher than for locally adapted natural forages (Heinke et al., 2020). Hence, growing fodder crops is only a viable alternative in areas where they are particularly productive. Finally, an important area for future research is how to allocate livestock production optimally to minimize water pollution.

Data availability

Data will be made available on request.

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