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Feed balances for ruminant livestock: gridded estimates for data–constrained regions

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ABSTRACT

Demand for animal–source foods and livestock feed are forecast to increase across sub-Saharan Africa. In this context, there is a need to estimate the availability of livestock feed to support decision–making at local, sub-national and national levels. In this study, we assess feed balances for ruminant livestock in Ethiopia and Burkina Faso. Feed availability was estimated using remotely sensed products and detailed feed composition data. Feed requirements were estimated for maintenance, growth, lactation, gestation and locomotion using a data–intensive model. Biomass available as animal feed was estimated to be 8.6 tonnes of DM per hectare in the Ethiopian highlands and midlands, 3.2 tonnes DM per hectare in the Ethiopian lowlands, 2.9 tonnes DM per hectare in Burkina Faso's Sudanian agro-ecological zone and 1.0 tonne DM per hectare in the Sahel. The energy requirements of lactating cows were estimated to be 62.1 Megajoules (**MJs**) per animal per day in the Ethiopian highlands and midlands, 62.7 MJ in the Ethiopian lowlands, 88.5 MJ in Burkina Faso's Sudanian agro-ecological zone and 53.1 MJ per animal per day in the Sahel. Feed scarcity hotspots are most prominently located in the Ethiopian highlands and the Sahelian agro-ecological zone of Burkina Faso. Demand–side policy and investment initiatives can address hotspots by influencing herd sizes, nutritional requirements and herd mobility. Supply–side policy and investment initiatives can secure existing feed resources, develop new sources of feed and incentivise trade in feed resources. Improving feed balances will be of value to decision–makers with the aims of optimising livestock productivity, minimising exposure to climatic shocks and minimising greenhouse gas emission intensity.

Implications

Demand for animal–source foods are forecast to increase across sub-Saharan Africa. Using an approach with global relevance, we assess the feed adequacy for ruminant livestock across two nations. Our results indicate that the Ethiopian highlands and the Sahelian zone of Burkina Faso are prominent deficit hotspots. Interventions can address hotspots by influencing herd sizes, requirements and mobility, and by securing feed resources, developing new sources of feed and incentivising feed trade. Improving feed balances will be of value to decision–makers with the aims of optimising livestock productivity, minimising exposure to climatic shocks and minimising greenhouse gas emission intensity.

Introduction

Ruminant livestock have a unique function in the bioeconomy, converting low-value biomass to high-quality outputs (Muscat et al., 2020). The availability of biomass for human activity is becoming increasingly constrained globally. Biomass constraints across sub-Saharan Africa (**SSA**) are being driven by a growing

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demand for staple crops, animal−source foods and bioenergy (Kalt et al., 2020). Constraints will be exacerbated as SSA populations continue to grow over the coming 40 years (Vollset et al., 2020; Enahoro et al., 2021). Global demand for food, feed and fuel is forecast to increase by 154% between 2015 and 2050 (von Jeetze et al., 2022). Similarly, demand for livestock feed has been forecast to increase substantially across SSA in order to meet the growing demand for animal−source foods (Enahoro et al., 2021). It is not clear how the current natural resource base will support these growing needs as urbanisation increases and the impacts of climate change intensify. These trends in biomass demand necessitate monitoring programs for forward planning of feed supply and feed demand – feed balances.

Livestock feed availability has been modelled in numerous ways. The most detailed analyses have been conducted at subnational scales, integrating ground measurements and satellite−derived biomass estimates (e.g. Meshesha et al., 2019 in Harshin, Ethiopia; and MAFR, 2020 in Burkina Faso). The most prominent models for policy development have incorporated estimates of biomass available for ruminant livestock consumption as well as estimates of livestock requirements (including Herrero et al., 2013; Fricko et al., 2017; Calvin et al., 2017; van Vuuren et al., 2017). These alternative approaches provide critical lessons for developing effective livestock feed balance estimates. The most salient of these lessons relate to the topics of land use classification, biomass estimation and ruminant livestock feed requirements – as summarised in the following paragraphs.

The area attributed to different land uses –such as cropland, grassland and shrubland– has a significant bearing on feed balance estimates. In approximating land use, there are trade-offs between quality, temporal resolution and scalability – where quality here is defined as a combination of spatial resolution and accuracy. High-quality products can be readily produced to accurately represent land use and phenology at sub-national level; however, scaling these products is expensive in terms of computation and validation (e.g. Meshesha et al., 2019 classify land uses and compare with a high concentration of "ground control points"). Similarly, existing high-quality gridded products are often limited by their spatial extent and temporal resolution (e.g. Rahimi et al., 2021). Coarser products at the global scale also suffer from limitations in temporal resolution and have been augmented using national and subnational statistics to temporally extrapolate and attribute land area to specific crops (e.g. GLC2000 1 000 m in Emmerling et al., 2016; and in ESA 300 m land cover maps in Goldewijk et al., 2017). These coarser inputs used in integrated assessment models are also limited in their ability to accurately represent sub-national conditions (Krisztin et al., 2015).

Biomass production can be approximated using a range of models, including: EPIC, Century, LandscapeDNDC, Copernicus DMP, LPJml and G-range (Williams, 1995; Parton et al., 1993; Haas et al., 2013; Copernicus, 2018; Rolinski et al., 2018; Sircely et al., 2019). These models incorporate inputs on soils, climate, land use, satellite−derived indices, fertiliser use and irrigation to estimate biomass production and biomass partitioning, which can be undermined by any one data input. Pasture−specific models also incorporate interactions between grazing and short- and long-term pasture productivity, which is desirable yet difficult to achieve when livestock movements are not known. Regional and global models have been developed for food insecurity early-warning, as well as for policy development purposes. Models developed for early warning systems quantify anomalies in biomass availability using satellite imagery and approximate the level of stress on agricultural systems using proxies for biomass demand (as summarised by Nakalembe et al., 2021). These early warning systems are valuable for raising the alarm in anomalous years, but do not lend themselves to forward planning.

Ruminant livestock feed requirements have been approximated using mechanistic models (e.g. Herrero et al., 2008), data−intensive models (e.g. Herrero et al., 2013; Rahimi et al., 2021) and liveweight-based proxies (e.g. Meshesha et al., 2019; Piipponen et al., 2022). These methods all require information on livestock population by species, herd composition, liveweights and an indication of the type of livestock system. More detailed models include information on feed nutritional profile as well as weight gain, milk yield, locomotion and draught power. The suitability of these methods depends on the quality of data available and the level of uncertainty tolerated by decision−makers.

Reliable feed balances have been lacking for SSA nations. Previously developed feed balance estimates at national scale have had limitations in estimating both supply and demand of feed (Assouma and Mottet, 2020). In this study, our objectives have been to assess the energy balance of ruminant livestock feed at national scale while still being relevant sub-nationally and over time. From this overarching objective, two sub-objectives have been to i) estimate feed availability using existing high-quality gridded estimates that are available globally and over time, and ii) estimate ruminant livestock feed requirements using a data−intensive model that is scalable across SSA and other data-constrained regions globally.

Material and methods

Study area

Our study area spans the extent of Ethiopia's 1.10 million km^2 landmass in East Africa and Burkina Faso's 0.27 million km^2 landmass in West Africa (presented in Supplementary Fig. S1). Ethiopia has the largest livestock population in Africa, with over 70 million head of cattle, 40 million sheep and 50 million goats in 2019 (CSA, 2021). Approximately 74% of the cattle population are reared in highland mixed crop-livestock systems and 25% of cattle are reared in pastoral or agro-pastoral systems (FAO, 2018a). There are three seasons in the north of Ethiopia (> 6°N), including Bega dry season (October to January), Belg short rains (February to May) and Kiremt long rains (June to September). In the south of Ethiopia, there is a bimodal rainfall pattern with the long rains spanning March to May and short rains spanning October to November (Alhamshry et al., 2020). Burkina Faso had approximately 10 million head of cattle, 11 million sheep and 17 million goats in 2019 (FAO, 2022). Approximately 87% of the cattle population are reared in pastoral or agro-pastoral systems, 11% are reared in semi-intensive systems and approximately 2% are reared in intensive systems (FAO, 2018b). There are two dominant seasons in Burkina Faso (Zampaligré et al., 2022), namely the dry season (October to June for the Sahelian zone, November to May for the northern and southern Sudanian zones) and wet season (July to September for the Sahelian zone; May/June to October/November for the northern and southern Sudanian zones).

Potential DM production for ruminant consumption

Biomass availability for ruminant livestock consumption was estimated using gridded products on land use, above-ground dry matter productivity (**DMP**), crop type, phenology, biomass burning and protected area demarcations.

We used existing estimates for net DM productivity (Copernicus, 2018). Summarising the Copernicus (2018) technical documentation: gross above-ground dry matter production (GDMP) in kilograms per hectare (kg/ha) was approximated using Eq. (1). Absorbed photosynthetically active radiation was calculated as the product of incident solar radiation (R), the fraction of radiation available for photosynthesis (εC) and the fraction of radiation that is observed to be absorbed (fAPAR). GDMP is then the product of APAR, maximum light use efficiency (εLUE), temperature stress limitation (εT), and the CO_2 fertilisation effect (εCO_2). DM production was then calculated as the product of GDMP and the autotrophic respiratory fraction (εAR) – the fraction of carbon lost through respiration. The autotrophic respiratory fraction is assumed to be 0.5 (Eq. (2)). The resulting product is an estimate of total DM production per hectare every 10 days. Drought stress, nutrient deficiencies, and pests and plant diseases are omitted from the DMP product. As a consequence, the product might better be called "potential DMP".

$$GDMP = R \times \epsilon C \times fAPAR \times \varepsilon LUE \times \varepsilon T \times \varepsilon CO_2 \quad (1)$$

$$DMP = GDMP \times \varepsilon AR \quad (2)$$

To estimate the total DM availability for ruminant consumption, we first attributed total DMP to land use categories based on proportional coverage. The proportion of each land use category per grid cell was taken from Buchhorn et al. (2020), including cropland, grassland, shrub land and forest (see Supplementary Box S1 for methodology and Copernicus, 2019 for quality assessment). The proportion of cropland in this product was found to under represent arable land, so we used the region-specific cropland product from Digital Earth Africa (DEA, 2022; See Supplementary Fig. S2). Ruminant feedable crop DM was calculated using the spatial production allocation model estimates of the 2017 cropping seasons (IFPRI, 2020). Only feedable crops were incorporated in the calculation, removing the following: coffee, coco, tea, tobacco, oil palm, coconut, other oil, cotton, rice, potato, tropical fruit and temperate fruit. Crop residues were calculated as the reciprocal of the harvest index – defined as the proportion of grain from above-ground biomass at harvest. Harvest index estimates were tabulated for 31 crops using references from the Feed Assessment Tool database and published literature (Duncan et al., 2023). We assumed that crop residues were not available for feeding in locations with burn scars visible in satellite imagery in the postharvest period. Biomass estimates for crop by-products in Ethiopia were estimated based on Central Statistical Agency (CSA, Ethiopia) reports and conversion factors from the literature, representative of 2018–19 – compiled as an extension to the work by Feyisa et al. (2022). There was not sufficient data on crop by-products in Burkina Faso to allow for its inclusion in our model. The availability of crop by-products in Burkina Faso are considered marginal and inconsequential for feed balance estimates (FAO, 2014).

Availability of grass and browse were estimated based on DM production by season, tree density and use restrictions. The proportion of grassland and shrub land covered by trees was based on estimates of tree cover at 30 m resolution from Reiner et al. (2023). The proportion of grass that could be utilised was restricted to 55% in the wet season(s) and 33% in the dry season(s) (due to insect herbivory, trampling and rejected patches in all seasons and the impact of grazing on regrowth in the wet season (Krause, 1977; Hiernaux et al., 2012). Biomass grown on cropland outside of the cropping season was assumed to be utilised to a maximum of 33% (same as grass in the dry period). The proportion of browse that could be utilised was restricted to range between 5 and 38% of total DM production, with a median of 16% (median from Sanon et al., 2007; upper limit from Rahimi et al., 2021). Grazing–prohibited forests were excluded from feedable DMP estimates.

Biomass estimates of cultivated fodder production in Ethiopia were estimated by multiplying the area of each improved forage species with dry-matter yield estimates. Areas cultivated were estimated from the 5–year mean (in Tigray from 2014/15 to 2018/19 and elsewhere 2016/17 to 2020/21). Dry-matter yield estimates were derived from mean values from published literature (obtained from Google Scholar search spanning 1980–2022). These data were only available at the second administrative level for Ethiopia (Feyisa et al., 2022). There was not sufficient data on cultivated fodder production in Burkina Faso to allow for its inclusion in our model. Data inputs used to estimate feedable biomass were resampled to 300 m and averaged by season as defined by the MODIS land cover dynamics product (Gray et al., 2019). For croplands, the growing period derived from the MODIS product was constrained to be between 90 and 220 days, allowing a continuous bimodal distribution across two cropping seasons – while removing outliers of up to 365 days.

Feed metabolisable energy concentration

The metabolisable energy (**ME**) concentration of feeds was approximated using regionalised and species-specific estimates from literature reviews and databases (Feyisa et al., 2022; Rahimi et al., 2021; Duncan et al., 2010). These approximations assumed a linear relationship between digestible energy (**DE**) and ME (Megajoules (**MJ**)/kg DM), predicted by NDF and CP (Seo et al., 2021). *In vitro* dry matter digestibility (**IVDMD**) as a percent of total DM is estimated using laboratory methods (e.g. Tilley and Terry, 1963). Digestible energy is calculated based on an equation by NRC (2001), establishing a relationship between organic matter (**OM**), *in vitro* organic matter digestibility (**IVOMD**) and DE. In the case of the SSA feed database, IVDMD was assumed to be a close proxy to IVOMD and in the absence of OM estimates, it was assumed to be 90% of DM. We preferentially used location-specific estimates and in the few cases where this was not possible, we approximated ME with estimates from other regions. A full summary of ME values and data sources is available in Supplementary Table S1 and Supplementary Table S2, and a summary has been made available in Table 1.

Livestock metabolisable energy requirement

Ruminant livestock metabolisable energy requirements were estimated using standard equations set out by CSIRO (2008). Requirements were estimated for maintenance, growth, locomotion, gestation and lactation for both dry and wet seasons (Eqs. (3) and (4)). Input data included population estimates, herd structure, starting liveweight, growth rates, pregnancy rates, milk yield, locomotion and proportion used for draught power work by species and animal class (Robinson et al., 2022; Rahimi et al., 2021; FAO, 2018a; FAO, 2018b; Wilkes et al., 2020). Data on draught power was only available for Ethiopia.

Herds and flocks were disaggregated into adult and young for sheep and goats, and into bulls, steers, cows, heifers and calves for cattle (Rahimi et al., 2021; Yetera et al., 2018). All parameters for cattle, sheep, goats, horses, donkeys and camels are tabulated in Supplementary Information (Supplementary Table S3 and Supplementary Table S4). Requirements for horses were estimated based on gridded population statistics and DM intake as a proportion of liveweight set out by Geor et al. (2013, p. 66). Requirements for donkeys and camels in Ethiopia were estimated based on sub-national population estimates (CSA, 2022) as well as liveweights and equations set out in FAO (2018d). There were no gridded or sub-national statistics on the donkey population for Burkina Faso so it was coarsely assumed that the ratio of donkeys to horses at national level was maintained sub-nationally (3:1). Donkey liveweights for Bukina Faso were taken from West Africaspecific estimates (Nininahazwe et al., 2017). Camels were excluded from requirement estimates of Burkina Faso as they were less than 1% of population head counts. Mules were excluded from the require-

Table 1
Ruminant feed utilisation, metabolisable energy (ME, MJ/kg DM), CP (%) and NDF (%) by country, region, type and season.

Country	Region	Feed type	Season	Utilisation (%) [†]	ME (SD)	CP	NDF
Ethiopia	National	Cultivated fodder	All	99	8.35 (1.18)	10.10	68.50
		Concentrates	All	100	9.5 (1.1)	21.2	44.6
	Highlands	Pasture	Dry	33	8.30 (0.90)	9.20	67.10
		Pasture	Wet	55	8.30 (0.90)	9.20	67.10
		Teff residue	All	80	7.31 (0.62)	5.28	79.16
		Browse	All	5–38	10.00 (1.69) [‡]	16.20	43.70
	Midlands	Pasture	Dry	33	7.90 (0.40)	8.20	70.40
		Pasture	Wet	55	7.90 (0.40)	8.20	70.40
		Teff residue	All	80	7.31 (0.62)	5.28	79.16
		Browse	All	5–38	10.00 (1.69) [‡]	16.20	43.70
	Lowlands	Pasture	Dry	33	7.75 (4.18)	6.30	77.00
		Pasture	Wet	55	7.75 (4.18)	6.30	77.00
		Teff residue	All	80	7.31 (0.62)	5.28	79.16
		Browse	All	5–38	10.00 (1.69) [†]	16.20	43.70
Burkina Faso	Sudanian	Pasture	Dry	33	6.50 (0.30*)	–	–
		Pasture	Wet	55	6.50 (0.30*)	–	–
		Maize residue	All	60	7.89 (0.00)	5.19	69.08
		Browse	All	5–38	8.10 (0.10*)	–	–
	Sahelian	Pasture	Dry	33	6.10 (0.30*)	–	–
		Pasture	Wet	55	6.10 (0.30*)	–	–
		Sorghum residue	All	60	6.37 (0.00)	5.16	68.63
		Browse	All	5–38	6.00 (0.20*)	–	–

– Data not available.
[*] $SD = \frac{mean}{\sqrt{min \times max}} \times \sqrt{mean^2 - \left(\sqrt{min \times max}\right)^2}$.
[†] Estimated proportion of total edible biomass used – as described in the ruminant edible biomass subsection.
[‡] ME approximated by linear regression with in-vitro DM digestibility (IVDMD).

ment estimates of Ethiopia and Burkina Faso as they were less than 1% of ruminant livestock population head counts.

The initial estimates of feed requirements were representative of circa 2015 at a 10 km resolution. Requirements were then extrapolated based on annual population statistics for cattle, sheep and goats (FAO, 2022). Horse donkey and camel populations were held constant over time. Annual metabolisable energy requirements were then calculated using Eq. (3).

$$MER_{annual} = \sum_{n=1}^{lenWS}(MER_{Ma} + MER_{Gr} + MER_{Lo}) + \sum_{n=1}^{lenDS}(MER_{Ma} + MER_{Gr} + MER_{Lo}) + \int_{Tri_3}^{term} MER_{Pr} + \sum_{n=1}^{LL} MER_{La} \quad (3)$$

where MER_{annual} is the metabolisable energy requirement for one animal over the course of the year, combining species and animal class–specific requirements by season for maintenance (MER_{Ma}), growth (MER_{Gr}), locomotion and draught power (MER_{Lo}), gestation (MER_{Pr}) and lactation (MER_{La}). MER_{Ma} includes energy requirements for wool growth/hair (e.g. approximately 6 g per day for wool sheep). MER_{Lo} was combined with draught power work, where the proportion of animals used for work were assumed to expend an additional 40% of their maintenance energy requirement for all of the wet season for bulls and for half of the year for other species (following the calculations in FAO, 2018d; utilising statistics on the proportion of animals in Ethiopia used for draught extracted from CSA (2022); assuming a high percentage of animals used for draught power in Burkina Faso of 90% for horses and donkeys nationally and 90% of bulls outside of the Sahel). MER_{Pr} is the integral of Eq. (4) from the third trimester (Tri_3) of gestation to full-term (term). MER_{La} is the sum of average requirements for the full lactation length (LL). MER_{Pr} and MER_{La} were only calculated for females that came to term, based on national average calving intervals. The total annual metabolisable energy requirements are then the sum product of requirements for the population of each species and animal class, where the total population is disaggregated based on information on herd structures. The equations for maintenance, growth, locomotion and lactation are described in detail by Ndung'u et al. (2019) and Goopy et al. (2018). Daily metabolisable energy requirements during gestation were estimated using Eq. (4).

$$MER_{Pr} = \frac{(B \times Cexp(-C \times t) \times SBW \times exp(A - B \times exp(-C \times t)))}{0.133} \quad (4)$$

In Eq. (4), SBW is the ratio of the expected birth weight to standard birth weights (assumed to be 1); A, B and C are parameters for energy requirements after blastocyst implantation; t is time in days from blastocyst implantation to term, where energy requirements are only significant in the last 12 weeks of gestation; the constant term in the denominator refers to an assumed efficiency of ME use of 13.3% (CSIRO, 2008).

Feed balances

An overview of the feed balance model design is presented in Fig. 1. Feed availability and livestock requirements were aggregated to the first administrative level (termed "region" for Ethiopia and Burkina Faso) as well as livelihood-elevation zones (see Supplementary Fig. S1 for zone maps). The Famine Early Warning System (**FEWS**) livelihood zones are used to differentiate between (agro)pastoral, mixed crop-livestock and cropping regions (FEWS, 2009). In the case of Ethiopia, FEWS livelihood zones were combined with three elevation zones, namely: lowlands (< 1 500 m), midlands (≥ 1 500 ≤ 2 300 m) and highlands (> 2 300 m); agropastoral and pastoral zones were combined for the presentation of results as these zones were generally neighbouring which would potentially allow biomass to be utilised across systems; highland and lowland (agro)pastoral zones were combined into one zone, where the one highland agro-pastoral zone was considered to have too small an extent to be presented on its own – which is a livelihood zone named "Abijata Shala Jido Agro-Pastoral". In the case of Burkina Faso, FEWS livelihood zones were reduced from nine to five zones, where Ouagadougou was combined with the Central Plateau zone to form a zone labelled "Central mixed" (agropastoral and crop-livestock) and the three west and south-west livelihood zones were combined to form a zone labelled "Crop-

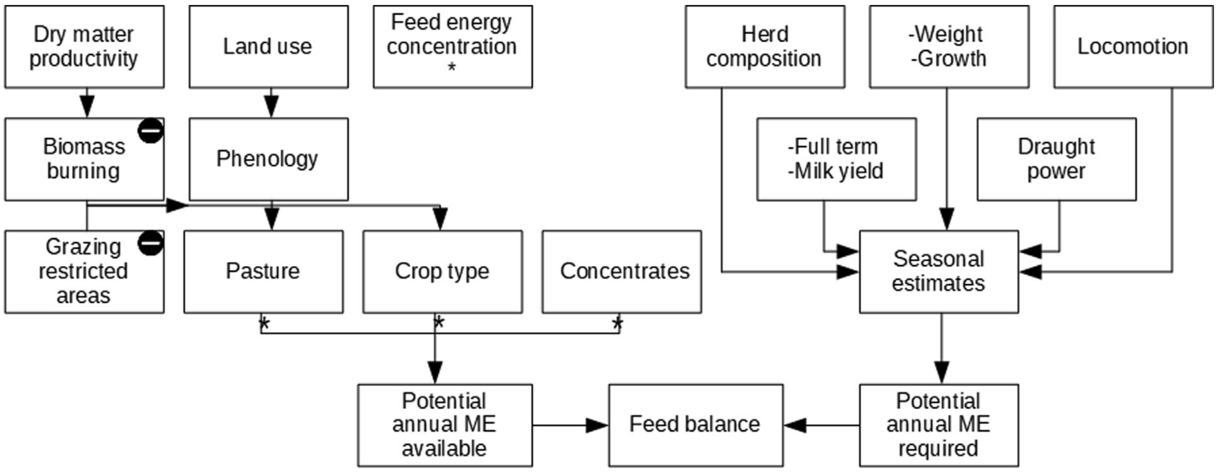

Fig. 1. Feed balance for ruminant livestock model design. A minus (–) indicates that biomass is excluded where relevant based on the specific input. An asterisk (*) indicates that feed concentration values are incorporated in subsequent calculations. ME = Metabolisable energy.

ping" (which also includes crop-livestock systems and fruit trees). The remaining three FEWS livelihood zones were used in their original form, labelled as "(Agro)pastoral Sahel" (consisting of agro-pastoral and pastoral systems), "North mixed" and "South mixed" (both consisting of agro-pastoral and crop-livestock systems). This differentiation avoids biases that can be introduced by aggregating across different systems and provides a basis for targeting interventions to broad system classifications.

Feed balance estimates were then calculated as the proportion/-multiple of requirements met from available feed resources within those aggregated zones. We then compared our feed balance estimates to that of previous studies and government statistics, presented in Supplementary Fig. S3 (comparing against Rahimi et al., 2021 in Burkina Faso, and MAFR, 2020 in Ethiopia). The uncertainty around these estimates was estimated based on the range of browse utilisation proportion, ME concentration values and livestock feed requirement parameters. The uncertainty analysis was based on published literature on minimum and maximum values for each relevant parameter. All analyses were conducted using the R programming language (R core team, 2022). Comparisons of results with previous studies and government statistics were carried out by way of linear regression and Spearman's rank correlation coefficient.

Results

The total biomass available as animal feed in Ethiopia was 443 million tonnes (Mt) of DM, averaging 8.57 tonnes DM per hectare in the highlands and midlands and 3.18 tonnes DM per hectare in the (agro)pastoral/lowland zones (Table 2 and Fig. 2). The higher average yield in the Ethiopian highlands and midlands reflects favourable growing conditions. In the highlands and midlands grass accounted for 25% of total ME, crop residue accounted for 38%, biomass from postharvest growth accounted for 22%, cultivated grass accounted for 5%, browse accounted for 9% and concentrates accounted for an estimated 1%. In the (agro)pastoral/lowland zones, grass accounted for 61% of total ME, crop residue accounted for 15%, biomass from postharvest growth was 10% and browse accounted for 14% of the total energy available.

In Burkina Faso, the total DM availability was 65 Mt, averaging 2.93 tonnes DM per hectare in the Sudanian agro-ecological zone (**AEZ**; comprised of the following zones: "Central", "Mixed crop-livestock (north)", "Mixed crop-livestock (south)" and "Cropping") and 0.95 tonne DM per hectare in the (agro)pastoral Sahel zone. In the Sudanian, AEZ grass accounted for 52% of total ME, crop residue accounted for 26%, biomass from postharvest growth accounted for 20% and browse accounted for 2% of the total energy available. In the (agro)pastoral Sahel, AEZ grass accounted for 94% and other biomass sources combined accounted for 6% (Table 2 and Fig. 2). The ME availability estimates are available as maps in Supplementary Fig. S4. A breakdown of feed sources over time is available in Supplementary Fig. S5.

The composition and uncertainty of feed ME by livelihood zone are presented in Fig. 2. In the highlands and midlands, there was a high degree of uncertainty around crop residue and browse energy availability. In Ethiopian (agro)pastoral zones, the uncertainty due to grass ME input values ranged by 20% of the total. In Ethiopia's lowland mixed crop-livestock zones, there was uncertainty around browse, grass (± 25%) and crop residue (± 20%) availability. In Burk-

Table 2
Annual feed availability in total DM, yield and proportion of metabolisable energy (ME) for ruminants by country and zone (2019).

Country	Zone	DM (Mt)	Yield (t/ha)	Energy supply (ME EJ*)	Grass (%ME)	Crop residue (%ME)	Postharvest growth† (%ME)	Cultivated grass (%ME)	Browse (%ME)	Concentrates (%ME)
Ethiopia	Highlands / Midlands	227	8.57	1.40	25	38	22	5	9	1
	(Agro)pastoral / Lowlands mixed	216	3.18	1.30	61	15	10	0	14	0
Burkina Faso	Sudanian‡	64	2.93	0.33	52	26	20	–	2	–
	(Agro)pastoral Sahel	1	0.95	0.07	94	3	2	–	1	–

* 1 Exajoule = 1 000 000 Terajoules; 1 Terajoule = 1 000 000 Joules; based on mean ME values.
† Biomass that grows after harvest, including weeds and grasses, excluding crop residues, cultivated fodder and concentrates.
‡ Includes Central zone, Mixed crop-livestock (north) zone, Mixed crop-livestock (south) zone and Cropping zone.

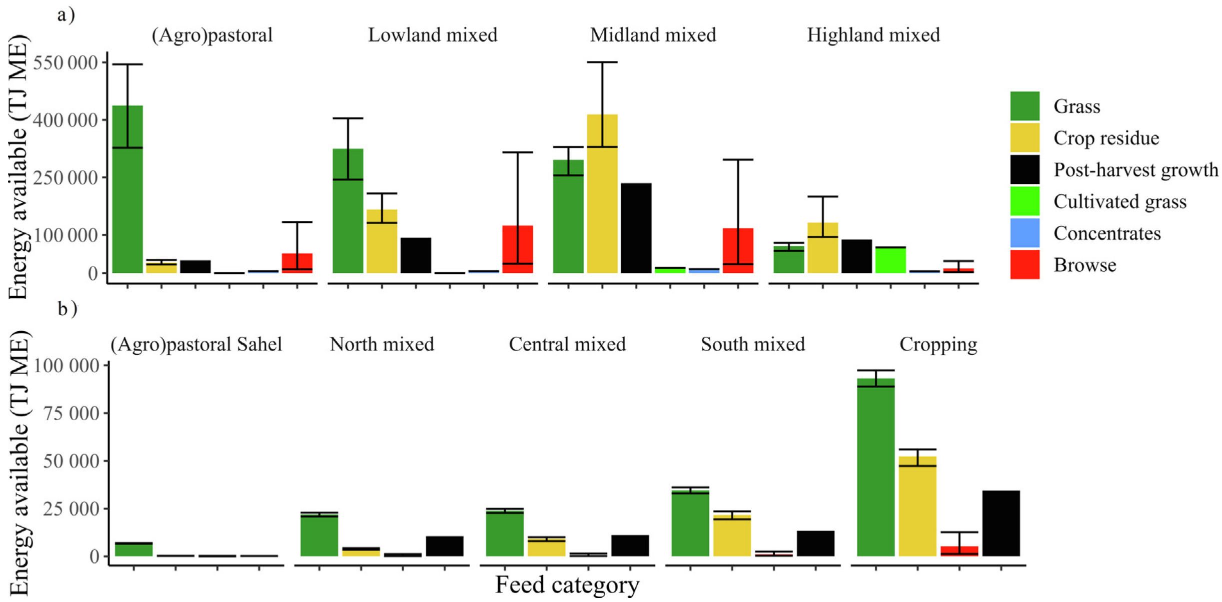

Fig. 2. Metabolisable energy (ME) availability for ruminant livestock from feed sources in 2019 (TJ ME/year). (a) Ethiopia. (b) Burkina Faso. Uncertainty due to ME concentration represented by error bands. Uncertainty of browse is also attributed to utilisation (5–38%).

ina Faso, there was a lower level of uncertainty due to input values – except for browse. In all disaggregated zones, browse was consistently the most uncertain digestable energy source, crop residue was consistently the second most uncertain (± 10% of mean), followed by the availability of grass ME (± 5%).

The estimated daily energy requirements of livestock are presented in Table 3. Energy requirements for livestock in (agro)pastoral and lowland mixed crop-livestock zones of Ethiopia were estimated to be higher than their highland and midland counterparts. Cattle had the highest requirements of the six species, where bulls required 67.9 MJ per animal per working day in (agro)pastoral, lowland mixed crop-livestock zones and 106.0 MJ per animal per working day in the highland and midlands. Adult female cows required 63.7 MJ per animal per day in (agro)pastoral, lowland mixed crop-livestock zones and 61.7 MJ per animal per day in the highland and midlands and 68.9 MJ per animal per day in periurban locations. Requirements for maintenance exceeded other energy demands for cows and sheep in all zones, as well as for goats in the (agro)pastoral and other lowland zones. Energy for lactation accounted for over 33% of the total requirements for lactating cows in all zones. For sheep and goats, maintenance requirements were marginally higher in the (agro)pastoral and other lowland zones due to the higher expected liveweight of adults.

In Burkina Faso, requirements for working bulls in the Sudanian agro-ecological zone were 63.1 MJ per animal per day and in the Sahel, requirements were 47.5 MJ per animal per day. Requirements for cows in the Sudanian agro-ecological zone were 52.4

Table 3
Metabolisable energy requirements of adult female ruminant livestock by country, zone and species (MJ day^{-1}).

Country	Zone	Species / class^	MER_{Ma}	MER_{Gr} †	MER_{Lo} ‡	MER_{Pr} §	MER_{La}	Total
Ethiopia	Periurban	Cow	34.5 (28.7–41.5)	–	0.2 (0.2–0.3)	3.5 (3.5–3.5)	30.7 (22.5–39.8)	68.9
	Highlands /	Cow	34.5 (28.7–41.5)	–	1.2 (1.0–1.4)	3.5 (3.5–3.5)	22.5 (18.3–29.7)	61.7
	Midlands	Bull (work)	45.5 (37.6–54.6)	40.6 (19.8 – 95.4)	19.8 (16.6–23.7)	–	–	106.0
		Sheep	4.8 (4.5–5.2)	–	0.2 (0.1–0.2)	0.3 (0.3–0.3)	1.7 (1.5–2.2)	7.0
		Goat	4.7 (4.4–5.0)	–	0.2 (0.1–0.2)	0.4 (0.3–0.4)	5.2 (4.4–6.5)	10.5
	(Agro)pastoral/	Cow	35.2 (29.1–41.4)	–	3.7 (3.1–4.3)	3.5 (3.5–3.5)	21.3 (15.8–28.4)	63.7
	Lowlands mixed	Bull (work)	45.0 (37.2 – 53.3)	–	22.9 (19.0–27.1)	–	–	67.9
		Sheep	5.5 (5.1–5.8)	–	0.5 (0.5–0.5)	0.3 (0.3–0.3)	1.3 (1.1–1.5)	7.6
		Goat	4.9 (4.6–5.0)	–	0.4 (0.4–0.4)	0.4 (0.3–0.4)	3.5 (2.9–4.1)	9.2
Burkina	Periurban	Cow	31.3 (30.3–32.3)	6.3 (6.1–6.7)	0.1 (0.1–0.1)	–	36.6 (12.8–106.5)	74.3
Faso	Sudanian ¶	Cow	31.3 (30.3–32.3)	6.3 (6.1-–6.7)	2.5 (2.4–2.5)	–	12.3 (10.5–14.6)	52.4
		Bull (work)	44.4 (41.4 – 47.5)	4.6 (4.3 – 4.9)	22.5 (19.5 – 25.4)	–	–	71.5
		Sheep	5.2 (3.9–5.5)	3.7 (3.5–3.9)	0.9 (0.5–1.2)	–	0.8 (0.7–0.9)	10.6
		Goat	4.4 (4.1–4.7)	3.2 (3.0–3.2)	0.7 (0.5–1.0)	–	4.0 (3.6–4.6)	12.3
	(Agro)pastoral	Cow	33.9 (31.5–36.5)	1.1 (1.0–1.2)	3.1 (2.9–3.4)	–	14.0 (12.0–17.1)	52.1
		Bull	39.0 (38.1 – 40.0)	5.1 (4.8–5.4)	3.4 (3.3 – 3.5)	–	–	47.5
	Sahel	Sheep	5.2 (4.9–5.6)	0.0 (0.0–0.0)	0.7 (0.6–0.9)	–	0.7 (0.6–0.9)	6.6
		Goat	4.6 (4.2–5.1)	0.0 (0.0–0.0)	0.6 (0.5–0.8)	–	4.0 (3.7–4.8)	9.2

Abbreviations: MERMa = Metabolisable energy requirements for maintenance; MERGr = Metabolisable energy requirements for growth; MERLo = Metabolisable energy requirements for locomotion; MERPr = Metabolisable energy requirements for gestation; MERLa = Metabolisable energy requirements for lactation

^ Bulls not used for draught, steers, calves, kids, lambs, horses, donkeys and camels not presented in table but included in total feed balance.

† Seasonal growth data not available for adult female livestock in Ethiopia. Assumed to average to zero over the course of a year.

‡ Includes draught power. Note: draught power assumed to apply to a proportion of adult male cattle, horses and donkeys.

§ Metabolisable energy requirements for pregnancy included in maintenance for Burkina Faso. Average over 365 days.

¶ Includes Central zone, Mixed crop-livestock (north) zone, Mixed crop-livestock (south) zone and Cropping zone.

MJ per animal per day and in the Sahel, requirements were 52.1 MJ per animal per day. Requirements for maintenance were estimated to be the highest component for all species and regions, except in periurban locations. Periurban locations had high energy requirements for lactation, requiring 36.6 MJ per day. The requirements for goat lactation were also higher than that of sheep due to the higher estimated annual milk yield. The ME requirements are available as maps in Supplementary Fig. S6.

As shown in Fig. 3, the adequacy of locally available metabolisable energy for ruminant livestock in Ethiopia was most constrained in highland mixed crop-livestock zones, closely followed by midland mixed crop-livestock zones. Despite the limitations of available feed resources in these zones, there was sufficient metabolisable energy in the local landscape to meet over 89% of all requirements for maintenance, growth, lactation, gestation, locomotion and draught power in all years. This apparent deficit may be attributable to our conservative estimate for draught power, potentially overstating metabolisable energy requirements. The apparent surplus of feed in lowland mixed crop-livestock zones is most likely due to the relatively low human and livestock populations in Gambella and Benishangul Gumuz Regions as a result of high instances of malaria and tsetse fly infestation.

In 2019, the adequacy of locally available metabolisable energy for ruminant livestock in Burkina Faso was most constrained in the northern mixed crop-livestock zone (58% of requirements locally available) and the Sahel (70% of requirements). The apparent deficit in the northern mixed crop-livestock zone may be attributable to uncertainty around cow milk yield – where the requirement is almost three times that of the Sahel. The central zone, the southern mixed crop-livestock zone and the cropping zone had sufficient local feed resources to meet all estimated livestock requirements.

In both Ethiopia and Burkina Faso, the variability over time is attributable to DM productivity of feed sources rather than livestock requirements – which increase linearly from the most recent census estimates. In Ethiopia, there was an anomalous year in (agro)pastoral zones in 2018, with increased grass DM production. In Burkina Faso, there was a decrease in feed availability in the Sahel in 2016 and 2017, bringing feed adequacy to 62% of requirements – meaning the region was below maintenance adequacy from local resources. In the southern mixed crop-livestock zone, feed availability increased in 2016 and 2017 based on an increase in grass and crop residue resources. In the observed period, there was no discernible trend in either country, region or zone.

There was substantial uncertainty around feed balance estimates. As noted by Wilkes et al. (2020), feed composition, feed energy concentration and animal liveweight are the most uncertain and influential variables in Ethiopia. In Ethiopia, lowland mixed systems had the widest range of estimated values largely due to uncertainties in browse, grass and crop residue metabolisable energy estimates. In the highlands and midlands, uncertainty around crop residue and browse metabolisable energy availability compounded with uncertainty of livestock parameters to increase the range of likely adequacy values. In Burkina Faso, the uncertainty of crop residue and grass metabolisable energy availability were the most influential supply−side factors (Fig. 2) and milk yield was the most influential demand−side factor quantified in this study (Table 3).

Our estimates resulted in fewer instances of sub-maintenance level scenarios in comparison to previous studies of Ethiopia and Burkina Faso. There was greater alignment in linear association and rank order of administrative zones when compared to a previously published remotely sensed estimate for Burkina Faso (ρ = 0.88) than there was for bottom-up estimates from Ethiopia (ρ = 0.43) and Burkina Faso (ρ = 0.50). These differences are attributable to supply−side factors such as the estimation of crop aftermath and browse feed resources. These comparisons are visualised in Supplementary Fig. S3.

Discussion

The availability of biomass for feed is constrained in a number of livestock−producing regions of Ethiopia and Burkina Faso. This study identifies where these constraints are most pressing and where there is an "excess" of biomass. Importantly, we found that both countries exhibited notable differences in the composition of biomass in different zones (Table 2), which has implications for the feasibility of potential interventions for improving ration digestibility and mitigating greenhouse gas emissions. Stemming from these results, there are a number of socio-economic, policy and methodological considerations that warrant discussion.

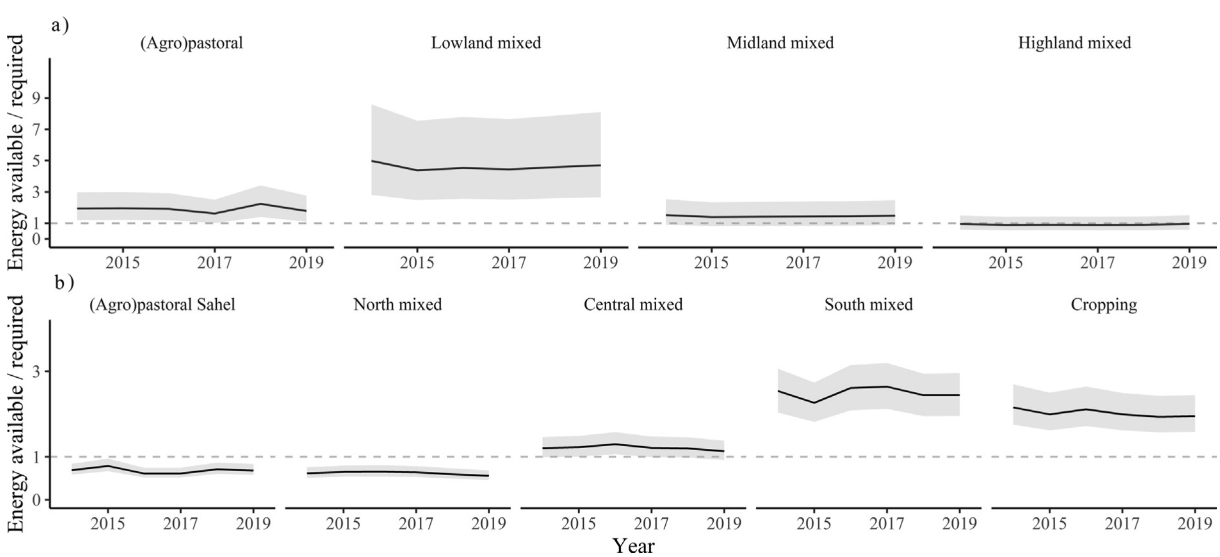

Fig. 3. Energy balance of ruminant livestock from feeds over time by livelihood zone (J ME available / J ME required/year). (a) Ethiopia. (b) Burkina Faso. Uncertainty due to ME concentration and livestock parameters represented by grey bands. Dashed line at 1 where feed is sufficient for all estimated requirements (maintenance, growth, locomotion, draught power, gestation and lactation) for the zone. The requirement side of the balance is inclusive of cattle, sheep, goats, horses, donkeys and, for Ethiopia, camels. ME = Metabolisable energy.

Feed futures

Croplands and grazing lands cover over 30% of Earth's ice-free land area (estimates ranging between 30 and 57% in Grogan et al., 2022; Piipponen et al., 2022). Globally since 2000, cropland area has increased, grazing land area has decreased and the productivity of both land uses has been intensifying (Godde et al., 2018; Potapov et al., 2022). The dynamics across SSA are more variable, where, for example, in semi-arid zones, croplands and grazing lands have been expanding and intensification has been limited. These changes in land use contribute to the complexity of estimating livestock feed availability.

Demand for feed is expected to increase substantially, concomitant with increases in livestock populations as well as improvements in productivity per animal. These changes will occur in the context of a more variable climate and elevated levels of CO_2. In Ethiopia, populations of all livestock species would need to almost double by 2050 to meet growing demand where gains in productivity are expected to be most notable in beef and dairy enterprises (FAO, 2018c). In Burkina Faso, demand for milk and meat is forecast to more than triple leading to increased demand for feed production and food imports (FAO, 2020).

There are several interacting factors that will influence the sustainability of meeting future feed demands. Factors that have negative implications for feed futures include rates of land degradation, crop area expansion, extreme weather events, drought and demand for bioenergy. Factors that have positive implications for feed futures include novel protein innovations that convert other sources of biomass more cost-effectively (e.g. insects, single-cell algae or bacteria for feed or food; Thornton et al., 2023) and productivity improvements for food and fibre production. In a future of increased demand and ongoing threats to sustainability, biomass resources need to be actively monitored for effective management.

Feed scarcity hotspots

Biomass resources in Ethiopia and Burkina Faso are vast (Table 2). Grass is the most abundant feed source in most locations and crop residues dominate the Ethiopian highlands (in agreement with FAO, 2018a; FAO, 2018b). These resources sustain large livestock populations with varying potential for expansion and intensification. The highland mixed crop-livestock zone is the most feed−constrained in Ethiopia, where local resources are sufficient for livestock requirements with limited scope for increasing productive output or herd/flock expansion; the scope for feed imports in this region is also limited due to economic and logistical factors. The potential to expand feed trade with the western lowland region of Ethiopia is constrained, where the apparent abundance of feed is attributable to i) low human and livestock populations due to disease risk and ii) the dominant local forage species – *Hyparrhenia rufa (Nees)*– maturing rapidly and is unpalatable for much of the year.

Feed scarcity is most pressing in Burkina Faso where the northern mixed crop-livestock zone and the Sahelian agro-ecological zone do not have sufficient local feed resources to meet livestock energy requirements. Apparent deficits do not necessarily equate to negative energy balances in livestock but may rather indicate either an overestimate of requirements or an underestimation of available feed resources. In contrast, there appears to be scope to develop markets for inter-regional feed exports or herd/flock expansion in southern regions of Burkina Faso where there is an apparent excess of suitable biomass.

The demand side of feed scarcity hotspots may be systematically overestimated due to milk yield and population input data, as well as digestive passage limitations due to protein and water availability. Feed requirements may also be overestimated due to the lack of seasonality in livestock population estimates, where the census statistics represent the maximum annual count and real populations are more dynamic (Fetzel et al., 2017). In comparison, uncertainty due to liveweight gain, locomotion and gestation were relatively low (Table 3). These findings highlight the importance of greater regional disaggregation of milk yield estimates and the use of more accurate and temporally disaggregated livestock population estimates in quantifying the demand side of feed scarcity hotspots.

The supply side of feed scarcity hotspots may be influenced by several factors. Factors quantified in this study relate to the estimation of metabolisable energy, which is represented as error bands around feed balance estimates (Fig. 3). Given the width of these error bands, we argue that there is a need to improve input data availability on utilisation and metabolisable energy concentration in specific locations. Despite including high−resolution data on tree cover, browse resources are highly uncertain. This uncertainty is due to limitations in our understanding of utilisation and energy concentration. The uncertainty of browse resources has a substantial impact on the estimates of feed availability in Ethiopia in midland and lowland mixed crop-livestock zones. Grassland utilisation and energy concentration are also highly uncertain, particularly in lowland locations; these estimates could be improved by better modelling plant-livestock interactions (Herrero et al., 1998; Sircely et al., 2019) and by reducing the uncertainty in seasonal metabolisable energy estimates. Crop residue metabolisable energy estimates were most uncertain in the Ethiopian highland and midland zones. The uncertainty of crop residue metabolisable energy will be mitigated as more geo-located feed samples become available which can then be linked with cultivar, soil, climatic and management factors for more accurate prediction (Reddy et al., 2003). Crop residue utilisation is also uncertain as there is some degree of spatial heterogeneity (Duncan et al., 2016). The importance of these crop residues in Ethiopia will only increase as croplands expand to meet demand for cereals (Assefa et al., 2022).

On the supply side, there are also factors not quantified in this study which may have resulted in a systematic underestimation, including cross-border transhumance, purchased feed, imported feed, over grazing and the influence of the spatial distribution of water-points. Firstly, pastoralist communities in the Sahel are known to migrate into Mali and Niger and further south to coastal countries such Benin, Ghana, Côte d'Ivoire and Togo in times of scarcity which may explain the apparent deficit in that region. Secondly, regions that are close to processing facilities and markets will be more able to purchase feed to supplement deficits when compared with other regions (e.g. Amprako et al., 2020). Feed imported from other countries is not included in this analysis; depending on the quality of import statistics, these data could be incorporated in future analyses. Thirdly, there is anecdotal evidence that overgrazing is common practice (exceeding the pasture's ability to regenerate, leading to medium- to long-term loss in production) which may result in higher short-term utilisation, particularly in years of lower production like 2016 and 2017 in the Sahel and the historic El Niño drought year in 2015 in Ethiopia. Finally, in arid and semi-arid lands, access to water points influences the risk of energy deficits due to drought (Accatino et al., 2017).

Feed scarcity hotspots are most prominently located in the Ethiopian highlands and the Sahelian agro-ecological zone of Burkina Faso. However, uncertainties around these estimates necessitate caution when used for decision−making. In addition to the unquantified uncertainties described in the paragraphs above, the role of military conflict will be an important consideration for both Ethiopia (war in 2020–2022/ongoing conflict) and Burkina Faso (extremist-insurgent attacks from 2015-ongoing; two coups d'etat in 2022). Despite limitations, it is evident that the ranking of these hotspots is consistent with previous assessments, demonstrating more realistic non-starvation estimates (Supplementary Fig. S3). Given the rank order consistency between estimates, these hotspot locations represent priority locations for monitoring and intervention. Extending this analysis to identify hotspots in other SSA countries would be limited by data availability on feed items and livestock parameters. Similarly, intra-annual analyses would require monthly or seasonal data on feed energy concentration and livestock populations, which is not available for any SSA nation.

Policy and investment implications

Ethiopia and Burkina Faso's livestock sectors benefit from policy and investment initiatives that have been designed to meet multiple development objectives (detailed by Shapiro et al., 2015 for Ethiopia and Ashley, 2020 for Burkina Faso). These initiatives are extensive in scope; however, their objectives have only been attained in part. In this section, we consider how improved feed balance monitoring programs can inform the implementation of policy and investment initiatives for a sustainable livestock sector. We focus on initiatives that would influence the demand and/or supply of local feed resources.

Demand−side policy and investment initiatives can influence herd sizes, nutritional requirements and herd mobility. Both countries are implementing initiatives on livestock genetics, product quality, livestock migration and disaster risk preparedness. Livestock genetic and product quality initiatives may lead to intensification in high−potential locations which in turn is expected to reduce the growth in herd sizes and increase demand for higher−quality feeds. In Ethiopia, this will take place in the highlands and midlands, where feed is most scarce and the base diet is dependent on crop residues with limited processing to improve quality. In Burkina Faso, the northern mixed crop-livestock and central zones will be of most concern where local feed resources are already limited. Livestock migration and disaster risk preparedness will influence feed demand in pastoral regions by facilitating freedom of movement and incentivising destocking to pre-empt severe shortages. In Burkina Faso, outward migration and destocking may have been an advisable strategy in 2016 and 2017 given the reduced levels of feed, while in other years inward migration for neighbouring countries could have been directed to specific locations.

Supply−side policy and investment initiatives can contribute to securing existing feed resources, developing new sources of feed and incentivising trade in feed resources. Both countries are implementing initiatives on feed conservation, specialised zoning for fodder cultivation and improved adoption of forage species. Burkina Faso is also implementing initiatives on agro-silvopastoralism. To address supply−side limitations, there are also opportunities to develop markets for inter-regional and international trade, informed by feed balance estimates – which is lacking from current strategy documents. Facilitating international trade would require feed balance estimates to be carried out in neighbouring countries (e.g. Burkina Faso's neighbouring countries Benin, Côte d'Ivoire and Togo where there are surplus feedable resources).

As shown from feed market studies in some African countries, there is a clear disconnect in the expected relationship between price and nutritional quality (Ayantunde et al., 2014, 2022, 2023; Melesse et al., 2023) which is an indication of the absence of quality standardisation. Feed market quality standardisation is important to ensure that consumers pay a premium for quality products. Establishment of nutritional databases of major feed resources for different regions is essential for the establishment of nutritive value-based pricing.

Initiatives on feed conservation and cultivated forage adoption are expected to maintain or improve feed availability and quality in the context of a changing climate and expanding cropland extents. Existing initiatives focus on promoting new forage species and practices. This focus may underestimate the latent value of existing biomass resources. For instance, in the Ethiopian highlands and midlands and cropping regions of Burkina Faso, there is an opportunity to focus initiatives on crop residues; crop residue storage and treatment methods could be combined with dual-purpose plant breeding strategies to maximise quantity and quality (Blümmel et al., 2020). Neglecting investments in crop residue improvement would undermine intensification strategies and eventually see a greater share of biomass used for other purposes such as bioenergy.

As proposed by current supply−side initiatives, (agro)pastoral regions and Burkina Faso more broadly would benefit from the introduction of drought−tolerant grass species. Decision makers in these regions would also benefit from an improved understanding of available browse resources. We can now pinpoint locations impacted most severely by drought or of importance for managing browse resources. Such spatially explicit information could lower the cost of planning, implementation and monitoring of such initiatives (Rich et al., 2020).

Effectively managing the demand and supply of feed will have implications for biogenic emissions of methane –a potent short−lived climate pollutant. Feed adequacy and feed quality influence the amount of energy lost as CH_4. The proportion of energy lost as methane reduces as (in)adequacy improves from sub-maintenance to an excess of requirements (Goopy et al., 2020; Hales, 2019). The quality of the ration –influenced by species, variety, management and treatment– also reduces methane emission intensity (McAllister et al., 1996). These relationships are non-linear which means that small improvements upon feed constraints can reduce emission intensity substantially.

Conclusions

Achieving an increase in the benefits of livestock keeping while meeting environmental objectives –sustainable livestock intensification– will require targeted policies and investments informed by a robust spatially and temporally relevant evidence base (McDermott et al., 2010). The growth in earth observation capabilities has provided a means to implement wide-scale feed balance assessments, which are a critical component of the required evidence base. This development avoids the need for expensive data collection across entire countries and improves consistency between countries. In this study, we have developed a model to estimate feed supply and demand at a moderate resolution (0.3 km for supply and 10 km for demand). Our study has highlighted key development and policy issues, as well as areas for methodological improvement. This emerging evidence base can support decision−makers in attaining the threefold benefit of optimising livestock productivity, minimising exposure to climatic shocks and minimising greenhouse gas emission intensity.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2024.101199.

Ethics approval

Not applicable.

Data and model availability statement

Data not already in the public domain will be available upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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