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The U.S. Government's Global Hunger & Food Security Initiative

Realizing economic and environmental gains from cultivated forages and feed reserves in Ethiopia

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Abstract

The livestock sector in Ethiopia is characterized by low productivity due to inadequate supply of affordable high-quality animal feed year-round, with more acute gaps in the drought-prone regions of the country. This paper presents the economic benefits and insights into the role of cultivated forages, such as densification into pellets, in bridging gaps in feed supply. Nutrient requirement calculations for feedlot and dairy animals and meeting those requirements using cultivated forage- based diets are presented. However, forage crops need a viable forage seed supply system to assure access to quality assured seeds. This study thus explores the role of forage seed systems and presents intervention areas for Ethiopia.

Results suggest diets containing greater than 85% cultivated forages can sustain daily body weight gain up to 1 kg in growing animals. The costs of nutrients from cultivated forages are up to 15-fold lower than those from conventional feed resources. The diets based on pelleted cultivated forages decrease costs of feeding animals during a 100-day drought period by 4-fold, fattening animals by 2.3-fold, and cost of feed for milk production by 4-fold. Utilization of cultivated forages could reduce methane emissions with abatement value between $165 and $240 USD per 1000 kg of body weight gain in the fattening sector. For the dairy sector, the abatement value would range from
$1350 to $2400 USD per million liters of milk production. For the drought period of 120 days, the value of methane reductions would be between $5500 and $11,400 USD per 1000 animals.

Keywords: forages, seed systems, feed reserves, economics, policy, animal nutrition, greenhouse gas emissions

Review Methodology: The authors conducted an extensive literature review to identify gaps, especially in the nutrient and economic analyses for forages, applied to the Ethiopian context. Databases included Google search engine, USAID projects database, USAID Ethiopia, CGIAR, and Ethiopian Ministry of Agriculture sites. We leveraged the literature published by Dr. Makkar as a starting point for animal feeding and nutrition. We used the references from the articles obtained by this method to check for any additional relevant material. Quantitative data were collected from an array of sources. For example, dairy processing centers' data were provided by the IFPRI (International Food and Policy Research Institute) Ethiopia, information on quarantine facilities and locations of warehouse facilities was provided by staff from the Ethiopian Ministry of Agriculture, and information on feedlots was collected from literature as well as through conversations with stakeholders using structured survey instruments. The data on road networks were taken from Open Street Map (OSM). Suitability analyses for agro-climatic adaptation used global climate databases, with criteria and associated thresholds based on
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2F%2Fwww.tropicalforages.info&e=fa4695b0&h=f3962795&f=n&p=y . Authors conducted two surveys—one was on gathering information using global case studies from Kenya, Tunisia, India, and Mexico. The second survey was concentrated on forage seed value chain and livestock output market locations from national stakeholders in Ethiopia.

Introduction

Livestock play a critical role in the agricultural transformation process in Ethiopia, contributing up to 47% in agricultural gross domestic product (GDP). The livestock sector in Ethiopia supports the livelihoods of about 80% of rural people [1]. Different strategic national plans, such as Livestock Master Plan (LMP) and Growth Transformation Plan (GTP)), have set high targets for livestock productivity [2], to address current gaps. For example, if no investment is made in raising livestock productivity, projections for the year 2028 show a national deficit of 53% for all meats (1.332 million tons) and 24% for cow milk (1987 million liters) due to expected increases in demand [3].

One of the main reasons for low productivity is shortage of high-quality affordable animal feed, particularly in the dry season [4]. Droughts are common in Ethiopia, and their frequency has increased in the last decade [5], which is attributed to the ongoing climate change. Uncertainties in growing times and seasons have increased vulnerabilities in many areas. During drought periods, the cost of manufactured feed increases by around 20% due to high competition for feed ingredients, resulting in shortages and reduced accessibility. The cost of transport of, for example, hay in the form of bales is much more expensive compared with that of grains or manufactured feed. During the drought in 2019, using United Nations Central Emergency Response Fund (CERF) allocation and the European Civil Protection and Humanitarian Aid Operations (ECHO) funding, a total of 8000 tons of animal feed were distributed to 24,000 households, benefiting 230,000 animals such as goats and lactating cows [6].

This study explores the role of cultivated forages in contributing to a sustainable high-quality feed supply to the Ethiopian livestock sector. A recent assessment projects a deficiency of approximately 20% feed on dry matter and approximately 50% on both energy and protein bases in Ethiopia [7].The increased cultivation of improved forages and their processing through innovative technologies would help to bridge gaps between the availability and the demand of feed in Ethiopia, especially during dry periods and emergency situations. The inclusion of improved cultivated forages also enhances the feed quality, which decreases methane emissions per unit livestock product from ruminants [8, 9]. As methane is a potent greenhouse gas, this has important implications for climate change mitigation.

Cultivated forages are more balanced in terms of energy and protein than conventional feed ingredients, which are either rich in protein (e.g., oilseed cakes) or energy (e.g., grains). Hence, a balanced feed can be formed containing substantial amounts of cultivated forages. Feeding a balanced diet increases the feed-use efficiency (more production from less feed), which in turn translates into more efficient use of resources especially land and water, for roughage production is both land and water dependent [10].

However, forages in loose form have low bulk density and are difficult to handle, transport, and store. This study proposes feed preservation technologies, such as forage-based pellet formation, that provide opportunities to increase the bulk density manifold and thus decrease the cost of transport and storage. In addition, it enhances the shelf-life of cultivated forages.

The success of forage production depends on a well-established, viable, and sustainable forage seed system. Currently in Ethiopia, there is very low supply of high- quality and diverse forage seeds [1]. Ethiopia's livestock sector depends on naturalized or native pastures in the drier low-potential areas, and on some cultivated forages (grasses and legumes) and crop residues in the high- potential areas. So far, cultivation of forages is not widespread and where it happens, it often is based on recycling seeds and/or vegetative planting materials [11]. Seed production of forages is complex as different forage crops require different agronomic practices, specific techniques of harvesting, threshing, and seed processing [12]. Unlike cereals and other food crops, currently there do not exist any established private or public forage seed production and marketing systems in Ethiopia. The seed supply system is weak due to inadequate extension systems focusing on forage development. Additionally, the existing forage seed market is dispersed and is not linked between suppliers and buyers—there is very little market information [13]. Innovative solutions, bringing the public and private sector together to unblock the forage seed supply system, are lacking.

Currently in Ethiopia, there is no widespread feed preservation based on cultivated forages. Mobilizing high-quality feed preparation and preservation technology, such as densification of cultivated forages in the form of pellets, will create a new potential market for cultivated forages to cater to dairy production, the fattening industry, and quarantine centers. It will thus be imperative to strengthen market linkages and demand-pull factors, from forage seed to crops to feed and finally livestock output markets. These strengthened linkages along the forage and livestock value chains are expected to potentially increase the need for high-quality forages and thus the need for forage seeds of improved varieties.

This study provides compelling evidence on the comparative advantages and benefits of cultivated forages in animal feeding and proposes business models that mobilize high-quality feed preservation technology in Ethiopia. These options are well aligned with the vision of the Ethiopian government [1].The proposed way forward, built on empirical observations and global case studies, could bridge gaps between productive highlands and drought-prone lowlands in Ethiopia, and smoothen cyclical fluctuations in high-quality feed supply. The study further illustrates the monetized benefits of abatement in greenhouse gas emissions for methane that could result due to adoption of cultivated forages in animal feeding.

Analyses approach

A multi-pronged approach was used that included rigorous spatial data analyses, review of global case studies, and structured interviews with international and national key informants. First, data were collected on location of feedlots, dairy centers, and quarantine facilities to determine the spatial distribution of the demand sinks for cultivated forages in Ethiopia. Next, justification for the selected cultivated forages and an approximate demand for forage seeds of improved varieties was estimated for Ethiopia. Using structured interviews with stakeholders in India, Tunisia, Mexico, and Kenya, market opportunities for pellets based on cultivated forages were assessed.

The authors then explored the nutritional feasibility of feeding cultivated forage-based diets for four scenarios—fattening sector for beef animals, low-to-moderate milk-yielding dairy cows, high-milk-yielding dairy cows, and beef cattle during drought period; and assessed the economic feasibility of feeding cultivated forage-based pellets to different types of animals (under both wet and dry conditions) in Ethiopia. The overarching multi-step approach of the study is schematically illustrated in Fig. 1. In a final step, the potential methane emission reductions were calculated.

Potential demand sinks for cultivated forages in Ethiopia

Data were collected on the locations of quarantine centers and feedlots provided by the Ministry of Agriculture of Ethiopia; locations of the dairy processing centers were provided by the International Food and Policy Research Institute (IFPRI). Data were spatially plotted to display locations of the potential demand sinks (Fig. 2). Major demand sinks for the cultivated forages explored in this study are quarantine stations, dairy, and commercial feedlots, each of which is discussed below.

Quarantine stations

The government of Ethiopia has established two new animal quarantine stations: Mille and Jigjiga. The former is in Afar region, to facilitate the export of live animals *via* Djibouti port, while Jigjiga is in the Somali region, for export *via* Berbera in Somaliland. To meet the GTP II targets of the government [2], the feed requirement for the Mille quarantine station is estimated to be 94,500 tons/year [14]. Assuming the same feed requirement for the Jigjiga quarantine station, the annual feed requirement totals to 189,000 tons.

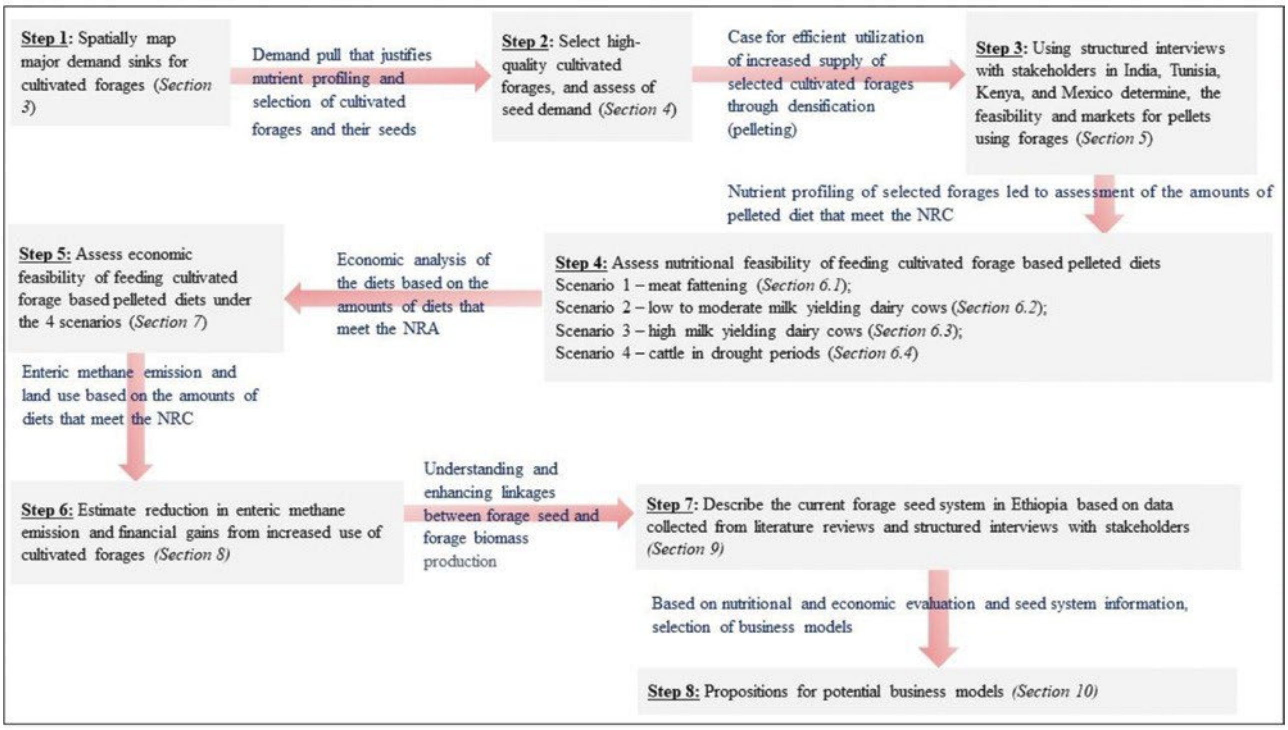

Figure 1. Study approach—schematic illustration.

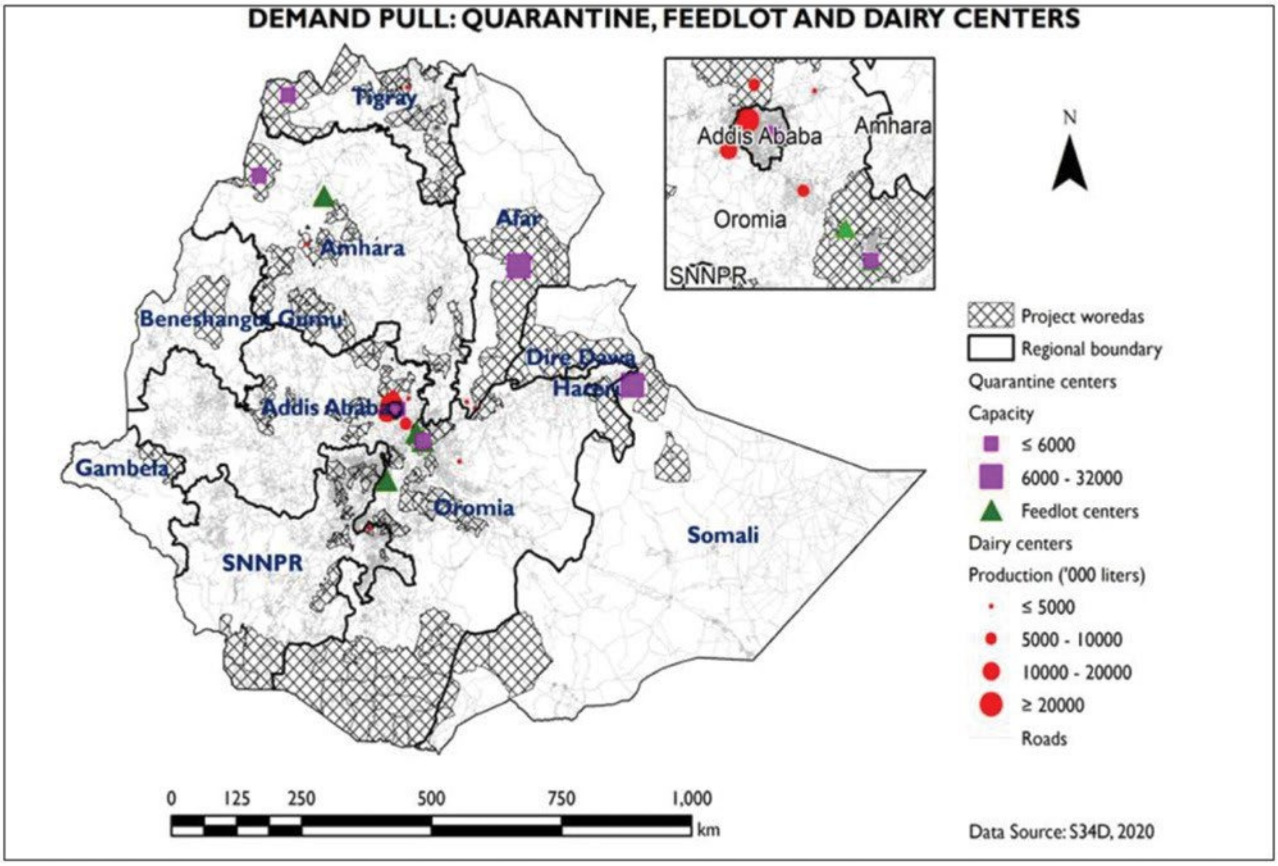

Figure 2. Spatial illustration of demand sinks for cultivated forages.

Dairy

Rearing of crossbred cows has increased over time, and the demand for dairy products, especially in the urban and peri-urban areas of Ethiopia, has been on the rise. The number of dairy processing farms has tripled from 8 to 25, over the last decade [15].

Commercial feedlots

An integrated fattening and quarantine practice is followed by commercial feedlots, and most such integrated units are in areas around Adama, with around 300 farms that fatten animals. Each farm has fattening capacity of 100–1500 animals [16]. There are at least two fattening cycles of 4 months per year. About 88% of farmers fatten 100–500 cattle, while 12% farmers fatten 1000–1500 cattle [17]. Although the exact number of cattle fattened per year is not known, the study extrapolated by taking the averages from the above data. Approximately, 203,400 animals are fattened per annum and our estimation shows that about one ton of feed is required to fatten one animal in a 4-month cycle. The current requirement of cultivated forage-based feed for commercial feedlots in areas around Adama, therefore, is 203,400 tons per annum, not considering potential storage losses. Furthermore, according to FAO [16], Verde Beef Processing Plc. and Allana Group beef operators, both located in Ethiopia, have annual capacity to fatten 130,000 and 73,000 animals, respectively. If these are running at full capacity, the annual amount of feed required is expected to be an additional 203,000 tons.

A huge market pull for feed already exists, which is likely to increase when the government quarantine stations become completely operational and run at full capacity. This feed requirement is evenly spread throughout the year and is not seasonal, implying a potential huge market pull for cultivated forages. Assuming feed in Ethiopia comprises of 70% roughage and 30% concentrate, and 33% of the feed roughage originates from the cultivated forages, and a strong demand pull for the cultivated forages exists in the quarantine stations and the commercial feedlot sector. An additional demand for cultivated forages also exists in the dairy and smallholder fattening sectors.

Forage seed systems in Ethiopia

Ultimately, the success of forage development and adoption critically depends upon the establishment of a sound forage seed production system.The vision of the Ethiopian seed sector is to increase the performance of the sector to become more competitive, inclusive, transparent, responsive, innovative, resilient, and sustainable [13].

The authors conducted a desk-based literature review and interviews with key stakeholders in Ethiopia. During interviews, the authors used structured questionnaires to understand the forage seed value chain. The respondents were stakeholders who implemented forage-related activities on the ground. Our sample of respondents covered ninety- six woredas (Ethiopian administrative unit analogous to counties) across four main regions—Oromia, Southern Nations, Nationalities, and Peoples' Region (SNNPR), Amhara, and Tigray.

The forage seed system in Ethiopia is underdeveloped at present. About 70% of forage seeds are exchanged through the informal seed system. The majority of the formal seed exchanges is through large institutional buyers such as NGOs and government offices. The main forage crop varieties supplied are oat (*Avena sativa*), vetch (*Vicia* spp *villosa*), Rhodes grass (*Chloris gayana*), Napier/elephant grass (*Cenchrus purpureus* syn. *Pennisteum purpureum*,), *Sesbania* spp, Desho grass (*Pennisetum pedicellatum*), cowpea (*Vigna unguiculata*); and sometimes Alfalfa (syn. Lucerne; *Medicago sativa*) (syn. Lucerne), *Desmodium* ssp, *Brachiaria* spp. (syn. *Urochloa* spp.), and fodder beet (*Beta vulgaris*) [12, 18]. The forage seed system is characterized by unarticulated demand, weak regulation and seed certification, limited technical knowledge and capacity for both forage seed and forage crop production, and lack of incentives for farmers and private sector actors to participate in seed multiplication and marketing [18].This has resulted in low adoption and use of improved forage species and varieties that are released by the variety registration system and cataloged in the national variety register [19].

Given very little forage seeds are produced or otherwise made available (through imports, e.g.) by the formal seed system. Stakeholders have proposed to use the Quality Declared Seed (QDS) standard [11]. QDS is recognized by the 2013 Ethiopian Seed Proclamation [20] and provides an alternative certification scheme that could help formalize the informal seed system actors to produce quality-assured seeds by providing flexibility to seed producers, including cooperatives [11]. However, such a scheme may not be the most suitable for bred forages, which gains in importance elsewhere and would need to consider regulations around intellectual property rights (IP). It is to be noted QDS is not yet accepted across all countries of the region, which could have implications for intra-region seed movements.

The forage seed system is marked by weak extension system, and market linkages between the value chain actors are broken. There is a general lack of market information. Farmers tend to prefer those forage varieties that use similar production technologies as food and cash crops that are familiar to them. For example, they prefer perennial crops that are propagated by cuttings such as desho grass and annual forages like *Vigna unguiculata* [4, 12].

Forage seed value chain

Results from survey reveal that perennial forage crops are more preferred than annuals. Several forage species were used including Alfalfa, Desho, oat, vetch, Rhodes, Lablab (*Lablab purpureus*), Elephant grass. Fig. 3 illustrates the forage seed value chain in Ethiopia.

Currently, researchers are supplying the early generation seeds (EGS) in non-consistent manner in a very limited volume. The recipients would multiply the seed in a disorganized manner, and the quality is very difficult to verify. Thus, the small volume of the EGS would not reach a significant number of farmers or users. Moreover, farmers are also operating cooperative-based seed production and supply of forage crops. A consideration would also be important for bred varieties with IP protection, which would require Ethiopia-based seed distribution as part of the seed supply system.

On the demand side, recent developments show a growing awareness of improved forage crops, especially in areas where animal fattening and dairy production are practiced. However, little awareness of improved forage crops, weak market linkages, and inadequate supply of high-quality forage seeds lead to low country-wide adoption of forages. Currently, there are only a few private entities that produce certified forage seeds; however, most of that are sold to institutional buyers such as government and non-governmental agencies [4].

Respondents from the survey indicated competition for land with food crops such as wheat, teff, sorghum, maize, and cash crops such as coffee, chat, and cotton-limiting availability of land for forage cultivation especially in the zones of Arsi and West Shoa in Oromia, North Shoa,West Gojam, South Gondar in Amhara, Mekele and Eastern Tigray (in Tigray), and South Omo and Gamo Gofa zones in SNNPR. However, the proportion of crossbred cattle is increasing in the zones of Southern and Central Tigray in Tigray region,West Gojjam, East Gojam and South Gondar in Amhara region, East Shoa, East Wollega and West Shoa in Oromia region, and Wolayta, Hadiya, and Kembata Tembaro zones in the SNNPR. Figs.A1 and A2 depict the perception from stakeholders surveyed in this study, and the strengths, weaknesses, opportunities, and threats as reviewed from stakeholder surveys, respectively.

Little or no improvement has been made on forage seed yield since the start of the formal forage seed system while prices were growing high (Table A1). Yields of legumes show remarkable increase, while yield decline was reported for grasses. This may be due to several factors ranging from varieties to agronomic practices.Nevertheless, introduction of technologies that would enhance forage seed yield, especially for grass species and introduction of a transparent seed marketing system, which assure proper profit sharing among the players can lower the current high prices of forage seed. Traders may be official agents for seed producers and should be ready to claim reasonable margins for the seed they sell to users.

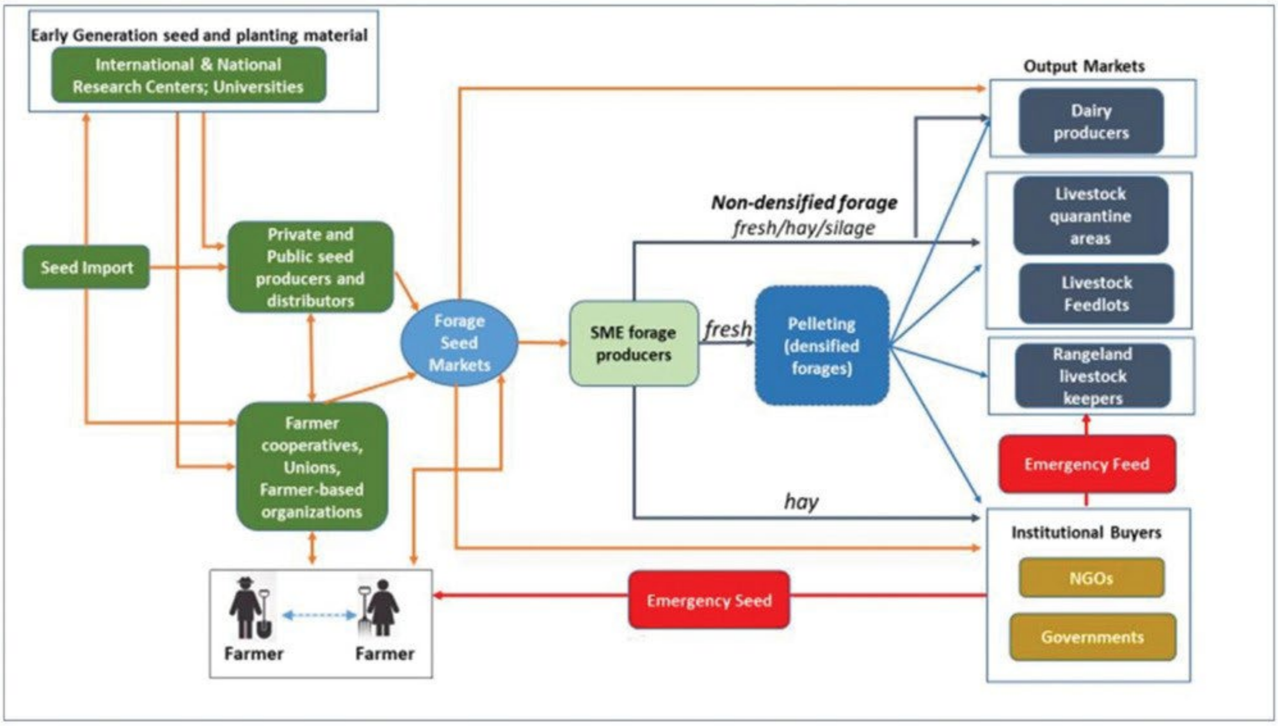

Figure 3. Forage seed value chain in Ethiopia—illustrative.

High / *Medium* / *Low*	Cluster	Region	Level of current forage cultivation (area/importance)	Competition with food/ cash crops	Commercial fattening (%) (range 1–30%)	Commercial dairy (%) (range 1–85%)
	Central Highlands	*Amhara*	Medium	High	Medium	High
		Oromia	Medium	Medium	High	High
		SNNPR	Medium	Low	Low	Medium
	Northern Zone	*Amhara*	Medium	High	Medium	Medium
		Tigray	Low	Low	Medium	High
	Southern Zone	*SNNPR*	Low	High	High	Low

Figure A1. Perception surveyed from stakeholders.

In Ethiopia, food crop seed marketing is an activity of short period of time unless off-seasons are considered. Forage seeds, on the other hand, are sold majorly at two peak periods of the year. Usually, the seed price is lower at harvest time and prices would increase to the maximum at the planting time. In an assessment study conducted in the SNNPR, it was reported that on average 58% price increases on 13 forage crops (Table A2). This aligns with the results of this study where respondents confirmed that forage seeds prices to be highest during May to June (planting time).

Demand for forage seed in Ethiopia—an approximation

Cultivated forages include a variety of annual and perennial grasses, herbaceous and dual-purpose legumes, and multipurpose trees and shrubs. A meta-analysis by Paul *et al.* [22] revealed that improved forage germplasm had on average 2.6 times higher herbage productivity than local controls, with the strongest effect in grasses. In addition to increasing livestock productivity, forages provide environmental benefits. Rao *et al.* [23] describe how the sustainable intensification of forage-based systems yields a range of environmental co-benefits

STRENGTHS

- Various interests and enthusiastic partners
- Several improved varieties are released and garnerin among smallholders
- Several improved varieties are highly suitable in Ethiopia
- Demand for forages is on the rise through increased animal production

WEAKNESSES

- Shortage of quality forage seed supply, including Early Generation Seeds (EGS)
- Limited technical capacities
- Lack of market linkages
- Shortage of high-quality feed; seasonality
- Land and extension services
- High transport and storage costs

OPPORTUNITIES

- Strengthen forage seed system starting with supply of EGS
- Develop training material (traditional and digital) to increase capacity on the ground to provide tailored extension services; raise awareness
- Develop new and strengthen existing market linkages
- Introduce high-quality feed preservation techniques

THREATS

- Droughts
- Internal conflicts
- High fluctuations in cost elements
- Pests (alien weed prosopis)

Figure A2. Strengths, weaknesses, opportunities, and threats (SWOT)—forage seed value chain.

Table A1. Development in seed yield of some forages.

	Production record (kg/ha)		
Forage types	QDS producers (2020)	FLDP (1988–1993)	Difference (kg/ha)
Panicum	275	300	(25)
Rhodes	325	400	(75)
Oats	500	1500	(1000)
Lablab	1200	500	700
Cow pea	1000	800	200
Pigeon pea	1500	1000	500

Table A2. Forage seed price fluctuations in 2013 crop season in SNNPR.

	Selling price in low and peak demand seasons		
Forage seed	Minimum selling price	Maximum selling price	% change in price
Alfalfa	300	500	60.00
Cow pea	20	35	57.14
Desmodium	200	700	28.57
Lablab	25	35	71.43
Leucaena	35	45	77.78
Oat	50	75	66.67
Panicum	80	250	32.00
Pigeon pea	20	35	57.14
Rhodes	150	380	39.47
Sesbania sesban	40	60	66.67
Siratro	35	45	77.78
Tree Lucerne	100	160	62.50
Vetch	35	55	63.64

Source: Zekarias *et al.* [21].

leading to improved resilience to climate vulnerability and mitigation of climate change.

Choice of forage crops

The following criteria were used to choose cultivated forages for this study:

(i) *Species that are registered and available in Ethiopia*. Since commercial cultivation of forages requires availability of, and access to, sufficient amounts of quality seeds for the forages in question, we narrowed in first instance to forages registered and available in Ethiopia [19], thereby ensuring access to the seeds.

(ii) *Nutrient contents and yields*. The forages selected produce relatively high biomass yields that are also of good nutrient concentration and digestibility, thereby making available the desired nutrients for maintenance, growth, production, and reproduction of animals.
(iii) *Local adaptation*. Further, the forages should be adapted to diverse Ethiopian ecologies especially in the highlands where rain-fed production is possible or in areas where irrigation could be employed [19, 24, 25].

This study utilized the following improved forages, complementing other feed options: *Panicum maximum* (syn. *Megathyrsus maximus*), *Brachiaria* (syn. *Urochloa*) hybrid Mulato II, *Chloris gayana* and *Avena sativa* (Grasses), *Lablab purpureus*, and *Vigna unguiculata* (Legumes). These forages are not only productive and nutritious under good management, fulfilling diverse production niches but are also adaptable and do well under irrigation. Biophysical suitability criteria and associated thresholds for these forages were taken from Tropical Forages: an interactive selection tool by Cook *et al.* [26] and confirmed by forage experts of The Alliance of Bioversity International and CIAT and ILRI (International Livestock Research Institute) (Table A3). The four forage grasses contain moderate protein and energy levels (*Panicum*, Rhodes, *Brachiaria*, Oat) and the two legume forages are rich in protein and moderate in energy (Lablab, Cowpea), thus complementing each other.Table 1 provides a summary of the attributes of the selected species andTable A4 describes their attributes.

The select forage crops exhibit different ranges of agro-ecological suitability. Together, they provide options for growing forages across large areas of Ethiopia, though with a general trend of higher suitability in the highlands, due to more favorable agro-climatic conditions. In comparison with the annual/bi-annual legumes, the capacity to stay green and persistence of the perennial grasses extends further into the drier areas, with Rhodes grass being more adaptable than *Brachiaria* Mulato II and *Panicum maximum* being the most demanding in terms of agro-ecological conditions. Oat, an annual, fits in a wide range of altitude 1750–3000 meters above sea level [27]. All forages stated can be grazed or used under cut-and-carry and are suitable for hay or silage.

The suitability analysis for forage adaptation did not consider irrigation.In areas with ample surface or groundwater resources, irrigated forage production would further increase the area in Ethiopia where these forages have production potential [25, 28] including the dry lowlands.

The forages have various attributes that contribute to ecosystem health and services. Except oat, the other forages do well in humid to semi-arid areas, with better water-use efficiency and with deep rooting system that contributes to soil carbon through turnover [28–30]. *Brachiaria* species through brachialactone compounds could contribute to nitrification inhibition thereby minimizing nitrate (NO_3) and nitrous oxide emissions (N_2O), the first polluting water resources, the latter a highly potent greenhouse gas that contributes to global warming [31]. *Panicum* and Rhodes grasses so far do not exhibit major diseases and pests of economic importance in the region. However, lablab, cowpea, and oat are often affected by fungal rusts associated with moist conditions, while *Brachiaria* hybrids are attacked by spidermites, though varietal tolerance is diverse. Spidermites appear mostly during dry weather, but the spidermites are phobic to wet conditions, and disappear during rains or under irrigation.

In Ethiopia, many farmers prefer to cultivate perennial forages, which occupy the allocated piece of land without having to replant seasonally, for example, *Panicum maximum*, *Brachiaria* hybrid, and *Chloris gayana* for grasses and Alfalfa (*Medicago sativa*) for legumes. However, some farmers prefer short-lived forages that would allow growing other crops thereafter. For this reason, we incorporated oat (*Avena sativa*), an annual forage grass [32], and annual/bi-annual legumes cowpea (*Vigna unguiculata)* and *Lablab purpureus.*

Estimation of forage seed demand in Ethiopia

The accurate amount of forage seed required is not known for Ethiopia. Using available figures from the literature, we calculated the approximate amount of forage seeds that would be required for bridging the feed demand shortfall, as cited in Ethiopia Feed inventory [7].

While we show the expected forage seed requirement, the issue of land available for cultivation comes to the fore. A comprehensive study on land availability including potential for small-scale forage irrigation revealed substantial suitable land for forage production in Ethiopia [24]. According to this study, approximately 90,000 square km is highly suitable for the currently most used Desho grass (*Pennisetum pedicellatum*), which is indigenous in Ethiopia, at 85% suitability level in arable lands. In hectares, this translates to 9,000,000, a size 12.7 times as much the land estimated for Lablab or Cowpea (Table A5), the highest among the species in consideration under this study.While the arable land is diverse in rain-fed cropping in Ethiopia, a study on available water for small scale irrigation in agricultural lands (rain-fed and water from water bodies) showed the possibility of increasing forage production, especially in the dry season with water storage ranging from 2.89 to 1722 mm [25].

Annual Feed Demand of ruminants (cattle, sheep, goats) (AFD) comprises of roughages and concentrates.

(i) Annual Roughages Demand,ARD (70% of AFD). Feed in developing countries, including Ethiopia, generally comprises of 70% roughage and 30% concentrate.Therefore, roughage demand was taken as 70% of feed demand.
(ii) Annual Roughages Deficit, ARDef (21.2% of ARD).The deficit prevails with all roughages considered (natural pastures, cultivated forages, and crop residues) that is the basal diet, and it is 21.2%.
(iii) Annual Cultivated Forage Deficit—ACFDef (33% of ARDe to account for recommended cultivated forage inclusion in roughage for sustainable food production systems).

Table A3. Forage types and thresholds used for the suitability analysis.

			Temperature (°C)		Precipitation (mm)		Length of growing Season		Elevation (m)		Soil pH		Soil organic carbon (mg/ha)	
Forage	Common name	Type	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Brachiaria	Mulato II Hybrid	Perennial grass	15	35	700	2615	24	52	0	1800	4.6	8	10	1000
Chloris gayana	Rhodes grass	Perennial grass	5	50	310	4030	24	52	0	2400	4.5	10	20	1000
Lablab purpureus	Lablab	Annual legume	3	30	500	3000	11	52	0	2000	4.5	7.5	10	1000
Avena sativa	Oat	Annual grass	5	26	500	1000	11	52	1600	2000	4.5	8.6	20	1000
Vigna unguiculata	Cowpea	Annual legume	25	35	650	1100	10	16	0	1500	4	7	20	1000
Panicum maximum	Panicum	Perennial grass	15	30	1100	2500	24	52	0	2000	5	8	10	1000

Table 1. Selected forage species for the study and their agronomic attributes.

Forage	Seed-rate (kg/ha)	Days to first cut (perennials)	Days to regrowth cutting (perennials)	Days to cutting after sowing (annuals)	Potential yield (t/ha/year)
Panicum	3	75–90	30–45	–	20
Rhodes grass	3	90–150	60	–	15
Oat	100	–	–	95	28
Lablab	20	–	–	90	8
Cowpea	20	–	–	70–90	8
Brachiaria-Mulato II	8	90	30–45	–	17

–, implies not applicable.

AFD = 115,740,000 tonnes.

ARD = 115,740,000 × 0.70 = 81,018,000 tonnes [(factor of 0.70 based on (i)].

ARDef = 81,018,000 × 0.212 = 17,013,780 tonnes [(factor of 0.212 based on (ii)].

ACFDef = 17,013,780 × 0.33 = 5,614,547 tonnes [(factor of 0.33 based on (iii)].

As cultivated forages are intended for supplementation, we scaled back estimations at 33% of the deficit of the basal diet (roughages i.e. 70% of the diet).We have taken this level of the 33% replacement of roughages with cultivated forages, keeping in mind sustainability of the food system since land used for cultivation of forages can potentially compete with the food grain crops. A level of 33% of cultivated forages in the total roughage part is the minimal to elicit a good animal production response under developing country scenarios, provided the concentrate feeds (30% of the diet) have a good protein level. Additionally, for sustainability of the food systems, it is prudent that the concentrate portion of the diet comprises of those components (e.g., agro-processing by-products) that do not compete with human food. Furthermore, the rest of the roughages, besides cultivated forages, should be crop residues, tree leaves, and pasture biomass, among other human non-edible biomass.

To meet the deficiency of cultivated forages, as calculated above, the seed requirement is calculated using the following assumptions.

- For each of the forage type, seed system is functioning, and therefore, enough seed is available and 100% adop- tion to cover the dry matter deficit.
- Forage seed supply and demand pull are growing with smooth policy support.
- The selected forages are adopted to the extent of 20% for grasses and 10% for legumes at the annual rate of 10% each.

Adoption rate

Adoption would happen simultaneously for the various forage species and not in a year but over years. Forage adoption in eastern African countries varies depending on the area, with humid and sub-humid areas standing higher chances of adoption under rain-fed conditions [33].The study using economic surplus model showed that the adoption rate in the Mixed crop and livestock, Rain-fed, Arid/ semi-arid (MRA); Mixed crop and livestock, Rain-fed, Humid/sub-humid (MRH); and Mixed crop and livestock, Rain-fed, Temperate/tropical highlands (MRT) zones of Ethiopia have higher potential than the much drier lowlands [34]. From the study, the high-potential zones MRA, MRT, MRH come with adoption likelihood of 2, 3, 4 on a scale of 1–5, where 1 = not at all likely, and 5 = very likely. By interpolation, the Ethiopian scores for the three zones (MRA, MRT, and MRH) translate to 25%, 50%, and 75% respectively of adoption.We took a conservative figure of 20% for grasses and 10% for the legumes (excluding alfalfa) for the extent of adoption.The legumes are difficult to grow and maintain, and hence, their adoption likelihood is expected to be lower.

If the entire cultivated forage deficit for 1 year is to be met by these six forages, a total of ≈7700 tonnes of forage seed would be required in the first year (Table 2). However, their adoption rate would differ and taking an average annual adoption rate of 10%, the amount of seed required for the first, second, and third years would be respectively 773, 1454, and 2135 tons (Table 2). As such, at any adopting level, appreciable amount of seeds would be required, and therefore the essence of functional forage seed system in Ethiopia.

Seed replacement rate

For the perennial forages, once the stand is established, it could stay for a long time before replanting. Specifically, a grass stand of the perennial grasses considered here could produce for up to 8–10 years or even longer with the good management. Keeping the forage grasses weed-free and top dressing with nitrogenous fertilizers annually are key for the longevity of the perennial forages (often where the producers fail, necessitating a fresh planting).While the establishment is possible from seeds or vegetatively using splits, the splits are bulky, which increases the labor cost, especially if the land size is extensive. Legumes fix atmospheric nitrogen, but the addition of phosphorus especially at planting bolsters their performance. On the other hand, annual forages require planting afresh once harvested; therefore, seed is required seasonally. Mostly in eastern Africa, there are two rainy seasons in a calendar year hence seed requirement for annual forages up to twice a year.

Farmers in Ethiopia can easily borrow some management skills from food crops they are familiar with. For example, on seed size that determines the depth of seed placement,

Table A4. Quality attributes of the selected forage species.

Forage type	Crude protein (% dry matter, DM)	Crude fibre (% DM)	Neutral detergent fibre (% DM)	Acid detergent fibre (% DM)	Lignin (% DM)	In vitro organic matter digestibility (%)	Organic matter digestibility (%)	Metabolizable energy, MJ/kg DM	DM as fed (%)
Panicum maximum	11.2 ± 4.3 (n = 2396)	37.3 ± 3.7 (n = 2218)	72.3 ± 6.5 (n = 245)	43.4 ± 5.4 (n = 178)	6.1 ± 1 (n = 177)	65	59.2 ± 6.5 (n = 50)	8.0	22.7 ± 7.4 (n = 1835
Rhodes grass (*Chloris gayana*[2])	9.0 ± 2.8 (n = 262), [9.6–12.4][9], [9.8][10]	36.9 ± 3.9 (n = 235)	75.0 ± 3.4 (n = 28), [65.0–67.0][9], [62.7][10]	43.0 ± 3.3 (n = 22)	6.0 ± 1.7 (n = 12)	—	60.4 ± 7.5 (n = 18), [65][10]	8.5, 9.01	24.9 ± 6.2 (n = 197)
Forage oats (*Avena sativa*)[3]	10.5 ± 4.1 (n = 66), [4.8–7.6][11]	30.2 ± 3.5 (n = 37)	54.2 ± 8.1 (n = 37), [58.6–68.3][11]	31.0 ± 6.3 (n = 37), [37.0–43.9][11]	4.5 ± 1.1 (n = 10), [5.4–7.2] [11]	[43–62][11]	67 ± 5.9 (n = 19)	9.3	26.3 ± 6.7 (n = 43)
Lablab purpureus)[4]	18.4 ± 3.1 (n = 92)	28.2 ± 3.1 (n = 59), [23.7][12]	44.6 ± 4.3 (n = 49), [25.3][12]	32 ± 4.7 (n = 62), [12.2][12]	7.2 ± 1.8 (n = 21), [4.4][12]	—	67	9.2	22.1 ± 7.3 (n = 23)
Cowpea (*Vigna unguiculata*)[5]	18.1 ± 2.8 (n = 24), [17.3][13]	24.1 ± 6.1 (n = 18)	38.6 ± 6.6 (n = 13), [43.3][13]	27.1 ± 6.8 (n = 14), [34.2][13]	4.6 ± 1.4 (n = 5), [6][13]	[67.1][13]	71.2	9.8, [10.1][13]	20.9 + 5.6 (n = 9)
Brachiaria -hybrid	(10–17)[14]	31.4	68.1	37.2	5.1	67.2–71.4	55.2	7.3–9.1	
Alfalfa[6]	20.6 ± 3.4 (n = 1832)	26.7 ± 4.1 (n = 1187)	39.3 ± 6.3 (n = 1305)	30.9 ± 5.0 (n = 1451)	7.6 ± 1.8 (n = 1224)	—	68.5 ± 5.5 (n = 112)	9.4	19.9 ± 3.1 (n = 1277)
Mixed natural grass hay in Ethiopia[7]	[6.4]	—	[73.2]		[7.5]	[57.2]	—	—	—

[1]Feedipedia: https://www.feedipedia.org/node/480
[2]Feedipedia: https://www.feedipedia.org/node/500
[3]Feedipedia: https://www.feedipedia.org/node/12192
[4]Feedipedia: https://www.feedipedia.org/node/233
[5]Feedipedia: https://www.feedipedia.org/node/275
[6]USAID.SPS-LMM Program. Feed Resources and Feeding Management.
[7]Afr. J. Agric. Res. 8(46):5841–5844 (2013). Grown under sub humid climatic conditions of western Ethiopia.
[8]Trop.Sci. 46(2):87–91 (2006). Cultivated in Awassa, Ethiopia.
[9]Grass and Forage Science, 69, 635–643 (2013). Grown in Rift Valley in Ethiopia. [10]Trop. Sci. 47: 188–196 (2007). Study in Ethiopia, included CIAT varieties as well. [11]Trop Anim Health Prod (2018) 50:1271–1277. Study conducted in Ethiopia.
[12]J Anim Sci Adv 2014, 4(1): 682–689. Grown in western Oromia. Includes ILRI accession and cultivar WWT.
[13]Tropical Forage fact sheet https://core.ac.uk/download/pdf/159238435.pdf
[14]Tropical Grasslands – Forrajes Tropicales (2014) Volume 2, 197–206.

Table A5. Forage seed required for selected forages.

Common name	Seed-rate (kg/ha)	Potential dry matter yield (tonnes/ha)	Forage area required (FAR) (ha)	Forage seed required (FSR) for meeting the deficit by one of the selected forages (tonnes)
Panicum	3	20	280,727	842
Rhodes grass	3	15	374,303	1123
Forage r oat	100	28	200,520	20,052
Lablab	20	8	701,818	14,036
Cowpea	20	8	701,818	14,036
Lucerne/Alfalfa	8	18	311,919	2495
Mulato II	8	17	330,267	2642

Panicum and Rhodes grass are like Teff; Cowpea and Lablab to common garden pea; and *Brachiaria* and oat to wheat. Therefore, farmers can easily adapt to land preparation and planting using their technical expertise with food crops.

To sum, the forages proposed in this study—*Panicum maximum*, *Brachiaria*- Mulato II, *Chloris gayana* and *Avena sativa* (Grasses), *Lablab purpureus*, and *Vigna unguiculata* (Legumes)—are not only productive and nutritious under good management, but also are adaptable and do well under irrigation.The outlook for the seed requirement for the above forages for a four- and ten-year horizon is approximately 7200 and 38,700 tons, respectively.With the given proposition, awareness creation on the opportunities of forage cultivation, feed planning, and budgeting, coupled with capacity development of farmers, are some of the key requisites for forage seed uptake. Development and adoption of forage business cases with financial margins could precipitate uptake of forage cultivation in with knock- on effect on forage seed demand, which in turn would contribute to increased livestock productivity in Ethiopia.

Feasibility of forage-based pelleting—learnings from global case studies

Densification of forages to form pellets is currently being practiced in many countries, for example, Kenya, Tunisia, Mexico, and India. The authors conducted a survey with key stakeholders in these countries to assess the feasibility of forage-based pelleting (approach and questionnaire used are presented in Table A6).

Results from the survey indicate increased interest in the forage densification technologies and high potential for increasing livestock production and productivity, as well as for managing emergencies. The introduction of the novel densification technology to form pellets could improve preparedness against natural calamities and save animals from hunger and death during emergencies.

In comparison, densification in the form of silage or bailage is not an attractive option since silage contains up to 4–5 times more water than pellets, which increases the cost of transport of the nutrients between the forage production sites and areas affected by droughts.The shelf-life of densified forages in the form of pellets is higher than that of silage or bailage.The pellets can be stored for up to 9 months in dry and rodent-free places. These can even be air lifted to the remotest places to avert disasters.

Besides the benefits provided by easier transport and storage [35], feed pellets make it possible to supply feeds of uniform quality throughout the year, reducing price volatilities. Additionally, animals tend to select ingredients of high quality and leave those of poor quality when fed in loose form leading to wastage and decreased efficiency of feed utilization. This constraint can also be mitigated through densification as it does not allow animals to select ingredients.

Furthermore, the intake of pelleted feeds is higher and so is the nutrient availability from the consumed feeds to the animals. The release of nutrients from the pellets is more sustained and synchronized with the nutrient requirements of animals.This decreases methane emission from ruminants and enhances the feed-use efficiency [36]. The use of densified products as animal feed offers an attractive option that could contribute to mitigation of ongoing climate changes in addition to enhancing livestock productivity and production.

Formation of a balanced total mixed ration (TMR) from individual components by farmers requires knowledge of nutrient contents of the components.However,livestock farmers in developing countries often do not have this knowledge nor the technical capacity.Thus,capacity building is key.

These learnings illustrate that densification of cultivated forages could be an option for Ethiopia to increase supply of high-quality feed, especially in dry areas and during long drought periods.

Nutritional, economical, and environmental assessments of cultivated forages

Nutritional evaluation

It is important to fulfill ME and CP requirements of animals through a diet. For assessing the nutritional suitability of forage-based diets, the requirements of ME and CP were calculated, and then, the amount of the forage-based diet that meets the requirements of nutrients (CP and ME) was estimated. All ME and CP values reported here are on dry

Table 2. Annual forage seed requirement (AFSR) in tons.

Forages	AFSR forages grown simultaneously deficit[a]	Annual FSR for the first 10 years[b] (tons)									
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Panicum	168	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8
Rhodes grass	225	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5
Forage oat	4010	401	802	1203	1604	2005	2406	2807	3208	3609	4010
Lablab	1404	140	280	420	560	700	840	980	1120	1260	1400
Cowpea	1404	140	280	420	560	700	840	980	1120	1260	1400
Brachiaria	528	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8	52.8
Regeneration seed[c] (perennials)	—	—	—	—	—	—	—	—	102	102	102
Total	**7739**	**773**	**1454**	**2135**	**2816**	**3497**	**4178**	**4859**	**5652**	**6323**	**7004**

[a]When 100% of annual cultivated forage deficit met in the first year by growing simultaneously the four grasses @ 20% each and two legumes (leaving aside Alfalfa).
[b]10% increase per annum (a life span of 10 years was taken for the perennial grasses).
[c]For the three perennial grasses.

Table A6. Key informant Questionnaire for the Study on practicability of forage into pellets in India, Mexico and Tunisia.

Introduction
Supporting Seed Systems for Development (S34D) is an USAID funded Feed-the-Future Global Activity led by Catholic Relief Services (CRS) with its consortium partners, of which ABC-CIAT-PABRA is one. The goal of S34D is to improve functioning of the high-impact integrated seed systems through expanding crop-variety choices for smallholders at the last-mile. Under S34D, CIAT and CRS are seeking to bridge gaps between development and emergency and chronic seed systems through development of viable business models in Ethiopia, while at the same time creating jobs especially for women and youth along the value chain. This is especially so for the sub-Saharan countries that have lagged behind compared to other places on the globe in livestock productivity. To avoid reinventing the wheel and potential pitfalls, we pursue to borrow lessons from countries already using the technologies including India, Mexico and Tunisia.

Objective and justification
Ethiopia ranks one of the highest countries with livestock. However, the livestock productivity is quite low. CIAT and CRS are seeking to understand the viability and practicability of turning grown forages into compacted forms for exmple pellets/cubes/leaf meals/blocks in Ethiopia. Given the vast distances between areas of forage production and consumer regions, we would examine whether it is economically sound to use densified forages to provide basal diet or densified total mixed ration containing forages in feedlots and fodder banks specially during emergencies such as frequent droughts in the Ethiopian lowlands. Lessons from India, Mexico and Tunisia will inform the current undertaking.

FORAGES throughout this document refers to CULTIVATED/GROWN FORAGES

Consent
Your participation in this interview is guided by the principle of **free, prior and informed consent (FPIC).** The interview shall be one-off and will take approximately 40 minutes. Your participation is voluntary and you can withdraw anytime during the interview should you feel the need to. The information provided is confidential and will only be used for the purposes of this study, and information kept up to when analysis and reporting shall be complete. If you or your organisation would want to get the report after analysis, we would be happy to share. Analysis would be in aggregated form without identifying individuals.

Should you have any questions after the session, please feel free to contact Dr Michael Peters, M.PETERS-CIAT@ CGIAR.ORG . Alternatively, you may contact CIAT, C/o ICIPE, Duduville Campus off Kasarani Road, P.O. Box 823-00621, Nairobi, Kenya.

*******Thank you!**
****

Section 1: interviewee particulars	
1.1	Name:
1.2	Country:
1.3	Organization of affiliation
Section 2: the technology	
2.1	What key grown forages are used for cattle production in your country
2.2	Which forages are grown under rain-fed and irrigation?
2.3	Taking grown forages generally across the country, what is the form of use, as proportionate of the overall available forage?

2.1

	Common name	Scientific name
1.		
2.		
3.		
4.		
5.		
6.		

2.2

	Rain-fed	Irrigated
1.		
2.		
3.		
4.		

2.3

Forage form	Percentage (%)
Fed as fresh	
Hay	
Silage	
Pellets	
Cubes	
Leaf meals	
Blocks	
Other, specify	

Note: All values in the percentage (second column) should add up to 100.

Table A6. Continued.

2.4 Who are your main clients for the densified products (e.g. cooperatives, farmers' organization, private traders, etc.)?

	Pellets	Cubes	Blocks	Other product:
1.				
2.				
3.				
4.				
5.				

Remarks, if any:

List animals (e.g. dairy cows, beef animals, etc.) to which pellets, cubes and blocks or any other densified product are fed

	Pellets	Cubes	Blocks	Other product:
1.				
2.				
3.				
4.				
5.				

Remarks, if any:

2.5 From the production site of the forage pellets, cubes and blocks (or other densified forage products), what is the furthest distance (km) they are consumed/utilized?

	Pellets	Cubes	Blocks	Other product:
Km				

2.6 How are forage pellets, cubes and blocks (or other densified forage compounded products) transported to the furthest consumer points?
What is the transportation cost per kilometer?
Since the transport cost would vary with the payload and/or capacity of the transport mode, what is the load (tonnes) of the vehicle for which the cost per kilometer you have given?

		Pellets	Cubes	Blocks	Other product:
Transport mode	1.				
	2.				
Cost/Km	1.				
	2.				
Load (tonne)	1.				
	2.				

Remarks, if any:

2.7 What are the advantages and disadvantages of using forage pellets (or other densified forage products) given the conditions in your country?

	Advantages	Disadvantages
1.		
2.		
3.		
4.		
5.		

Remarks, if any:

Table A6. Continued.

2.8	What is the type and total cost of forage densification machine of different capacities that includes all the components e.g. mower, grinder, mixture, pelleting machine and packaging? Are they mobile or not (tick the appropriate)?

	Machine capacity (tons/8 h shift)	State type: Pellet/Cube/ Block	Total Cost (US$)	Mobile	Not mobile
1.					
2.					
3.					
4.					
5.					
6.					

If your unit is not mobile, do you see advantage of having a mobile unit in your settings:

Another remarks, if any:

2.9	What is the cost of each of the components of the forage densification units? Note: Sum of costs of all the components should be equal to the total cost given in the previous table

		Cost (US$)					
	Machine capacity (tonnes/8 h shift) and type*	Mower	Picker	Grinder	Mixer	Only densifying unit (pellet, cube or block making machine)	Packaging machine
1.							
2.							
3.							
4.							

*from previous table and type that is pellet, cube or block production If we have missed any component, please list that and include its cost Any other remarks, if any:

3.0	Keeping tables 2.8 in mind, could you please list operational cost/8 h shift, and list the capacity (tons/8 h shift). (Note: the capacity is being again requested to avoid any confusion)

	Pellets	Cubes	Block	Other product
Capacity (tonnes/8 h)				
	Operational cost in US$ per 8 h shift			
Additives e.g. binder or vitamins/minerals if any				
Electricity				
Labour				
Packaging material				
Others, specify:				
Others, specify:				

Table A6. Continued.

3.1 What are the packing units in kg that you produce for pellets and cubes for selling; and block weight in kg that your machine produces

	Unit (kg/bag for Pellet and Cubes, and kg/block)			
	Pellet	**Cube**	**Block**	**Any other product:**
Remarks, if any				

3.2 What advice would you give to someone about to start business on cultivated forage pellets (or other densified forage products)? What constraints have you encountered in the business and what feedback/preferences for densified forage products (pellets, cubes, blocks) do consumers have?

	Dos	Don'ts
1.		
2.		
3.		
4.		
5.		

	Constraints	Feedback
1.		
2.		
3.		
4.		

3.3 What is the adoption percentage of forage pellets, cubes and blocks in your country with reference to livestock keepers? Is it increasing, decreasing or remains the same?

Pellets

Adoption (%) (tick one)	Increasing	decreasing	Remains same
	Tick one		
1–20			
21–40			
41–60			
61–80			
81–100			

Cubes

Adoption (%) (tick one)	Increasing	decreasing	Remains same
	Tick one		
1–20			
21–40			
41–60			
61–80			
81–100			

Blocks

Adoption (%) (tick one)	Increasing	decreasing	Remains same
	Tick one		
1–20			
21–40			
41–60			
61–80			
81–100			

Remarks, if any:

Table A6. Continued.

3.4	What has been the role of women in the forage pellets or other densified forage products chain including feeding to livestock? 1. 2. 3. 4. 5. Do pellets or other forage densified products businesses employ youth? [yes] [no] tick one What are the opportunities to engage youth in this business? 1. 2. 3. 4. 5.
3.5	Compared to other grown forage products (e.g. silage, hay or fresh), in your country, how would you rate the importance of grown-forage pellets or other densified forage products? ☐ Very high ☐ High ☐ Moderate ☐ Low ☐ Very low How is the potential to scale forage pellets (or other densified forage products) production in your country? ☐ Very high ☐ High ☐ Moderate ☐ Low ☐ Very low Remarks, if any:
That is the end of the interview, thank you for agreeing and taking your time.	

matter basis. The analyses assess whether forages chosen in this study alone or as a mix are of sufficient nutritional quality to meet the nutrient requirements of beef and dairy animals. For most of the animals in Ethiopia, the potential average daily growth rate varies from 0.5 kg to 1.0 kg under different production systems, depending on breed and feeding regimes [16,37,38]. In rare cases, for example, for Ethiopian Hararghe Highland cattle (*Bos indicus*), an average daily growth rate of 1.3 kg has been observed in experimental conditions [38].

Four settings are illustrated: fattening sector for beef animals, low-to-moderate mild-yielding dairy cows, cattle during drought period, and high-milk-yielding dairy cows. For the first three settings, a forage-based feed containing 10% crude protein (CP) and 9.3 MJ/kg metabolizable energy (ME) on dry matter basis (Feed-A) was chosen. For the last setting (high-milk-yielding dairy cows), a feed of higher nutritive value containing 14% CP and 9.3 MJ/kg ME on dry matter basis (Feed-B) was taken. These compositions were taken due to ease of formulation of these feeds with the forages identified in this study.

Fattening for beef animals: Three scenarios (Scenario I: starting body weight (BW) of animals 250 kg, growth rate of 1 kg/day, and fattening duration of 100 days; Scenario II: starting BW of animals 260 kg, growth rate of 0.75 kg/day, and fattening duration of 120 days; and Scenario III: starting BW of animals 260 kg, growth rate of 0.50 kg/day, and fattening duration of 180 days were considered. The final BW of animals was 350 kg for all three scenarios.

The equations used for ME requirements of animals were based on [39].

ME requirement for maintenance x MJ/day = 0.53 kg BW 0.75; and
ME requirement for growth y/day = 37 MJ/kg BW gain.
CP requirement was calculated from the digestible crude protein (DCP) values:
DCP for maintenance, g/day = 3.2 kg BW 0.75; and DCP for growth, g/day = 0.3 g BW gain.
The CP digestibility of forage-based diet was taken as 65%; therefore:

CP requirement for maintenance, g/day = DCP × 100/65 = 4.923kg BW 0.75;
CP requirement for growth, g/day = DCP × 100/65 = 0.462g BW gain.

The key assumptions for the analysis were: (a) the animals have genetic potential to achieve above-listed daily body weight gains, (b) the diets have sufficient minerals and vitamins, and animals have free access to water, (c) the animals do not suffer from diseases, and (d) the animal would not be able to consume a diet at a level >3.5% of the body weight.

Low-to-moderate dairy cows: We calculated the nutrient (ME and CP) requirements of maintenance for dairy cattle weighing from 250 to 350 kg and milk production from 2 to 10 L, to assess whether cultivated forage-based diet of 10% CP and 9.3 MJ/kg of ME (Feed-A) could meet these thresholds.

We used [40] values for ME and CP requirements:

- ME requirement (MJ/day) for maintenance of dairy animals: 0.48 × (BW in kg)$^{0.75}$
- ME requirement for milk production: 5.3 MJ/l milk.
- CP requirement (g/day) for maintenance of dairy animals: 4 × (BW in kg)$^{0.75}$.
- CP requirement for milk production: 85 g/l milk.

The key assumptions in the analysis were (a) the diets have sufficient calcium and other minerals and vitamins, and animals have free access to water, (b) the animals do not suffer from diseases, and (c) the dairy animal would not be able to consume diets at a level >3.8% of the BW.

High-yield dairy cows: For dairy animals of higher genetic potential (e.g., crossbred), yielding daily milk of 15 L or more, a diet of higher CP and ME would be required and these scenarios are discussed below. For dairy animals, a diet of CP of 14% and ME of 9.3 MJ/kg (Feed B) would be possible by mixing any of the three non-legume forages (Panicum, *Brachiaria*, and Rhodes) with any of the two legumes (cowpea and lablab) identified for cultivation in this study, in the ratio of around 1:1 (w/w).We calculated nutrient requirements for high-yielding dairy cows and assessed whether Feed-B could meet those requirements.

Cattle during drought period: The approach used for calculation of ME and CP requirement for maintenance of animals was the same as presented above for beef animals. The equations used were:

- ME requirements of animals for maintenance, MJ/day = 0.53 × (kg BW)$^{0.75}$; and
- CP for maintenance, g/day = 4.923 × (kg BW$^{0.75}$).

The key assumption for the analysis was hay used in drought conditions in Ethiopia has the same contents of ME and CP as taken from the literature.

Meeting nutrient requirements of beef animals through forage-based diets

For each of the three scenarios, ME requirements and the amounts of forage-based feed needed to meet those ME requirements are presented in Table A7.This is followed by presentation of CP requirements of animals and conversion of these into percent CP in the forage-based feed (by taking the amount of the forage-based feed that meets the ME requirements as stated in the previous sentence). If these percent values are ≤10%, it implies that the forage- based feed of 10% CP and 9.3 MJ/kg ME will be able to meet the nutrient requirements. The results show that a cultivated forage-based diet of 9.3 MJ/kg ME and 10% CP would be able to achieve average growth rate from 0.5 to 1 kg/day to arrive at the final BW (slaughter weight) of 350 kg (Table A7).To achieve these growth rates, intakes of forage-based diets would be from 2.5 to 3.0% of BW.

For the animals to grow from an initial BW of 250 kg to final BW of 350 kg in 100 days (Scenario 1), the total amount of feed required is 795 kg/animal. Daily feed required varied from 2.57 to 3.02% of the BW, which an animal can normally consume, and these amounts would meet both the ME and CP requirements. In Scenario 2, the total feed required is 961 kg/animal for the total fattening period of 120 days, and in Scenario 3, the feed required is 1443 kg for the fattening period of 180 days (Table A7). Increase in daily growth rate would decrease the amount of feed required per kg of BW gain. As an example, if we compare Scenarios 2 and 3. The initial (260 kg) and final (350 kg) weights of animals are the same in both these scenarios, giving net gain of 90 kg in 120 days for Scenario 2 and in 180 days for Scenario 3. The feed used in these scenarios is 961 kg and 1443 kg, giving feed-use efficiency values of 961/90 (10.7) and 1443/90 (16.0), respectively. In Scenario 2, 10.7 kg of feed is required for 1 kg BW gain, and this value for Scenario 3 is 16 kg. Increase in daily average growth rate (kg) from 0.5 to 0.75 increases the feed-use efficiency by almost 50%. Feed is an expensive commodity, and feed production is highly energy demanding.The higher the energy need, the higher the greenhouse gas emission. Furthermore, the lesser the feed consumed, lesser is land and water required to produce the feed and methane production from rumen of animals—an overall "win-win" situation of economic meat production and decrease in greenhouse gas emission [9, 41]. So, an increase in average daily BW gain would decrease cost of feeding as well as greenhouse gas emission per unit of meat production.

Generally, animal's upper limit of feed intake is approximately 3.5% of the BW. In the crop-livestock mixed systems, farmers could have hay or straws from their own fields, and these are at no-cost to the farmers. However, hay and straw are low in nutritive value (CP value of 4.5%– 6% and ME of 5–7 MJ/kg), and they alone cannot not meet ME and CP requirements for growth. In such a situation, these low nutritive value feed resources could be mixed with the cultivated forages, provided that the intake does not exceeds 3.5% of the BW. This would reduce the cost of feeding. For feedlot animals in Ethiopia, an intake of up to 4.61% of BW has been recorded [38]. This study also showed that for Ethiopian Hararghe Highland (*Bos indicus*) bulls, a feed intake of 4.61% of the BW of a diet containing 6.1% CP (the diet comprising of 6 kg hay containing 5.5%

Table A7. Metabolizable energy (ME) and crude protein (CP) requirements of beef animals and the need for forage-based feed of 10% CP and 9.3 MJ/kg ME for the three scenarios.

Scenario 1. Metabolizable energy requirement

Starting body weight (BW)-Final BW, (kg)	Metabolizable energy (ME) as MJ/animal							
	Maintenance/ day (x)	Maintenance/ 25 days (x × 25)	Growth/ 25 days (y)	Maintenance + growth for 25 days (x × 25 + y)	Total ME required/animal/ day (x × 25 + y)/25	kg/day ration of 9.3 ME (x × 25 + y)/9.3	Ration/day as % of body weight	Total ration kg/animal for 25 days [(x × 25 + y)/9.3] × 25
250–275	33.32	833.0	925	1758.0	70.3	7.56	3.02	189.0
276–300	35.79	894.8	925	1819.8	72.8	7.83	2.85	195.7
300–325	38.20	955.1	925	1880.1	75.2	8.09	2.70	202.2
325–350	40.57	1014.2	925	1939.2	77.6	8.34	2.57	208.5
Total for 100 days								**795.4 kg/100 days***

ME requirements: maintenance (x): MJ/day = 0.53 × (kg Body weight)$^{0.75}$; and for growth (y)/day = 37 MJ/kg body weight gain.

For this scenario, to enhance the accuracy of feed requirements of animals, the calculations of the requirements (both ME and CP) were made in a graded manner, comprising of four BW block-intervals (kg): 250–275, 275–300, 300–325, and 325–350.

Scenario 1 Crude protein requirement

Starting body weight (BW)-Final BW, (kg)	Crude protein (CP)/animal				
	g CP for maintenance/day	g CP for 1 kg growth/day	Total CP g/day	kg diet calculated to meet ME requirement*	% CP in diet
250–275	309.5	462	771.5	7.56	10.2
275–300	332.5	462	794.5	7.83	10.2
300–325	354.9	462	816.9	8.09	10.1
325–360	376.8	462	838.8	8.34	10.1

* From above table; CP digestibility of forage-based diet = 65%; therefore: CP for maintenance, g/day = 4.923 × (kg BW$^{0.75}$); CP for growth, g/day = 0.462 × g body weight gain. Conclusion: The forage-based pellets (CP 10% and ME 9.3 MJ/kg) would meet the nutrient requirements to achieve daily body weight gain of 1 kg.

Scenario II. Metabolizable energy requirement

Starting body weight (BW)-final BW, (kg)	Metabolizable energy (ME) as MJ/animal							Total ration kg/animal for 33.3 days [(x × 33.3 + y)/9.3] × 33.3
	Maintenance/ day (x)	Maintenance/ 33.3 days (x × 33.3)	Growth/ 33.3 days (y)	Maintenance + growth for 33.3 days (x × 33.3 + y)	Total ME required/ animal/day (x × 33.3 + y)/33.3	kg/day ration of 9.3 ME (x × 33.3 + y)/9.3	Ration/day as % of body weight	

						20 × 9.3		
		830.0	740	1570.0	78.5	8.44	2.52	168.8
260–285	34.32	1142.7	1232.1	2374.8	71.3	7.67	2.95	255.4
285–310	36.76	1224.2	1232.1	2456.3	73.8	7.93	2.78	264.1
310–335	39.16	1303.9	1232.1	2536.0	76.2	8.19	2.64	272.7
335–350	41.50	Maintenance/ 20 days (x × 20)	Growth/ 20 days (y)	Maintenance + growth for 20 days (x*20 + y)	Total ME required/ animal/day (x × 20 + y)/20	Ration kg/day of 9.3 ME (x × 20 + y)/		Total ration kg/Animal for 20 days [(x × 20 + y)/20 × 9.3] × 20

Total for 120 days	**961 kg/120 days***

ME requirements: maintenance (x): MJ/day = 0.53 × (kg body weight)$^{0.75}$; and for growth (y)/day = 37 MJ/kg body weight gain.

For this scenario, to enhance the accuracy of feed requirements of animals, the calculations of the requirements (both ME and CP) were made in a graded manner, comprising of four BW block-intervals (kg): 260–285, 285–310, 310–335, and 335–350.

Scenario II Crude protein requirement

Starting body weight (BW)-final BW, (kg)	Crude protein (CP)/animal				
	g CP for maintenance/day	g CP for 0.75 kg growth/day	Total CP g/day	kg diet calculated to meet ME requirement*	% CP in diet
260–285	318.8	346.5	665.3	7.67	8.7
285–310	341.5	346.5	688.0	7.93	8.7
310–335	363.7	346.5	710.2	8.19	8.7
335–350	385.5	346.5	732.0	8.44	8.7

* From above table; CP digestibility of forage-based diet = 65%; therefore: CP for maintenance, g/day = 4.923 × (kg BW$^{0.75}$); CP for growth, g/day = 0.462 × g body weight gain. Conclusion: The forage-based pellets (CP 10% and ME 9.3 MJ/kg) would meet the nutrient requirements to achieve daily body weight gain of 0.75 kg.

Scenario III. Metabolizable energy requirement

Starting body weight (BW)-final BW, (kg)	Metabolizable energy (ME) as MJ/animal							
	Maintenance/ day (x)	Maintenance/ 50 days (x × 50)	Growth/50 days (y)	Maintenance + growth for 50 days (x × 50 + y)	Total ME required/ animal/day (x × 50 + y)/50	kg/day ration of 9.3 ME (x × 50 + y)/9.3	Ration/ day as % of body weight	Total ration kg/animal for 50 days [(x × 50 + y)/9.3] × 50
260–285	34.32	1715.8	1850.0	3565.8	71.3	7.67	2.95	383.4
285–310	36.76	1838.1	1850.0	3688.1	73.8	7.93	2.78	396.6
310–335	39.16	1957.8	1850.0	3807.8	76.2	8.19	2.64	409.4
335–350	41.50	Maintenance /30 days (x × 30)	Growth/30 days (y)	Maintenance + growth/30 days (x × 30 + y)	Total ME required/ animal/day (x × 30 + y)/30	Ration kg/day of 9.3 ME (x × 30 + y)/30 × 9.3		Total ration kg/ animal/30 days [(x × 30 + y)/30 × 9.3] × 30
		1245.0	1110.0	2355.0	78.5	8.44	2.52	253.2
Total for 180 days								**1443 kg/180 days***

ME requirements: maintenance (x): MJ/day = 0.53 × (kg body weight)$^{0.75}$; and for growth (y)/day = 37 MJ/kg body weight gain (for source see Scenario I).

For this scenario, to enhance the accuracy of feed requirements of animals, the calculations of the requirements (both ME and CP) were made in a graded manner, comprising of four BW block-intervals (kg): 260–285, 285–310, 310–335, and 335–350.

Continued

Table A7. Continued.

Scenario III. Crude protein requirement					
	Crude protein (CP)/animal				
Starting body weight (BW)-final BW, (kg)	g CP for maintenance/day	g CP for 0.5 kg growth/day	Total CP g/day	kg Diet calculated to meet ME requirement	% CP in diet
260–285	318.8	231	549.8	7.67	7.3
285–310	341.5	231	572.5	7.93	7.3
310–335	363.7	231	594.7	8.19	7.3
335–350	385.5	231	616.5	8.44	7.3

CP digestibility of forage-based diet = 65%; therefore: CP for maintenance, g/day = 4.923 × (kg BW^0.75); CP for growth, g/day = 0.462 × g body weight gain. Conclusion: The forage-based pellets (CP 10% and ME 9.3 MJ/kg) would meet the nutrient requirement.

CP and 4 kg maize containing 7.1% CP) supported an average daily body gain of 1.3 kg, from an initial BW of 220 kg to a final slaughter weight of 339 kg. These results suggest that the forage-based diet of 9.3 MJ/kg ME and 10% CP would also be able to sustain daily body gain of 1.3 kg at intake level of >3.5% of the BW.

Through animal nutrition practices, higher daily growth rate could be achieved through (a) increase in genetic potential of animals and (b) feeding a balanced diet to both the existing animals (unimproved) and of the improved ones. Certainly, the above options need to go together with improvement in animal health and other farming practices including housing and free availability of clean drinking water to animals, which will potentially enhance overall farm efficiency. Based on information reported in the literature [17] and received from local experts through consultations, the commercial feedlot farmers do not buy the prepared feed from the feed manufacturers because farmers find the cost of these prepared feeds prohibitive. Therefore, for adoption of the cultivated forage-based total mixed ration (TMR) by feedlot farmers, its cost must be substantially lower than the cost of the feed they themselves prepare on-farm by buying individual feed ingredients and mixing them.

Meeting nutrient requirements of low-to-moderate milk- yielding dairy cows through cultivated forage-based diets

For each of the three body weights of animals (from 250 to 350 kg), initially, ME requirements for maintenance and milk production, and amount of the cultivated forage-based feed needed to meet those ME requirements are presented in Table A8.This is followed by presentation of CP requirement of animals and the CP present in the amount of the forage- based feed that meets the ME requirements.

The percent intakes of the cultivated forage-based diets that meet both the ME and CP requirements are between 1.62% and 3.58% of the BWs, which the animals can consume. It is evident from the results that the forage-based diet containing 10% CP and 9.3 MJ/kg ME would be able to support daily milk yield of only 2 L. For

Table A8. Metabolizable energy (ME) and crude protein (CP) requirements of low to moderate milk yielding dairy animals, and the need for forage-based feed of CP 10% and ME of 9.3 MJ/kg.

Metabolizable energy						
Body weight (kg)	Milk production litres/day	Maintenance ME/ day, MJ	ME for milk production/day, MJ	Total ME/day, MJ	kg diet/day of 9.3 MJ/kg ME	% Body weight
250	2	30.18	10.6	40.78	4.38	1.75
	5	30.18	26.5	56.68	6.09	2.44
	8	30.18	42.4	72.58	7.80	3.12
	10	30.18	53	83.18	8.94	3.58
300	2	34.60	10.6	45.20	4.86	1.62
	5	34.60	26.5	61.10	6.57	2.19
	8	34.60	42.4	77.00	8.28	2.76
	10	34.60	53	87.60	9.42	3.14
350	2	38.84	10.6	49.44	5.32	1.77
	5	38.84	26.5	65.34	7.03	2.34
	8	38.84	42.4	81.24	8.74	2.91
	10	38.84	53	91.84	9.88	3.29

Crude protein

Body weight (kg)	Litres milk production/ day	g CP require for maintenance/ day	g CP required for milk/day	g Total CP required/ day (x)	kg diet/day of 9.3 MJ/ kg ME*	g CP in diet containing 10% CP (y)	g CP deficiency/ day (y-x)	kg Noug cake as supplement (314 g CP/ kg Noug cake)	kg cotton seed cake as supplement (370 g CP/kg cotton seed cake
250	2	251.5	170	421.5	4.38	438.5	+17.0	0	0
	5	251.5	425	676.5	6.09	609.4	−67.0	0.214	0.181
	8	251.5	680	931.5	7.80	780.4	−151.1	0.481	0.408
	10	251.5	850	1101.5	8.94	894.4	−207.1	0.660	0.560
300	2	288.3	170	458.3	4.86	486.0	+27.7	0	0.
	5	288.3	425	713.3	6.57	657.0	−56.3	0.179	0.152
	8	288.3	680	968.3	8.28	828.0	−140.4	0.447	0.379
	10	288.3	850	1138.3	9.42	941.9	−196.4	0.625	0.531
350	2	323.7	170	493.7	5.32	531.6	+37.9	0	0
	5	323.7	425	748.7	7.03	702.6	−46.1	0.147	0.125
	8	323.7	680	1003.7	8.74	873.6	−130.1	0.414	0.352
	10	323.7	850	1173.7	9.88	987.5	−186.1	0.593	0.503

*Values in this column are from previous table; these amounts of feed meet the ME requirements.

higher milk yields, forage-based diets must be of higher CP and ME. The deficiency in CP observed on feeding diet of 10% CP and 9.3 MJ/kg ME could be met by supplementation with oilseed cakes such as noug cake or cotton seed cake. The CP levels in the above diets vary between 10.6% and 12% (Table A8). On supplementation with the aforesaid oilseed cakes, the highest dry matter intake per day is 3.8% of the BW for animal of 250 kg BW yielding 10 L milk/day (for the rest, it varies from 2% to 3.3%), which the animals can consume. Dry matter intake of 4% of the BW has been reported in the literature [42]. The results show that for dairy animals, forage-based diet (9.3 MJ/kg ME and CP of 10%) would be able to meet both ME and CP requirements for only 2 L of milk production/day. However, for higher production, a supplementation of either noug cake or cotton seed cake would be required, and the contribution of the cultivated forage-based feed in the diet, as dry matter, would be between 93% and 100%.

Meeting nutrient requirements of high-milk-yielding dairy cows through forage-based diets

Feeding of a diet formed by mixing non-legume and legume forages identified in this study in 1:1 ratio, along with a small amount of maize (or any other energy source) as a supplement, would be able to meet nutrient requirements to yield the following: 15 L of milk/day from animals of 300 kg and 350 BWs; up to 20 L/day from animals of 400 kg and 450 kg BWs; and up to 25 L of milk/day from animals of BW 500 kg (Table A9). Maize has 9% CP, and hence, CP intake would exceed by 70–117 g/day (4.4%–6.9%) from the required CP by animals,which is insignificant compared with the total CP requirement (Table A7).This diet as pellet would contain >90% of the 1:1 forage mix.Approximately 76%–81% of the peri-urban dairy farmers in Ethiopia purchase feed resources [43, 44], around 94% of them feed green forages and 20% purchase green feeds [37]. The forage-based densified feed in the form of pellets (forages and maize mixed before densification) would also be a good feed for dairy farmers.

Meeting requirements for Cattle during droughts

For animals weighing from 250 to 300 kg, daily consumption of 3.58–4.11 kg of the forage-based diet (CP of 10% and ME of 9.3 MJ/kg) would meet the maintenance nutrient requirements of animals (Table A10). These consumption levels are between 1.37% and 1.42% of the BW, which is below the threshold level beyond which the animals cannot consume the feed. For hay of 7 MJ/kg ME 6.4% CP, daily consumption levels of hay for animals of 250–300 kg BW are 4.76–5.46 kg, which are 1.82%–1.90% of the BW of animals. Hay is slightly deficient in CP (Table A11); however, it can be fed during emergencies to maintain animals. Increase in intake of hay (from those calculated above) by a small amount could overcome the CP deficiency.

It is evident from the data that the forage-based diet (CP of 10% and ME of 9.3 MJ/kg) would meet the maintenance nutrient requirements of animals and hence can be fed during droughts.

Economic evaluation

To assess the economic feasibility of feeding the cultivated forage-based pellets to different types of animals and under different situations including normal and drought situations, we first assess costs of production of cultivated forages in Ethiopia without taking costs of pellet formation and transport. Then, an economic analysis is conducted of the two types of feed (Feed-A and Feed-B) formation and their usage for a wide range of animals. Next, the cost of cultivated forage-based pelleted feed is calculated for beef animals, low-to-moderate, and dairy animals and finally for animals during drought conditions.

Cost of production of cultivated forages vis-à-vis conventional feed ingredients

For assessing costs of the production of conventional feed ingredients, two feed millers were contacted and an average of the two values for each ingredient has been used. The selling prices of hay and concentrate feed used as a supplement, both during normal and drought periods, were collected from feed dealers in Ethiopia and average values were used for the analysis.The total dry matter production and cost of production of the five identified forages have been taken from Appendix A Table A12. The source of CP and ME data is from the literature including the feedipedia database (www.feedipedia.org). The cost of production of the cultivated forages and the conventional feed ingredients were compared on the bases of per kg CP and per 1000 MJ for ME. All costs presented are in American dollars, USD.

Economics of cultivated forage-based pellet production

Two types of feed were considered under nutritional evaluation: Feed-A containing 10% CP and 9.3 MJ/kg ME, and Feed-B containing 14% CP and 9.3 MJ/k ME. Using the nutritional quality data and the cost of production of the identified forages, Feed-A can be prepared either exclusively or by a mix of cultivate forage such a *Panicum*, *Brachiaria*, or Rhodes mixed with a small amount of forage oats (it may be noted that molasses is used as a binder during pelleting and this will also be an addition provider of ME, and its cost has been included in the running cost/ ton).The cost of production (US$) of these non-leguminous cultivated forages is from 10.91 to 14.54, while that of forage oat is 24.24 (Table A12). The costs are as fed basis (dry feed with ~10% moisture). The ME of the feed based on these cultivated forages could also be enhanced by adding a small amount of grains or distillers' grains.

The cost of such a feed (mainly based on the three non-leguminous forages), at the production site, can be taken as 17 US$/ton (a slight margin beyond the cost of production of these forages has been kept in assessing the production cost), while for Feed-B, because of higher CP content, *Panicum*, *Brachiaria* or Rhodes would need to be mixed in 1:1 ration with either lablab or cowpea. Both lablab and cowpea production costs are the same (61.5 US$/ton). Cost of Feed-B at production site is expected to be (17 + 61.5)/2 = 39.25 US$.

Table A9. Feeding of non-legume and legume mixed diet in 1:1 ratio, containing 14% crude protein (CP) and 9.3 MJ/kg of metabolizable energy (ME) to high milk yielding cows.

Body weight (BW) (kg), x	Litres milk production/ day	g CP require for maintenance/ day	g CP required for milk/day	g Total CP required/day	kg diet/day of 14% CP feed, y	Diet as % of BW (y × 100)/x	MJ of ME in diet containing 9.3 MJ/kg feed that meets CP requirement (y × 9.3)	MJ of ME required/day for maintenance plus milk	ME deficiency/ day (MJ)	kg maize as daily supplement (maize: 13.6 MJ/ kg)
300	15	288.3	1275	1563.3	11.2	3.72 [3.97]	103.9	114.1	10.3	0.75
	20	288.3	1700	1988.3	14.2	4.73 [4.94]*	132.1	140.6	8.5	0.63
	25	288.3	2125	2413.3	17.2	5.75 [5.91]*	160.3	167.1	6.8	0.50
350	15	323.7	1275	1598.7	11.4	3.26 [3.52]	106.2	118.3	12.1	0.89
	20	323.7	1700	2023.7	14.5	4.13 [4.35]*	134.4	144.8	10.4	0.77
	25	323.7	2125	2448.7	17.5	5.00 [5.18]*	162.7	171.3	8.7	0.64
400	15	357.8	1275	1632.8	11.66	2.92 [3.17]	108.5	122.4	14.0	1.0
	20	357.8	1700	2057.8	14.70	3.67 [3.90]	136.7	148.9	12.2	0.9
	25	357.8	2125	2482.8	17.73	4.43 [4.63]*	164.9	175.4	10.5	0.8
450	15	390.8	1275	1665.8	11.9	2.6 [2.9]	110.7	126.4	15.7	1.2
	20	390.8	1700	2090.8	14.9	3.3 [3.5]	138.9	152.9	14.0	1.0
	25	390.8	2125	2515.8	18.0	4.0 [4.2]*	167.1	179.4	12.3	0.9
500	15	422.9	1275	1697.9	12.1	2.4 [2.7]	112.8	130.3	17.5	1.3
	20	422.9	1700	2122.9	15.2	3.0 [3.3]	141.0	156.8	15.7	1.2
	25	422.9	2125	2547.9	18.2	3.6 [3.8]	169.3	183.3	14.0	1.0

*Animal would not be able to consume these amounts, and hence this diet cannot support respective milk yields. Values in square parentheses are the intake values when maize is fed along with the forage-based diet.

Table A10 Amount of cultivated forage-based feed of 9.3 MJ/kg metabolizable energy (ME) and 10% crude protein (CP) required to. meet the ME and CP requirements of animals.

Body weight, BW (kg)	Maintenance ME requirement/day	kg diet/day of ME of 9.3 MJ/kg (x)	Percent diet of BW	g CP requirement/ day (y)	g CP from diet containing CP 10% (x × 10)	Surplus g CP/ day (x × 10) − y
250	33.32	3.58	1.43	309.5	358.3	48.8
275	35.79	3.85	1.40	332.5	384.9	52.4
300	38.2	4.11	1.37	354.9	410.8	55.9

Table A11. Amount of hay of 7 MJ/kg metabolizable energy (ME) and 6.4% crude protein (CP) required to meet the ME and CP requirements of animals.

Body weight, BW (kg)	Maintenance ME requirement/ day	kg/day hay of ME of 7 MJ/kg	Percent diet of BW	g CP Requirement/ day	g CP from diet containing CP 10%	Deficiency g CP/day	Extra hay required, kg/d*	Total hay required* (kg)
250	33.32	4.76	1.90	309.5	304.7	−4.9	0.07	4.83
275	35.79	5.11	1.86	332.5	327.2	−5.2	0.08	5.19
300	38.2	5.46	1.82	354.9	349.3	−5.6	0.09	5.55

*Energy would slightly exceed than the req.

Table A12. Cost of forage production by taking 10-year production level* on a cultivation of 500 ha.

Forages	Potential dry matter yield (ton/500 ha) for 10 years*	Total production cost (US$) for 10 years from 500 ha	Cost US$/ ton dry matter	Cost US$/kg Crude Protein (CP)	Cost US$/ 1000 MJ ME	Based on one-year production, number of Tropical Livestock Units (TLU) that can be fed for one year**
Panicum maximum	100,000	1,090,815.75	10.91	0.097	1.299	3704
Rhodes (Chloris gayana)	75,000	1,090,815.75	14.54	0.162	1.711	2778
Forage Oat (*Avena sativa*)	140,000	3,393,393.27	24.24	0.231	2.606	5185
Lablab purpureus	40,000	2,458,564.21	61.46	0.334	6.681	1481
Cowpea (*Vigna unguiculata*)	40,000	2,458,564.21	61.46	0.340	6.272	1481
Brachiaria-(hybrid)	85,000	1,116,327.32	13.13	0.109	1.602	3148

*A 10-year production aggregation was taken because some forages are annual/biannual and some perennials. Annuals/biannuals need to be sown repetitively and thus have a recurrent seed/plant cost; and perennials are sown once in the time period and have limited maintenance costs e.g. weeding, nutrients.
**One TLU = 250 kg body weight; dry matter (DM) consumption per day @3% of body weight (average taken from the previous section) that is 7.5 kg DM/day.

For economic analysis, the cost of production at the production site taken is Feed-A US$17/ton and Feed-B 39 US$/ton. *These costs are without densification as pellets.* Based on the information gathered from the case studies, the cost of pelleting or block formation is taken to be 17.76 US$/ton. So, at the cultivated forage production site, the cost of production of cultivated forage-based pellets is expected to be 34.76 US$/ton for Feed-A and 57.01 US$/ton for Feed-B. For further economic analysis, these costs were rounded to 35 and 57 US$/ton, respectively. If it is transported to other regions, the cost of transport needs to be accounted for. Based on the transport costs gathered from Ethiopia and other countries, this is taken to be 4.9 US$/ton/100 km.

The key assumptions for this analysis were that (a) the cost of densification in Ethiopia will be the same as the average cost derived from the case studies in other countries; (b) the sale prices of various ingredients collected from dealers represent the correct prices in Ethiopia, and (c) the transport cost gathered represents the correct cost for entire Ethiopia and would remain same for short- and long-distance transports.

Cost of fattening and milk production using cultivated forage-based pelleted feed

Using the same costs of production as above, we calculate the cost of fattening animals at or near the pellet production site and at a distance 600 km away from the site. For the feedlot animals, the use of Feed-A (10% CP and 9.3 MJ/kg ME) meets the nutrient requirements of animals that daily gain up to 1 kg BW. The amount of Feed-A required for meeting these requirements was taken from Section 3.1.1.The methodology for calculation of these requirements is given in Section 3.1.

For calculation of cost of milk production from low-to-moderate milk-yielding cows, the cost of Feed-A was taken, while that from high-yielding cows the cost of Feed-B was taken. These costs have been given in the previous section. The amounts of Feed A and Feed-B required are presented in Sections 3.1.2 and 3.1.3, respectively. The methodology for calculation of these requirements is given in Section 3.1. The costs of Noug cake and maize used in the calculations are presented in Table 5.

Cost of cultivated forage-based pelleted feed for high-milk-yielding dairy cows

The cost for production of cultivated forage-based pellets (Feed-B) is taken from Table 4, and the amount of feed required is from Section 3.1.3.

Cost of feeding during drought using cultivated forage-based pelleted feed

The main objective of providing feed during droughts is to keep the animals alive. Due to scarcity of feeds during drought, the amount of feed fed should be just sufficient to meet the maintenance requirement of ME and CP. The calculation of maintenance ME and CP requirements is described in Section 3.1.The cost of Feed-A is given above.

Cost of production of cultivated forages vis-à-vis conventional feed ingredients

Both during normal times and droughts, the costs per unit of nutrient (CP and ME) supply from hay and commercial feed used as a supplement are much higher than those from the cultivated forages. A summary of these findings is given in Table 3. The data show that the costs per unit of nutrient supply to animals from the cultivated forages are much lower than those from the conventional feed ingredients, and hay and concentrate feeds, suggesting that meeting nutrient requirements of animals would be much cheaper if they were fed diets based on cultivated forages.

The costs of nutrient supply from the cultivated forages are based on only the production cost, while those from other ingredients are based on the sale price that also includes the profit component. The costs of production of cultivated forages have been derived using a 500-ha plantation and if it is run as a business entity, substantial lower cost of nutrient supply to the animal from the cultivated forages would allow the business entity to generate a sufficient profit and sell them at a price lower than those of the conventional feed resources currently being used.

Economics of cultivated forage-based pellet production

Cost per unit of nutrients of Feed-A (10% CP and 9.3 MJ/kg ME) and Feed-B (14% CP and 9.3 MJ/k ME) is shown in Table 4, on comparison of these costs with those of the conventional feed ingredients sold in the market (Table 5, the costs per unit of CP or ME of the cultivated forage- based pellets are much lower, both at the production site and in areas 600 km away).

Similarly, there is a wide gap between the cost of these cultivated forage-based pellets both at the production site and in areas away 600 km from the production site when compared with hay and concentrate feeds currently sold, both during normal and the drought period (Tables 6 and 7). For example, the cost per ton of Feed-A at production site and in areas 600 km away is 35 and 64.4 US$,

Table 3. A summary of costs per unit of nutrients from cultivated forages identified for cultivation, conventional feed ingredients, hay, and concentrate feeds during normal and drought periods.

Feed resources	Cost US$/ton dry matter	Cost US$/kg crude protein	Cost US$/1000 MJ ME
Cultivated forages	10.91–61.46	0.097–0.340	1.299–6.681
Protein sources: oilseed cakes	182.42–446.14	0.47–1.03	14.91–42.49
Energy sources: wheat bran, maize	195.20, 265.90	1.22, 3.32	17.27, 19.55
Normal time			
Hay at production site	88	1.38	12.57
Concentrate feed at production site	279.2	1.99	25.15
Hay near Adama (feedlot areas)	92	1.44	13.14
Concentrate feed near Adama (feedlot areas)	283	2.02	25.50
Drought time			
Hay at production site	135	2.11	19.29
Concentrate feed at production site	349	2.49	31.44
Hay in drought areas*	224	3.50	32.0
Concentrate feed in drought areas*	374	2.67	33.69
Harvest period			
Teff straw, near Adama	60	1.46	7.58
Wheat straw, near Adama	77	2.41	12.22
Dry period			
Teff straw, near Adama	94	2.29	11.91
Wheat straw, near Adama	128	4.01	20.36

*Drought areas approx. 600 km away from Adama; 1 US$ = 35.86 Birr.

Table 4. Costs per unit of nutrients of two cultivated forage-based pellets (Feed-A and Feed-B).

Feed	US$/ton at production site	US$/ton at 600 km away from production site	Cost US$/kg CP at production site	Cost US$/1000 MJ ME at production site	Cost US$/kg CP at 600 km from production site	Cost US$/1000 MJ ME at 600 km from production site
Feed-A	35.0	64.4	0.35	3.76	0.64	6.92
Feed-B	57.0	86.4	0.41	6.13	0.62	9.29

Feed-A: 10% CP and 9.3 MJ/kg ME; and Feed-B: 14% CP and 9.3 MJ/kg ME.

Table 5. Cost as sold in the market and cost on nutrient basis of important feed ingredients in Ethiopia.

Ingredients	Cost[1] (Birr)/ ton, as sold	US$/ton[2]	Crude protein (CP) kg/ton[3]	Metabolizable energy (ME) as MJ/ton[3]	Cost US$/kg CP	Cost US$/ 1000 MJ ME
Nougseed cake	11,640	324.60	314	9000	1.03	36.07
Soybean meal	16,000	446.18	530	10,500	0.84	42.49
Groundnut cake	12,000	334.63	400	11,700	0.84	28.60
Cottonseed cake	9000	250.98	370	11,900	0.68	21.09
Rapeseed cake	6470	180.42	380	12,100	0.47	14.91
Sunflower cake	9200	256.55	310	8000	0.83	32.07
Wheat bran	7000	195.20	160	11,300	1.22	17.27
Maize	9535	265.90	80	13,600	3.32	19.55

[1]Average cost from two feed millers in August 2020.
[2]One US$ = 35.86 Birr.
[3]From www.feedipedia.org

respectively, while costs of hay per ton are 88 US$ during the normal period and 135 US$ during the drought period at the production sites. The cost of hay per ton in the drought areas during the drought period is 224 US$. The quality of Feed-A is much better than that of hay and can be delivered at a cost of 64.4 US$/ton to the drought areas. This provides an opportunity for the commercial enterprises producing the cultivated forage-based pellets to generate profit and to sell at a much lower cost than the hay.

Selling a feed of much better quality (e.g., Feed-A) than currently being used (hay) in dry areas will enhance the adoption and applicability of the cultivated forage-based pellets. If we compare the cost of production of Feed-B, and the currently used concentrate feed in the feedlot and dry areas (Tables 6 and 7), the choice is in favor of using Feed-B.

In addition, both during normal and drought periods, the costs of forage-based pellets at per ton dry matter as well as based on per unit of nutrients are much lower than those of the hay and concentrate feeds, both at production site and in the drought-prone areas (Tables 6 and 7). It may be noted that the costs derived for cultivated forage-based pelleted feeds do not include the profit; however, these costs are substantially lower than those for feeds used currently. A pellet-making business entity could be run at a profit and still sell the pelleted feed at a price lower than those of the feeds currently used.

It is evident from the above that it would be cheaper to produce milk and meat or to maintain animals during droughts using the cultivated forage-based pelleted diets, when compared with the currently used feeds.

Cost of beef cattle production using cultivated forage-based pelleted feed

The total feed required is 961 kg for the total fattening period of 120 days when the animals are growing at a daily growth rate of 0.75 kg, and the feed required is 1443 kg for the fattening period of 180 days at a daily growth rate of 0.50 kg. Taking the cost of Feed-A (Table 5), the costs of feed for one animal for these three scenarios are 51.2, 61.9, and 92.9 US$, respectively. The cost per kg of daily BW gain comes to 0.51, 0.69, and 1.03 US$ when daily BW gain is 1, 0.75, and 0.50 kg, respectively. Consequently, and as mentioned earlier, it would be cheaper to produce meat from animals of good genetic potential (e.g., those growing at 1 kg/day) than those from animals of poorer genetic potential (e.g., those growing at 0.5 kg/day).

In these calculations, the cost of feed at a site 600 km away from the pellet production site (64.4 US$/ton) has been taken, and if the feedlots are located nearer than 600 km, the cost of production would be lower than these values. Currently, we do not have cost of the feed that feedlot farmers prepare on-farm by mixing individual ingredients, but since the cost per unit of ingredients from the densified cultivated forages is substantially lower than those from the conventional concentrate ingredients and hay used by the feedlot farmers (Tables 4–6), it is safe to conclude that the cost of fattening animals would be much lower using the densified cultivated forage-based feeds.

The authors attempted to calculate the cost of feed using "Treatment 2" data reported in Gebremariam [35] in which a daily growth rate of 1 kg was obtained in Ethiopian Hararghe Highland (*Bos indicus*) bulls when fed a daily diet containing 6 kg of hay and 4 kg of wheat bran. By taking an average cost of

Table 6. Drought time costs of hay (H) and concentrate feeds (CF) at production site (PS) and in drought areas (DA) approx. 600 km away (costs are in US$).

H cost/ton (PS)	H cost/ton (DA)	CF cost/ ton (PS)	CF cost/ ton (DA)	H cost/kg CP (PS)	H cost/1000 MJ of ME (PS)	H cost /kg CP (DA)	H cost/1000 MJ of ME (DA)	CF cost/kg CP (PS)	CF cost/1000 MJ of ME (PS)	CF cost / kg CP (DA)	CF cost/1000 MJ of ME (DA)
135	224	349	374	2.11	19.29	3.50	32.0	2.49	31.44	2.67	33.69

Hay (H): crude protein (CP) 6.4% and metabolizable energy (ME) 7 MJ/kg; concentrate feed (CF): CP of 14% and ME 11.1 MJ/kg. PS for hay: Sululta, north of Addis Ababa; PS for CF: near Adama.
Notes: DA cost of 1 day diet, US$/animal/day, following FAO recommendation: 1 kg CF and 3.5 kg H = 1.158; or 115.8 US$/100 days. Cost in US$ of one ton diet = 1.158 × 1000/4.5 = 257.3. In some situations, hay is difficult to transport into the dry areas because of its bulky nature and short supply. Under these conditions, 2 kg of CF and 1.5 kg of H is also suggested. By taking these values, cost of one ton diet = 309.7 US$.

Table 7. Normal time costs of hay (H) and concentrate feeds (CF) at production site (PS) and in areas around Adama (feedlot areas) approx. 118 km away from Sululta (all costs are in US$).

H cost/ton (PS)	H cost/ton (Near Adama)	CF cost/ ton (PS)	CF cost/ ton (Near Adama)	H cost/kg CP (PS)	H cost/1000 MJ of ME (PS)	H cost /kg CP (near Adama)	H cost / 1000 MJ of ME (near Adama)	CF cost/kg CP (PS)	CF cost/1000 MJ of ME (PS)	CF cost /kg CP (near Adama)	CF cost/1000 MJ of ME (near Adama)
88	92	279.2	283	1.375	12.57	1.44	13.14	1.99	25.15	2.02	25.50

Hay (H): crude protein (CP) 6.4% and metabolizable energy (ME) 7 MJ/kg; concentrate feed (CF): CP of 14% and ME 11.1 MJ/kg. PS for hay: Sululta, north of Addis Ababa; PS for CF: near Adam.

hay as 114 US$/ton (Table 3) and of wheat bran as 195.2 US$/ton (Table 5), cost of diet per kg of daily BW gain comes to 1.46 US$.This is almost threefold higher than the cost of diet based on cultivated forage-based pellets (0.51 US$/kg BW gain; Scenario 1 above). In addition, use of densified cultivated forage-based feeds by the feedlot farmers offers several other benefits, which were discussed in the Section 2.5.

In conclusion, the cost per kg of daily BW gain comes to 0.51, 0.69, and 1.03 US$ when daily BW gain is 1, 0.75, and 0.50 kg, respectively. At these daily body weight gains, the costs of feed for one animal to fatten are 51.2, 61.9, and 92.9 US$ at a site 600 km away from the pellet production site.

Cost of milk production from low-to-moderate milk-yielding dairy cows using cultivated forage-based pelleted feed

From animals weighing 250, 300, and 350 kg, a daily amount of Feed-A of 4.38, 4.86, and 5.32 kg respectively can support daily milk yield of 2 L (Table A8), giving feed cost per liter of milk to be 0.145, 0.161, and 0.177 US$, respectively (average 16.1 US dollar cents). Here also, the cost of Feed-A at a site 600 km away (64.4 US$/ton) has been taken. In case, Feed-A is used close to the production site, and feed cost per liter of milk is expected to be 0.0788, 0.0875, and 0.0962 US$, respectively (average 8.75 US dollar cents).

For obtaining daily milk of 10 L from animals weighing 250, 300, and 350 kg, daily amounts of Feed-A and Noug cake required are given in Table A8.Taking cost of Feed-A at a site 600 km away from the pellet production site (Table 5) and the market price of Noug cake (324.6 US$/ton) (Table 6), the daily feed cost comes to 0.808, 0.828, and 0.848 US$ for 10 liters of milk production from animals weighing 250, 300, and 350 kg, respectively.This translates to the feed cost per liters of milk of 0.081, 0.083, and 0.085 US$ (average 8.3 US dollar cent). This cost of milk production is almost half of that of when cows give 2 L of milk per day, as presented in the previous paragraph.

The higher the daily milk production by an animal, the lower the cost per liter of milk production. The reason for this is that the higher proportion of the feed (and of the feed cost) goes for meeting the maintenance requirement of the cow that yields lower milk. Furthermore, the same amount of daily milk produced by a cow of lower BW is more cost effective than from a cow of higher BW.This again is due to higher maintenance requirement of a cow of higher BW. One of the objectives of the animal breeders could be to breed animals of lower BW without compromising milk production. The feed cost per liter of milk production will be lower in places nearer to the production site of cultivated forage- based densified feeds. To sum, the higher the daily milk production by an animal, the lower the cost per liter of milk production. In addition, the same amount of daily milk produced by a cow of lower BW is more cost effective than from a cow of higher BW. Using the cultivated forage- based pelleted diets, an average cost of milk production per liter was 8.75 US dollar cents at or near the pellet production site, while at a site 600 km away, the cost increased almost twofold (16.1 US dollar cents).

Cost of milk production from high-milk-yielding cows using cultivated forage-based pelleted feed

For dairy animals, Feed-B containing 14% CP and 9.3 MJ/kg of ME has also been evaluated (Section 3.1.3). As demonstrated in Section 3.1.33, feeding of a diet formed by mixing Feed-B and a small amount of maize (or any other energy source) as a supplement would be able to meet the nutrient requirements of cows to yield: 15 L of milk/day from animal of 300 kg and 350 BWs; up to 20 L/day from animals of 400 kg and 450 kg BWs; and up to 25 L of milk/day from animals of BW 500 kg.

Taking cost of Feed-B at 600 km away from the production site (86.4 US$/ton;Table 4) and of market selling price of maize (265.90 US$/ton;Table 5), the daily feed cost comes to 1.195, 1.221, 1.509, 1.553, and 1.838 US$. This translates to 0.0797, 0.0814, 0.0755, 0.0777, and 0.0735 US$ per liter milk (average 7.76 US dollar cents). The cost of milk production close to the production site is much lower.According to a survey conducted in 2016–2017 [45], feed cost per liter milk was 0.49 and 0.30 US$ for small and large farms, respectively (average of 39 US dollar cents). Feed cost of 35 US dollar cent per liter of milk has been reported for Kenya [46]. The cost per liter of milk production from feeds based on cultivated forage-based pellets obtained in this analysis is about 8 US dollar cents.

In conclusion, using cultivated forage-based pelleted feed, average milk production cost per liter was 7.76 US dollar cents. Although the cost of milk production using the conventional feeds could not be surveyed, this cost is almost fivefold lower than the cost calculated using the feed requirement data from a research paper, wherein feed requirement and milk production have been recorded for an experiment conducted in Ethiopia.

Cost of feeding animals during droughts using cultivated forage-based pelleted feed

Currently, hay of ME of 7 MJ/kg and CP of 6.4% is used in the drought areas as emergency feed, and if this is replaced by Feed-A for animals weighing 250–300 kg, a substantial saving could be made. Taking the costs of these feeds in drought areas (Tables 4 and 6) and the daily maintenance nutrient requirement (Tables A10 and A11), daily savings of US$ 0.828 and US$ 0.950 (average 0.889 US$) per animal could be obtained. In a dry spell of 100 days, saving per animal turns out to be 88.9 US$, or for 1000 animals' 88,900 US$, if the cultivated forage-based pellets/blocks are sold at no profit.

During emergencies,the recommendation by international organizations is to feed either 1 kg of concentrate feed and 3.5 kg of hay, or 2 kg of concentrate feed and 1.5 kg of hay daily. In some situations, hay is difficult to transport into the dry areas because of its bulky nature and short supply, and therefore, the latter feed is preferred. These recommendations are for survival of the breeding stocks. The daily costs of the former and the latter diets come to 1.158 US$ and 1.084 US$, respectively, giving values of 257.3 and 309.7 US$/ton, respectively. These costs are almost fourfold higher than that of the cultivated forage-based pelleted feed.

In conclusion, the cost of feeding the animals in drought condition using the cultivated forage-based pelleted feed is much lower than that on feeding hay, which is currently used. In a dry spell of 100 days, saving per 1000 animals is expected to be 88,900 US$, provided the cultivated forage- based pellets are sold at no profit. Such a margin will allow the pellet making business entity to generate profit and sell the product at a cost lower than those of the currently used feeds.

Environmental assessment

We look at two different environmental footprint dimensions of livestock production. First, we provide learning around the decrease in greenhouse gas emissions (GHGe). The bulk of livestock-related GHG emissions originate from four main categories of processes: enteric fermentation, manure management,feed production,and energy consumption along livestock supply chains. Enteric fermentation is the largest source of emissions in cattle production.Worldwide, emissions from enteric fermentation amount to 1.1 gigatons CO_2 equivalents, representing 46% and 43% of the total emissions in dairy and beef supply chains, respectively [47]. In this study, we calculate the reduction in methane emissions from enteric fermentation due to increased use of cultivated forages as animal feed in Ethiopia.We used the cost of carbon pegged by the current US administration to monetize these GHG emission mitigation gains as an illustration and to provide a benchmark for comparisons with other animal feeds—when it comes to GHG emission reductions.

Second, the already existing competition for land between crop and livestock production in Ethiopia is expected to persist as demand for income, food, fuel, and feed continues to rise [48]. We therefore estimated the reduction in the amount of land that is required to grow the animal feed ingredients due to the increased use of cultivated forages therein.

The methane emissions associated with the enteric fermentation of the animals fed on the different diets and the number of hectares needed to grow the feed ingredients were calculated using the following steps:

Step 1: Estimate daily Metabolizable Energy (ME) and Crude Protein (CP) requirements of animals:

Using nutrient requirement values for maintenance, growth, and milk production, daily ME and CP requirements of animals were calculated.

Step 2: Estimate daily Intakes of Dry Matter (DMI) and Gross Energy (GEI)

a. Daily DMI (kg) of feed was calculated using ME and CP contents of feeds under study that meets the daily ME and CP requirements of animals.
b. Daily GEI (MJ) = Daily DMI (kg) × 18.45 (18.45 is the factor as per International Panel on Climate Change (IPCC)) 2019 guidelines [49]
c. GEI for one lactation of 305 days in MJ (GEI_{305d}) = Daily GEI × 305
d. GEI for a growth period of x days in MJ (GEI_x) = Daily GEI × x.

Step 3: Calculate CH_4 emissions from enteric fermentation

a. EntericFermCH_4 Lactation (kg) = GEI_{305d} × Y_m/100/55.65.
b. EntericFermCH_4 Growth (kg) = $GEI_x \times Y_m$/100/55.65

Y_m, the methane conversion factor, set to 6.3 (as per the (IPCC) 2019 guidelines) [49].

Step 4: Calculate CH_4 emission intensity (i.e., the CH_4 emissions per unit of milk or meat)

a. Dairy: CH_4 emission intensity (kg CH_4/L milk) = EntericFerm$_{CH4}$ Lactation in kg/Lactation milk yield in liters
b. Beef: CH_4 emission intensity (kg CH_4/kg body weight gain) = EntericFermCH_4 Growth in kg/kg weight gain in x days

Step 5: Calculate land requirements (i.e., the hectares of land needed to grow the feed ingredients)

a. DMI_i = DMI * $fraction_i$
b. LR = $\sum DMI_i / Yield_i$

DMI_i, the dry matter intake of feed ingredient i (kg). $fraction_i$, the fraction of the animal diet constituted of feed ingredient i.

$Yield_i$, the yield of the crop from which feed ingredient i is produced (kg/ha).

Table A13 shows the yields of crops used for preparing feeds. We calculated the enteric CH_4 emission and land requirements for three cases—feedlot animals, dairy animals, and for animals during drought period.

Step 6: Calculate the social costs.

Using the social cost of methane pegged by the United States government [50], we calculated the monetized benefits of abatement values per 1000 kg of body weight gain in the fattening sector, and for 1 million liters of milk production in the dairy sector.

Potential environmental co-benefits

Feedlot animals

For the feedlot animals, we compared the CH_4 emissions and land requirements associated with three distinct growth scenarios. The baseline scenario (Table 8) represents a typical scenario whereby animals gain on average 0.5 kg weight/day and take 180 days to increase from 260 kg to the selling weight of 350 kg.

Scenario 1 assumes that the livestock producers take full advantage of the improved forage-based feeding and by increasing daily weight gain to 1 kg/day, taking 100 days to fatten a 250-kg animal to the required 350 kg.

Scenario 2 is an intermediate scenario in which a total weight gain of 90 kg is accomplished in 120 days, at a growth rate of 0.75 kg/day.

Comparisons of methane emissions and land requirements for baseline, scenarios 1 and 2, are provided in Table 8 and Table A14, respectively.

Dairy animals and livestock during drought

For the dairy animals and animals during drought, we provide estimates for two types of feed—hay/concentrated, and feed using cultivated forages. The dairy animals, with body weight between 300 and 500 kg, are assumed to produce between 15 and 20 L of milk per day. The animals during drought were assumed to weigh between 250 and 500 kg. See Table 9 for methane emissions and Table A15 for land requirements.

Tables 8 and 9 show the monetized benefits using the social cost of carbon (as CO_2) put forth by the current US administration [50]. The social cost of methane is $1500 per ton. Using cultivated forages could significantly reduce methane emissions with abatement value ranging between $165 and $240 USD per 1000 kg of body weight gain in the fattening sector. For dairy sector, the abatement value would be between $1350 and $2400 USD per million

Table A13. The yields of the crops of which the feed items are produced.

Feed ingredient	Associated crop	Yield (MT dry matter/ha)
Noug cake, cotton seed cake	By-product	NA
Hay	Native or naturalized pasture	4
Feed A	Brachiaria grass	17
Feed B	Brachiaria/forage legume mix	14.5
Maize	Maize	3

Table 8. Comparison of methane emissions, methane emission intensities associated with different scenarios of fattening a beef animal.

Scenarios	CH_4 emissions during fattening period (kg CH_4/animal/fattening period)	Environmental Gain (kg CH_4/ animal/fattening period)	CH_4 emission intensity during fattening period (kg CH_4/kg weight gain)	Environmental gain (kg CH_4/kg weight gain during fattening period)	Monetized value per 1000 kg of weight gain (USD)
Baseline*	30.10		0.33		
Scenario 1	16.62	13.48 (45%)	0.17	0.16 (48%)	240
Scenario 2	20.09	10.01 (33%)	0.22	0.11 (33%)	165

*Average daily gain in growing animal in Ethiopia is 0.5 kg. The values in parentheses are percent gain from the baseline.

Table A14. Comparison of land requirements for the feed production associated with different scenarios of fattening a beef animal.

Scenarios	Land requirement (hectares needed to grow the feed crops-annually)	Reduction in land requirement
Baseline*	0.85	–
Scenario 1	0.47	0.38 (45%)
Scenario 2	0.57	0.28 (33%)

*Average daily gain in growing animal in Ethiopia is 0.5 kg.

Table 9. Comparison of methane emissions and methane emission intensities associated with dairy animals and animals fed during drought periods.

Scenarios	CH_4 emissions (kg CH_4/animal/ period#)	Environmental gain# (kg CH_4/ animal/period)	CH_4 emission intensity (kg CH_4/ 1000 L of milk)	Environmental gains (kg CH_4/1000 L of milk)	Monetized value per million liters of milk (USD)
Dairy animals (hay/conc)*	79–126		17.2–18.7		
Dairy animals (cultivated forages)	76–122	3–4	16.3–17.1	0.9–1.6	1350–2400
Animals during drought (hay)*	12.7–21.3		Not applicable		
Animals during drought (cultivated forages)	9–13.9	3.7–7.6	Not applicable	Not applicable	5550–11,400

*The diets that meet the nutrient requirement.
#For dairy animals, we have taken a typical lactation period of 305 days; for animals during drought we took a period of 120 day.

Table A15. Comparison of land requirements for the feed production associated with dairy animals and animals fed during drought periods.

Scenarios	Land requirement (hectares needed to grow the feed crops-annually)	Reduction in land requirement
Dairy animals (hay/conc)*	0.34–0.75	
Dairy animals (cultivated forages)	0.31–0.50	0.03–0.25
Animals during drought (hay)*	0.44–0.74	
Animals during drought (cultivated forages)	0.08–0.12	0.36–0.62

*The diets that meet the nutrient requirement.

liters of milk production. For the drought period of 120 days, the value of methane reductions would be between $5500 and $11,400 USD per 1000 animals. Somali, Oromia, Afar, Southern Nations, Nationalities, and Peoples (SNNP), Dire Dawa, and Harari regions of Ethiopia are generally affected by droughts.With 18 million cattle in these regions, the monetized value per drought period could be between $99 million and $198 million. Given that millions of animals are fattened, and billions of liters of milk are produced in Ethiopia [3], these figures represent significant opportunities for climate change mitigation and must be taken into consideration while estimating benefits from adoption of cultivated forages in the livestock sector.

In addition, there is less land needed for the production of feed resources. That is, more land will be available for food/cash crop production or the conservation of forests or other natural ecosystems.As such, forage-based feeding offers a triple-win:economic,social as well as environmental gain, and is one of the promising climate-smart feeding interventions [41].

Outlook

This study recommends two business models that will potentially bridge gaps in forage seed systems and strengthen the supply of high-quality animal feed thus reducing cyclical fluctuations, especially during drought periods. This integrated approach is illustrated in Fig. 4.

Model 1: cultivation of improved forages and their densification for use in quarantine and fattening centers

We propose three regions—Afar, Somali, and SNNPR— for cultivation of improved forages and their densification into pellets. Our analysis has demonstrated that a pelleted diet comprising of >85% of the selected improved grasses can give a daily body weight gain of up to 1 kg, implying that animals in commercial feedlots and quarantine stations can be raised almost entirely using improved cultivated forages. This feed is also suitable for feeding animals during droughts, wherein the main aim is to maintain the animal.

Choice of regions for the model

Afar. Mille quarantine station is in Afar. Afar is a dry region. During droughts, livelihoods of many pastoralists are lost due to death of thousands of animals, mainly due to unavailability of feed.

The regional government has already built large irrigation facilities for sugarcane cultivation, which can also be used for cultivation of improved forages.The regional government has a 700-ha cultivated forage plantation in which *Panicum* and Rhodes grasses are cultivated for formation of baled hay for supplying "free-of-cost" to pastoralists during droughts. The regional government is keen on establishing more of such cultivated forage plantations. The densification unit in Afar would also allow inclusion of sugarcane tops (a by-product) in the pellets along with the cultivated improved forages. However, pastoralist community needs to be involved in the selection and use of large plantation areas since these lands are currently used for grazing of animals. The cultivated forages in the pellet form can be stored in warehouses, for use during droughts. The surplus amount, if any, can also be transported to feedlot areas near Adama.

Somali region. Jijiga quarantine station is in this region. The region is affected by droughts and is also close to other areas where droughts are frequent. Feed banks can also be established in this region, to provide pelleted feed during droughts.

SNNPR. The irrigation facilities and community development programs have been developed and are being further strengthened through the earlier and ongoing projects, for example, Resilience in Pastoral Areas (RiPA) and Land Governance Activity (LGA) in these regions. The region is close to the commercial feedlot areas near Adama and to the drought-affected areas.

Proposed approach

The cultivation of improved forages could be in large plantation areas, for example 500-ha farm, as has been established in Afar by the regional government or it could be in small farms of 50–150 ha. A large farm of 500-ha plantation has potential to produce approximately 10,000 tons of dry forage in a year.To convert such an amount of biomass into pellets, a fixed high-pressure pelleting machine of capacity 20–25 tons pelleted feed production per 8-h shift is proposed, while for the smaller plantations (50–150 ha), mobile high-pressure pelleted machine of

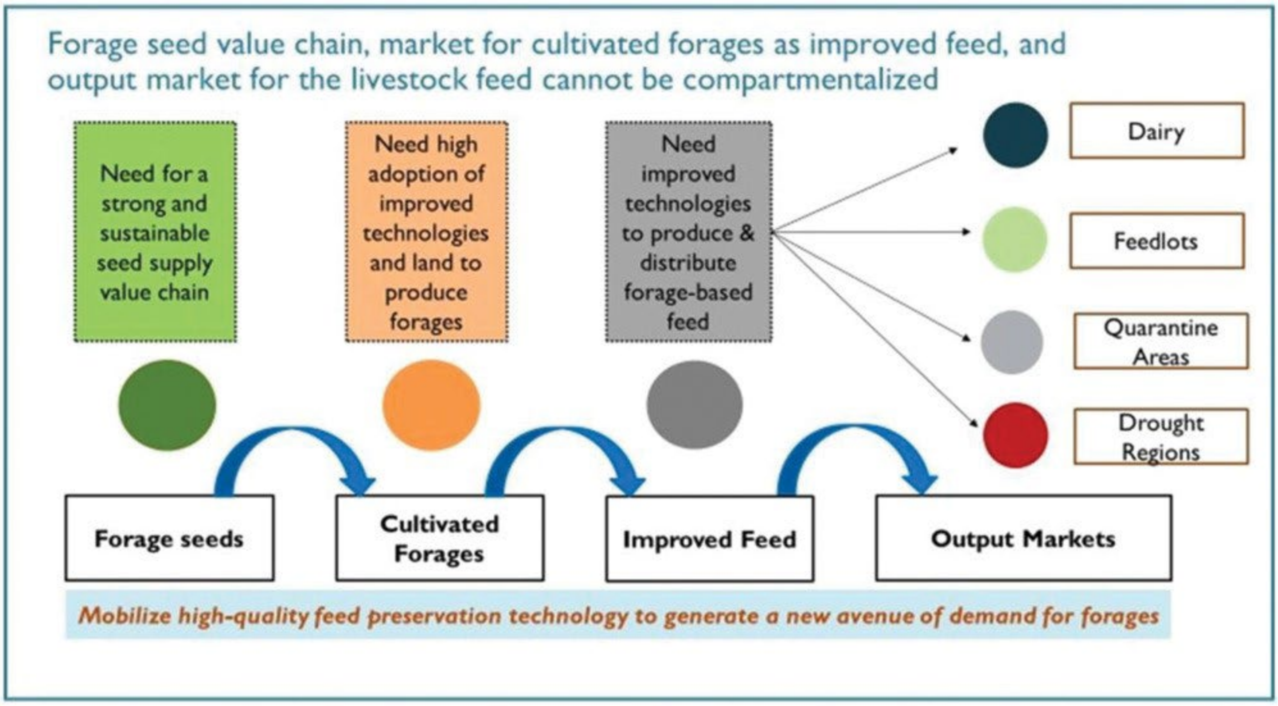

Figure 4. Integrated business models—a proposition.

5–8 tons pelleted feed production per 8-h shift could be used.The forage cultivation and densification sites must be close to each other, to avoid transport of loose forages to the densification unit.

Formation of pellets from forages requires high-pressure, unlike the pellet formation for poultry feed that contains soft materials such as grains and oilseed cakes.The high-pressure densification units are currently unavailable in Ethiopia and for the initial phase, these need to be imported. Countries that are producing these machines, at a reasonable cost, are China, India,Turkey, among others. Government of Ethiopia is giving priority to improve agricultural mechanization in the country. The capacity of local workshops needs to be enhanced so that these high-pressure densification machines could be produced locally in the long term.

Feed reserves

It is imperative to enhance availability of feed in lowlands. One of the options is the establishment of feed banks in the regions affected by droughts. This would decrease drought-induced livestock mortality, reduce feed prices, and supply volatility. The pelleted feed can be stored near the drought-prone areas, for distribution to agro- pastoralists/pastoralists during drought stress.

Two case studies from India and Mongolia were reviewed [51]. In India, the feed bank created by farmers' organizations and village authorities has decreased the cost of feeding to dairy animals and increased farmers' profit, while in Mongolia, the strategic feed reserves by federal and regional governments and private farmers provide feed to animals during severe winters when the temperature is around minus 40°C and the grazing pastures are unavailable and/or inaccessible.

In Ethiopia, pelleted feeds can be potentially stored in warehouses owned by the WFP (World Food Programme) and NDRMC (National Disaster and Risk Management Center).The operation of these warehouses could potentially be managed through public-private partnerships. This approach would enable greater feed distribution in the drought and stress-prone regions within the country.

Sustainability

According to IUCN [52], three Ps that stand for *Profit, People* and *Planet* have been used to describe the sustainability, implying economic growth, social equity, and ecological soundness. Using the three-P definition of sustainability, an approach or a technology is sustainable if it enhances income of value chain actors (Profit), benefits environment (Planet), and benefits society, especially with respect to empowerment of women and youth, and creation of jobs (People). The proposed business model contributes to all the three 3-P dimensions of sustainability, as illustrated below.

Profit dimension

Decrease in feed cost and increase in farmers' income. Our economic analysis shows cultivated forage-based pelleted feeds could be provided at 80 US$/ton (after generating 25% profit) in regions where quarantine stations and commercial feedlots are located. This selling cost of pelleted feed is much lower than the feed being used.

Currently, the feed used is prepared on-farm by mixing conventional feed ingredients. The nutrient supply from conventional feed ingredients is three to fivefold higher than that from the cultivated forage-based-feeds, as shown in our analysis (Table 3). Feed cost is approx. 75% of the cost of meat production [14]. Reduction in the cost of feed would increase income of the farmers.

Decrease in regional feed disparities, feed costs and volatility in feed costs. The conventional feed ingredients are produced in highlands and there is severe feed shortage in lowlands, especially in the dry periods. The cost of feed increases both in lowlands and highlands during droughts (Tables 3, 6, and 7). The feed banks of cultivated forage- based pelleted feed near the site of use would contribute to decreasing regional feed disparities, feed costs, and volatility in feed costs.

Planet dimension

Decrease in greenhouse gas emissions from the livestock sector. Feeding cultivated forage-based TMR in the form of pellets has other advantages, for example, higher nutrient availability in the animal body, lower feed wastage on-form, which enhances overall feed-use efficiency,and decreases greenhouse gas emission from the livestock production system.

Increase in soil health. Some cultivated forages, for example, annual leguminous forages, for being short-term crops, integrate well with the annual cropping pattern, which enhances soil health and increases overall productivity of the system.

People (ethical) and profit dimensions

Decrease in food-feed competition and in feeding cost. This novel approach of fattening animals using a TMR based almost entirely on improved cultivated forages would decrease the use of concentrate-based feeds (currently fed) prepared on-farm or purchased from feed manufacturers. The concentrate feed is expensive (Tables 3, 6, and 7) and generally contains grains and soybean that compete with human food.

People and profit dimensions

Empowerment of women and youth. Use of cultivated forage- based pelleted TMR decreases workload and time for rearing animals, and thus provides opportunities for other constructive activities. Labor cost is also expected to be lower.

People, profit and planet dimensions

Decrease in malnutrition, especially in growing children and pregnant women, and increase in profitability and natural resource use. Increase in cultivation of improved forages and their densification to pellets would increase feed availability of good nutritional value in commercial feedlots, quarantine areas, and dry areas, resulting in increased production of animal products and productivity, and consumption of animal source foods.

Model 2: cultivated forage production in highlands and their distribution in native form (without densification) to smallholder dairy farmers

Ethiopia's dairy sector is commercializing, and dairy is intensively practiced in the highlands. The demand for cultivated forages is very high in the region. Smallholder dairy farmers (rearing 2–3 dairy cows) generally have small pieces of land (<1 ha). This implies strong competition for land (for food, feed, and cash crops) and limits the amount of on-farm produced forages, especially so in the dry season. This results in low and variable (seasonality of) dairy production. This is a constraint for dairy processing investment.

However, farmers located in the same region who have substantial pieces of land (around 15 ha) could be targeted to cultivate improved forages as a business entity.This kind of model concept is similar to the Thailand case study [53]. The cultivated forages (without densification) can be provided to smallholder dairy farmers. Surplus forage, if any, could be converted to hay, silage, or pellets using small pelleting machines for supply during the scarcity periods.

The distribution of cultivated forages could be efficiently managed using a mobile phone application or short message service (SMS) systems. Extension services will be able to provide training to the farmer on cultivation of improved forages, silage formation, and pelleting.

Conclusions

Ethiopia has a large livestock population, and the role of the livestock sector is increasing as the urban and peri-urban population is on the rise. However, livestock productivity has substantial yield gaps due to constraints in quality and quantity of timely and affordable feed supply. The present research shows the role that improved cultivated forage could play in bridging that gap, as well as enhancing economic benefits by reducing cost of feed and providing environmental benefits through reductions in greenhouse gas emissions. To address low livestock productivity in Ethiopia, including overcoming feed deficiency during dry periods and emergency situations, inclusion of improved forages in the feed supply is inevitable.

The authors have provided evidence that illustrates the cost per nutrient for improved forages is up to 15-fold lower than that of conventional feed resources. Furthermore, the study posits that introducing innovative feed preservation technology through the densification of cultivated forages into pellets could also serve as a solution during the drought periods in Ethiopia. This would help reduce the seasonal fluctuations of feed supply.

Densification of cultivated forages decreases the costs of (a) keeping the animals alive during a 100-day drought period by 4 times, (b) fattening animals by 2.3 times, and
(c) providing feed for milk production by 4 times. It is cheaper to produce meat from animals of good genetic potential

(e.g., those growing at 1 kg/day) than from animals of poorer genetic potential (e.g., those growing at 0.5 kg/day). Likewise, it is cheaper to produce milk from dairy animals of high genetic potential.

Using cultivated forages could significantly reduce methane emissions with abatement value ranging between $165 and $240 USD per 1000 kg of body weight gain in the fattening sector. For the dairy sector, the abatement value would be between $1350 and $2400 USD per million liters of milk production. For the drought period of 120 days, the value of methane reductions would be between $5500 and $11,400 USD per 1000 animals.

However, for cultivated forages to play this crucial role, Ethiopia needs a viable and sustainable forage seed supply system, where the value chain for forage seeds is strengthened by adequate supply of early generation seeds through partnerships between private and public seed enterprises, federal and regional agricultural research institutes (such as Ethiopian Agricultural Research Institute), and CGIAR centers such as ABC-CIAT and ILRI. The roles and responsibilities of the EGS production need to be transparent and streamlined. In addition to the starter seeds, leveraging ongoing seed system development by practitioners could help formalize the informal seed system and increase production of high-quality forage seeds of improved varieties. Adequate technical capacity building of extension agents and market linkages to the livestock output markets are required to support the business models that would produce and distribute cultivated forages. Given the important role the informal seed system plays in Ethiopia, we believe the models proposed above will bridge gaps between formal and informal seed systems and strengthen linkages between stakeholders and what is finally grown in the smallholder fields. To expand the commercialization and production of quality assured forage seeds, the quality declared seed (QDS) protocols must be utilized. This process would also bridge the gaps between the various seed systems prevalent in Ethiopia. Technical capacity building and awareness creation through tailored extension services could be conducted through developing content that is focused on forage seed multiplication and forage crop cultivation.

The study proposes to formulate a balanced ration in the form of pellets composed of over 70% cultivated forages for different class of animals: fattening animals and dairy animals that give up to 25 liters of milk/day. The end users need training on feeding of cultivated forage-based pellets (e.g., how much for 0.5 kg/day gain in body weight, 1 kg/day gain in body weight, etc., and likewise for dairy animals). So far, farmers involved in fattening in Ethiopia have not used cultivated forage-based diets. Most of them use concentrate feeds and straws. To shift them from concentrate-based feeding to cultivated forage-based pellet feeding (because former is expensive), training is required in collaboration with extension and development agents.

On the policy side, collaboration with the government of Ethiopia and private sector entities could strengthen the capacity of agricultural equipment manufacturers engaged in the livestock sector in Ethiopia. Public-private partnerships could facilitate the functioning of the warehouse sites for the established feed banks and garner support of livestock pastoral communities. Policies and regulations around maintaining feed reserves in the country need to be transparent and well-understood by regional and local stakeholders within the country. Although the quarantine facilities are operational, their capacities could be increased, thereby further expanding the demand-pull for high-quality feed as that reflected through the cultivated forages.

The business models illustrated in this study focus on creating a new demand avenue for cultivated forages by using demand-pull mechanisms through introduction of densification technologies. At the same time, the authors suggest interventions on the supply side that would increase the production of high-quality forage seeds of the improved forage crop varieties. Currently, the forage feed production projects in Ethiopia focus on hay production and baling. This approach has an inherent disadvantage of loss of forage leaves that are of better quality than rest of the forage plant, thus decreasing quality of the final product (baled hay). Loss of forage is higher when forages are used in loose form or when transported as hay bales. In addition, the cost of transport and storage is high. Introduction of densification technology will densify the forages as pellets that have higher density than the hay bales. This would reduce the costs of transport and storage increase of shelf-life.

The proposed approach of pelleting will enable mixing of other locally available biomass, vitamins, and minerals to form a balanced feed, which is not possible when hay is used. Feeding of balanced Total Mixed Ration (TMR) as pellet will substantially improve feed efficiency with noted benefits in terms of animal productivity as well as resource- use efficiency (land and water) and greenhouse gas emission intensity.

To realize the full potential of the livestock sub-sector in Ethiopia, the importance of cultivated forages cannot be overemphasized. However, interventions need to target both supply and demand sides to ensure adequate supply of forage-based feed throughout the year—especially in the drought-prone lowlands. Engagements and partnerships between public and private entities require efficient policies and practices that strengthen the enabling environment. For that, coordination, collaboration, and colocation between different ongoing projects in Ethiopia would be a necessary step in the right direction.

Conflict 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.

Author contributions

Dr. Bhramar Dey led the overall conceptualization, design, and execution of the study, especially the development of the data-driven business model propositions and policy recommendations. Rest of the authors supported the design and execution of the study. In addition, Ms. An Notenbaert conducted the spatial analyses and led the assessment of environmental impacts of cultivated forages. Dr. Harinder Makkar led the nutritional and economic analyses and supported the environmental impact of cultivated forages and forage seed estimation studies. Dr. Solomon Mwendia led the forage seed estimation and choice of forages considered in this study. Mr. Sahlu served as the local consultant and conducted all field-level surveys in Ethiopia. He also provided valuable local context and input to the forage seed system discussions. Dr. Michael Peters led the forage seed system component of the work, and provided valuable inputs for the nutrition and economic analyses.

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Data availability statement

All data are in the tables.

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