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Linked Economic and Animal Systems (LEAS) Model

Technical Documentation

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ABSTRACT

The herd dynamics model (HDM) component of the Linked Economic and Animal Systems (LEAS) model specifically documented here is developed in the context of the Feed the Future Innovation Lab for Livestock Systems financed by the United States Agency for International Development (USAID) and managed by the University of Florida’s Institute of Food and Animal Sciences. The main objective of this project is to develop a comprehensive analytical approach or systems model capable of assessing (i) how animal herd or flock sizes change over time and in response to on-farm policies; (ii) how alternative national trends and policies affect future development of the livestock system as a whole; (iii) how changes in livestock policies affect people working throughout the livestock system; and (iv) how changes in animal-source food (ASF) production and prices affect the real incomes and consumption patterns of different population groups. The HDM developed provides a highly detailed description of the cattle sector while laying a framework that can be easily adapted to other types of livestock. The model allows one to closely examine the performance of the livestock sector disaggregated by agroecology zones or regions. The HDM is linked both ways with a core economywide model through economic variables such as relative prices of livestock activities, prices and availability of intermediate inputs including feed, and changes in supply of livestock capital in the meat and milk production sectors. Given the complex interplay in the livestock sector such as offtake decisions, death rates, milk and meat yield, and feeding practices (through quality indexed feed demand), the HDM developed under this project is a fully dynamic livestock sector model that provides several avenues for policy analysis on livestock management, the sector’s future trajectory, and its dynamics, given risks and opportunities within the sector and beyond.

Keywords: herd dynamics model, demographic dynamics, linked model, livestock sector policy, Ethiopia

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1 INTRODUCTION

Ethiopia's economy grew rapidly over the last decade. Underlying this is a steady process of agricultural transformation, with many farmers adopting improved technologies and/or shifting from subsistence to commercial practices (Bachewe, et al., 2018). The expansion of Ethiopia's agriculture-food system (that is, expansion beyond agriculture or farming itself) has contributed significantly to national economic growth and structural transformation over the last decade (Dorosh, et al., 2018). Research conducted by the International Food Policy Research Institute (IFPRI), under a Feed the Future Innovation Lab for Livestock Systems subaward, found that commercialization, urbanization, and rising incomes have together increased demand for higher-value foods, especially animal source foods (ASFs) (see Minten et al. 2018). Unfortunately, the production of ASF has not kept pace with demand, leading to higher prices in both rural and urban areas, which have, in turn, limited growth in households' actual consumption of ASF (Abegaz, et al., 2018; Minten, et al., 2018). Growth in Ethiopia's livestock system over the last decade can therefore be characterized as demand-driven but supply-constrained. The latter was shown to be mainly a result of the country's continued dependence on expanding herd sizes, rather than adopting productivity-enhancing technologies (Bachewe, et al., 2018). This inability to significantly raise farm productivity and prevent prices from rising represents a missed opportunity, especially given the importance of ASF for household incomes, poverty reduction, and nutritional outcomes in Ethiopia (Benfica & Thurlow, 2017).

The livestock system's current growth trajectory may prove unsustainable, as grazing lands become scarcer and farmers must purchase more animal feed. Grazing land scarcity is particularly relevant for farmers located closer to urban areas. These farmers almost exclusively rely on purchased industrial feeds (Minten, et al., 2020). The cost of a nutritious diet in Ethiopia is already high (Bachewe, et al., 2017), but this could worsen if supply-constraints are not adequately addressed. Fortunately, research by IFPRI and others has identified bottlenecks and policies that, if overcome or reformed, could improve the performance of Ethiopia's livestock system. Most studies focus on supply-side interventions, such as farmers' access to animal feed, medicines, and veterinary services. Investing in animal research and advisory services, for example, could promote greater use of improved technologies and practices, leading to higher on-farm productivity. However, recent dairy-sector-focused research showed the importance of alleviating demand-side constraints and addressing bottlenecks throughout the value chain (e.g., Minten et al. 2020). Interventions include helping farmers access higher-value urban markets and providing the price incentives and infrastructure needed for local farms and firms to safely supply and profitably compete in domestic markets, especially against imported ASF items.

Three major implications emerge from the existing research on livestock systems in Ethiopia. First, it is insufficient to focus solely on raising on-farm production levels. Instead, a livestock systems approach is needed that accounts for the downstream linkages connecting producers and consumers. Second, since livestock growth is currently demand-driven, the future trajectory of the livestock system may depend more on developments in the broader economy than within the livestock sector itself. Third, studies (for example, Shapiro et al 2017; USAID, 2013) have identified the kinds of policies needed to address supply-side constraints. These will require targeted investment in the livestock system, including government spending.

The three major implications above motivate the development of a systems-based analytical approach – the Linked Economic and Animal Systems (LEAS) model – that tracks the livestock system, measures its linkages to the broader economy, and accounts for the downstream linkages connecting producers and consumers. Such an approach should ideally capture all segments of the supply chain, as well as interactions between livestock and the rest of the economy. Only then is it possible to assess the direct and indirect linkages between the livestock system and national development outcomes, such as economic growth, job creation, poverty reduction, and improved nutritional outcomes in both rural and urban areas.

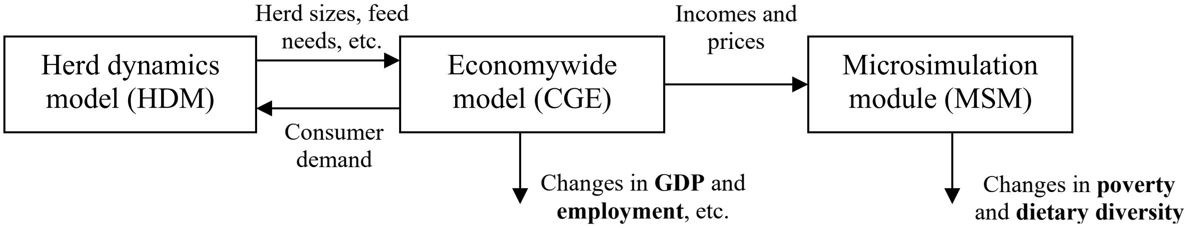
This report documents the LEAS model that is designed to assess (i) how animal herd or flock sizes change over time and in response to on-farm policies; (ii) how alternative national trends and policies affect the future development of the livestock system as a whole; (iii) how changes in livestock policies affect people working throughout the livestock system; and (iv) how changes in ASF production and prices affect the real incomes and consumption patterns of different population groups. The LEAS model integrates a herd dynamics model (HDM) that is linked both ways with an economywide model. The economic model is further linked top-down with a survey-based microsimulation model (MSM). Since the core economic model and the microsimulation module have been frequently used and discussed elsewhere (Benfica and Thurlow 2017; Arndt, et al., 2012), this technical document focuses on the HDM component of the LEAS model. Whenever appropriate, illustrative results from the MSM and the core economic model are presented and discussed.

The rest of the model documentation is organized as follows. Section 2 introduces the structure of the LEAS model. Section 3 provides detailed structural features, data requirements, and selected equations of the HDM. Section 4 presents how the HDM is linked with the coder economic model. While section 5 illustrates the HDM and some results from the economic model, the last section concludes.

2 THE LINKED ECONOMIC AND ANIMAL SYSTEMS (LEAS) MODEL

In line with the major implications that emerge from a closer look at a number of research findings, the economic reality, and the potential risks the Ethiopian economy finds itself in, we develop a more sophisticated integration of advanced economic modeling with a traditional herd dynamics model. The integrated model framework is referred to as the Linked Economic and Animal Systems (LEAS) model (Figure 2.1). The first component of the LEAS model is a herd dynamics model (HDM). This is a lifecycle (stock-flow) model that tracks annual herd/flock sizes disaggregated by age, sex, breed/strain, and agroecology zone. The HDM helps to estimate reproduction, births, deaths, and offtakes (slaughtering) for different types of animals (such as cattle, chickens, sheep, and goats). The model is calibrated to historical data from Ethiopia's Agricultural Sample Surveys (AgSS), and information from past studies on the livestock system.

Figure 2.1. The LEAS model framework with information flows and outcome indicators



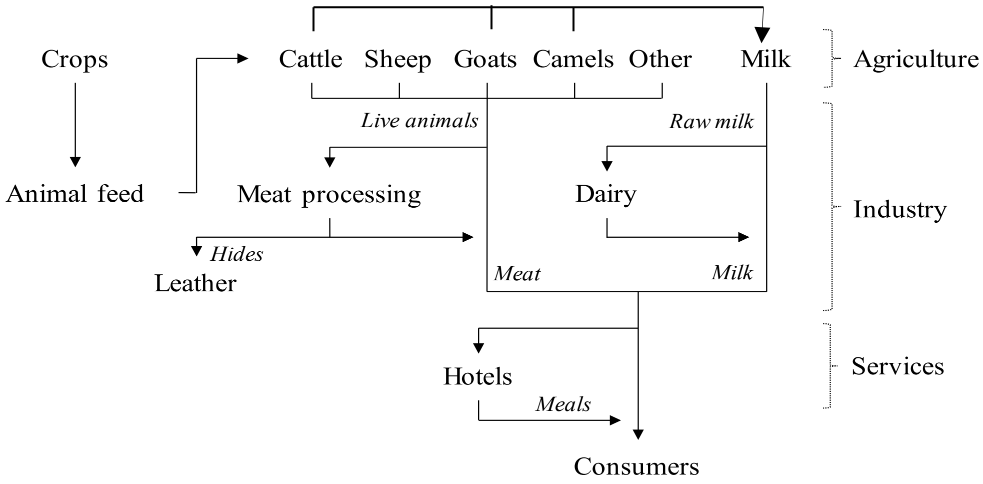
Source: Authors compilation.

Note: CGE = computable general equilibrium.

Given information on consumer demand for animal products and the profitability of animal offtake activities, the HDM estimates offtake requirements, remaining herd sizes, and annual feed requirements. Certain policy interventions are embedded within the HDM, such as public provision of medicines to improve animal health or access to improved feed to increase on-farm livestock productivity. The HDM also incorporates parameters and variables for analyzing shocks (drought, disease, etc.) to the livestock system. Since the core economic model and the microsimulation module have been used and discussed elsewhere (Benfica and Thurlow 2017; Arndt, et al., 2012), this technical document focuses on the HDM component of the LEAS model.

Whereas the HDM can be redesigned as a standalone model, its value is high when linked to an economywide model that captures the functioning of the overall economy, including the interactions between producers and consumers within detailed sectors and subnational regions. More specifically, the integrated framework includes a recursive dynamic computable general equilibrium (CGE) model known as IFPRI's Rural Investment and Policy Analysis (RIAPA) model. RIAPA is based on IFPRI's core CGE model (Diao & Thurlow, 2012) and was jointly developed by IFPRI and the International Fund for Agricultural Development (IFAD). RIAPA is specifically designed to identify policy priorities and evaluate the impacts of investments in food system value chains (see, for example, Benfica and Thurlow 2017). The proposed structure of the livestock system within RIAPA is shown in Figure 2.2 (note that poultry and eggs are covered but not shown). RIAPA allows us to evaluate the direct and indirect impacts of livestock policies; trace effects throughout the livestock system, food system, and national economy; and link changes in production and prices to changes in employment and household incomes (including rural non-farmers and consumers in urban areas).

Figure 2.2. Structure of the livestock system's product flows in the economywide model



Source: Authors compilation.

The LEAS model framework includes a survey-based MSM that measures the impacts of livestock system growth and policies on household-level outcomes, including poverty and dietary diversity (Arndt, et al., 2012). The MSM is based on Ethiopia's 2010/11 Household Consumption and Expenditure Survey (HCES), which can easily be updated to the 2015/16 survey when there is access to it. Changes in incomes and prices for different household groups in the CGE model are passed down to their corresponding households in the HCES, where real consumption levels are updated and compared to the official poverty line. The poverty analysis can also be complemented by an entropy-based measure of dietary diversity. The prevailing access to diets can be compared to an aspirational (least-cost) diet that meets daily calorie and micronutrient requirements.

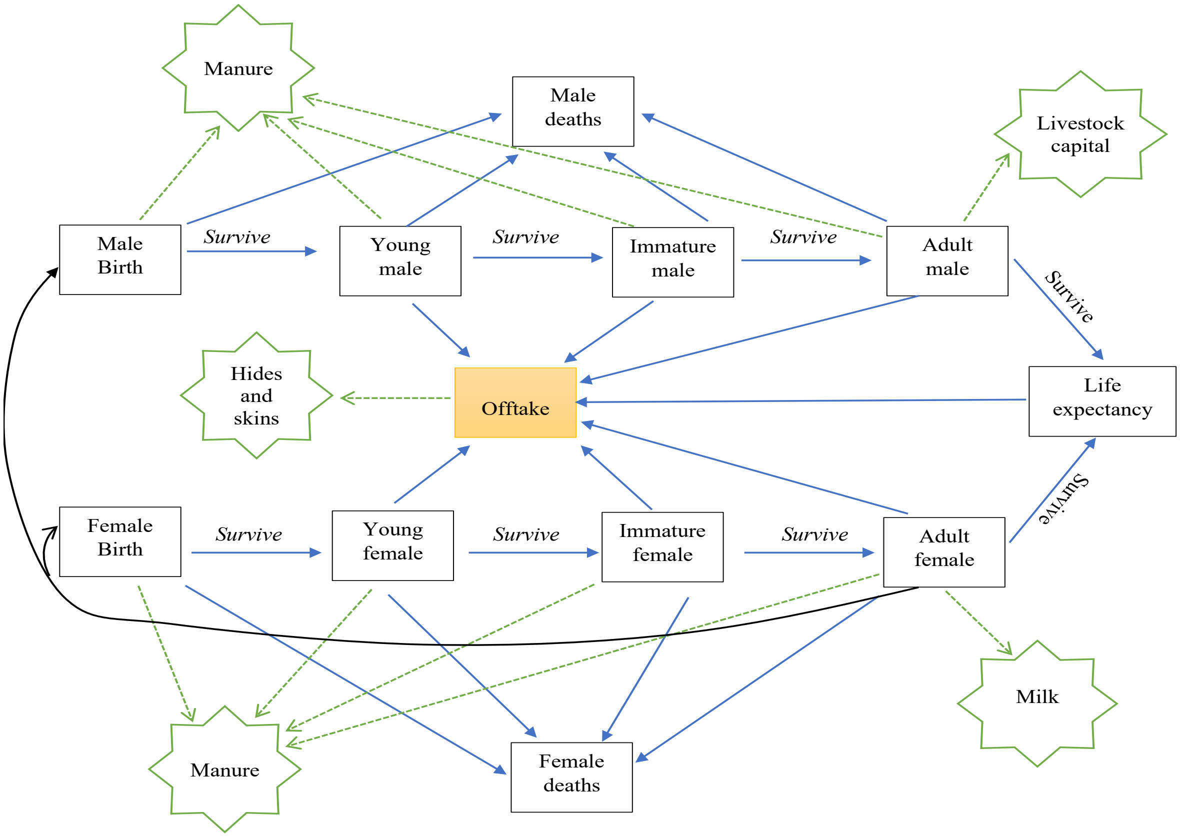
Overall, the integrated LEAS model allows us to quantify more consistently (i) how animal herd or flock sizes change over time and in response to policies; (ii) how alternative national trends and policies affect the future development of the livestock system as a whole; (iii) how changes in livestock policies affect people working throughout the livestock system; and (iv) how changes in ASF production and prices affect the real incomes and consumption patterns of different population groups. The HDM developed captures the different segments of livestock value chains, including farmers and input suppliers (for example, producers or importers of feed, etc.). The model situates the livestock system within the broader agricultural and national economic systems. Its interaction with an economywide model means that it includes equally detailed information on both livestock and non-livestock-related value chains. Overall, the model developed provides a comprehensive, but tractable, tool for government analysts and researchers in Ethiopia that can be readily used to enhance livestock sector forecasts and provide more robust and relevant evidence for identifying, evaluating, and motivating pursuit of livestock policy priorities.

3 THE HERD DYNAMICS MODEL (HDM)

3.1 The HDM structure and data

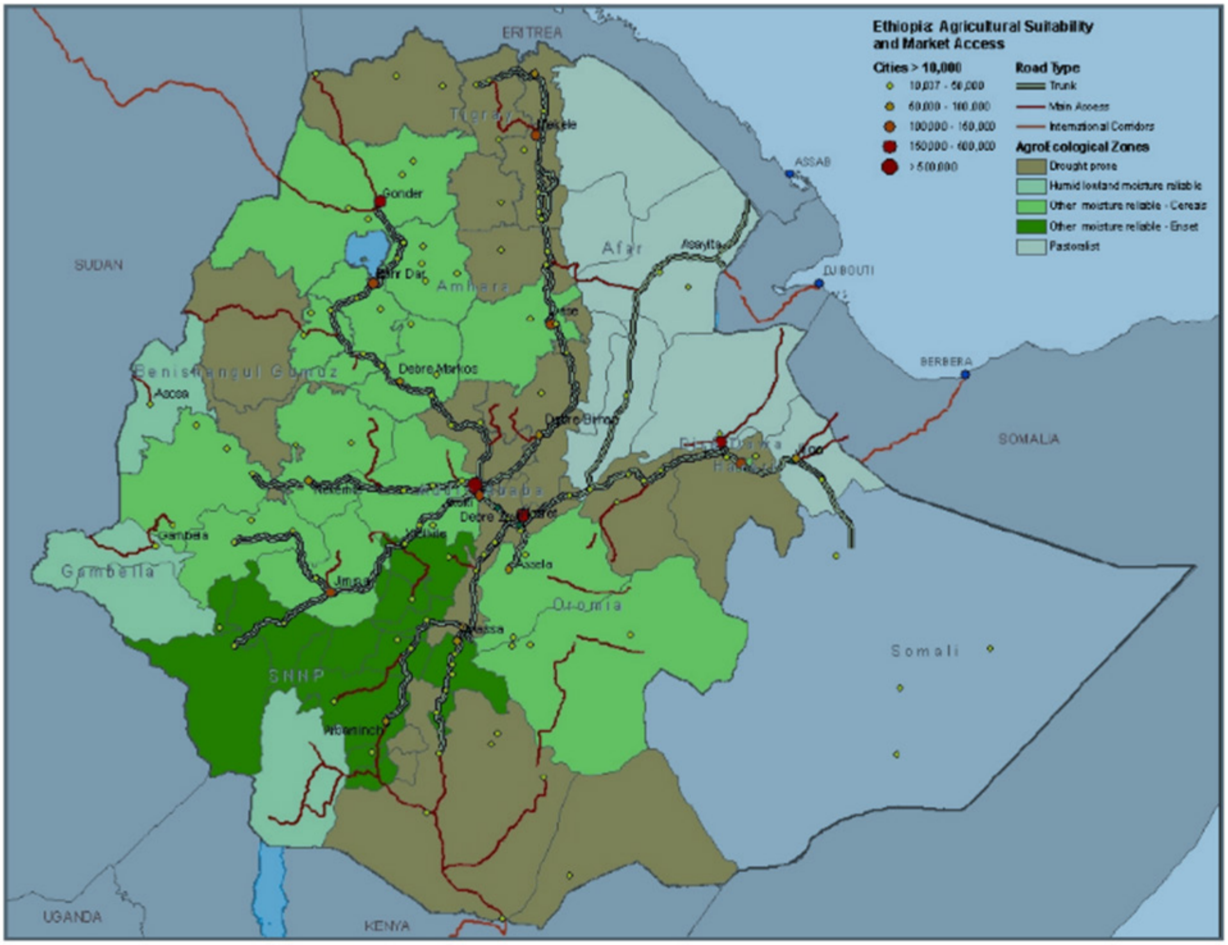
We used several data sources to build the HDM. The principal source of data is the livestock modules of Ethiopia's AgSS that stretch between 2003 and 2017 (CSA, 2003-2017). The AgSS includes rich information on herd/flock size by age group, sex, and spatially. Although we build a database for small ruminants and poultry too, the HDM we report on here focuses on cattle only (Figure 3.1). We build the cattle database for each of the (i) humid lowland, (ii) cereal-based humid highland, (iii) *enset*-based humid highland, (iv) drought-prone areas, and (v) pastoralist (arid lowland plains) agroecological zones. These agroecological zones are distinguished by climate, moisture availability, and main land use (see Figure 3.2 and Tebekew et al. (2009)). Table 3.1 also reports the cattle number (2017) and share of each zone in total national area.

Figure 3.1. Schematic representation of the herd dynamics – cattle



Source: Authors compilation.

Figure 3.2: Agroecological zones of Ethiopia



Source: Tebekew et al. (2009)

Table 3.1. Number of cattle and share of each agroecological zone in total national area

Agroecological zone	% area (2007)	Cattle number (in million)
Humid lowlands	9%	2.6
Cereal-based humid highlands	31%	29.5
Enset-based humid highlands		9.7
Drought prone	30%	16.7
Pastoralist (arid lowland plains)	30%	1.9
Total	100%	60.4

Source: Percent of each zone from Chamberlin and Schmidt (2011) and cattle number from CSA (2017).
Note: Drought prone includes both drought prone highland and drought prone lowland areas in the country.

Unlike many other HDMs that relied on broader age cohorts, we build single-age cattle HDM. Although the surveys provide some useful information, they were not directly usable as the cattle data were reported at irregular and aggregate age groups (under 6 months; 6 months - under 1 year; 1 year - under 3 years; 3 years - under 10 years; and 10 years and older). What makes the generation of a single-age cattle database more problematic was the lack of internally consistent demographic parameters – birth rate, death rate, offtake rate, etc. – for each age level and sex. To put it differently, the age and sex-specific values in X and matrix A of the population growth model below are largely unknown. To generate usable cattle data, we needed to transform the original data such that a smoothed and demographically consistent lifetable is constructed using a multi-step procedure.

The first step in this regard is to approximate a baseline lifetable for the Ethiopian cattle population using the recent cattle population data (by sex and age group) that corresponds to the core CGE model's base year, 2017. Whereas the 2017 livestock survey, as is the case for other subsequent similar surveys, provides livestock population by unequal age cohorts separately for female and male, we first generate a year-by-year frequency by splitting equally the population in each cohort by the number of years of the cohort. We then repeatedly applied a nonparametric robust nonlinear smoother algorithm on Stata® until a realistic and stable age structure is achieved (see Annex Table 8.1). The same procedure is done on the cattle survey data for the 2003 – 2016 period. The 2017 smoothed population frequency forms the base year cattle data. Meanwhile, the population parameters are estimated using mean values of "initial" survival and fecundity rates over the 2003 – 2017 period and the Leslie-matrix model approach (Leslie, 1945; Caswell, 2001). The advantages of this approach have been described in the population modeling literature (Upton, 1989; Caswell, 2001). An annual Leslie matrix model of the form below is constructed for the cattle herd in Ethiopia.

$$X_{t+1}=A*X_t$$

where Xt is the age-sex population vector at time t and A is the annual projection matrix that predicts the age-sex population vector a year later. We build separate Leslie matrix models for the female and male herd. Hence, each component of Xt represents the number of animals of a given age at time t for each sex. Matrix A contains sex and age-specific survival and fecundity rates of the population, that is, parameters which define how the population size by age changes over a year (see below). The survival rates to the next age class are a function of mortality and net offtake rates, where net offtake is defined as offtake minus intake and represents the productivity of the herd (Lesnoff, et al., 2000). In tropical livestock-production systems, offtake consists of all animals leaving the herd in the form of own slaughtering and sales of livestock. However, intake involves all animals entering the herd system, that is, purchases and receipts of gifts. Fecundity rates, that is, the measure of the expected number of living newborns during a year per cow, are also a function of parturition and net-prolificacy rates.[1]

We build a cattle population matrix of 13 age levels (age 0 to age 12) including one for new births. As such, matrix A takes the form:

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[1] Parturition is the process of giving birth after the end of the gestation (pregnancy) period, and the net-prolificacy rate is the average number of calves born alive per parturition.

$$A = \begin{pmatrix} f_0 & f_1 & f_2 & f_3 & \cdots & f_9 & f_{10} & f_{11} & f_{12} \\ s_0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & s_1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & s_2 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & s_3 & \cdots & 0 & 0 & 0 & 0 \\ . & . & . & . & \cdots & . & . & . & . \\ . & . & . & . & & . & . & . & . \\ . & . & . & . & & . & . & . & . \\ 0 & 0 & 0 & 0 & \cdots & s_9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & s_{10} & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & s_{11} & s_{12} \end{pmatrix}$$

where $f_i = patrt_i * prol_i$ denotes the fecundity of an individual cow of age i (which is 0 up to age 3 and beyond age 10 because they are not expected, under normal circumstances, to be fertile), $part$ is parturition rate, $prol$ is prolificacy rate, $s_i = (1\text{-}mr_i)$ is the survival rate of a cattle to the next age, and mr is mortality rate inclusive of natural death dr and offtake rate ofr. The survival rates si are closely adjusted using adjustment coefficients θ_i to give the average livestock growth rates observed during the 2003 – 2017 period. We assume that once the animal reaches age 12, its productivity significantly declines and it will finally be culled. Parameters f_i and s_i are determined such that they yield the average long-term growth trend (2003 – 2017) observed for Ethiopia's cattle population at broader age group and overall levels. [Due to some data issues, the average growth rates observed from the surveys were adjusted downwards to achieve realistic demographic parameters.] We assume that cows of age 3 to 10 are reproductive.

Once the desired rates of survival are derived, mortality rates are directly extracted. The subsequent question is how to identify the share of natural deaths and offtake levels out of the composite mortality rate figures by age and sex. The livestock literature (Shapiro, et al., 2017) shows that death rates range between 5 to 12%, whereas offtake rates average around 11%.[2] Since these death and offtake rates are expressed as a share of the full size of the herd, a challenge was posed by our stepwise approach of deriving the end period herd size after separately accounting for these two types of removal of part of the herd – death and offtake. Hence, for stock of cattle x at a given age i, we use the relationship below to split mr_i to dr_i and ofr_i for females and males separately and populate Table 3.2.

$$mr_i x_i = dr_i x_i + (x_i - (dr_i x_i))x_i$$
$$mr_i = dr_i + ofr_i - dr_i ofr_i$$

Let s_i be the share of dr_i in mr_i.

$$mr_i = s_i mr_i + ofr_i - s_i mr_i ofr_i$$
$$ofr_i = \frac{(mr_i(1-s_i))}{(1-s_i mr_i)}$$

Once system-consistent demographic parameters are computed using the above procedure, together with these, the newly constructed 2017 livestock data is then used for calibrating the livestock model for t years over the future. In fact, the HDM calibrated with the 2017 smoothed cattle population data, and the

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[2] These rates are scaled as appropriate to generate a baseline meat production level close to the country's reported current production.

estimated demographic parameters – which are assumed to be constant across time – generate a stable population structure running through $t+13$ years (that is, by 2030). See Annex Table 8.1.

One special feature of the population-growth matrix model we build is its stable structure (versus steady-state growth as in Lesnoff et al., 2000 and Lesnoff, 2009 - 13) where we compute demographic rates, including offtake rates under which the herd age and sex structure (and NOT its size) would be the same at the beginning and end of the study period. Although it is technically possible to build the matrix model at a 1-month time step, we constructed an annual model. Annual population models have been used to study the productivity of livestock across different farming systems or to test the efficacy of various herd management programs (Cossins & Upton, 1988; Upton, 1989; Bekure, et al., 1991). However, annual models cannot account for seasonal variation in production traits and offtake patterns (e.g., for cultural/religious reasons) which influence the demographic structure, and that could be particularly relevant when studying small ruminants such as sheep and goat flocks.

Table 3.2 below reports the lifetable of female and male cattle population in the cereal-based humid highlands of Ethiopia in 2017. This table was constructed using the approach described above. The cereal-based humid highlands contribute to over 50% of total cattle stock in the country. The lifetables of cattle in all five agroecological zones are reported in Annex Table 8.2.

Table 3.2. Lifetables of female and male cattle (in '000 and %) in cereal-based humid highlands

Age	**Female**						**Male**					
(*i*)	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i
0	2,658	2,658	-	0.13	0.13	-	2,385	2,439	-	0.13	0.13	-
1	1,303	2,238	-	0.13	0.13	-	1,154	2,056	-	0.13	0.07	0.07
2	1,303	1,889	-	0.13	0.13	-	1,154	1,736	-	0.13	0.06	0.08
3	1,399	1,634	0.56	0.11	0.04	0.07	1,289	1,503	-	0.11	0.05	0.06
4	1,399	1,473	0.56	0.07	0.02	0.05	1,289	1,356	-	0.07	0.03	0.04
5	1,399	1,384	0.56	0.03	0.01	0.02	1,289	1,275	-	0.03	0.01	0.02
6	1,399	1,317	0.56	0.02	0.00	0.01	1,289	1,214	-	0.02	0.01	0.01
7	1,399	1,220	0.56	0.04	0.01	0.03	1,289	1,125	-	0.04	0.02	0.03
8	1,399	1,075	0.56	0.09	0.02	0.07	1,289	993	-	0.09	0.03	0.06
9	1,399	883	0.56	0.15	0.04	0.12	1,289	817	-	0.15	0.06	0.10
10	123	652	0.56	0.24	0.06	0.19	120	605	-	0.24	0.09	0.17
11	123	393	-	0.38	0.09	0.32	120	368	-	0.37	0.14	0.28
12	123	123	-	0.68	0.16	1.00	120	120	-	0.66	0.24	1.00

Source: Result from the HDM component of the LEAS model for Ethiopia. Authors compilation.
Note: ID_i= initial simple extrapolated age structure of the population in 2017, SD_i= smoothed age distribution based on the Leslie matrix and the procedure above, f_i= fecundity rate, mr_i= mortality rate (inclusive of natural deaths and offtake), dr_i= death rate, and ofr_i= offtake rate.

Overall, in the baseline Ethiopian cattle population, females represent 55% and the annual fertility rate (that is the ratio of new births to the total female population within the fertile age range of 3 – 10 years) is 50%, which is close to other estimates (Shapiro, et al., 2017) for cattle in Ethiopia. The data also shows that females constitute about 52% of total live births. Further, the average herd structure (new births, juveniles, sub-adult, and adult) is very consistent with the cattle herd structures reported by Negassa et al. (2015) and Lesnoff et al. (2002).

3.2 Algebraic statement of the HDM

Once the database for calibrating the HDM is assembled, the next fundamental step is getting the mathematical model together. The HDM uses a number of sets with members assigned. The following are the main sets for this model.

RG = *{Regions}* = *{X, Hu_L, Hu_H_c, Hu_H_e, Dro_p, Pas}*[3]
TYPE = *{Animal type}* = *{Bov, poul, smlr, oliv}*[4]
SEX = *{Animal sex}* = *{M - male, F - female}*
AGE = *{Age group in years}* = *{Y0*Y12}*

The module also has dynamic sets that are defined as subsets of some of the above sets.

$AGEJ_{AGE}$	juveniles (> 0 months < 12 months)	/ *Y0* /
$AGES_{AGE}$	sub-adults (≥ 12 months < 36 months)	/ *Y1, Y2* /
$AGEA_{AGE}$	adults (≥ 36 months)	/ *Y3, Y4, ... ,Y10* /
T	time periods	/ *T0, T1, ..., TN* /
TC_{T}	active time periods	/ *T1, ..., TN* /

3.3 Calibrating the base data

The first step in calibrating the HDM is getting together the data relevant to run the model. Most of the data used to calibrate the model can be obtained from livestock sector surveys which can be available on an annual basis in several countries. When the survey data are not adequate in some instances, the information is complemented by published data in the literature from case studies.

The baseline data is recorded (exported to) and managed in Microsoft Excel® and converted to a GDX (GAMS data exchange) file as part of the model. The original data on the stock of livestock by region (*RG*), type (*TYPE*), sex (*SEX*) of the animal, and age (*AGE*) is recorded in a data sheet *lvData*. *lvX* refers to the baseline stock of an animal (further identified by region, sex, type, and age). *AGE* refers to the age of the animal in years (for the cattle model) that can also be easily defined in shorter age classes – e.g., in month – that can work more appropriately for small ruminants and poultry. There are also several parameters recorded in *lvData* including death rate (*lvDr*), offtake rate (*lvYr*), final culling (*lvCr*), parturition rate (*lvBpart*), net prolificacy rate (*lvBprol*), and share of female in live births (*lvBsex*), all of which defined per year are assumed to remain fixed.

It is desirable to define some of the livestock demographic parameters from the outset. Death rates (*lvDr*) are a measure of the mortality rate that would occur without deliberate measures of slaughtering and culling – the mortality rate that is largely due to natural causes. By offtake, we are referring to the number of animals sold or slaughtered out of a system during a period. Final culling represents a key stock management practice and refers to removing animals from the herd when the animal's economic value is deteriorating for age reasons. Parturition rate is a measure of the average probability of live births and occurs at the end of pregnancy. This parturition rate applies only to the fertile age class of the adult females in the population. *lvBsex* also refers to the average proportion of females from new live births.

In some cases, some countries (in a national model) and some regions (within a nation) could "import" animals. The baseline information on the intake activities by region also needs to be recorded (*lvN*) and

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[3] *Hu_L* = humid lowland, *Hu_H_c* = cereal based humid highland, *Hu_H_e* = *enset*-based humid highland, *Dro_p* = drought prone areas, and Pas = pastoralist zones. *X* refers to the "national" region in the economic model.

[4] *Bov* = Bovine, *poul* = Poultry, *smlr* = small ruminants (constituting sheep and goats), and *oliv* = other livestock including equines and camel.

accounted for. This will be specifically relevant as a policy response in a post-shock period to rebuild the animal stock in a region after a significant decline in herd size.

The first few equations relate to importing into the modeling framework the baseline stock and demographic parameters discussed above that are used to calibrate the HDM. In addition, to make the dynamic computation of input demand easier, we first define a number of equations as presented below from the initial data. Feed demand is a derived demand that depends on the size of the herd. We break down the dry matter equivalent of the feed demand in the livestock sector into four components: raw feed (*RawFeed*), improved feed (*ImprFeed*), crop residue (*CroResDryMat*), and green fodder (*FoddDryMat*). Total dry matter demand (*DryMat*) by the livestock system in the country [Eq. 1] is determined by the total liveweight of animals (*lwlvX_1*) in the system and the dry matter requirement per kilogram of live weight of the animals per day multiplied by 365 days. Liveweight per animal by type and age is identified in the baseline data. The amount of raw feed demand [Eq. 2] is determined by the predetermined share of raw feed in total dry matter use (*RawSh*). The livestock survey includes indicative data on feed source. The productivity of the livestock sector depends significantly on access to improved feed. The improved feed use is determined by its underlying share (*ImprSh*) in total animal feed at the base [Eq. 3]. The livestock sector also relies on crop residues and green fodder. In addition to the raw feed component, crop residue (*CroResDryMat*) as a source of animal feed provides another way to link the crop and the livestock sectors. Whereas *CroResDryMat* is defined as the *CroResSh* proportion of *DryMat* [Eq. 4], fodder in total animal feed demand is the net of the above three components from total *DryMat*. Integration of the feed system with the economic model is further detailed in the input demand block presented below.

$$DryMat_{RG,TYPE,SEX,AGE,T} = 365 * lwlvX\_1_{RG,TYPE,SEX,AGE,T} * lvDATA_{RG,TYPE,SEX,AGE,'DryMat'} \quad [1]$$

$$RawFeed_{RG,TYPE,SEX,AGE,T} = \Sigma_{SEX,AGE}\left(RawSh_{TYPE} * DryMat_{RG,TYPE,SEX,AGE,T}\right) \quad [2]$$

$$ImprFeed_{RG,TYPE,SEX,AGE,T} = \Sigma_{SEX,AGE}\left(ImprSh_{TYPE} * DryMat_{RG,TYPE,SEX,AGE,T}\right) \quad [3]$$

$$CroResDryMat_{RG,TYPE,SEX,AGE,T} = \Sigma_{SEX,AGE}\left(CroResSh_{TYPE} * DryMat_{RG,TYPE,SEX,AGE,T}\right) \quad [4]$$

Once the initial data is recorded, the animal stock is transferred to the next age group at the beginning of the current year [Eq. 5] and old animals are culled at the start of the year [Eq. 6]. Hence, all animals at the last age level (13 years old) last year vanish at the beginning of the current year.

$$lvX_{RG,TYPE,SEX,AGE,T} = lvX_{RG,TYPE,SEX,AGE,T-1} \quad [5]$$

$$lvC_{RG,TYPE,SEX,AGE,T} = lvX_{RG,TYPE,SEX,AGE,T} * lvCr_{RG,TYPE,SEX,AGE,T} \quad [6]$$

$$lvX_{RG,TYPE,SEX,AGE,T} = lvX_{RG,TYPE,SEX,AGE,T} - lvC_{RG,TYPE,SEX,AGE,T} \quad [6a]$$

Juveniles (*AGEJ*) among cattle are less than one year old and are determined by births. The share of females in live birth (*lvBsexf*) are assumed to be identical for all reproductive-female age groups and are obtained from the baseline data. [Eq. 7] and [Eq. 8] calculate male and female births respectively and depend in addition to *lvBsexf* on adult female population (*AGEA*), *lvBpart*, and *lvBprol*. Total number of new births is provided by [Eq. 9].

$$lvB_{RG,TYPE,'M',T} = \sum_{AGEA} \left(lvX_{RG,TYPE,'F',AGEA,T} * lvBpart_{RG,TYPE,AGEA,T} * lvBprol_{RG,TYPE,AGEA,T} \right) * (1- lvBsexf_{RG,TYPE}) \qquad [7]$$

$$lvB_{RG,TYPE,'F',T} = \sum_{AGEA} \left(lvX_{RG,TYPE,'F',AGEA,T} * lvBpart_{RG,TYPE,AGEA,T} * lvBprol_{RG,TYPE,AGEA,T} \right) * lvBsexf_{RG,TYPE} \qquad [8]$$

$$lvX_{RG,TYPE,SEX,AGEJ,T} = lvB_{RG,TYPE,SEX,T} \qquad [9]$$

Deaths during the year are calculated by applying age- and sex-specific death rates [Eq. 10]. Death rates are assumed to be fixed over time but can be linked to positive interventions such as improved access to veterinary services, or negative shocks such as drought and animal diseases.

$$lvD_{RG,TYPE,SEX,AGE,T} = lvX_{RG,TYPE,SEX,AGE,T} * lvDr_{RG,TYPE,SEX,AGE,T} \qquad [10]$$

The initial offtake rates are calculated after accounting for deaths during the year and following the relationship in [Eq. 11]. *lvYrPrAdj* is the initial offtake rate *lvYr* adjusted for change in relative prices of the cattle sector indicating the relative profitability of slaughtering animals (more on this below). The assumption is that offtake rates increase as the profitability of slaughtering animals increases.

$$lvY_{RG,TYPE,SEX,AGE,T} = lvX_{RG,TYPE,SEX,AGE,T} * lvYrPrAdj_{RG,TYPE,SEX,AGE,T} \qquad [11]$$

Livestock herders purchase animals and bring them into the livestock system for reasons including restocking after a bad year, such as one marked by drought or animal pandemics. Herders could also use intakes to increase the genetic mix/potential of the herd. If the farmer buys cattle just in their most productive periods or buys high-yield breeds as replacements of older ones, the herd can have higher average milk productivity. The same is true for meat offtake. This animal intake is represented by *lvN*. The final stock of animals after accounting for births, deaths, offtake, and intake is provided by [12].

$$lvX_{RG,TYPE,SEX,AGE,T} = lvX_{RG,TYPE,SEX,AGE,T} + lvN_{RG,TYPE,SEX,AGE,T} \qquad [12]$$

3.4 The demography block

Once the baseline data is calibrated and the system is replicated, the dynamics are established through a number of model functions built on the baseline demographic information and dynamics of price and input data that affect the performance of the cattle sector. With the stock of cattle at the beginning of the year expressed as *lvX*, the size of offtake is determined by the price-adjusted offtake rate given by [Eq. 14] where the price index (*LDPI*) that determines the decision to slaughter or offtake is a function of the cattle sector's relative profitability expressed as the sector's price (*PAR*) relative to the economywide producer price index (*DPI*) [Eq. 13]. It is mapped to the type of animals to reflect the animal-type-specific offtake prices. Both *LDPI* and *PRA* are defined at the "national" region (*X*) level. *lvPEla* is the animal-type-specific price elasticity of the offtake rate and is set to 0.2 for cattle. As the relative price of the cattle sector increases, farmers find offtaking profitable and increase their offtake rates, and hence the number of animals slaughtered/sold out of the system.

$$LDPI_{RG,TYPE,TC} = \left(\sum_{a\$maptypea(TYPE,A)} PAR.L_{A,'X'} / DPI.L \right) / \left(\sum_{a\$maptypea(TYPE,A)} PAR0_{A,'X'} / DPI0 \right) \qquad [13]$$

$$lvYrPrAdj_{RG,TYPE,SEX,AGE,TC} = lvYr_{RG,TYPE,SEX,AGE,TC} * LDPI_{RG,TYPE,TC}^{lvPEla_{TYPE}} \qquad [14]$$

The current pace of growth of livestock in Ethiopia is unsustainable, and already faces carrying capacity problems that affect both the productivity of the livestock sector and the offtake decisions of farmers. To capture the effect carrying capacity utilization *(lvCCUtil_TLU)* has on the offtake rate, we introduced system-specific carrying capacity *(lvCC_TLU)* expressed in tropical livestock units by region as in [Eq. 15]. In a multiple livestock type model, the stock of each animal type can be converted to TLUs using the conversion factor *Conv_f* obtained from FAO.

$$lvCCUtil\_TLU_{RG,TC)} = [\textstyle\sum_{TYPE,SEX,AGE} lvX_{RG,TYPE,SEX,AGE,TC} * Conv\_f_{TYPE}]/lvCC\_TLU_{RG} \qquad [15]$$

The effect of carrying capacity utilization is introduced in the carrying capacity adjusted offtake rate *lvYrCapAdj* as in [Eq. 16]. The effect of the carrying capacity is imposed on the incremental section of the stock change (*t* — *t-1*) which ensures that the stock does not forcefully decrease in time *t* from its *t-1* value under the prevailing agroecological condition. $lvCaryEla_{AGE}$ is the age-specific carrying capacity elasticity of offtake rate. The livestock sector research shows that farmers selectively cull older animals during resource stresses (Griffith, 2010). Total offtake rate is the sum of *lvYrPrAdj* and *lvYrCapAdj*.

$$lvYrCapAdj_{RG,TYPE,SEX,AGE,TC} = [(lvX_{RG,TYPE,SEX,AGE,TC} - lvX_{RG,TYPE,SEX,AGE,TC-1}) * lvCCUtil\_TLU_{RG,TC-1}{}^{lvCaryEla_{AGE}}]/lvX_{RG,TYPE,SEX,AGE,TC} \qquad [16]$$

The stock of animals after accounting for these two types of offtake rates is approximated by [Eq. 17].

$$lvX_{RG,TYPE,SEX,AGE,TC} = lvX_{RG,TYPE,SEX,AGE,TC} * (1 - lvYrAdj_{RG,TYPE,SEX,AGE,TC} - lvYrCapAdj_{RG,TYPE,SEX,AGE,TC}) \qquad [17]$$

3.5 Input demand block

The performance of the livestock sector and its stock level depend on access to feed. The demand for feed depends on the average baseline live weight ($lvDATA_{*,*,*,*,'live\_wt'}$) of the animal which is obtained from the literature on animal sciences. The total live weight of the stock is given by [Eq. 18] and total dry matter demand per year is calculated as in Eq. 19 based on the animals' dry matter requirement per kg of their weight per day ($lvDATA_{*,*,*,*,'DryMat'}$). The feed requirement per year is calculated upon the mid-year cattle population which is expressed as an average of *lvX* in the current year and the previous year (see Eq. 18). The four components of feed supply and demand are given by similar functional relationships as in [Eq. 1] – [Eq. 4] above and updated by changes in the price of the cattle sector (*PAR*). However, in the dynamics, we also represented the interlinkages between the feed demand from the livestock sector and the supply of feed in the economic model. We also assume that the total area of cropland determines the supply of crop residues as feed sources. The animals' demand for fodder is assumed as a residual of the dry matter demand considering the demand for all the other feed types [Eq. 25].

$$lwlvX\_1_{RG,TYPE,SEX,AGE,TC} = \left[(lvX_{RG,TYPE,SEX,AGE,TC} + lvX_{RG,TYPE,SEX,AGE,TC-1})/2\right] * lvDATA_{RG,TYPE,SEX,AGE,'live\_wt'} \qquad [18]$$

$$DryMat_{RG,TYPE,SEX,AGE,TC} = 365 * lwlvX\_1_{RG,TYPE,SEX,AGE,TC} * lvDATA_{RG,TYPE,SEX,AGE,'DryMat'} \qquad [19]$$

$$RawFeed_{RG,TYPE,SEX,AGE,TC} = RawSh_{TYPE} * DryMat_{RG,TYPE,SEX,AGE,TC} * \left[\textstyle\sum_{a\$maptypea(TYPE,A)} PAR.L_{A,\,RG} / \left(\textstyle\sum_{a\$maptypea(TYPE,A)} PAR0_{A,\,RG}\right)^{lvPEla_{"Bov"}}\right] \qquad [20]$$

$$RawFeedTot_{RG,TYPE,TC} = \textstyle\sum_{SEX,AGE} RawFeed_{RG,TYPE,SEX,AGE,TC} \qquad [21]$$

$$ImprFeed_{RG,TYPE,SEX,AGE,TC} = ImprSh_{TYPE} * DryMat_{RG,TYPE,SEX,AGE,TC} * \left[\sum_{a\$maptypea(TYPE,A)} PAR.L_{A,\,RG} / \left(\sum_{a\$maptypea(TYPE,A)} PAR0_{A,\,RG}\right)^{lvPEla_{"Bov"}}\right] \quad [22]$$

$$ImprFeedTot_{RG,TYPE,TC} = \sum_{SEX,AGE} ImprFeed_{RG,TYPE,SEX,AGE,TC} \quad [23]$$

$$CroResDryMat_{RG,TYPE,TC} = CroResSh_{"Bov"} * \sum_{SEX,AGE} DryMat_{RG,TYPE,SEX,AGE,T0} *(1+ \left[\sum_{FLND,A} QF.L_{FLND,A,"X"} / \sum_{FLND,A} QF0_{FLND,A,"X"} -1\right]) \quad [24]$$

$$FoddDryMat_{RG,TYPE,TC} = \sum_{SEX,AGE} DryMat_{RG,TYPE,SEX,AGE,TC} - RawFeedTot_{RG,TYPE,TC} - ImprFeedTot_{RG,TYPE,TC} - CroResDryMat_{RG,TYPE,TC} \quad [25]$$

The productivity of the livestock sector does not only depend on the supply of feed but mainly on the quality of the feed available. Hence, we measure the supply of quality-adjusted feed using the following assumptions on the relative quality of each of the four feed sources: *ImprFeed* = 0.4(1= benchmark quality score); *RawFeed* = 0.3(0.75); *CroResDryMat* = 0.15(0.375) and *FoddDryMat* = 0.15(0.375)). The quality-adjusted feed is expressed as in [Eq. 26].

$$FeedQ_{RG,TYPE,TC} = ImprFeedTot_{RG,TYPE,TC} *1 + RawFeedTot_{,RG,TYPE,TC} *0.75 + CroResDryMat_{RG,TYPE,TC} *0.375 + FoddDryMat_{RG,TYPE,TC} *0.375 \quad [26]$$

Once the derived demand for raw (marked as "*crfeed*") and improved feed (marked as "*cfeed*") is determined, we link the feed demand (jointly marked as "*crpfeed*") to the appropriate intermediate input in the economic model through the parameter (*ica*) that measures the share of intermediate input in total aggregate intermediate demand in an activity. In the core economic model for Ethiopia, the cattle ("*acatt*") sector uses maize, sorghum, rice, and wheat as raw feed and a small amount of processed feed "*cfeed*." However, as we alter the share of raw and improved feeds as in [Eq. 27] and [Eq. 28], the condition that the sum of the shares of all intermediate inputs by an activity equals 1 will no more be valid. Hence, we proportionately reduce the share of those intermediate inputs other than raw and improved feed (marked as "*crpfeedn*") [Eq. 29] such that the condition is maintained. Since the economic model is a national model that does not perfectly match with the regionalization in the HDM, the economic variables and parameters are for the national region *"X"*.

$$ica_{crfeed,"acatt","X"} = ica0_{crfeed,"acatt","X"} * \left(1 + \left(\sum_{RG,TYPE} RawFeedTot_{RG,TYPE,TC} / \sum_{RG,TYPE} RawFeedTot_{RG,TYPE,TC-1} -1\right)\right) \quad [27]$$

$$ica_{"cfeed","acatt","X"} = ica0_{"cfeed","acatt","X"} * \left(1 + \left(\sum_{RG,TYPE} ImprFeedTot_{RG,TYPE,TC} / \sum_{RG,TYPE} ImprFeedTot_{RG,TYPE,TC-1} -1\right)\right) \quad [28]$$

$$ica_{crpfeedn,"acatt","X"} = ica0_{crpfeedn,"acatt","X"} - \left(ica_{crpfeedn,"acatt","X"} / \sum_{crpfeednp} ica0_{crpfeednp,"acatt","X"}\right) * \left(\sum_{crpfeed} ica_{crpfeed,"acatt","X"} - \sum_{crpfeed} ica0_{crpfeed,"acatt","X"}\right) \quad [29]$$

3.6 Production block

Input-availability-adjusted live weight *lvWtAdj* is given by [Eq. 30] and depends on the relative change in quality-adjusted feed availability and the elasticity of live weight to change in feed quality. Feed-quality-adjusted live weight of cattle per year is calculated upon the mid-year cattle population [Eq. 31].

$$lvWtAdj_{RG,TYPE,SEX,AGE,TC} = lvDATA_{RG,TYPE,SEX,AGE,'live\_wt'} * \left[FeedQ_{RG,TYPE,TC} / FeedQ_{RG,TYPE,TC-1}\right]^{lvDATA_{RG,TYPE,SEX,AGE,'lvEla'}} \quad [30]$$

$$lwlvX_{RG,TYPE,SEX,AGE,TC} = \left[(lvX_{RG,TYPE,SEX,AGE,TC} + lvX_{RG,TYPE,SEX,AGE,TC-1})/2\right] * lvWtAdj_{RG,TYPE,SEX,AGE,TC} \quad [31]$$

Milk production in Ethiopia and tropical Africa is almost entirely obtained from cattle. In fact, 83 percent of all milk produced in Ethiopia comes from cattle (USAID, 2013). Milk offtake from live animals (*lvYrMilk* in [Eq. 32]) depends on the average liter of milk offtake per cow ($lvDATA_{*,*,'F',AGEA,'Milkday'}$), parturition rate ($lvBpart_{*,*,*,AGEA,*}$), change in intermediate input availability (*QINTA.L/QINT0*), and the elasticity of milk offtake to intermediate input availability. Total milk production from a mid-year stock by animal type is calculated from [Eq. 33].

$$lvYrMilk_{RG,TYPE,'F',AGEA,TC} = \left[\begin{array}{c} lvDATA_{RG,TYPE,'F',AGEA,'Milkday'} * lvDATA_{RG,TYPE,'F',AGEA,'MilkOfft'} \\ * lvBpart_{RG,TYPE,AGEA,TC} \end{array}\right] * \left[\Sigma_{a\$maptypea(TYPE,A)} QINTA.L_{A,RG} / \Sigma_{a\$maptypea(TYPE,A)} QINTA0_{A,"X"}\right]^{lvDATA_{RG,TYPE,"F",AGEA,'lvEla'}} \quad [32]$$

$$proMilkTot_{RG,TYPE,TC} = \left[\Sigma_{AGEA}\left(lvX_{RG,TYPE,'F',AGEA,TC} + lvX_{RG,TYPE,'F',AGEA,TC-1}\right)/2\right] * lvYrMilk_{RG,TYPE,'F',AGEA,TC} \quad [33]$$

Meat is produced from the slaughtering of animals that are obtained through offtake (*lvY*) and final culling (*lvC*) of animals. In [Eq. 34], we calculate the live weight of animals slaughtered from which we generate total meat offtake (*meatOfftTot* in [Eq. 35]) that depends on carcass weight per animal or animal-specific meat yield ($lvDATA_{*,*,*,*,'mYield'}$). We obtain a baseline estimate of age and sex-specific meat yield from the livestock literature.

$$lvWtOfCul_{RG,TYPE,SEX,AGE,TC} = \left[lvY_{RG,TYPE,SEX,AGE,TC} + lvC_{RG,TYPE,SEX,AGE,TC}\right] * lvWtAdj_{RG,TYPE,SEX,AGE,TC} \quad [34]$$

$$meatOfftTot_{RG,TYPE,TC} = \Sigma_{SEX,AGE}\left(lvWtOfCul_{RG,TYPE,SEX,AGE,TC} * lvDATA_{RG,TYPE,SEX,AGE,'mYield'}\right) \quad [35]$$

In addition to meat and milk, hides and skins are important economic byproducts of the livestock sector. As animals are slaughtered for meat, an inevitable consequence is the production of hides and skins. [Eq. 36] calculates offtake-related hides and skins (*hskOfft*) using per capita skin yield *sYield*. Manure is another byproduct of live animals that has an important economic value both as a source of natural fertilizer and household energy. It is straightforward to add an equation that calculates cattle manure production in this HDM.

$$hskOfft_{RG,TYPE,SEX,AGE,TC} = \left[lvY_{RG,TYPE,SEX,AGE,TC} + lvC_{RG,TYPE,SEX,AGE,TC}\right] * lvDATA_{RG,TYPE,SEX,AGE,'sYield'} \quad [36]$$

4 LINKING THE HDM TO THE CORE ECONOMIC MODEL CONSTRUCTION OF THE MODEL BASELINE

The advantage of the integrated LEAS modeling framework we developed is the bi-directional link between the HDM and the core economic (CGE) model. The link from the economic model to the HDM is already created in the demographic, input demand, and production blocks above through model prices (*PAR, LDPI, DPI*), quantity (*QINT, QINTA*) and factor (*QF*) variables. Indicating the relative profitability of livestock activities, these activity and input prices influence milk and meat offtake decisions by farmers. Access to intermediate inputs (*QINT, QINTA*) also determines livestock sector productivity such as the live weight of cattle and the milk offtake per milking cow. The dynamics in the livestock model are also linked back to the CGE model through the annual growth rate in livestock sector capital, as shown in [Eq. 37 – 38]. The stock of livestock capital in the cattle sector (*acatt*) depends on the rate of growth in meat offtake. Also, the trajectory of livestock capital for milk production (*amilk*) is a positive function of the rate of growth of total milk offtake.

$$QF_{FLIV,"acatt",RG} = QF_{FLIV,"acatt",RG} * (1 + meatOfftTot_{RG,"Bov",TC} / meatOfftTot_{RG,"Bov",TC-1} - 1) \qquad [37]$$

$$QF_{FLIV,"amilk",RG} = QF_{FLIV,"amilk",RG} * (1 + proMilkTot_{RG,"Bov",TC} / proMilkTot_{RG,"Bov",TC-1} - 1) \qquad [38]$$

Feed demand also creates another linkage that passes from the livestock model to the economic model since feed is a derived demand from livestock. This linking channel is already described in the input demand block above.

5 ILLUSTRATING THE HDM WITH A DROUGHT SHOCK

Droughts are the single greatest risk facing the livestock sector in Ethiopia. To test for the robustness of the HDM described above and examine the dynamics of the cattle sector in Ethiopia, using the LEAS model introduced above, we designed a drought shock scenario that is compared with a baseline outcome. IFPRI's RIAPA economywide model, calibrated on a 2017 Social Accounting Matrix (SAM) for Ethiopia, is the economic model used for the analysis. The Ethiopia economic model has detailed accounts including 80 commodities (31 in agriculture), 13 factors of production (labor, land, and capital), and 15 representative farm and non-farm (rural and urban) households categorized by expenditure quintile. Eight of the sectors in this model are livestock-related primary and processing sectors. For the scenario analysis, we assume a onetime drought that removes almost 30 percent of the cattle population, which is not unrealistic given the country's recent experiences (Desta & Coppock, 2002; Desta & Oba, 2004). Outcomes under this drought scenario are compared against results under the baseline scenario. The baseline scenario represents the current economic trajectory and cattle sector growth trend. Using the LEAS model framework, we run the model for the 2017-2030 period.

Death and offtake rates are crucial demographic parameters that drive the cattle herd dynamics as well as milk and meat offtake levels. Whereas age- and sex-specific death rates used in the HDM are time-invariant and do not respond to the variables in the economic model, meat offtake rates change dynamically as the model solves recursively over the future in response to cattle sector activity prices and the country's assumed livestock carrying capacity. The time-invariant nature of death rates is apparent in Table 5.1, in which death rates are fixed at the 2017 levels for the baseline scenario. Under the drought scenario, the 2018 death rates increase by about 30 percentage points temporarily from the base values before the initial death rates are maintained henceforth.[5] As is the case for the offtake rates, the death rates are calculated at single age levels in the HDM but reported here at the average level by sex. The difference in death rates across sex and agroecology drives the changes in cattle stock and cattle sector output discussed below in Table 5.2.

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[5] We do not calculate the economic and environmental value of dead animal carcasses.

Table 5.1. Death and offtake rates under alternative scenarios

		Baseline scenario			Drought scenario	
		2017	2018	2030	2018	2030
Death rate						
Humid lowland	Male	5.5%	5.5%	5.5%	36.9%	5.5%
	Female	5.6%	5.6%	5.6%	36.9%	5.6%
	Total	5.6%	5.6%	5.6%	36.9%	5.6%
Cereal-based humid highland	Male	5.9%	5.9%	5.9%	35.9%	5.9%
	Female	6.8%	6.8%	6.8%	36.8%	6.8%
	Total	6.4%	6.4%	6.4%	36.4%	6.4%
Enset-based humid highland	Male	8.3%	8.3%	8.3%	37.5%	8.3%
	Female	6.9%	6.9%	6.9%	36.1%	6.9%
	Total	7.5%	7.5%	7.5%	36.7%	7.5%
Drought-prone areas	Male	5.9%	5.9%	5.9%	36.2%	5.9%
	Female	6.6%	6.6%	6.6%	36.9%	6.6%
	Total	6.3%	6.3%	6.3%	36.6%	6.3%
Pastoralist areas	Male	14.9%	14.9%	14.9%	43.9%	14.9%
	Female	8.4%	8.4%	8.4%	37.4%	8.4%
	Total	10.5%	10.5%	10.5%	39.5%	10.5%
Offtake rate - price adjusted						
Humid lowland	Male	6.2%	6.2%	5.4%	6.2%	8.1%
	Female	6.4%	6.4%	5.7%	6.4%	8.5%
	Total	6.3%	6.3%	5.5%	6.3%	8.3%
Cereal-based humid highland	Male	7.0%	7.0%	6.1%	7.0%	9.2%
	Female	7.8%	7.8%	6.8%	7.8%	10.2%
	Total	7.3%	7.3%	6.4%	7.3%	9.6%
Enset-based humid highland	Male	10.7%	10.7%	9.3%	10.6%	14.0%
	Female	8.3%	8.3%	7.3%	8.3%	10.9%
	Total	9.6%	9.6%	8.4%	9.5%	12.5%
Drought-prone areas	Male	6.8%	6.8%	6.0%	6.8%	9.0%
	Female	7.5%	7.5%	6.5%	7.4%	9.8%
	Total	7.1%	7.1%	6.2%	7.1%	9.3%
Pastoralist areas	Male	19.9%	19.9%	17.5%	19.9%	26.2%
	Female	8.1%	8.1%	7.1%	8.1%	10.7%
	Total	12.8%	12.8%	11.2%	12.8%	16.8%
Offtake rate - due to carrying capacity constraint						
Humid lowland	Male	-	2.5%	6.8%	-*	2.0%
	Female	-	2.3%	7.5%	-	2.4%
	Total	-	2.4%	7.1%	-	2.1%
Cereal-based humid highland	Male	-	1.5%	4.0%	-	0.7%
	Female	-	1.6%	4.9%	-	0.9%
	Total	-	1.5%	4.4%	-	0.8%
Enset-based humid highland	Male	-	1.1%	3.2%	-	0.3%
	Female	-	1.2%	3.4%	-	0.4%
	Total	-	1.2%	3.3%	-	0.3%
Drought-prone areas	Male	-	1.8%	4.8%	-	0.9%
	Female	-	1.8%	5.6%	-	1.1%
	Total	-	1.8%	5.1%	-	1.0%
Pastoralist areas	Male	-	1.3%	6.7%	-	0.8%
	Female	-	2.0%	6.9%	-	1.3%
	Total	-	1.7%	6.8%	-	1.1%

Source: The LEAS model for Ethiopia.
Note: *No carrying capacity effect when the stock declines.

Table 5.2. Simulated changes in cattle stock and meat and milk offtake

		Baseline scenario			Drought scenario	
		Value	Change from 2017		Change from 2017	
		2017	2018	2030	2018	2030
Cattle stock (in '000)						
	Male	1,279	3.1%	17.4%	-29.7%	-1.5%
	Female	1,565	3.1%	19.7%	-30.2%	-0.2%
Humid lowland	Total	2,844	3.1%	18.7%	-30.0%	-0.7%
	Male	15,606	1.7%	16.4%	-29.9%	-16.9%
	Female	16,938	2.2%	19.9%	-30.1%	-13.2%
Cereal-based humid highland	Total	32,544	2.0%	18.2%	-30.0%	-15.0%
	Male	4,444	1.5%	16.7%	-30.3%	-26.3%
	Female	6,349	1.6%	16.7%	-29.9%	-21.0%
Enset-based humid highland	Total	10,794	1.5%	16.7%	-30.0%	-23.2%
	Male	8,566	2.2%	17.4%	-29.7%	-12.3%
	Female	9,708	2.4%	19.5%	-30.2%	-10.4%
Drought-prone areas	Total	18,273	2.3%	18.5%	-30.0%	-11.3%
	Male	755	2.2%	19.8%	-32.1%	-17.8%
	Female	1,629	2.8%	21.1%	-29.1%	-6.1%
Pastoralist areas	Total	2,385	2.6%	20.7%	-30.0%	-9.8%
	Male	30,650	1.9%	16.8%	-29.9%	-16.3%
	Female	36,190	2.2%	19.3%	-30.1%	-12.9%
National	Total	66,840	2.1%	18.2%	-30.0%	-14.5%
Meat offtake in kg (in '000)						
Humid lowland		29,485	3.1%	53.5%	-50.3%	5.9%
Cereal-based humid highland		342,746	3.1%	37.6%	-41.6%	-10.3%
Enset-based humid highland		107,334	3.1%	27.2%	-40.5%	-18.4%
Drought-prone areas		192,872	3.1%	41.8%	-43.8%	-6.5%
Pastoralist areas		31,032	3.1%	41.5%	-41.4%	-1.5%
National		703,469	3.1%	38.0%	-42.4%	-9.4%
Milk production in liter ('000)						
Humid lowland		142,824	3.1%	64.5%	-12.7%	19.8%
Cereal-based humid highland		1,593,662	3.1%	68.2%	-12.3%	5.6%
Enset-based humid highland		587,282	3.1%	65.5%	-12.0%	-3.4%
Drought-prone areas		909,100	3.1%	67.0%	-12.4%	8.8%
Pastoralist areas		175,330	3.1%	67.1%	-11.7%	13.1%
National		3,408,198	3.1%	67.2%	-12.2%	5.9%

Source: The LEAS model for Ethiopia.

As reported in Table 5.1, the price-adjusted offtake rate slowly adjusts over time. The LEAS model shows that under the baseline scenario the price-adjusted offtake rate declines roughly by 1 percent per year between 2017 and 2030. This dynamic change is identical across all agroecological zones considered in the HDM since they are responding to the national-level cattle sector price change (the economic model behind the LEAS model is a national model), and we also assume spatially identical price elasticity of offtake rate. The decline in the price-adjusted offtake rate indicates a deterioration in the profitability of animal offtake activity over time due to a decline in relative price. The decline in the relative price of the cattle sector price is because of a faster increase in livestock sector capital. By contrast, the cattle offtake rate increases markedly over the 2017–2030 period (by 2.5 percent per year on average) under the drought scenario since relative prices of the cattle sector increase. This increase in the price-adjusted offtake rate further slows down the cattle stock recovery (Table 5.2).

In addition to a change in the relative price of offtake activities, carrying capacity also affects farmers offtake decisions. We assume that the effect of the carrying capacity constraint does not kick in at the base (that is, 2017). The HDM shows that as the number of cattle increases, farmers decide to sell or slaughter more animals. The offtake rate exclusively associated with the carrying capacity increases over time, tripling between 2018 and 2030. The higher the growth rate (see Table 5.2), the higher the offtake rate accounted for by carrying capacity. Since the carrying capacity constraint is assumed to affect offtake decisions only when the stock increases, the carrying-capacity-adjusted offtake rate is the same as the price-adjusted offtake rate during the drought year. Also, the drought significantly reduces the pressure on feed and pasture in the post-drought periods, leading to a very small effect of carrying capacity constraint on animal sales and slaughtering decisions even a decade after the drought.

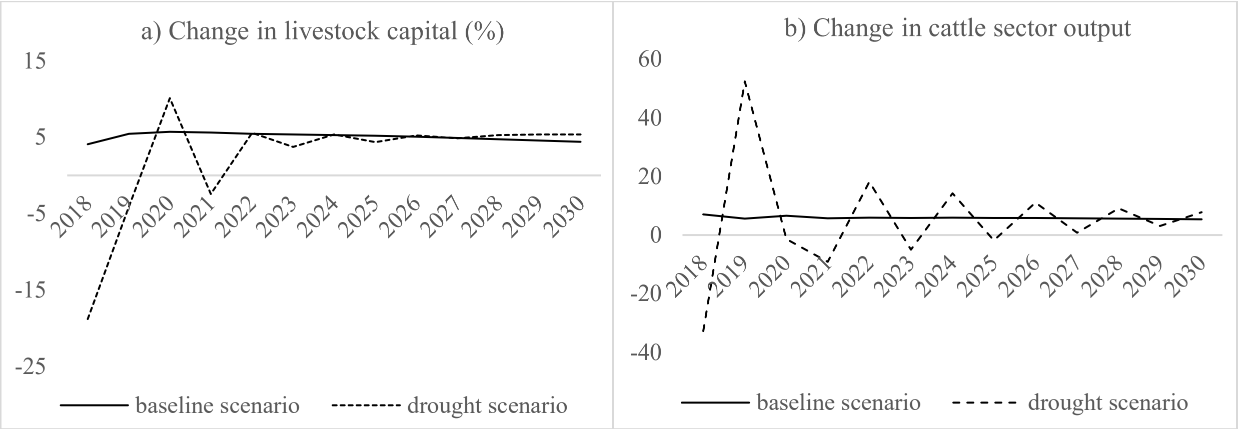
Table 5.2 shows that the cattle stock grows by 2.1% at the national level in 2018 under the baseline scenario, with faster growth rates in lowland humid and pastoralist areas. This high growth in cattle stock in these two areas is consistent with the country's livestock sector survey data (CSA, 2003-2017). At the current growth trend, the number of cattle is expected to reach 79 million by 2030, growing by one-fifth. Drought significantly changes the cattle sector dynamics. The cattle stock declines in 2018 by the drought-shock level, with a slight deviation between males and females depending on their underlying death rates (that is, there is a slight difference in the baseline death rates for males and females - see Annex Table 8.2). The HDM shows that the cattle stock will be unable to return to its pre-shock periods within 10 to 15 years unless aggressive restocking is considered by farmers in collaboration with support from the government and development agents. The LEAS model suggests that the cattle herd will be nearly 15 percent lower than the baseline by 2030 due to the simulated shock that removes 30 percent of the herd in 2018. The recovery is faster for the humid lowland areas since the baseline death rate in the region is assumed to be one of the lowest in the country, while the offtake rate is one of the least. The female cattle stock is more likely to recover faster than the male stock due to the generally lower offtake rate since females are usually kept longer in the herd for milking and reproduction purposes. In this rapid assessment of the impact of drought on the recovery dynamics of the cattle herd, we do not consider alternative drought management options usually taken by farmers - such as selective culling, etc., which would ultimately affect the age-sex structure of the cattle stock.

Meat and milk represent the main economic returns from cattle. Such a high shock to the cattle sector can considerably affect post-shock meat and milk offtake. Table 5.2 further shows that the meat offtake increases at the baseline (at the assumed level of slightly higher than the cattle stock growth) from the current level of meat production of about 703 million kg (this is slightly lower than some estimates for the country but is adequate to demonstrate the model). With the current trend, meat production is expected to increase by over 40 percent in the coming 12-13 years. However, drought can alter this considerably. A onetime 30 percent decline in the cattle stock could lead to a more than proportionate 40 percent decline in meat production during the drought year. It could take the country more than a decade to recover its meat production at the national level, although regions with relatively lower baseline death rates could show meat production exceeding the pre-drought periods.

The HDM further shows a current national milk production level of about 3.5 billion liters, which is close to the national estimate from cattle. The model shows a moderate increase in milk production in 2018 under the baseline scenario. However, milk output could increase by over 65 percent by 2030 from the 2017 levels, growing by 5.0 percent annually. The drought scenario shows a 12 percent decline in milk production during the drought year. This decline is significantly lower than the effect on meat production since female cattle are affected at a slightly lower rate by the drought itself and their size usually recovers faster than the males' during the post-drought periods due to generally lower offtake and death rates. In addition, we assume that milk offtake depends on the mid-year cow population. As a result, the national level of milk production by the end of the simulation period exceeds the base level (that is, 2017).

One aspect of the link between the HDM and the economic model is through livestock capital updating. By contrast to the usual exogenous increase in livestock capital assumed in most economic models, the livestock capital growth in the LEAS model follows the growth rate periodically updated by the HDM. Under the baseline scenario, livestock capital in the cattle sector grows by 4.1 percent in 2018 and roughly close to 5.1 percent per year over 2018–2030 (Figure 5.1– a). The growth of livestock capital significantly drops as a result of the simulated drought - decreasing by 18.8 percent in 2018 and growing at a 2.8-percentage-point-lower rate (on average) than the baseline trend over the 2030 period. We also observe that livestock capital under the drought scenario changes cyclically before it stabilizes over time. This difference in livestock capital growth in the cattle sector under the baseline and drought scenarios is expected to have considerable implications for the cattle sector's performance. In fact, the LEAS model shows a 32.8 percent decline in cattle sector output during the drought year and an average growth of 5.0 percent over 2018 - 2030, which is lower by 1 percentage point than the sector's long-term growth under the baseline scenario (Figure 5.1 – b).

Figure 5.1. Simulated changes in cattle sector livestock capital and output (%)



Source: The LEAS model for Ethiopia

For demonstration purposes, we also analyze the impact of the drought shock on selected sub-sectors of the economy. Table 5.3 reports GDP under the baseline scenario for the base year (that is, 2017), drought year (that is, 2018), and simulation final year (that is, 2030). It also reports percentage deviation in output between the drought and baseline scenarios during the corresponding years. The core economywide model shows a noticeable gap between the baseline GDP and the GDP under the alternative drought scenario. The loss in cattle due to drought at the simulated level would lead the economy to contract by 1.6 percent in 2018 and by 1.4 percent in 2030, showing the permanent level effect of the drought shock on the economy over the medium and long run. Agriculture GDP shrinks by 5.1 percent and 8.1 percent in 2018 and 2030 compared to the value projected under the baseline scenario due to very slow recovery of the livestock sector, which is down by 18 percent and 26 percent in 2018 and 2030, respectively, compared to the baseline scenario. The cattle and milk production sub-sectors are the most affected. The nonagricultural sector as a whole was largely unaffected and continued accelerating, slowing down the negative overall effect on GDP in the medium and long run. The meat processing sector is one of the nonagricultural sectors most affected under the drought scenario, contracting by 24.1 percent and 36.8 percent in 2018 and 2030, respectively, compared to the baseline outcome. The widening effect on milk and meat GDP over time is because these sectors were among the fast-growing sectors under the baseline scenario.

Table 5.3. Simulated changes in GDP of selected sectors

	Baseline scenario (in bill. of local currency)			Drought scenario (in % change) *		
	2017	2018	2030	2017	2018	2030
Total GDP	1,858	1,974	4,313	0.0	-1.6	-1.4
Agriculture	584	613	1,127	0.0	-5.1	-8.1
Livestock	164	174	359	0.0	-18.0	-26.2
Cattle	51	53	105	0.0	-37.5	-27.4
Milk	84	89	207	0.0	-12.8	-73.0
Meat	1	1	6	0.0	-24.1	-36.8
Non-agriculture	1	1	3	0.0	-0.1	1.0

Source: The LEAS model for Ethiopia.

Note: *Results are in percentage deviation from values of corresponding years of the baseline scenario.

6 CONCLUSIONS

Although Ethiopia is endowed with large livestock resources, the per capita consumption of ASF is very low and prices of livestock products are high and increasing. Studies on the sector over the past few years have documented that focusing solely on raising on-farm production levels is not adequate and a livestock systems' approach to the problem that accounts for the downstream linkages is needed. Livestock growth is currently demand driven and the future trajectory of the livestock system may depend more on developments in the broader economy. Studies also suggest that policies needed to address the supply-side constraints will require more investment in the livestock system. Finding a holistic solution to these challenges requires the development of a systems-based analytical approach that tracks the livestock system and measures its linkages with the broader economy.

In line with these, we developed an integrated approach – the LEAS model – that links the herd dynamics to an economic model which in turn passes information to a module that helps to assess changes in poverty, household consumption, and dietary diversity. Since the economic model and microsimulation components of this integrated model have been well documented, this technical document focuses on the HDM. We present (i) the data requirements, (ii) the potential data transformation needed to be able to use the model, (iii) how the livestock system is solved, (iv) the link in both ways between the HDM and the economic model, and (v) a brief demonstration of the integrated model using a drought scenario.

The HDM described in this technical document can easily be adapted to study livestock systems other than cattle – including small ruminants and poultry. If the required stock/flock data is available to build the benchmark stock/flock size and estimate system-consistent animal demographic parameters, what is required is to increase the time-frequency of the HDM rather than the annual time-frequency the model is currently set upon. Considering a monthly time frequency would be relevant to handle the dynamics of small ruminants and associated management decisions by farmers.

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8 ANNEX

Annex Table 8.1. Estimated demographic structure of the cattle population in Ethiopia

	Age in year	2017				2030			
		Female		Male		Female		Male	
		Size	Share	Size	Share	Size	Share	Size	Share
Humid lowland	0	233	14.9%	214	16.7%	418	14.9%	385	16.3%
	1	200	12.8%	178	13.9%	359	12.8%	322	13.6%
	2	173	11.1%	147	11.5%	310	11.1%	269	11.4%
	3	153	9.8%	125	9.8%	275	9.8%	230	9.7%
	4	141	9.0%	112	8.7%	252	9.0%	206	8.7%
	5	134	8.5%	104	8.1%	239	8.5%	194	8.2%
	6	127	8.1%	99	7.7%	227	8.1%	185	7.8%
	7	118	7.5%	91	7.1%	210	7.5%	171	7.2%
	8	103	6.6%	79	6.2%	183	6.5%	150	6.3%
	9	83	5.3%	63	4.9%	148	5.3%	121	5.1%
	10	60	3.8%	44	3.5%	106	3.8%	85	3.6%
	11	33	2.1%	23	1.8%	60	2.1%	45	1.9%
	12	6	0.4%	1	0.1%	11	0.4%	2	0.1%
Cereal-based humid highlands	0	2439	15.6%	2658	15.7%	4002	15.7%	3666	15.8%
	1	2056	13.2%	2238	13.2%	3370	13.2%	3084	13.2%
	2	1736	11.1%	1889	11.1%	2844	11.1%	2599	11.2%
	3	1503	9.6%	1634	9.6%	2460	9.6%	2247	9.7%
	4	1356	8.7%	1473	8.7%	2217	8.7%	2023	8.7%
	5	1275	8.2%	1384	8.2%	2084	8.2%	1898	8.2%
	6	1214	7.8%	1317	7.8%	1982	7.8%	1803	7.7%
	7	1125	7.2%	1220	7.2%	1837	7.2%	1669	7.2%
	8	993	6.4%	1075	6.3%	1619	6.3%	1469	6.3%
	9	817	5.2%	883	5.2%	1330	5.2%	1207	5.2%
	10	605	3.9%	652	3.8%	982	3.9%	892	3.8%
	11	368	2.4%	393	2.3%	592	2.3%	541	2.3%
	12	120	0.8%	123	0.7%	185	0.7%	176	0.8%
Enset-based humid highlands	0	998	15.7%	918	20.6%	1342	15.7%	1235	20.6%
	1	845	13.3%	717	16.1%	1135	13.3%	966	16.1%
	2	716	11.3%	549	12.4%	963	11.3%	741	12.3%
	3	623	9.8%	426	9.6%	837	9.8%	575	9.6%
	4	564	8.9%	347	7.8%	758	8.9%	469	7.8%
	5	531	8.4%	305	6.9%	713	8.4%	412	6.9%
	6	504	7.9%	283	6.4%	677	7.9%	383	6.4%
	7	464	7.3%	262	5.9%	624	7.3%	355	5.9%
	8	405	6.4%	230	5.2%	544	6.4%	312	5.2%
	9	326	5.1%	187	4.2%	439	5.1%	253	4.2%
	10	232	3.6%	134	3.0%	311	3.6%	182	3.0%
	11	126	2.0%	74	1.7%	169	2.0%	101	1.7%
	12	16	0.2%	11	0.3%	21	0.2%	15	0.3%

Annex Table 8.1 (*continued*). Model of estimated demographic structure of the cattle population

	Age in year	2017				2030			
		Female		Male		Female		Male	
		Size	Share	Size	Share	Size	Share	Size	Share
Drought-prone areas	0	1499	15.4%	1378	16.1%	2339	15.4%	2158	15.9%
	1	1272	13.1%	1151	13.4%	1984	13.1%	1808	13.3%
	2	1082	11.1%	961	11.2%	1688	11.1%	1515	11.2%
	3	943	9.7%	823	9.6%	1472	9.7%	1302	9.6%
	4	855	8.8%	736	8.6%	1335	8.8%	1167	8.6%
	5	806	8.3%	689	8.0%	1259	8.3%	1095	8.1%
	6	767	7.9%	655	7.6%	1198	7.9%	1044	7.7%
	7	710	7.3%	607	7.1%	1108	7.3%	971	7.2%
	8	623	6.4%	536	6.3%	973	6.4%	859	6.3%
	9	508	5.2%	441	5.1%	794	5.2%	710	5.2%
	10	371	3.8%	327	3.8%	579	3.8%	527	3.9%
	11	216	2.2%	199	2.3%	338	2.2%	322	2.4%
	12	55	0.6%	65	0.8%	86	0.6%	105	0.8%
Pastoralist areas	0	282	17.3%	259	34.3%	470	17.3%	428	34.9%
	1	230	14.1%	180	23.9%	384	14.1%	295	24.1%
	2	187	11.5%	115	15.2%	312	11.5%	186	15.2%
	3	156	9.6%	67	8.9%	260	9.6%	107	8.8%
	4	137	8.4%	36	4.8%	227	8.4%	58	4.7%
	5	126	7.7%	21	2.8%	210	7.7%	33	2.7%
	6	119	7.3%	17	2.2%	199	7.3%	26	2.1%
	7	111	6.8%	16	2.2%	184	6.8%	25	2.0%
	8	98	6.0%	15	2.0%	162	6.0%	24	1.9%
	9	80	4.9%	13	1.7%	133	4.9%	20	1.6%
	10	59	3.6%	10	1.3%	98	3.6%	14	1.2%
	11	35	2.1%	5	0.7%	58	2.1%	8	0.7%
	12	10	0.6%	1	0.1%	16	0.6%	1	0.1%

Source: The LEAS model for Ethiopia.

Annex Table 8.2. Lifetables of female and male cattle (in '000 and %) in Ethiopia

A) Humid lowland

Age	Female						Male					
(*i*)	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i
0	233	233	-	0.13	0.13	-	211	214	-	0.13	0.13	-
1	109	200	-	0.10	0.10	-	76	178	-	0.13	0.06	0.07
2	109	173	-	0.10	0.10	-	76	147	-	0.13	0.06	0.07
3	135	153	0.52	0.07	0.03	0.05	105	125	-	0.10	0.05	0.06
4	135	141	0.52	0.04	0.01	0.03	105	112	-	0.06	0.03	0.04
5	135	134	0.52	0.01	0.00	0.01	105	104	-	0.02	0.01	0.01
6	135	127	0.52	0.00	0.00	0.00	105	99	-	0.00	0.00	0.00
7	135	118	0.52	0.04	0.01	0.03	105	91	-	0.03	0.01	0.02
8	135	103	0.52	0.09	0.02	0.07	105	79	-	0.08	0.03	0.06
9	135	83	0.52	0.15	0.04	0.12	105	63	-	0.16	0.06	0.11
10	6	60	0.52	0.25	0.06	0.20	1	44	-	0.26	0.10	0.18
11	6	33	-	0.41	0.10	0.35	1	23	-	0.45	0.16	0.34
12	6	6	-	0.81	0.19	1.00	1	1	-	0.96	0.35	1.00

B) Cereal-based humid highlands

Age	Female						Male					
(*i*)	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i
0	2,658	2,658	-	0.13	0.13	-	2,385	2,439	-	0.13	0.13	-
1	1,303	2,238	-	0.13	0.13	-	1,154	2,056	-	0.13	0.07	0.07
2	1,303	1,889	-	0.13	0.13	-	1,154	1,736	-	0.13	0.06	0.08
3	1,399	1,634	0.56	0.11	0.04	0.07	1,289	1,503	-	0.11	0.05	0.06
4	1,399	1,473	0.56	0.07	0.02	0.05	1,289	1,356	-	0.07	0.03	0.04
5	1,399	1,384	0.56	0.03	0.01	0.02	1,289	1,275	-	0.03	0.01	0.02
6	1,399	1,317	0.56	0.02	0.00	0.01	1,289	1,214	-	0.02	0.01	0.01
7	1,399	1,220	0.56	0.04	0.01	0.03	1,289	1,125	-	0.04	0.02	0.03
8	1,399	1,075	0.56	0.09	0.02	0.07	1,289	993	-	0.09	0.03	0.06
9	1,399	883	0.56	0.15	0.04	0.12	1,289	817	-	0.15	0.06	0.10
10	123	652	0.56	0.24	0.06	0.19	120	605	-	0.24	0.09	0.17
11	123	393	-	0.38	0.09	0.32	120	368	-	0.37	0.14	0.28
12	123	123	-	0.68	0.16	1.00	120	120	-	0.66	0.24	1.00

C) *Enset*-based humid highlands

Age	**Female**						**Male**					
(*i*)	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i
0	998	998	-	0.13	0.13	-	932	918	-	0.13	0.13	-
1	528	845	-	0.13	0.13	-	368	717	-	0.20	0.10	0.11
2	528	716	-	0.13	0.13	-	368	549	-	0.22	0.09	0.13
3	536	623	0.54	0.11	0.04	0.07	312	426	-	0.21	0.09	0.13
4	536	564	0.54	0.07	0.02	0.05	312	347	-	0.17	0.07	0.10
5	536	531	0.54	0.04	0.01	0.03	312	305	-	0.10	0.04	0.07
6	536	504	0.54	0.03	0.01	0.02	312	283	-	0.05	0.02	0.03
7	536	464	0.54	0.06	0.01	0.04	312	262	-	0.05	0.02	0.03
8	536	405	0.54	0.11	0.03	0.08	312	230	-	0.10	0.04	0.07
9	536	326	0.54	0.18	0.04	0.14	312	187	-	0.17	0.06	0.11
10	16	232	0.54	0.27	0.06	0.22	11	134	-	0.27	0.10	0.19
11	16	126	-	0.44	0.10	0.38	11	74	-	0.43	0.16	0.33
12	16	16	-	0.87	0.21	1.00	11	11	-	0.84	0.31	1.00

D) Drought-prone areas

Age	**Female**						**Male**					
(*i*)	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i
0	1,499	1,499	-	0.14	0.14	-	1,427	1,378	-	0.13	0.13	-
1	777	1,272	-	0.12	0.12	-	654	1,151	-	0.13	0.07	0.07
2	777	1,082	-	0.12	0.12	-	654	961	-	0.13	0.06	0.08
3	815	943	0.55	0.10	0.03	0.07	697	823	-	0.11	0.05	0.07
4	815	855	0.55	0.06	0.02	0.04	697	736	-	0.07	0.03	0.04
5	815	806	0.55	0.02	0.01	0.02	697	689	-	0.03	0.01	0.02
6	815	767	0.55	0.02	0.00	0.01	697	655	-	0.01	0.00	0.01
7	815	710	0.55	0.04	0.01	0.03	697	607	-	0.04	0.01	0.02
8	815	623	0.55	0.09	0.02	0.07	697	536	-	0.08	0.03	0.06
9	815	508	0.55	0.16	0.04	0.12	697	441	-	0.15	0.05	0.10
10	55	371	0.55	0.25	0.06	0.20	65	327	-	0.23	0.08	0.16
11	55	216	-	0.40	0.09	0.33	65	199	-	0.37	0.13	0.27
12	55	55	-	0.74	0.17	1.00	65	65	-	0.66	0.24	1.00

E) Pastoralist areas

Age	Female						Male					
(*i*)	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i	ID_i	SD_i	f_i	mr_i	dr_i	ofr_i
0	282	282	-	0.17	0.17	-	232	259	-	0.17	0.17	-
1	92	230	-	0.15	0.15	-	40	180	-	0.28	0.14	0.16
2	92	187	-	0.15	0.15	-	40	115	-	0.34	0.15	0.23
3	128	156	0.66	0.13	0.05	0.09	24	67	-	0.40	0.18	0.27
4	128	137	0.66	0.09	0.03	0.06	24	36	-	0.44	0.18	0.32
5	128	126	0.66	0.04	0.01	0.03	24	21	-	0.40	0.15	0.30
6	128	119	0.66	0.02	0.00	0.01	24	17	-	0.19	0.07	0.13
7	128	111	0.66	0.04	0.01	0.03	24	16	-	0.01	0.00	0.01
8	128	98	0.66	0.08	0.02	0.07	24	15	-	0.02	0.01	0.01
9	128	80	0.66	0.15	0.03	0.12	24	13	-	0.13	0.05	0.08
10	10	59	0.66	0.24	0.06	0.19	1	10	-	0.24	0.09	0.17
11	10	35	-	0.38	0.09	0.32	1	5	-	0.42	0.15	0.32
12	10	10	-	0.71	0.17	1.00	1	1	-	0.86	0.31	1.00

Source: The LEAS model for Ethiopia.
Note: ID_i= initial simple extrapolated age structure of the population in 2017, SD_i= smoothed age distribution based on the Leslie matrix and the procedure above, f_i= fecundity rate, mr_i= mortality rate (inclusive of natural deaths and offtake), dr_i= death rate, and ofr_i= offtake rate.

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