Invited review: a position on The Global Livestock Environmental Assessment Model (GLEAM)

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Abstract:	The livestock sector is one of the fastest growing subsectors of the agricultural economy and, while it makes a major contribution to global food supply and economic development, it also consumes significant amounts of natural resources and alters the environment. In order to improve our understanding of the global environmental impact of livestock supply chains, FAO has developed GLEAM, the Global Livestock Environmental Assessment Model. The purpose of this paper is to provide a review of GLEAM. Specifically, it explains the model architecture, methods and functionality, i.e. the types of analysis that the model can perform. The model focuses primarily on the quantification of GHG emissions arising from the production of the 11 main livestock commodities. The model inputs and outputs are managed and produced as raster datasets, with spatial resolution of 0.05 decimal degrees. GLEAM v 1.0 consists of five distinct modules: (a) the Herd Module; (b) the Manure Module; (c) the Feed Module; (d) the System Module; (e) the Allocation Module. In terms of the modelling approach, GLEAM has several advantages. For example spatial information on livestock distributions and crops yields enables rations to be derived that reflect the local availability of feed resources in developing countries. GLEAM also contains a herd model that enables livestock statistics to be disaggregated and variation in livestock performance and management to be captured. Priorities for future development of GLEAM include: improving data quality and the methods used to perform emissions calculations; extending the scope of the model to include selected additional environmental impacts and to enable predictive modelling; and improving the utility of GLEAM output.

Invited review: a position on The Global Livestock Environmental Assessment Model (GLEAM)

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Running head: The Global Livestock Environmental Assessment Model

Abstract

The livestock sector is one of the fastest growing subsectors of the agricultural economy and, while it makes a major contribution to global food supply and economic development, it also consumes significant amounts of natural resources and alters the environment. In order to improve our understanding of the global environmental impact of livestock supply chains, FAO has developed GLEAM, the Global Livestock Environmental Assessment Model. The purpose of this paper is to provide a review of GLEAM. Specifically, it explains the model architecture, methods and functionality, i.e. the types of analysis that the model can perform. The model focuses primarily on the quantification of GHG emissions arising from the production of the 11 main livestock commodities. The model inputs and outputs are managed and produced as raster datasets, with spatial resolution of 0.05 decimal degrees. GLEAM v 1.0 consists of five distinct modules: (a) the *Herd Module*; (b) the *Manure Module*; (c) the *Feed Module*; (d) the *System Module*; (e) the *Allocation Module*. In terms of the modelling approach, GLEAM has several advantages. For example spatial information on livestock distributions and crops yields enables rations to be derived that reflect the local availability of feed resources in developing countries. GLEAM also contains a herd model that enables livestock statistics to be disaggregated and variation in livestock performance and management to be captured. Priorities for future development of GLEAM include: improving data quality and the methods used to perform emissions calculations; extending the scope of the model to

include selected additional environmental impacts and to enable predictive modelling; and improving the utility of GLEAM output.

Keywords

Livestock, environmental assessment, models, life-cycle analysis, climate change.

Implications

GLEAM is intended to provide a level of analysis that has sufficient technical rigour, but can also be translated into practical advice to decision-makers (e.g. governments, project planners, producers, industry and civil society organizations). It is hoped that its features, such as the ability to derive rations for livestock in developing countries, and to capture variation in livestock performance and management, will support improvement of the environmental performance of livestock production.

Introduction

The livestock sector is one of the fastest growing subsectors of the agricultural economy. Demand for all the main livestock commodities are forecast to increase significantly between now and 2050 (see Alexandratos and Bruinsma, 2012). While the livestock sector makes an important contribution to global food supply and economic development, it also uses significant amounts of natural resources and impacts on the environment (see e.g. Steinfeld et al., 2006; Herrero and Thornton, 2013; Leip et al. 2015). One of the most important global impacts arises from the emission of greenhouse gases (GHG) along livestock supply chains, which are estimated to make a significant contribution to overall anthropogenic GHG emissions (Gerber et al. 2013).

If the GHG emissions intensities (Ei) (i.e. the kg of GHG per kg of animal product) of livestock commodities are not reduced, the forecast increases in production will lead to proportionate increases in GHG emissions, compromising efforts towards climate change mitigation. It is therefore essential that ways are found to improve the efficiency and reduce the Ei of livestock production (while noting that such supply-side improvements may be complemented by measures to reduce demand, Bajželj et al. 2014, Lamb et al. 2016). Improving our understanding of where and why emissions arise in livestock supply chains is an important step towards achieving this goal.

In order to improve our understanding of livestock's environmental impact, FAO has developed GLEAM, the Global Livestock Environmental Assessment Model (http://www.fao.org/gleam/en/). The primary motivation behind GLEAM was the desire to have a tool that enabled comprehensive, disaggregated and consistent analysis of the environmental performance of global livestock production to support the identification of improvement options. This is important as methodological inconsistencies between studies can make it difficult to determine whether apparent differences in results arise from differences in actual emissions or in methodologies, thereby complicating the identification of mitigation options.

The global GHG emissions produced by livestock have been quantified in the assessment reports for the United Nations Framework Convention on Climate Change (Smith *et al.,* 2007, 2014). In addition, there are several databases of global emissions, such as: US Environmental Protection Agency Global Emissions Database (EPA, 2012); European Commission Joint Research Centre's (JRC) EDGAR (Emissions Database for Global Atmospheric Research) (EDGAR, 2012); the World Resource Institute's CAIT (Climate Analysis Indicators Tool) (WRI 2013); and the FAOSTAT online database of agricultural GHG emissions (Tubiello et al., 2013). These analyses predominantly adopt IPCC (2006) tier-1-type approaches to the quantification of livestock emissions and focus on the emissions produced in one part of the supply chain, i.e. on-farm. GLEAM seeks to complement and add value to these analyses by using a herd model coupled with an IPCC (2006) tier 2 approach to computing emissions, thereby enabling key characteristics of the livestock populations (e.g. herd structures, animal performance, rations and manure management) to be captured in the calculations. Further, GLEAM adopts a life-cycle approach and calculates the emissions arising along the supply chain from cradle to retail point. This enables the Ei of specific commodities to be calculated rather than just the total emissions from an agricultural subsector. Finally the reliance on Geographical Information Systems provides spatially explicit analysis and flexibility in combining datasets and aggregating results.

Initial development of GLEAM has focussed on the GHG element, as FAO is committed to supporting member countries and stakeholders in the livestock sector to identify low-emission development pathways for animal production. The development of GLEAM is one part of continuing efforts by FAO to improve assessment of the sector's GHG emissions. Three technical reports present the results of the global analysis undertaken with GLEAM to date for: (a) the cattle dairy sector (Gerber et al. 2010); (b) the pig and chicken sectors (MacLeod et al. 2013); (c) the cattle, buffalo and small ruminant sectors (Opio et al. 2013). A fourth report provides a synthesis of the three technical reports and identifies options to reduce emissions (Gerber et al. 2013).

The purpose of this paper is to provide a review of GLEAM. Specifically, it presents an overview of the model architecture, methods and functionality. It then briefly compares GLEAM results with other studies and explains how differences can arise. In the last section, the advantages of GLEAM are discussed, along with challenges and priorities for development. GLEAM is undergoing continuous development, so any review can only provide a snapshot of the model at a given time. This review focuses on GLEAM version 1.0 (which was used to undertake the analysis for the reports cited in the previous paragraph), while highlighting some revisions introduced in version 2.0, and referring to the most up to date model description (FAO 2017).

Overview of GLEAM architecture, methods and functionality

GLEAM models the main livestock production activities and quantifies the related GHG emissions. It includes the following activities along the supply chain: (a) pre-farm emissions arising from the manufacture of inputs; (b) on-farm emissions during feed and animal production; and (c) post-farm emissions arising from the processing and transportation of products to the retail point. The GHG emissions included in GLEAM v1.0 are summarized in Table 1. GLEAM differentiates 11 main global livestock commodities, which are: meat and milk from cattle, sheep, goats and buffalo; meat from pigs; and meat and eggs from chickens. It also distinguishes between the main production systems, e.g. three distinct pig systems are defined which differ in terms of their herd parameters, rations, excretion rates, manure management etc. (see FAO 2017, section 1.5 for details of the production system classification used). It calculates the GHG emissions and commodity production for a given system within a grid of spatially defined cells, thereby enabling the calculation of the Ei for any desired combinations of commodities, farm systems and locations at different spatial scales. An example of GLEAM output is given in Figure 1.

TABLE 1 HERE

FIGURE 1 HERE

This flexibility of GLEAM derives from it being based in a geographic information system (GIS) environment, consisting of: (a) input data layers; (b) routines written in Python (http://www.python.org/) that perform calculations; and (c) procedures for running the model, checking calculations and extracting output. The basic spatial unit used in the GIS is the 0.05 x 0.05 degree cell (which measure ca. 5km by 5km at the equator). The emissions and production are calculated for each cell using input data of varying levels of spatial resolution (FAO 2017, section 1.4). The data used in GLEAM can be classified into (a) basic input data and (b) intermediate data. Basic input data is defined as primary data such as animal numbers, herd/flock parameters, mineral fertilizer application rates, temperature, etc. and are data taken from sources such as literature, databases and surveys. Intermediate data are values generated within GLEAM then used for subsequent calculations and include values for parameters such as herd structures and manure application rates.

Data availability, quality and resolution vary according to the parameter and country in question. In OECD countries there are often comprehensive national or regional data sets, and in some cases subnational data (e.g. for manure management in dairy in the United States of America). Conversely in non-OECD countries data are often unavailable, necessitating the use of regional default values (e.g. for many backyard pig and chicken physical performance parameters).

Livestock population sizes are based on FAOSTAT data and their geographic distribution is based on the Gridded Livestock of the World (GLW) model. Density maps from GLW are based on observed densities and explanatory variables such as climatic data, land cover and demographic parameters (Robinson et al., 2014).Data on fresh matter yields per hectare of main crops and their respective land area were taken from a modified version of Global Agro-Ecological Zones (GAEZ 3.0) and Haberl et al. (2007) to estimate the above-ground net primary productivity for pasture. Further detail on the derivation of input values is provided in: Opio et al. 2013; MacLeod et al 2013; and FAO (2017).

The overall structure of GLEAM v 1.0 is shown in Figure 2, and the purpose of each module is outlined below.

FIGURE 2 HERE

Herd Module

The functions of the herd module are:

1. Calculation of the herd structure, i.e. the proportion of animals in each cohort, and the rate at which animals move between cohorts;
2. Calculation of the characteristics of the animals in each cohort, i.e. the average weights and growth rates.

Emissions from livestock vary depending on animal type, weight, phase of production (e.g. whether lactating or pregnant) and feeding situation. Accounting for these variations in a population is important if emissions are to be accurately characterized. The use of the IPCC (2006) Tier 2 methodology requires the livestock population to be categorized into distinct cohorts. However, information on herd structure is generally not available from census data or from derived GIS maps. Consequently, a specific herd module was developed to characterize the livestock population by cohort, defining the herd structure, dynamics and production.

The herd module is based on GIS maps that define the total number of animals in each cell, by species and system (e.g. the number of backyard pigs). The total number of animals in a cell is disaggregated into distinct cohorts. For example, Figure 3 shows a cattle herd in which there are four cohorts of animals kept for breeding and production (in the box) plus animals that are “surplus” to breeding requirements and kept for production only. The number of animals in each cohort, and the number entering (e.g. AFin), dying (e.g. AFx) and culled or sold (e.g. AFexit) are calculated using data on rate parameters such as *mortality, fertility, growth and replacement rates*. The herd module also calculates growth rates and average weights for each cohort. The parameters and formulae used in the herd module are given in FAO 2017 (large ruminants section 2.1, small ruminants 2.2, pigs 2.3 and chickens 2.4).

FIGURE 3 HERE

Manure module

The manure module calculates the rates at which excreted N is applied to grass and cropland by: (a) multiplying the number of each animal type (dairy cattle, beef cattle, sheep, goats, pigs and poultry) in the cell by the N excretion rates (based on Tier 1 values from IPCC 2006), to calculate the amount of N excreted in each cell (N deposited directly on pasture by grazing animals is not included in this total, instead the N_2O emissions arising from this are calculated separately in the Feed Module); (b) calculating the proportion of the excreted N that is lost during manure management and subtracting it from the total N, to arrive at the net N available for application to land; (c) dividing the net N by the area of (arable and grass) land in the cell to determine the average rate of N application per ha. Note that this approach is different to the system module, in which detailed calculations of Nx are performed for each animal type using an IPCC (2006) Tier 2 approach (i.e. by calculating each animal's N intake, retention and excretion), which is then used to calculate the N_2O emissions arising from subsequent manure management. The Tier 1 N excretion rates were used in the Manure Module in order to simplify the modelling procedure (using the Tier 2 approach requires the model to be run for all the species simultaneously). In GLEAM v2.0 the Manure Module uses Tier 2 N excretion rates. Soil N_2O emissions from the deposition of organic N (via excretion and manure application) and synthetic N to grass and crops are calculated in the Feed Module. N_2O (and CH_4) arising during manure management are calculated in the System Module, using a Tier 2 approach (FAO 2017, section 4.4).

Feed module

The functions of the feed module are:

1. Calculation of the composition of the ration for each species, cohort and system;
2. Calculation of the nutritional values of the ration per kg of feed;
3. Calculation of the GHG emissions and land use per kg of feed.

The feed module determines the ration of the animal (i.e. the percentage of each feed material in the ration) and calculates the (N_2O, CO_2 and CH_4) emissions arising from the production and processing of the feed. It allocates the emissions to crop co-products (such as crop residues or oil seed meals) and calculates the Ei per kg of feed (on a dry matter (DM) basis). It also calculates the nutritional value of the ration, in terms of its energy and N content.

Determination of the ration. Animal rations are generally a combination of different feed materials. In GLEAM, the rations are comprised of 30 to 40 feed materials (depending on the species and system), which fall into the following categories: fresh grasses or grass-legume mixtures (grazed or cut and carry), conserved grasses or grass-legume mixtures, crop residues (straws and stovers), other roughages (such as banana stems, sugar cane tops and leaves), grains, grain by-products (meals, brans, brewers grains and molasses), oils, compound feed, non-crop feed materials (fishmeal, lime and synthetic amino acids) and swill (this refers to household food waste, rather than food industry wastes) – see FAO 2017, section 3.2 and 3.3. The composition of the feed ration depends on the animals' nutritional requirements, the availability and the price of feed materials. In some systems, such as broilers, layers and industrial pigs, the ration is comprised primarily of compound feed. In these systems the materials are sourced from various locations and traded internationally, and there is little link between where the feed material is produced and where it is utilized by the animal. For these animals the ration compositions are based on country national inventory reports, and the literature. Gaps in the literature were filled through discussions with experts and through primary data gathering (questionnaire surveys were undertaken to augment the data on chicken and dairy cattle rations).

In contrast, the bulk of the ration of ruminants and backyard pigs and chickens is comprised of feed materials sourced locally. Where data is lacking, the proportions of these local feed materials are calculated based on what is available where the animals are located. Figure 4 provides an explanation of how the rations are derived for ruminants; in developing countries the quality of roughage is adjusted depending on the balance of feed supply and demand within a cell, and the types of roughage is defined based on what is grown locally. This approach to estimating the local feeds in the ration results in distinct geographical differences in rations composition and nutritional value.

FIGURE 4 HERE

Once the composition of the ration has been determined, the nutritional values of each feed material are multiplied by the percentage of each feed material in the ration, to arrive at the average digestible energy and N content per kg of DM for the ration as a whole (FAO 2017, section 3.4). A single set of nutritional values is used for swill, although it is recognized that, in practice, the nutritional value of swill could vary considerably, depending on factors such as the human food diet from which the swill is derived.

Determination of the emissions per kg of feed. The methods used to quantify the emissions for each individual feed material are summarized in Table 2. GLEAM v 1.0 quantifies the emissions arising from land-use change (LUC)-induced changes in three carbon pools: (a) biomass (above and below ground), (b) dead organic matter and (c) soil organic carbon. It focuses on the expansion of the areas of land used for soybean cultivation and for grazing cattle in Latin America, which have been two of the most import LUC processes since 1990. GLEAM v2.0 extends the scope to include the expansion of palm oil plantations in Southeast Asia. Emissions are generally quantified according to IPCC Tier I guidelines (IPCC, 2006) and PAS2050 tool (BSI, 2008), combined with land use and trade data from FAOSTAT. Details of the approach used are provided in FAO (2017), section 6.1.5-6.1.6.

In order to calculate the Ei of the feed materials, the emissions need to be allocated between the grain and its co-products, i.e. the crop residue or by-products of crop processing. For example, once the total emissions arising from the growing of 1 hectare of wheat have been calculated, the emissions have to be divided between the wheat grain and straw, in order to calculate the emission per kg of grain and of straw. An economic allocation approach is used, i.e. one based on the financial value of the co-products (FAO 2017, section 6.5).

TABLE 2 HERE

System module

The Systems module was renamed the “Animal emissions module” in v2.0, in order to better reflect its functions, which are:

1. Calculation of the average energy requirement (in MJ) and feed intake (in kg DM) of each animal cohort;
2. Calculation of the total emissions and land use arising from the production, processing and transport of the feed;

3. Calculation of the CH_4 and N_2O emissions arising during the management of manure;
4. Calculation of enteric CH_4 emissions.

Calculation of animal energy requirement. The system module calculates the energy requirement of each animal cohort, which is then used to determine the feed intake (in kg of DM). The energy requirement and feed intake are calculated using an IPCC (2006) Tier 2-type approach, i.e. the energy required for each of the relevant metabolic functions is calculated separately then summed. The system module includes equations for the following metabolic functions: maintenance, growth, lactation, egg production, pregnancy, work and fibre production.

As the IPCC (2006) does not include equations for calculating the energy requirement of pigs or poultry, equations were derived from NRC (1998) for pigs and Sakomura (2004) for chickens (the formulae used to calculate energy requirements are given in FAO 2017, section 3.5). Energy requirement is adjusted to reflect the animals' level of activity, i.e. it is increased in situations where it is likely to be significantly higher, such as where ruminants are ranging rather than grazing, or for backyard pigs and poultry, which expend energy scavenging for food. The energy requirement of cattle and buffalo is also adjusted to reflect the amount of energy expended in field operations by animals that are used for draft.

Calculating feed intake, total feed emissions and land use. The feed intake of each animal cohort (in kg DM/day) is calculated by dividing the animal's energy requirement (in MJ) by the ration energy density (i.e. MJ/kg DM). The feed intake per animal in each cohort is multiplied by the number of animals in each cohort to get the total daily feed intake for the flock/herd. The feed emissions and land use associated with the feed production are then calculated by multiplying the total feed intake for the flock/herd by the emissions or land use per kg of DM taken from the feed module. Feed wastage (via spillage, losses in storage etc.) is not calculated, due to the lack of any comprehensive data set on this.

Calculation of CH_4 emissions arising from enteric fermentation. The enteric emissions are calculated using the IPCC (2006) Tier 2 approach. To better reflect the wide-ranging diet quality and feeding characteristics globally, GLEAM calculates specific values of Y_m (the per cent of gross energy intake converted to methane) for ruminants based on the following formulae:

$$Y_{m\ Cattle} = 9.75 - 0.05 \cdot DE$$

$$Y_{m\ mature\ sheep} = 9.75 - 0.05 \cdot DE$$

$$Y_{m\ lamb<1\ year} = 7.75 - 0.05 \cdot DE$$

Where DE is the average digestibility of feed, calculated in the Feed Module. These formulae are based on the assumption that Ym varies linearly with DE within the ranges defined in IPCC (2006, Table 10.12).

Two values of Y_m were used for pigs: 1 per cent for adult pigs and 0.39 per cent for growing pigs, based on Jørgensen *et al.* (2011, p. 617).

Calculation of CH_4 emissions arising during manure management. The CH_4 per head from manure is calculated using an IPCC (2006) Tier 2 approach, which entails (a) estimation of the volatile solids (VS) excretion rate per animal and (b) estimation of the proportion of the VS that are converted to CH_4 (FAO 2017, section 4.3). Once the VS excretion rate is known, the proportion of the VS converted to CH_4 during manure management per animal per year can be calculated using Equation 10.23 from IPCC (2006). The CH_4 conversion factor (MCF) depends on how the manure is managed. The manure management categories and emission factors (EFs) in IPCC (2006, Table A7), see FAO 2017, section 4.1, are used in GLEAM. The proportion of manure in each animal waste management system is based on official statistics (such as the Annex 1 countries' National Inventory Reports to the UNFCCC), other literature sources and expert judgment.

Calculation of N_2O emissions arising during manure management. The N_2O per head from manure is calculated using an IPCC (2006) Tier 2 approach, which requires (a) estimation of the rate of N excretion per animal, and (b) estimation of the proportion of the excreted N that is converted to N_2O. The N excretion rates are calculated using the formulae set out in FAO 2017, section 4.4. N intake depends on the feed DM intake and the feed N content, which are calculated in the System Module and Feed Module, respectively. N retention is the amount of N retained in tissue (either as growth, pregnancy live weight (LW) gain), milk or eggs. The rate of conversion of excreted N to N_2O depends on the extent to which the conditions required for nitrification, denitrification, leaching and volatilization are present during manure management. The IPCC (2006) default EFs for direct N_2O (IPCC, 2006, Table 10.21) and indirect N_2O via NH_3/NO_x volatilization (IPCC, 2006, Table 10.22) are used in this study, along with variable N leaching rates. The N leaching rates were based on Velthof et al. (2009), adjusted for agro-ecological zone (lower leaching rates were assumed in arid areas) and regional trends in manure management (regional variation in the presence of floors and roofs were defined based on expert opinion). The resulting regional average leaching rates are given in FAO 2017, section 4.4.4.

Computation of other emissions along the supply chain.

Emissions from direct (i.e. on-farm) energy use and indirect (embedded) energy. Indirect emissions arise in the extraction and processing of the materials (such as steel, concrete or wood) used to manufacture capital goods. GLEAM includes the emissions embedded in farm buildings, specifically animal housing and feed and manure storage facilities (FAO 2017, section 7.1). Direct on-farm energy includes the emissions arising from energy use on-farm in livestock production, such as ventilation, lighting and heating. Emissions from the energy used in feed production and transport are already included in the feed CO_2 category. The average rates of consumption of different energy sources per kg of commodity were estimated based on a review of published values. The average electricity consumption was then multiplied by the EF for electricity in each country, to calculate that county's emissions (FAO 2017, section 7.2).

Calculation of post-farm emissions. Emissions accounted for in the post-farm part of the supply chain include those arising from: (a) the transport and distribution of live animals and commodities (domestic and international), (b) processing and refrigeration, and (c) the production of packaging material. Excluded from the analysis were estimates of GHG emissions from on-site wastewater treatment facilities, emissions from animal waste at the slaughter site and the consumption part of the food chain (household transport and preparation) and disposal of packaging and waste. Further details of the method used to quantify post-farm emissions are given in FAO 2017, section 8.

Allocation module

The functions of the allocation module are: (1) summation of the total emissions for each animal cohort; (2) calculation of the amount of each commodity (meat, milk, eggs and fibre) produced; (3) allocation of the emissions to each edible output (meat, milk, eggs), non-edible output (fibre and manure) and services (draft power); and (4) calculation of the total emissions and Ei of each commodity. Emissions are allocated based on the methods outlined in Table 3. Live weight is converted to carcass weight and to bone-free meat by multiplying by species and system-specific (and in some cases, country-specific) conversion factors (FAO 2017, section 9.1).

Allocation to co-products and calculation of Ei. Within a herd or flock, some animals only produce meat, while others such as dairy cows or laying hens produce more than one edible output. The emissions are allocated to these edible co-products on a protein basis, which is illustrated in Table 4. Emissions related to non-edible outputs (e.g. fibre, manure used for fuel, draft power) are first calculated separately then deducted from the overall system emissions, before emissions are attributed to the edible outputs. The emissions are allocated to non-edible products on the basis of their economic value or, in the case of draft power, on the basis of the extra energy and feed intake required for working animals. Economic and physical approaches to allocation have different strengths and weaknesses, depending on the specific situation, see Ardente and Cellura (2012) for a review.

TABLE 3 HERE

TABLE 4 HERE

Emissions are allocated to the main commodities produced, i.e. meat, milk, eggs and fibre. In reality, there are usually significant amounts of other materials produced during processing, such as feathers and offal. However, the values of these can vary markedly between countries, and, in the absence of global datasets on the value of slaughter by-products, it was decided to allocate all the emissions to the main commodities. It is recognized that allocating no emissions to these can lead to an over allocation to the main commodities, and that the results should be interpreted accordingly.

Comparison with other studies

The Ei of livestock commodities can vary a great deal depending on the commodity in question and how it is produced (see Table 5). The factors driving variation in Ei are explored in detail in MacLeod et al. (2013) (pigs and chickens) and Opio et al. (2013) (cattle, buffalo, sheep and goats). The total emissions arising from livestock production, and potential ways of reducing them, are summarized in Gerber et al. (2013). Note that the emissions in Table 5 sum to 0.6Gt less than the 7.1Gt reported in Gerber et al. (2013, p15), the difference being that Table 5 does not include emissions allocated to non-food goods and services, such as draught power performed by oxen.

TABLE 5 HERE

Validation of GLEAM results is complicated by the absence of similar global livestock LCA studies with which to compare it. However, numerous national and regional level LCA studies exist, and the GLEAM results are compared with these in MacLeod et al. (2013) and Opio et al. (2013). In order to summarize these comparisons, the results for GLEAM were matched with other studies of the same location and system. The GLEAM results were adjusted (as far as possible) to have the same scope (i.e. the same system boundary and emissions categories) as the comparator study, and then plotted on scattergrams. The results of these comparisons are summarized in Table 6. The comparisons indicated that, while GLEAM produces quite different results from some individual studies, its overall results are broadly consistent with many other studies, and discrepancies can be explained with reference to the different methodologies and assumptions employed.

TABLE 6 HERE

Different studies often adopt different system boundaries, and include different emissions categories within their system boundary. An exact match between the study scope and GLEAM scope was not always possible, particularly where the fully disaggregated emissions were not reported.

Differences in ration compositions (i.e. the % of each feed material in the ration) can lead to significant differences in the feed and (to a lesser extent) the manure emissions. Assumptions made about some feed materials, such as soy, are particularly important. The expansion of soy production is argued to be one of the main drivers of LUC, and soy associated with LUC will have a much higher Ei than soy not associated with LUC. Therefore for livestock fed significant amounts of soy products, the total Ei is particularly sensitive to the assumptions made regarding: (a) the amount of soy in the ration, (b) where it is sourced from and (c) how the emissions per ha of soyl are determined. Feed emissions are also sensitive to the way in which soil N_2O is calculated, as the assumptions made about nutrient application rates, crop yields and rates of transformation of N inputs to N_2O.

Results for some species/systems can be sensitive to the assumptions made about how the manure is managed. For example, Figure 5 shows how the methane conversion factor for industrial pigs in East Asia varies between cells, in response to changing temperature, and between countries as the assumptions made about how manure is managed change.

Finally, the allocation required at different stages of analysis can produce significantly divergent results. For example, Nielsen et al. (2011) used systems expansion to credit broilers with avoided emissions from reduced fertilizer manufacture (manure) and mink feed (slaughter by-products).

FIGURE 5 HERE

Discussion

Advantages and added-value of GLEAM

GLEAM is comprehensive in scope and uses geo-referenced information for computation. Geography is highly important to the assessment of agro-ecological processes, which depend on factors such as soil quality, climate and land use that have contrasting spatial patterns. This is an improvement on global assessments that rely on national averages, and the GIS platform provides flexibility in combining datasets and aggregating results. GLEAM can also compensate for the shortage of global datasets on animal production and related resource use by enabling livestock statistics to be disaggregated into different systems and animal cohorts, and enabling the determination of feed rations where no datasets are available. Furthermore, GLEAM allows a wide range of parameters to be varied, thus enabling predictive modeling and design of mitigation interventions. Below we provide three examples of the advantages of GLEAM.

Disaggregating livestock statistics and determining herd structures

Livestock statistics are not always sufficiently disaggregated to perform emissions calculations. For example FAOstat provides total numbers of cattle and total numbers of milked cows, but not the total size of the dairy herd or beef herd, or their age structures. GLEAM can overcome this problem by using the Herd Module to calculate the size of the dairy herd from the number of milked cows. This then enables the size of the beef herd to be calculated by subtracting the dairy herd from the total head of cattle. Furthermore, for the Tier 2 approach, IPCC (2006, p10.10) recommend that it is “good practice to classify livestock populations into subcategories for each species according to age, type of production and sex”, so that the emissions calculations take into account differences in animal productivity and diet quality. GLEAM addresses the lack of data on livestock subcategory populations by using the Herd Module to determine the number of animals in each subcategory. This allows the emissions for each subcategory (or cohort) to be calculated separately, ensuring that breeding animals (and their replacements) are included in the calculations.

Investigating the effect of variation in key parameters

The inclusion of a wide range of parameters in the Herd Module (FAO 2017, section 2.1-2.4) provides significant scope for understanding how the physical performance and management of livestock influence Ei. For example, it enables us to compare the performance of two (or more) different systems or to undertake predictive modeling, i.e. to compare the performance of a system before and after a change.

Figure 6 illustrates how herd dynamics combine with other factors to determine Ei for two cattle systems in East Africa. The lines in the bottom half of each Sankey diagram represent movements of cattle between cohorts (including calves entering the herd). The number of cattle in each cohort is given in brackets, and is determined by the rates at which animals enter and exit the cohort, and their residence time in the cohort. For example, in the mixed system there are more cattle entering the “meat males” cohort than the “draft males” cohort each year, but the latter has a greater population due to the longer residence time in this cohort.

The number of cattle in each cohort is important as each produces protein and emissions at a different rate, depending on factors such as milk yield, growth rates and feed digestibility. For example, adult females emit less GHG per kg of protein produced than the draft males, and consequently have lower Ei. The greater number of draft males in the mixed system is one of the reasons for this system’s higher overall Ei.

The capacity of GLEAM to capture the effects of herd structure makes it a useful tool for evaluating mitigation measures. These evaluations can be achieved through either the direct inclusion of economic data and parameters in the GLEAM framework (e.g. Mottet et al., 2016), or by coupling GLEAM with existing economic models (such as GTAP (Hertel et al., 1999); CAPRI (Britz & Witzke, 2008); GLOBIOM (Havlik et al., 2014), IMPACT (Rosegrant et al., 2008) or IMAGE (Stehfest et al. 2014)) in a fashion similar to the way MITERRA links CAPRI and GAINS (Lesschen et al 2011).

FIGURE 6 HERE

Determination of local feed rations.

An understanding of ration composition is essential as it influences the emissions arising from feed production, enteric fermentation and manure management. For some systems, particularly in developing countries, a significant proportion of the ration consists of locally produced feed materials; however there is a lack of data on the composition of these rations. GLEAM addresses this problem by determining the local rations based on the spatial distributions of livestock and crops. This approach (summarized in Figure 4) enables rations to be derived which, at least partially, reflect what is grown locally and the overall balance of roughage supply and demand.

Challenges and priorities for the improvement of GLEAM

Livestock supply chains involve numerous and interdependent activities that are carried out with a variety of technology and resource implications across the globe. Developing GLEAM and its related database is an effort that will require commitment over time. While the model is operational for GHG emission and mitigation analysis, a number of priorities for improvement have already been identified: (a) continuously improving GHG calculations, (b) improving the utility of GLEAM output, (c) extending the scope to non-GHG flows and impacts and (d) improving the capacity to undertake predictive modeling.

Continuously improving GHG calculations.

Performing global analyses of livestock is a data-intensive task, and the development of GLEAM necessitated the use of numerous generalizations and projections. One of the priorities is therefore to improve the data quality and availability for key parameters in order to perform existing calculations with more valid input data and enable development of calculation methods. For example, priority areas include improving information on feed ration composition (particularly the amounts of feed materials associated with land use change and the seasonality in ration composition and availability), manure management (for key species/systems/locations such as pigs in East Asia) and on rates of energy use in crop production. The use of GLEAM to support country-level assessments is an effective way to progressively improve the model's database.

Improving data is particularly important when GLEAM is used to inform policy decisions in developing countries, where data quality can be poor and agriculture central to much of the population's livelihoods. Various projects have been carried out with GLEAM in developing countries, using the same approach and formulations, but adjusting it to the specific local requirements (see http://www.fao.org/gleam/in-practice/en/). In each project, the input data were revised and verified

Improved data could enable better determination of feed rations and potentially the introduction of formulae that better reflected the relationships between feed quality and animal productivity. Given the importance of soil N_2O, improving the EFs used to calculate soil N_2O emissions should also be a priority. The use of default Tier 1 EFs obscures actual patterns of GHG emissions and may introduce bias against certain farm systems, locations etc. Recent studies have determined Tier 2 EFs for the UK and China based on experimentation (Bell et al. 2015) and analysis of existing data (Shepherd et al. 2015). However lack of empirical evidence is a problem, particularly in sub-Saharan Africa where “fewer than fifteen studies of nitrous oxide emissions from soils have taken place” (Rosenstock et al. 2013), although Kim et al. (2016) have recently updated the research on N_2O in SSA.

Improving the utility of GLEAM output.

In order to make the results more comprehensible, and of greater utility in decision-making, methods of characterizing and communicating the uncertainty in the results need to be developed. The calculations in GLEAM involve hundreds of parameters, the values of which are subject to some degree of uncertainty and can have a significant impact on the results. Quantifying the uncertainty for the global results would require uncertainty ranges for many parameters, and is beyond the scope of the model at present. Instead, partial uncertainty analyses, for selected countries and systems, have been undertaken to illustrate the likely uncertainty ranges in the results and to highlight the parameters that make the greatest contribution to uncertainty (see MacLeod et al. 2013, p36, p60 and Opio et al. 2013, p74). Such approaches will be part of the ongoing development of GLEAM.

Extending the scope to non-GHG flows and impacts, and improving the capacity to undertake predictive modeling.

While estimating GHG emissions from the livestock sector is important, focusing on one dimension of environmental performance could lead to undesired policy outcomes. In order to avoid this, GLEAM is progressively being developed to measure non-GHG physical flows and impacts in terms of, for example, nutrient management, water consumption, water quality and biodiversity. Work to develop methods for quantifying nutrient use efficiency is underway (see Powell *et al.*, 2013). GLEAM is a potentially powerful tool for predictive modeling, e.g. for quantifying the impact of GHG mitigation measures (Henderson et al. 2015), but fully realizing this potential will require development of some of the formulae and improved data quality.

GLEAM is being developed at FAO, with support from partner organizations and related initiatives, such as the Livestock Environment Assessment and Performance (LEAP) partnership. In order to facilitate the development process, an interactive, user-friendly version of the model ("GLEAM-i") has recently been made publically available. GLEAM-i brings the core functionalities of GLEAM together in a single Excel file (available at: http://www.fao.org/gleam/resources/en/) enabling users to calculate the Ei for a specified region (i.e. a single cell). It is hoped that GLEAM-i will raise awareness of the role that agri-environmental modelling can play in policy formulation.

Conclusions

Improvements in our understanding of the ways in which GHG emissions arise in livestock supply chains are required in order to help the sector contribute to the overall climate change mitigation effort. To date, most studies have either focused on global emissions arising on-farm, or on the life-cycle emissions of specific commodities, locations and production systems. While such studies provide many valuable insights, they provide a limited basis for quantifying global emissions and judging the potential scale of mitigation. Furthermore, differences in methods can make inter-study comparison difficult, as different approaches, input data and assumptions can produce quite different results. GLEAM is therefore designed to complement existing studies by providing a spatially and temporally consistent and comprehensive way of quantifying the GHG emissions arising from global livestock production. Improving data quality for non-OECD countries and validating the results, will be a priority for GLEAM. This is important given that much of the agriculture mitigation potential lies in non-OECD regions (Smith *et al*., 2007, p499). GLEAM is both a comprehensive and spatially explicit database on the livestock sector and a tool to perform detailed biophysical analysis along the supply chains. It is hoped that its features, such as the ability to derive rations for livestock in developing countries, and to capture variation in livestock performance and management will support progress towards the improvement of the environmental performance of livestock production.

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References

Alexandratos N. and Bruinsma J 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Food and Agriculture Organization of the United Nations (FAO), Rome.

Ardente F and Cellura M, (2012) Economic allocation in life cycle assessment. J Ind Ecol 16(3):387–398

Bajželj, B., Keith S. Richards, Julian M. Allwood, Pete Smith, John S. Dennis, Elizabeth Curmi and Christopher A. Gilligan 2014 Importance of food-demand management for climate mitigation, Nature Climate Change, Vol. 4,pp. 924–929.

Bell MJ, Hinton N, Rees RM, Cloy JM, Topp, C.F.E, Cardenas L, Scott T, Webster C, Whitmore A, Williams J, Balshaw H, Paine F, Chadwick D (2015), Nitrous Oxide emissions from fertilised UK arable soils: Fluxes, emission factors and mitigation, Agriculture, Ecosystems and Environment 212, 134-147

Berglund M, Cederberg C, Clason C and och Lars Törner MH 2009. Jordbrukets klimatpåverkan – underlag för att beräkna växthusgasutsläpp på gårdsnivå och nulägesanalyser av exempelgårdar. Delrapport i JoKer-proJeKtet, Hushållningssällskapet Halland.

BPEX 2010. Pig cost of production in selected countries. AHDB, Stoneleigh Park, UK.

Britz, W., & Witzke, P. 2008. CAPRI model documentation 2008: version 2. Institute for Food and Resource Economics, University of Bonn, Bonn.

BSI. 2008. PAS 2050:2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. UK: British Standards Institution (BSI).

DCCEE 2010. National Inventory Report 2008, vol 1, Australian National Greenhouse Accounts, Department of Climate Change and Energy Efficiency, Canberra, Australia.

Defra 2006. Nitrogen and phosphorus output of livestock excreta: Final report, Defra project WT0715NVZ Defra, London, UK.

EDGAR 2012. Emissions Database for Global Atmospheric Research (EDGAR). Retrieved on 2 September 2013, from http://edgar.jrc.ec.europa.eu

EPA 2012. US Environmental Protection Agency Global Emissions Database. Retrieved on 2 September 2013, from www.epa.gov/climatechange/ghgemissions/global.html

ERM/Plant Research International 2003. Livestock Manures – Nitrogen Equivalents European Commission, Brussels, Belgium.

FAO 2017 Global Livestock Environmental Assessment Model Version 2.0 Model Description Revision 6, May 2017, Food and Agriculture Organization of the United Nations (FAO), Rome.

Gerber PJ, Opio C, Vellinga T, Henderson B and Steinfeld H 2010 Greenhouse gas emissions from the dairy sector – A life cycle assessment Food and Agriculture Organization of the United Nations (FAO), Rome.

Gerber, PJ., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Haberl, H., Erb, K.-H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht W. & Fischer-Kowalski M. 2007. Quantifying and mapping the global human appropriation of net primary production in Earth's terrestrial ecosystem. PNAS. 104: 12942-12947

Havlík, P., Hugo Valin, Mario Herrero, Michael Obersteiner, Erwin Schmid, Mariana C. Rufino, Aline Mosnier, Philip K. Thornton, Hannes Böttcher, Richard T. Conant, Stefan Frank, Steffen Fritz, Sabine Fuss, Florian Kraxner, and An Notenbaert 2014 Climate change mitigation through livestock system transitions PNAS 111 (10)

Henderson, B., A. Falcucci,, A. Mottet, L. Early, B. Werner, H. Steinfeld, and P. Gerber 2017 Marginal costs of abating greenhouse gases in the global ruminant livestock sector Mitigation and Adaptation Strategies for Global Change 22, 199-224

Herrero M and Thornton PK 2013. Livestock and global change: Emerging issues for sustainable food systems Proceedings of the National Academy of Sciences of the USA 110, 20878–20881

Hertel, T.W., 1999. Global trade analysis: modeling and applications. Cambridge, Cambridge University Press.

IIASA 2013a. The GAINS Model: A scientific tool to combat air pollution and climate change simultaneously. Retrieved on 3 September 2013 from http://www.iiasa.ac.at/web/home/research/researchPrograms/GAINS.en.htm

IIASA 2013b. GLOBIOM: A global model to assess competition for land use between agriculture, bioenergy, and forestry. Retrieved on 3 September 2013 from http://www.iiasa.ac.at/web/home/research/modelsData/GLOBIOM/GLOBIOM.en.html

IPCC. 2006. *IPCC guidelines for national greenhouse gas inventories*. Prepared by the National Greenhouse Gas Inventories Programme, (eds HS Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe) IPCC, Kanagawa, Japan

Jenssen TK and Kongshaug G 2003. Energy consumption and greenhouse gas emissions in fertiliser production. Proceedings No. 509. The International Fertilizer Society, York, UK

Jeroch H 2011. Recommendations for energy and nutrients of layers: a critical review, Lohmann Information, 46, 61–72.

Jørgensen H, Theil PK and Knudsen EBK 2011. Enteric methane emissions from pigs. In *Planet earth 2011 – global warming challenges and opportunities for policy and practice.* Published online by InTech. http://www.intechopen.com/books/planet-earth-2011-global-warming-challenges-and-opportunities-for-policy-and-practice

Kim D-G, Thomas AD, Pelster D, Rosenstock TS and Sanz-Cobena A 2016 Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: synthesis of available data and suggestions for further research, Biogeosciences 13, 4789-4809

Klimont Z and Brink C 2004 Interim Report IR-04-048 Modelling of Emissions of Air Pollutants and Greenhouse Gases from Agricultural Sources in Europe IIASA, Laxenburg, Austria

Kool A, Marinussen M and Blonk H 2012. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization GHG Emissions of N, P and K fertilizer production. Blonk Consultants, Gouda, The Netherlands.

Lamb A, Green R, Bateman I, Broadmeadow M, Bruce T., Burney J, Carey P, Chadwick D, Crane E, Field R, Goulding K, Griffiths H, Hastings A, Kasoar T, Kindred D, Phalan B, Pickett J, Smith P, Wall E, zu Ermgassen EKHJ, and Balmford

A 2016. The potential for land sparing to offset greenhouse gas emissions from agriculture. Nature Climate Change, 6 488-492

Leinonen I, Williams AG, Wiseman J, Guy J and Kyriazakis I 2012. Predicting the environmental impacts of chicken systems in the United Kingdom through a life-cycle assessment: broiler production systems. Poultry Science 91, 8-25.

Leip A, Weiss F, Wassenaar T, Perez I, Fellmann T, Loudjani P, Tubiello F, Grandgirard D, Monni S, Biala K, 2010. Evaluation of the Livestock Sector's Contribution to the EU Greenhouse Gas Emissions (GGELS) – Final Report. European Commission, Joint Research Centre, Ispra, Italy.

Leip A, Billen, G, Garnier, J, Grizzetti, B, Lassaletta, L, Reis, S, Simpson, D, Sutton. MA, de Vries, W, Weiss, F and Westhoek, H 2015 Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity Environ. Res. Lett. 10 115004

Lesschen, J.P., M. van den Berg, H.J. Westhoek, H.P. Witzke, O. Oenema 2011 Greenhouse gas emission profiles of European livestock sectors Animal Feed Science and Technology 166– 167 (2011) 16– 28

MacLeod M, Gerber P, Vellinga T, Opio C, Falcucci A, Tempio G, Henderson B, Mottet A. and Steinfeld H 2013. Greenhouse Gas Emissions from Pig and Chicken Supply Chains: A Global Life Cycle Assessment Food and Agriculture Organization of the United Nations (FAO), Rome.

Mottet, A., Henderson ,B.B., Opio, C., Falcucci, A., Tempio, G., Silvestri., S., Chesterman, S., and Gerber, P.J., 2016. Climate change mitigation and productivity gains in livestock supply chains: Insights from regional case studies. Regional Environmental Change. 1-13

Nielsen N, Jørgensen M and Bahrndorff S 2011. Greenhouse gas emission from the Danish broiler production estimated via LCA methodology. AgroTech/Knowledge Centre for Agriculture, Aarhus, Denmark.

NRC 1998. Nutrient requirements of swine: 10th Revised Edition. National Academy Press. Washington, USA.

Opio C, Gerber P, Vellinga T, MacLeod M., Falcucci A, Henderson B, Mottet A, Tempio G and Steinfeld H 2013. Greenhouse Gas Emissions from Ruminant Supply Chains: A Global Life Cycle Assessment Food and Agriculture Organization of the United Nations (FAO), Rome.

Petri A and Lemme A 2007. Trends and latest issues in broiler diet formulation. Lohmann Information, 42.

Powell JM, MacLeod M, Vellinga TV, Opio C, Falcucci A, Tempio G, Steinfeld H and Gerber P 2013. Feed–milk–manure nitrogen relationships in global dairy production systems Livestock Science 152, 261–272

Prabakaran R 2003. Poultry feed formulation and preparation Good Practice in Poultry Production in South Asia FAO Animal Production and Health Paper 159 FAO, Rome, Italy.

Prudêncio da Silva V, van der Werf HMG and Soares SR 2010. LCA of French and Brazilian broiler poultry production scenarios. XIIIth European Poultry Conference, Tours, France, 23-27 August 2010

Robinson T.P., Wint G.R.W., Conchedda G., Van Boeckel T.P., Ercoli V., Palamara E. 2014. Mapping the Global Distribution of Livestock. PLoS ONE 9(5): e96084. doi:10.1371/journal.pone.0096084

Rosegrant, M.W., Ringler, C., Msangi, S., Sulser, T.B., Zhu, T. and Cline, S.A. 2008. International model for policy analysis of agricultural commodities and trade (IMPACT): model description. International Food Policy Research Institute: Washington, DC, USA.

Rosenstock, T.S., M C Rufino, K Butterbach-Bahl and E Wollenberg (2013) Toward a protocol for quantifying the greenhouse gas balance and identifying mitigation options in smallholder farming systems Environmental Research Letters, Volume 8, Number 2

Sakomura NK 2004. Modelling Energy Utilization in Broiler Breeders, Laying Hens and Broilers, Brazilian Journal of Poultry Science/Revista Brasileira de Ciência Avícola 6, 1–11.

Shepherd, A., Xiaoyuan Yan, Dali Nayak, Jamie Newbold, Dominic Moran, Mewa Singh Dhanoa, Keith Goulding, Pete Smith and Laura M. Cardenas (2015) Disaggregated N2O emission factors in China based on cropping parameters create a robust approach to the IPCC Tier 2 methodology Atmospheric Environment Volume 122, 272–281

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O 2007. Agriculture. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change (eds B Metz, OR Davidson, PR Bosch, R Dave, LA Meyer), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Smith P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E. A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N. H. Ravindranath, C. W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. Tubiello, 2014 Agriculture, Forestry and Other Land Use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stehfest, E., van Vuuren, D.P., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, P., van Minnen, J., Muller, C., Prins, A., 2014. IMAGE by IMAGE 3.0. Netherlands Environmental Assessment Agency.

Steinfeld, H, Gerber PJ, Wassenaar T, Castel V, Rosales M and de Haan, C 2006 Livestock’s long shadow: environmental issues and options, Food and Agriculture Organization of the United Nations (FAO), Rome.

Tubiello FN, Salvatore M, Rossi S, Ferrara A, Fitton N and Smith P 2013. The FAOSTAT database of greenhouse gas emissions from agriculture Environmental Research Letters 8

Velthof G L, Oudendag D, Witzke HR, Asman WAH, Klimont Z and Oenema O 2009. Integrated assessment of N losses from agriculture in EU-27 using MITERRA-EUROPE. Journal of Environmental Quality 38, 402–417.

Wiedemann SG, McGahan E and Poad P 2012. Using life cycle assessment to quantify the environmental impact of chicken meat production. RIRDC publication, No.12/029. Rural Industries Research and Development Corporation, Canberra, Australia

Winiwarter, W., Hoeglund-Isaksson, L., Schoepp, W., Tohka, A., Wagner, F. and Amann, M. 2010 Emission mitigation potentials and costs for non-CO_2 greenhouse gases in Annex-I countries according to the GAINS model. Journal of Integrative Environmental Sciences. pp. 235-243.

WRI 2013 CAIT 2.0 WRI's climate data explorer Retrieved on 3 September 2013 from http://cait2.wri.org/wri#

You L, Crespo S, Guo Z, Koo J, Ojo W, Sebastian K, Tenorio TN, Wood S & Wood-Sichra U 2010. *Spatial Production Allocation Model (SPAM) 2000, Version 3. Release 2* (retrieved May 2009 from http://MapSPAM.info).

Table 1. Sources of GHG emissions included and excluded in GLEAM v1.0

Activity	Included	Excluded
Feed production	• Direct and indirect N_2O from: ○ Application of synthetic N ○ Application of manure ○ Direct deposition of manure by grazing animals ○ Crop residue management • CO_2[a] - energy use in field operations • CO_2[a] - energy use in feed transport and processing • CO_2[a] and N_2O - fertilizer manufacture • CO_2[a] - feed blending • CO_2[a] - production of non-crop feeds (fishmeal, lime and synthetic amino acids) • CH_4 - flooded rice cultivation • CO_2 - land use change related to soybean cultivation	• N_2O losses related to changes in C stocks • CO_2 from biomass burning • N_2O from biological fixation • N_2O and CO_2 from non-N fertilizers and lime • CO_2 from changes in (above and below ground) carbon stocks not arising from land use change
Non-feed production	• CO_2[a] - embedded energy related to manufacture of on-farm buildings and equipment	• CO_2 from production of cleaning agents, antibiotics and pharmaceuticals
Livestock production	• CH_4 - enteric fermentation • CH_4 and N_2O - manure deposition and storage • CO_2[a] - direct on-farm energy use for livestock, e.g. cooling, ventilation and heating	
Post farm-gate	• CO_2[a] - transport of live animals and products to slaughter and processing plants • CO_2[a] - transport of processed products to retail point • CO_2[a] and HFC's[b] - refrigeration during transport and processing • CO_2[a] - primary processing of meat (into carcasses or meat cuts), milk and eggs • CO_2[a] - manufacture of packaging	• CO_2 and CH_4 from on-site waste water treatment • CO_2 and CH_4 emissions from animal waste or avoided emissions from on-site energy generation from waste • CO_2 from retail and post-retail energy use • CO_2 CH_4 N_2O from waste disposal at retail and post-retail stages

a. The emissions factor also includes a small amount of CH_4 emissions arising during fuel extraction and processing
b. Hydrofluorocarbons

Table 2. Summary of the methods used to quantify feed emissions

Source of emissions	Approach to quantifying
Direct and indirect N_2O from crop cultivation;	• Synthetic N application rates were defined for each crop at a national level, based on existing data sets (primarily FAO's Fertilizer use statistics) and adjusted down where yields were below certain thresholds. • Manure N application rates were calculated in the manure module (FAO 2017, section 5). • Crop residue N was calculated using the crop yields and the IPCC (2006, p. 11.17) crop residue formulae. • N_2O emissions calculated using IPCC (2006) Tier 1 methodology
CH_4 arising from rice cultivation;	• The average CH_4 flux per ha of rice was calculated for each country using the IPCC Tier 1 methodology (IPCC 2006, ch 5.5)
CO_2 arising from land use change (LUC) for pasture and soybean expansion	• Rates of LUC are based on FAOSTAT average LUC rates 1990-2006. • Emissions arising from LUC calculated using IPCC (2006) Tier 1 (FAO 2017, section 6.1.5)
CO_2 from the on-farm energy use associated with field operations and on-farm crop processing	• The type and amount of energy required per ha, or kg of each feed material parent crop was based on values in the literature, then multiplied by the emissions factor for that energy source. The energy consumption rates were adjusted to consider the proportion of the field operations undertaken using non-mechanized power sources (FAO 2017, section 6.1.2)
CO_2 arising from the manufacture of fertilizer;	• The average European fertilizer EF of 6.8 kg CO_2-eq per kg of ammonium nitrate N was used (based on Jenssen & Kongshaug, 2003). In GLEAM v2.0 the scope is expanded to include emissions from the manufacture of a range of synthetic N, P and K fertilizers, and pesticides (FAO 2017, 6.1.1)
CO_2 arising from crop transport and processing;	• Swill and local feeds, by definition, are transported minimal distances and are allocated zero emissions for transport. Non-local feeds are assumed to be transported between 100 km and 700 km by road. In countries where more of the feed is consumed than is produced (i.e. net importers), feeds that are known to be transported globally (e.g. soymeal) also receive emissions that reflect typical sea transport distances. • Emissions from processing (e.g. milling, crushing and heating) were calculated for by-product feeds based on default rates of energy consumption (FAO 2017, section 6.1.3) . • The energy used in feed mills for blending non-local feed materials to produce compound feed and to transport it to its point of sale, were calculated based on the assumptions that 186 MJ of electricity and 188 MJ of gas were required to blend 1000 kg of DM, and that the average transport distance was 200 km (FAO 2017, section 6.1.4).
Production of non-crop feed materials	• Default values were used for fishmeal and synthetic amino acids (from Berglund *et al*. 2009) and for lime (from Kool *et al*. 2012)

Table 3. Summary of the approaches used to allocate emissions to livestock outputs

Output	Method of allocation
Meat	Allocated between edible co-products on the basis of their protein content (FAO 2017, section 9)
Milk	As for meat.
Eggs	As for meat.
Manure	Emissions related to manure storage were fully allocated to the livestock system.
	Emissions from manure applied to crops were allocated to livestock in situations where the crop was used for feed.
	Emissions from manure discharged into the environment were solely attributed to the livestock system.
Fibre	Emissions allocated based on the economic value of all system outputs – meat, milk, and fibre products.
Draft power	Additional emissions required for performing draft functions calculated (by subtracting the emissions of a non-draft animal from the emissions of an equivalent draft animal) and allocated to draft power services.
Slaughter by-products	No emissions allocated due to the lack of reliable global data on the value of these outputs.
Capital functions of livestock	No emissions allocated due to the lack of reliable global data on the value of these outputs.

Table 4. Formulae used to allocate emissions to meat and eggs on a protein basis (for example calculations, see FAO 2017, section 9.3)

	Part of flock producing eggs and meat (1)	**Part of flock producing meat only (2)**
Total emissions per annum (kg CO_2-eq)	Total emissions produced = E1	Total emissions produced = E2
Total protein produced per annum (kg)	Egg protein produced = $P1_e$ Meat protein produced = $P1_m$	Meat protein produced = $P2_m$
Ei of eggs Ei of meat	$= E1/(P1_e+P1_m)$ $= (E1*P1_m/(P1_e+P1_m) + E2)/(P1_m+P2_m)$	

Table 5. Total global production, emissions and Ei (from cradle to retail point). FPCM: fat and protein corrected milk CW: carcass weight

	Product	Production (Mt)	Emissions (Mt CO2e)	Ei (kgCO2e/ kg product)	Source
Dairy cattle: milk	FPCM	508.6	1419.1	2.8	Opio et al. 2013, p21
Dairy cattle: meat	CW	26.8	490.9	18.4	“”
Specialized beef cattle: meat	CW	34.6	2345.9	67.8	“”
Buffalo: milk	FPCM	115.2	389.9	3.4	Opio et al. 2013, p32
Buffalo: meat	CW	3.4	180.2	53.4	“”
Small ruminants: milk	FPCM	20.0	129.8	6.5	Opio et al. 2013, p37
Small ruminants: meat	CW	12.6	299.2	23.8	“”
Backyard pigs: meat	CW	22.9	127.5	5.6	MacLeod et al. 2013, p18
Intermediate pigs: meat	CW	20.5	133.9	6.5	“”
Industrial pigs: meat	CW	66.8	406.6	6.1	“”
Backyard chickens: eggs	EGGS	8.3	35.0	4.2	MacLeod et al. 2013, p46, Gerber et al. 2013, p38
Backyard chickens: meat	CW	2.7	17.5	6.6	“”
Layers: eggs	EGGS	49.7	182.1	3.7	“”
Layers: meat	CW	4.1	28.2	6.9	“”
Broilers: meat	CW	64.8	343.3	5.3	“”

Table 6. Comparison of GLEAM results with other studies

	GLEAM compared to other studies	**Number of studies in comparison**
Industrial pigs	~13% higher	14
Layers and broilers	20% (9%)[a] higher	14
Dairy cattle	30% higher	15
Beef cattle	~15% higher	6
Small ruminants	~10% lower	4
Buffalo	Not known	No comparable studies

[a.] 9% higher when Prudencio da Silva *et al*. 2010 is omitted

Figure captions

Figure 1 Regional average emission intensity of pig meat production from all three systems (regions with less than one per cent of total production are omitted) (LAC: Latin America and Caribbean, SSA: Sub-Saharan Africa, Manure MMS: emissions arising from manure management and storage). Source: MacLeod et al. 2013, p25.

Figure 2. Schematic representation of GLEAM v1.0

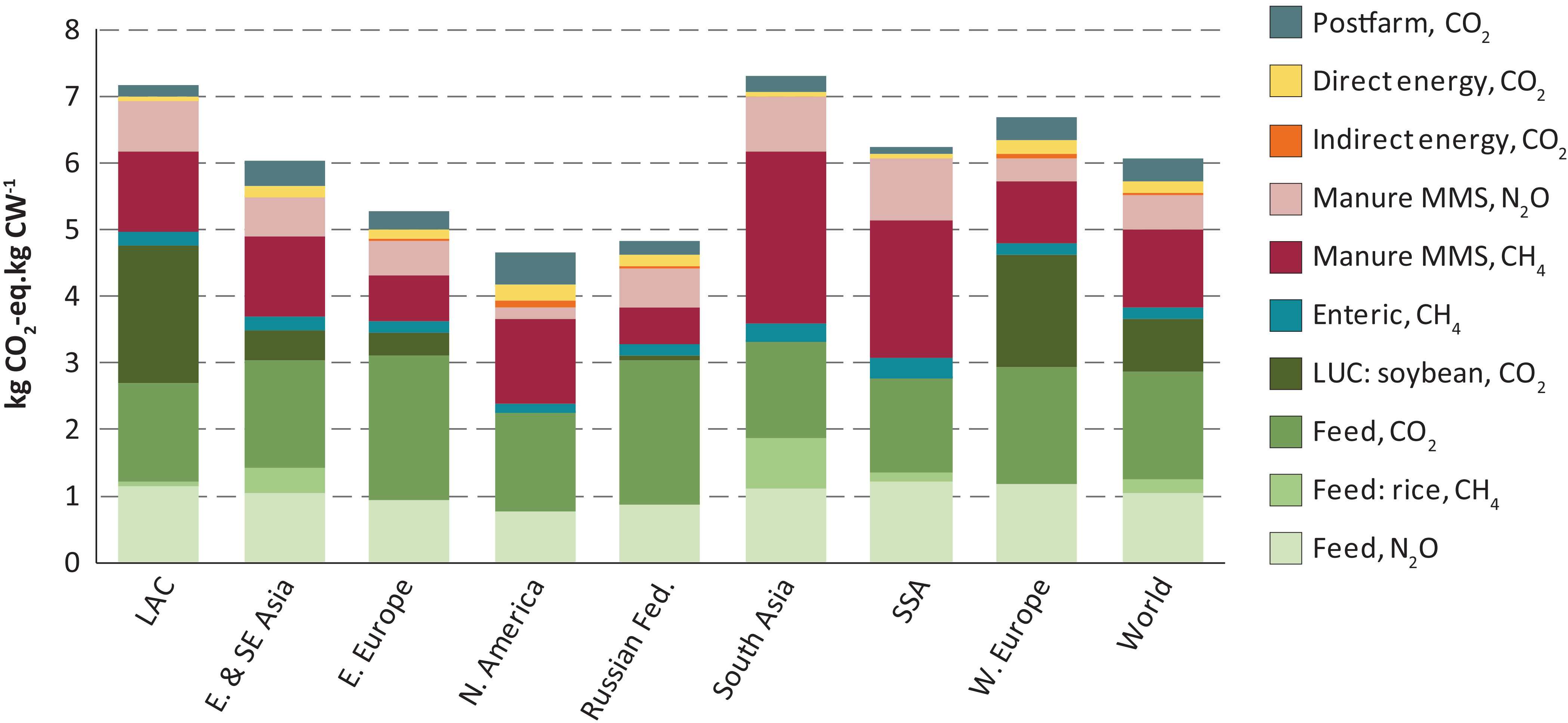
Figure 3. Schematic representation of the Herd Module. This example shows a cattle herd with 4 cohorts kept for breeding and production (in the box, i.e. AF, RF, AM, RM) and two kept for production only (MF and MM). AFin is the number of animals entering the cohort each year. AFexit is the number exiting via sale or voluntary culling while AFx is the number exiting via mortality or involuntary culling. CFin and CMin are the number of female and male calves available for replacement or meat production after neonatal mortality.

Figure 4. Schematic representation of the way in which ruminant rations are determined in the feed module.

Figure 5. Manure methane conversion factor (MCF) for industrial pigs in South Asia, East Asia and Southeast Asia. MCF is the percentage of Bo, the maximum methane producing capacity, that is achieved (see IPCC , 2006, p. 10.41)

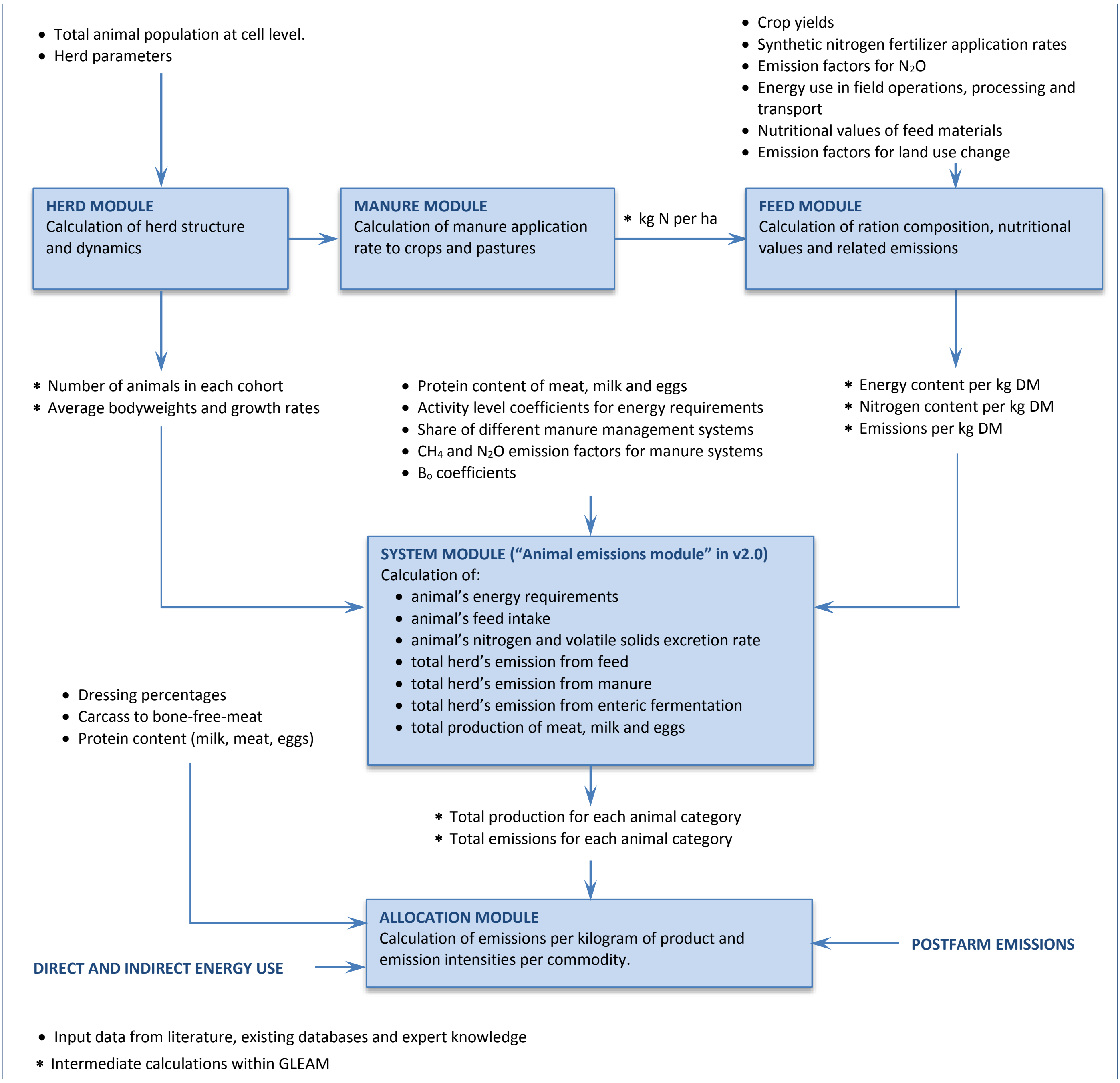
Figure 6. The herd dynamics, protein production and GHG emissions for two East African cattle systems: mixed (crop/livestock), and pastoral. The number of animals in each cohort is given in brackets, and the width of the arrows are proportional to the number of animals or the mass or protein/GHG emissions.

Figure1



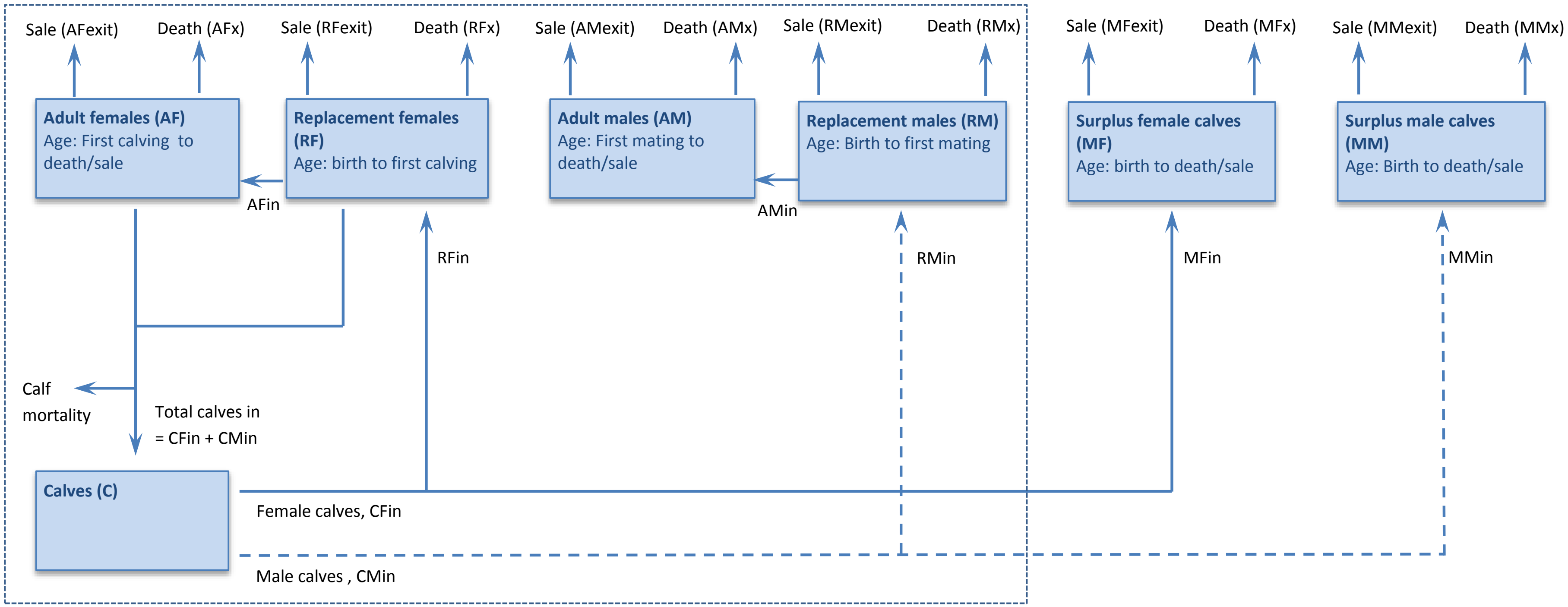
8
7
6
5
4
3
2
1
0
kg CO2-eq.kg CW-1
LAC
E. & SE Asia
E. Europe
N. America
Russian Fed.
South Asia
SSA
W. Europe
World
Postfarm, CO2
Direct energy, CO2
Indirect energy, CO2
Manure MMS, N2O
Manure MMS, CH4
Enteric, CH4
LUC: soybean, CO2
Feed, CO2
Feed: rice, CH4
Feed, N2O

Figure



Total animal population at cell level.
Herd parameters
Crop yields
Synthetic nitrogen fertilizer application rates
Emission factors for N_2O
Energy use in field operations, processing and transport
Nutritional values of feed materials
Emission factors for land use change
HERD MODULE
Calculation of herd structure and dynamics
MANURE MODULE
Calculation of manure application rate to crops and pastures
* kg N per ha
FEED MODULE
Calculation of ration composition, nutritional values and related emissions
* Number of animals in each cohort
* Average bodyweights and growth rates
Protein content of meat, milk and eggs
Activity level coefficients for energy requirements
Share of different manure management systems
CH_4 and N_2O emission factors for manure systems
B_o coefficients
* Energy content per kg DM
* Nitrogen content per kg DM
* Emissions per kg DM
SYSTEM MODULE ("Animal emissions module" in v2.0)
Calculation of:
animal's energy requirements
animal's feed intake
animal's nitrogen and volatile solids excretion rate
total herd's emission from feed
total herd's emission from manure
total herd's emission from enteric fermentation
total production of meat, milk and eggs
Dressing percentages
Carcass to bone-free-meat
Protein content (milk, meat, eggs)
* Total production for each animal category
* Total emissions for each animal category
ALLOCATION MODULE
Calculation of emissions per kilogram of product and emission intensities per commodity.
POSTFARM EMISSIONS
DIRECT AND INDIRECT ENERGY USE
Input data from literature, existing databases and expert knowledge
* Intermediate calculations within GLEAM

Figure3



Sale (AFexit)
Death (AFx)
Sale (RFexit)
Death (RFx)
Sale (AMexit)
Death (AMx)
Sale (RMexit)
Death (RMx)
Sale (MFexit)
Death (MFx)
Sale (MMexit)
Death (MMx)
Adult females (AF)
Age: First calving to death/sale
Replacement females (RF)
Age: birth to first calving
Adult males (AM)
Age: First mating to death/sale
Replacement males (RM)
Age: Birth to first mating
Surplus female calves (MF)
Age: birth to death/sale
Surplus male calves (MM)
Age: Birth to death/sale
AFin
AMin
RFin
RMin
MFin
MMin
Calf mortality
Total calves in = CFin + CMin
Calves (C)
Female calves, CFin
Male calves , CMin

Figure

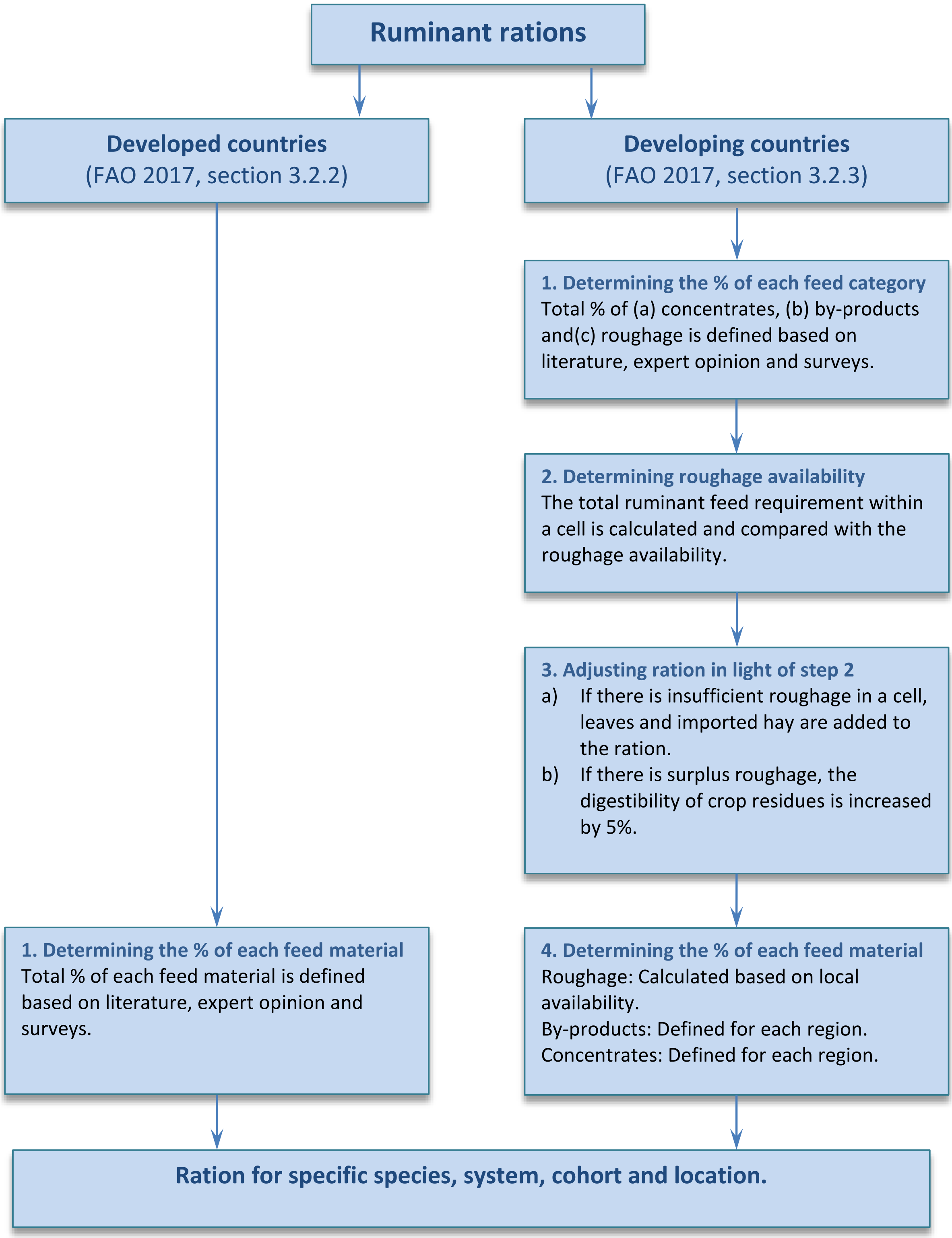
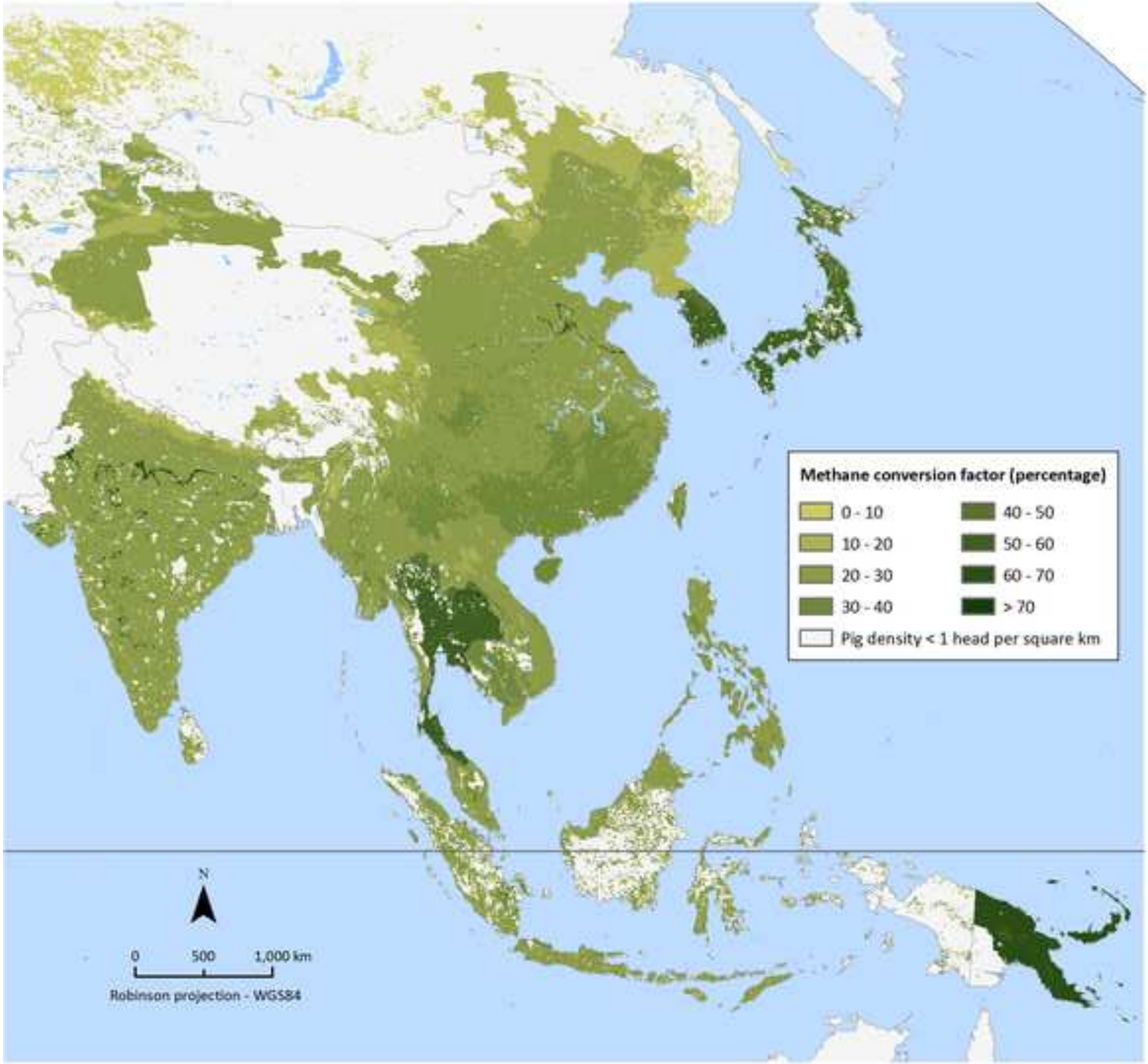
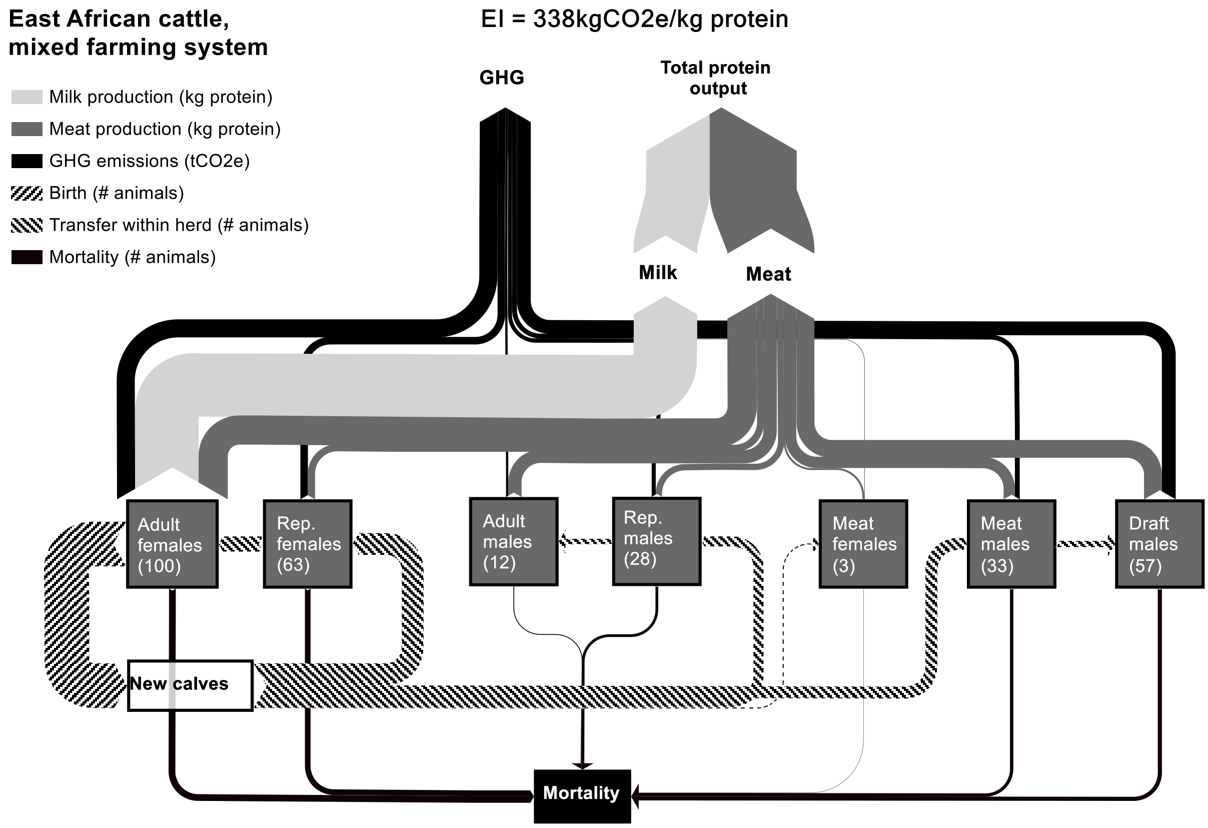
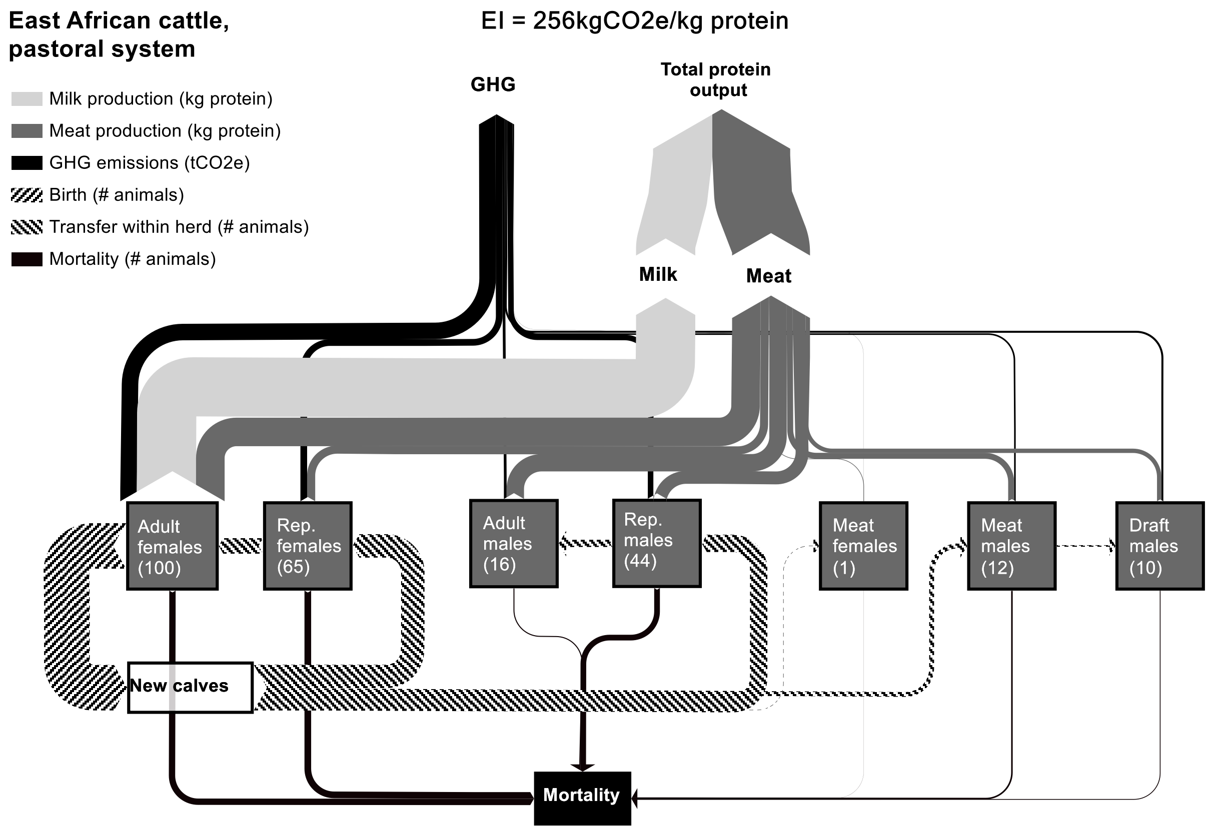

Ruminant rations
Developed countries
(FAO 2017, section 3.2.2)
Developing countries
(FAO 2017, section 3.2.3)
1. Determining the % of each feed category
Total % of (a) concentrates, (b) by-products and(c) roughage is defined based on literature, expert opinion and surveys.
2. Determining roughage availability
The total ruminant feed requirement within a cell is calculated and compared with the roughage availability.
3. Adjusting ration in light of step 2
a) If there is insufficient roughage in a cell, leaves and imported hay are added to the ration.
b) If there is surplus roughage, the digestibility of crop residues is increased by 5%.
1. Determining the % of each feed material
Total % of each feed material is defined based on literature, expert opinion and surveys.
4. Determining the % of each feed material
Roughage: Calculated based on local availability.
By-products: Defined for each region.
Concentrates: Defined for each region.
Ration for specific species, system, cohort and location.

Figure5


Methane conversion factor (percentage)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
> 70
Pig density < 1 head per square km
N
0
500
1,000 km
Robinson projection - WGS84

Figure


East African cattle,
mixed farming system
EI = 338kgCO2e/kg protein
Milk production (kg protein)
Meat production (kg protein)
GHG emissions (tCO2e)
Birth (# animals)
Transfer within herd (# animals)
Mortality (# animals)
GHG
Total protein output
Milk
Meat
Adult females (100)
Rep. females (63)
Adult males (12)
Rep. males (28)
Meat females (3)
Meat males (33)
Draft males (57)
New calves
Mortality


East African cattle,
pastoral system
EI = 256kgCO2e/kg protein
Milk production (kg protein)
Meat production (kg protein)
GHG emissions (tCO2e)
Birth (# animals)
Transfer within herd (# animals)
Mortality (# animals)
GHG
Total protein output
Milk
Meat
Adult females (100)
Rep. females (65)
Adult males (16)
Rep. males (44)
Meat females (1)
Meat males (12)
Draft males (10)
New calves
Mortality

Dear Sir/Madam,

RE: Submission of the revised version of "Invited review: a position on The Global Livestock Environmental Assessment Model (GLEAM)"

We have revised the paper quite substantially in light of the referees' comments. The changes made in response to each comment are set out in the tables below. There are a small number of comments that we haven't revised the paper in response to; for each of these we have provided a response explaining why.

We look forward to hearing from you.

Best wishes

Michael

Changes made in light of Editor's comments

	Page numbers cited in this column refer to the revised May 2017 version
Editor	**Changes made**
I agree with the recommendation of omitting the inclusion of the whole Description of the model, which is already available online and, which will be updated as the model gets modified.	References to SI replaced with references to most recent GLEAM model description (May 2017). Inserted L139: "GLEAM is undergoing continuous development, so any review can only provide a snapshot of the model at a given time. This review focuses on GLEAM V1.0, while highlighting some revisions introduced in version 2.0, and referring to the most up to date model description (FAO 2017)."
Points raised in relation with the example used to illustrate the model´s capability using UK sheep systems is a strong point for example raised by reviewer 1.	Done - Figure 6 now shows output and GHG emissions, along with the herd dynamics, for 2 East African cattle systems. 2 new para's inserted, see L594. Text notes that Ei is also influenced by factors other than herd dynamics.

Changes made in light of Reviewer 1's comments

<table>
<tr><td>Page numbers cited in the reviewers comments refer to the version submitted in January 2017</td><td>Page numbers cited in this column refer to the revised May 2017 version</td><td></td></tr>
<tr><td>Reviewer 1</td><td>Changes made</td><td>Response to ref</td></tr>
<tr><td>1. It would be useful if the authors identified the target users. This is done on the GLEAM website but not in the paper.</td><td>Inserted L60: "e.g. governments, project planners, producers, industry and civil society organizations"</td><td></td></tr>
<tr><td>2. The authors should make it clear that the GLEAM-i model is a single region ('cell') version of GLEAM, not the multicell version.</td><td>Inserted L707 "enabling users to calculate the Ei for a specified region (i.e. a single cell)"</td><td></td></tr>
<tr><td>3. There is no information concerning the operating system(s) under which GLEAM will operate.</td><td></td><td rowspan="4">It seems that there is some confusion about GLEAM and GLEAM-i nature. GLEAM is not a software developed in python (nor is GLEAM-i in visual basic), it's series of data and calculations implemented with ArcGIS (or excel for GLEAM-i, which doesn't use spatial data), Python is used only to automate the calculations implemented with ArcGIS. The reason why python was used for this is that it is integrated in ArcGIS and can be used to run the necessary tools from ArcGIS. ArcGIS was used because it's one of the most powerful and supported software for spatial analysis available, but it's not open source. What is important about GLEAM however are the input data and parameters and the equations described in the model description (FAO 2017). To implement GLEAM with another GIS software (e.g. an open source) one should just use the equations in FAO (2017) with the chosen program. The operative system(s) under which GLEAM operates are those required by ArcGIS (or the chosen GIS software, in case a different one is used).</td></tr>
<tr><td>4. It is not clear to me whether GLEAM includes a bespoke GIS or interacts with one or more of the commercial or open source GIS.</td><td></td></tr>
<tr><td>5. Is GLEAM open source? If so, where can the source code be accessed?</td><td></td></tr>
<tr><td>6. Why did the authors choose Python as a programming language? Given that there is a need here to process every cell globally in which there are livestock, it seems odd to choose a language that is interpreted at runtime rather than one that is compiled before running. This is particularly true if the authors have an ambition to add more complex treatment of biophysical processes in the future. I realise that an advantage of Python is that it can be implemented on a wide range of computing platforms and that there are implementations that allow Python to be dynamically compiled and enable concurrent processing (e.g. http://pypy.org/) but it still seems an odd choice to me.</td><td></td></tr>
</table>

7. The details given in the Supplementary Information are almost identical to those given on the GLEAM website. I think that provided the latter will be maintained (i.e. accessible in the longer term), it would be better just to provide a link to this. It would have the additional advantage that users would be aware of new developments.	References to SI replaced with references to most recent GLEAM model description (May 2017). Inserted L139: "GLEAM is undergoing continuous development, so any review can only provide a snapshot of the model at a given time. This review focuses on GLEAM V1.0, while highlighting some revisions introduced in version 2.0, and referring to the most up to date model description (FAO 2017)."	
8. How are the different versions of the model managed? For example, is version control software used?		See answer to comments 3, 4, 5 and 6.
9. How do the authors ensure consistency between the GLEAM software (coded in Python) and the relevant parts of the GLEAM-i software (which appears to be coded in Visual Basic)?		
10. If this model will be used to inform policy, it is important that there is good quality control of the product. This is particularly so, if it is to be applied to developing countries, since the consequences of errors could be life-threatening rather than just economically unfortunate. Could the authors indicate the measures they have taken? Two simple measures would be to check whether a. the birth rate for each livestock category in each cell equates to the sum of the rates of mortality + sale/culling, and b. the total input of N to the manure management system via excretion equates to the sum of the gaseous emission of N + the N applied to the soil.	Inserted L660. "Improving data is particularly important when GLEAM is used to inform policy decisions in developing countries, where data quality can be poor and agriculture central to much of the population's livelihoods. Various projects have been carried out with GLEAM in developing countries, using the same approach and formulations, but adjusting it to the specific local requirements (see http://www.fao.org/gleam/in-practice/en/). In each project, the input data were revised and verified."	
11. In the text, 'cell' is used to identify a geographic location whereas in some of the diagrams, there is reference to 'pixel'. Judging from the context, they appear to refer to the same thing, so should be called the same thing.	Done	
12. Using lowland/hill sheep in the UK as the example of herd dynamics seems curious to me, if the main beneficiaries of the model will be developing countries. Choosing an alternative example is not something upon which I would insist but I feel obliged to bring it to the authors' attention.	Done - Figure 6 now shows output and GHG emissions, along with the herd dynamics, for 2 East African cattle systems. 2 new para's inserted, see L594. Text notes that Ei is also influenced by factors other than herd dynamics.	

Line no	Comment		
230	There needs to be an explanation why Tier 1 N excretion rates are used in the Manure module and Tier 2 in the System module. I have a suspicion that it is to avoid having to deal with feedback between the manure N – feed quantity and quality – feed intake – N excretion. If so, it is understandable but does mean that there is an inconsistency between excretion values in the two modules.	Inserted, L255: "The Tier 1 N excretion rates were used in the Manure Module in order to simplify the modelling procedure (using the Tier 2 approach requires the model to be run for all the species simultaneously). In GLEAM v2.0 the Manure Module uses Tier 2 N excretion rates."	Yes, this is correct, we've added a para which hopefully clarifies why a different approach is used to quantify the total N/ha within a cell.
353	I do not understand what the authors did here. Table 10.12 of IPCC (2006) indicates that Tier 1 should use a Ym of 6.5% for all classes of cattle. Table 10.13 has values for sheep (and I could understand why the authors might want to linearly interpret between lambs and mature sheep).		These formulae are designed to provide Ym values that reflect the way that Ym varies with ration digestibility. The values generated by these formulae fall within range in Table 10.12, which has Ym of 3% +/- 1% for feedlot cattle and 6.5%+/-1% for other cattle, i.e. a Ym range of 2% to 7.5%. Using the formula Ym = 9.75-0.05*digestibility gives a range of Ym of 5.25% (when DE=90%) to 7.25% (DE=50%). It's a simplification, but hopefully a modest improvement on using the default 6.5% for all cattle.

460	Up until here, the text has described the structure and function of the model. From this line onwards, there is a comparison of model results with other studies. Nowhere can I see the details of the model inputs used e.g. which databases where used to obtain livestock number, crop shares, and for which year.	Inserted L192: "Livestock population sizes are based on FAOSTAT data and their geographic distribution is based on the Gridded Livestock of the World (GLW) model. Density maps from GLW are based on observed densities and explanatory variables such as climatic data, land cover and demographic parameters (Robinson et al., 2014).Data on fresh matter yields per hectare of main crops and their respective land area were taken from a modified version of Global Agro-Ecological Zones (GAEZ 3.0) and Haberl et al. (2007) to estimate the above-ground net primary productivity for pasture. Further detail on the derivation of input values is provided in: Opio et al. 2013; MacLeod et al 2013; and FAO (2017)"	
477	results from other studies…?	corrected	
491+	As the authors correctly point out, the assumptions concerning the source of soy feed have a great effect on the estimates of pre-chain GHG emissions, and this makes comparison between LCA studies difficult. The reader would be more able to form a judgement about the results from the current model if the emission intensities were partitioned into pre-chain, farm and post-chain fractions. This should also be possible for at least some of the existing studies. This would permit a more qualified comparison between studies for at least some of the livestock products in some regions. It would also allow the model estimates of farm emissions from different livestock categories for selected countries to be compared to the values reported by the countries themselves, under UNFCCC. In addition to providing an informative comparison for the reader, it would allow this paper to be more clearly differentiated from the Opio report, from	Inserted L510: "In order to enable a like-for-like comparison, the GLEAM results were adjusted (as far as possible) to have the same scope (i.e. the same system boundary and emissions categories) as the comparator study," L521: "An exact match between the study scope and GLEAM scope was not always possible, particularly where the fully disaggregated emissions were not reported"	It wasn't well explained in the paper, but the comparison of GLEAM results with other studies (undertaken in Opio et al (2013) and MacLeod et al (2013) and summarised in this paper) does try to perform a like-for-like comparison along the lines you suggest, i.e. the GLEAM results were adjusted to match the other studies' scope. An exact match isn't always possible, as studies sometimes disaggregate the emissions in different ways, some don't explain their emission categories properly and some don't bother to disaggragate at all... Hopefully the edits help to clarify.

	which much of the methodological text appears to have been derived.		
502	The authors write Results for some species/systems (such as industrial pigs in East Asia, see figure 5) can be sensitive to the assumptions made about how the manure is managed. but figure 5 just shows a map, not how model results are sensitive to assumptions.	Text clarified.	

732	The last part of the title should read 'Fluxes, emission factors and mitigation' and not 'Quantification and mitigation'	corrected	
776	Remove brackets from year	done	
781	The bibliographic details are incorrect.	corrected	
854	The Petri and Opio references should be swapped (wrong alphabetic order)	done	
870	Publication year is 2010a but no other reference from this author and year is listed. Reference is also incomplete.	corrected	
873	No publisher given	corrected	
934	Check formatting of title	Date of retrieval added.	
Fig 2	Protein content appears to be input twice (to System and Allocation modules). Is that correct? Where does the emission associated with land use change fit in?	LUC added to fig 2.	Yes, protein content is used in both modules.
Table 2	Why use ammonium nitrate as the default N fertiliser? According to the International Fertiliser Association's statistics, ammonium nitrate accounted for 6% of global N fertiliser consumption whereas urea accounted for 58%.	Inserted in Table 2: "In V2.0 the scope is expanded to include emissions from the manufacture of a range of synthetic N, P and K fertilizers, and pesticides (FAO 2017, 6.1.1)."	This is a mistake, and you are right to point it out. It means v1.0 overestimates energy use in fertiliser manufacture a bit. This was improved in v2.0
Table 4	Where are the variables defined?	Table revised	
Supplementary information (if retained)			
11	If the functional unit is a kg of protein, how is this converted into unit of product (see Table ?)	No changes made - SI not retained.	
42	Typographic error (d missing from land use in Table 1.2)	No changes made - SI not retained.	
Table 3.2	It would be interesting to know how Table 3.2 differs from Table 10A-4 in IPCC (2006)	No changes made - SI not retained.	

Changes made in light of Reviewer 2's comments

Page numbers cited in the reviewers comments refer to the version submitted in January 2018	*Page numbers cited in this column refer to the revised May 2017 version*
Reviewer 2	**Changes made**
Please include in the abstract some sentence saying "the aim of this paper is…" or something similar, as it is now is confusing for the reader.	Added to abstract: "The purpose of this paper is to provide a review of GLEAM. Specifically, it explains the model architecture, methods and functionality, i.e. the types of analysis that the model can perform."
The authors also provide an extensive, useful and well organized supplement section.	References to SI replaced with references to most recent (May 2017) GLEAM model description. Inserted L139: "GLEAM is undergoing continuous development, so any review can only provide a snapshot of the model at a given time. This review focuses on GLEAM V1.0, while highlighting some revisions introduced in version 2.0, and referring to the most up to date model description (FAO 2017)."
L559-572 The explanation of the utility of GLEAM by using the comparison of 2 type of sheep systems is very enlightening, however in my opinion does not show all the potentialities of GLEAM that are described in the paper. I can imagine that the 2 different diets of the 2 systems will have different GHG associated emissions of feed production that might affect the final Ei. This contribution could even go in opposite direction of the influence of the herd structure described here. Could you please provide the complete comparison?	Done - Figure 6 now shows output and GHG emissions, along with the herd dynamics, for 2 East African cattle systems. 2 new para's inserted, see L594. Text notes that Ei is also influenced by factors other than herd dynamics.
L151 You mention here "excretion rates" as an input that is parametrized per system separately (e.g. backyard, intermediate and intensive pigs), however in line 225 it is mentioned that you use general tier 1 excretion factors that are not split into that categories. Could you explain this better?	Inserted, L255: "The Tier 1 N excretion rates were used in the Manure Module in order to simplify the modelling procedure (using the Tier 2 approach requires the model to be run for all the species simultaneously). In GLEAM v2.0 the Manure Module uses Tier 2 N excretion rates."
L225-238 I understand that such a complex model requires different approaches in different parts. Only to be sure that I understood well: GLEAM is using constant excretion factors (tier 1) for estimating the total N excreted by the animals and tier 2 approaches for N2O emissions from manure including difference between intake and retention calculations, isn´t it?	Yes, this is correct, we've added a para which hopefully clarifies why a different approach is used to quantify the total N/ha within a cell.

L 226 (b) You mention here that once the amount of N excreta is estimated the second step is to calculate losses in management, however in table 1 is indicated that direct deposition on grasslands by grazing animals is previously calculated. If this previous step was performed, please indicate it here.	Inserted, L244: "(N deposited directly on pasture by grazing animals is not included in this total, instead the N2O emissions arising from this are calculated separately in the Feed Module); "
L493 Even if highly uncertain, since LUC is affecting significantly the final outcomes, a short description of the approach that was followed should be included in the main text.	Inserted L322: "GLEAM v 1.0 quantifies the emissions arising from land-use change (LUC)-induced changes in three carbon pools: (a) biomass (above and below ground), (b) dead organic matter and (c) soil organic carbon. It focuses on the expansion of the areas of land used for soybean cultivation and for grazing cattle in Latin America, which have been two of the most import LUC processes since 1990. GLEAM v2.0 extends the scope to include the expansion of palm oil plantations in Southeast Asia. Emissions are generally quantified according to IPCC Tier I guidelines (IPCC, 2006) and PAS2050 tool (BSI, 2008), combined with land use and trade data from FAOSTAT. Details of the approach used are provided in FAO (2017), section 6.1.5-6.1.6."

SUPL L 11 It is mentioned "The functional units used to report GHG emissions are expressed as a kg of carbon dioxide equivalents (CO2-eq) per kg of protein." However in Fig 1 is reported as kg -CO2-eq-kg CW	No changes made - SI not retained.
	No changes made - SI not retained.
	No changes made - SI not retained.
SUPL Is the title of Table 1 wrong?	No changes made - SI not retained.
L70 I also recommend the citation of Leip et al 2015 (Env. Res. Letters) that includes the detailed assessment of many impacts.	Cited
L81 I also recommend the citation of Lamb et al 2016 Nature CC	Cited
L 206. I imagine that the GIS data on animals proceeds from Robinson et al 2014 PLOS-ONE or Franceschini et al 2009. Citation is required in the main text.	Robinson et al 2014 cited, L196
L262 "oils" a comma or something is missing	comma added
L 263 Does the category "swill" include food industry wastes? If so, please indicate it.	clarified, L287
L 303 Please indicate here that you followed the economic allocation approach	done
L 431 edible-"output"	clarified

L452 If I understood well, only manure used of fuel is considered as an output and other manure emissions are allocated to products or crops, in this sentence the inclusion of "manure" is confusing.	clarified, L484
L453 Skins are not fibre?	clarified
L 500 Please replace "N to N2O" by "N inputs to N2O"	done
L 579 Please provide the current citation for the IMAGE model: Stehfest, E., van Vuuren, D.P., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, P., van Minnen, J., Muller, C., Prins, A., 2014. IMAGE by IMAGE 3.0. Netherlands Environmental Assessment Agency.	done
L633 The recent contribution by Kim et al 2016 (Biogeosciences) has updated the African research on N2O	Kim et al 2016 cited.
REFERENCES SECTION: Please reference FAO reports in the same way. E.g Macleod et al 2013 is referenced different than Gerber et al 2010	done