Food and Agriculture Organization of the United Nations

GLOBAL LIVESTOCK ENVIRONMENTAL ASSESSMENT MODEL

Version 3.0

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Model description

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The Global Livestock Environmental Assessment Model (GLEAM) is being developed in FAO since 2009, in collaboration with partners from other organizations.

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ABBREVIATIONS

CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
DM	Dry Matter
EE	Eastern Europe
EFA	Economic Fraction Allocation
ESEA	East Asia and South-East Asia
FUE	Feed Use Efficiency
GAEZ	Global Agro-Ecological Zones
GHG	Greenhouse gas
GIS	Geographic Information System
GLEAM	Global Livestock Environmental Assessment Model
GLW	Gridded Livestock of the World
IPCC	Intergovernmental Panel on Climate Change
LAC	Latin America and the Caribbean
LCA	Life-Cycle Assessment
LUC	Land-use change
MFA	Mass Fraction Allocation
MMS	Manure management system
N_2O	Nitrous oxide
NA	North America
NENA	Near East and North Africa
OCE	Oceania
OECD	Organization for Economic Cooperation and Development
RUS	Russian Federation
SA	South Asia
SSA	Sub-Saharan Africa
VS	Volatile solids
WE	Western Europe

1 CHAPTER 1 - INTRODUCTION

The Global Livestock Environmental Assessment Model (GLEAM) was developed to address the need for a comprehensive tool to assess interactions between livestock and the environment. GLEAM supports stakeholders in their efforts towards adopting more sustainable practices that ensure higher efficiency, improved livelihoods for farmers and mitigation of environmental impacts.

The present document describes the latest version of the model, GLEAM 3.0. It includes several improvements, updates and methodological changes compared to the previous version GLEAM 2.0. The most important updates and methodological changes include:

- New animal distribution maps: GLEAM 3.0 uses a customized version from Version 4 of the Gridded Livestock of the World (Gilbert et al., 2018), which is adjusted to 2015 animal numbers from FAOSTAT. GLW4 dataset available at https://www.fao.org/livestock-systems/global-distributions/en/.
- New crop layers: GLEAM 3.0 incorporates GAEZ 2015+ Data set (Frolking et al., 2020) for crops used as feed, this new release uses national-scale data on the fractional change in crop harvested area and production from 2010 to 2015, based on statistics for 160 crops from FAOSTAT and at a spatial resolution of approximately 10 km × 10 km at the equator.
- Update of the methods to calculate emissions to the latest 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
- Nitrogen modelling along the livestock supply chain based on material flows analysis and mass principle and closing of the nitrogene balance; total nitrogen inputs are equivalent to total nitrogen outputs (products, losses and stock change), taking into account loops and recycling of nitrogen (crop residues; manure application to cropland or grassland).
- Updated methodology to calculate the emissions associated with land-use change related to soy, palm and pasture.
- New methodology to represent animals in feedlots.
- Adjustment of emissions, inputs and parameters for the production of internationally traded feed items using updated bilateratial trade data for commodities.
- Updated distances and emissions for the international sea transport of traded feed items.
- New method to calculate postfarm emissions for domestic and international transport as well as primary processing

1.1 – MODEL OVERVIEW

GLEAM is a process-based model based on a Life Cycle Assessment (LCA) framework that simulates greenhouse gase emissions along livestock systems and allocates those to different commodities. It covers 11 main livestock commodities at global scale, namely meat and milk from cattle, sheep, goats and buffalo; meat from pigs; and meat and eggs from chickens. The calculations are generally performed for individual animal cohorts (TIER2). GLEAM runs in a Geographic Information System (GIS) environment and provides spatially expclicit estimates on greenhouse gas (GHG) emissions and commodity production by production system, thereby enabling the calculation of the emission intensity for any combination of commodity and farming systems at different spatial scales. The highest spatial resolution considered by the model is defined by squared cells of approximately 10 km × 10 km at the equator. The calculations in GLEAM are done for each of those pixels, all of wich have values (such as crop yields or animal numbers) associated with them.

GLEAM is built on six modules, each of which with a specific function that uses outputs from other modules in a specific sequence: the herd module, the feed ration and intake module, the animal emissions module, the manure module, the feed emissions module and the allocation module. The overall structure and the calculation sequence are shown in Figure 1.1. Each module is explained in detail in its corresponding chapter.

1.2 – GLEAM AND THE LCA FRAMEWORK

The LCA framework is defined in ISO standards 14040 and 14044 (ISO, 2006a, 2006b). It is a method widely accepted in agriculture and other industries to evaluate the environmental impact of products. It is also used to estimate the resource use and identify hotspots of environmental impact within a product's life cycle. The main strength of LCA lies in its ability to provide a holistic assessment of production processes in terms of resource use, pressures, and environmental impacts (ISO, 2006a, 2006b). The LCA approach also provides a framework to broadly identify effective approaches to reduce environmental burdens and is recognized for its capacity to evaluate the effect of a change within a production process on the overall life-cycle balance of environmental burdens. This approach enables the identification and exclusion of measures that simply shift environmental problems from one phase of the life cycle to another.

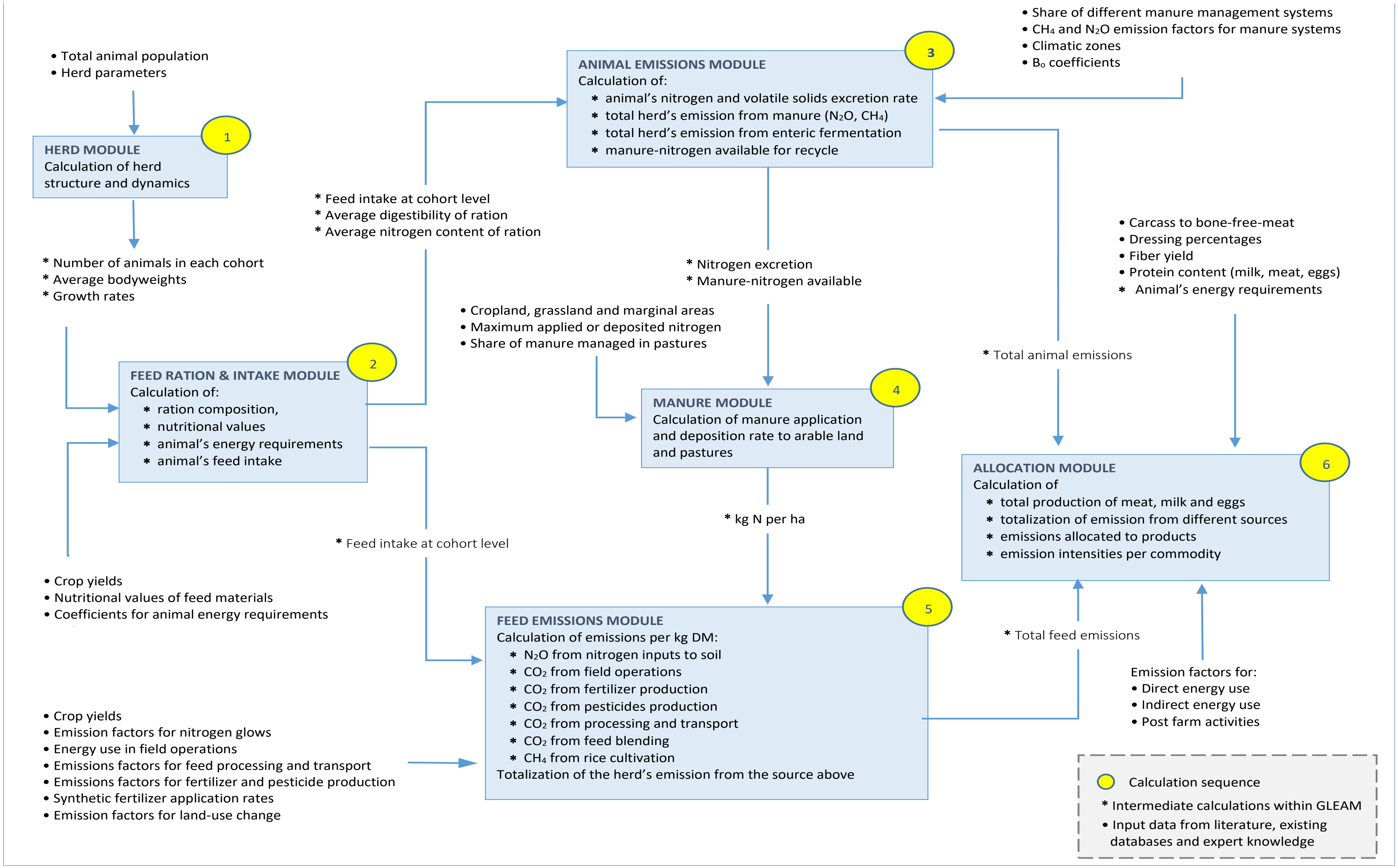
1.2.1 – Functional unit

The functional units used to report GHG emissions in GLEAM are expressed as "kg of carbon dioxide equivalents (CO_2-eq) per kg of protein in animal product". This choice allows the comparison between different livestock products. For the conversion of non- CO_2 gases, GLEAM uses the global warming potential over a 100-year period (GWP-100; Table 1.1) published in the 6th IPCC Assessment Report (Forster et al., 2021).

Table 1.1 GWP-100 values reported in the 6th IPCC Assessment Report

<table>
<tr><th rowspan="2">Greenhouse gas</th><th colspan="5">100 Year Time Period</th></tr>
<tr><th>SAR 1995</th><th>AR4 2007</th><th>AR5 2014</th><th>AR5 cc fb 2014</th><th>AR6 2021</th></tr>
<tr><td>CO_2</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>CH_4 fossil origin</td><td rowspan="2">21</td><td rowspan="2">25</td><td rowspan="2">28</td><td rowspan="2">34</td><td>29.8</td></tr>
<tr><td>CH_4 non fossil origin</td><td>27.0</td></tr>
<tr><td>N_2O</td><td>310</td><td>298</td><td>265</td><td>298</td><td>273</td></tr>
</table>

Figure 1.1 Overview of GLEAM structure

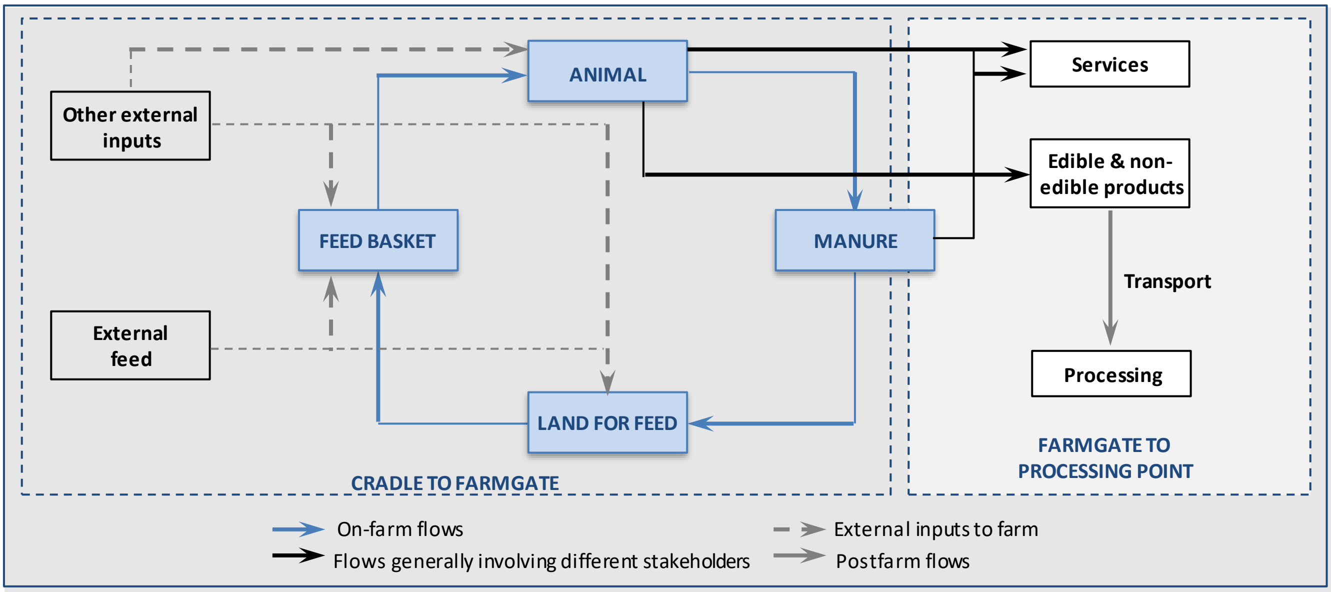


1.2.2 – System boundary

GLEAM covers the entire livestock production chain, from feed production to the processing point (Figure 1.2). The system boundary is defined from "Cradle-to-processing point". All emissions occurring at the final consumption are outside the defined system boundary and are thus excluded from this assessment. Livestock supply chains are complex, with a number of interacting unit processes that include crop and pasture production, manure management systems, feed processing and transport, animal breeding and management, and others. The LCA approach models the flow of all products through processes on-farm but also off-farm such as feed imports and exports of animal products or live animals. The model also covers other external inputs such as energy, fertilizers, pesticides and machinery use.

All of these do not only represent different activities in the supply chains, but also define the inter-linkages among production processes such as the link between animal performance, animal feed requirements (energy and protein requirements) and production of outputs such as manure, edible and non-edible products, services and emissions

Figure 1.2 System boundary used in GLEAM



1.3 – SOURCES OF EMISSIONS

GLEAM estimates emissions of the three major GHGs associated with livestock supply chains, namely methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). Table 1.2 shows the emission sources that are included in GLEAM.

Table 1.2 Emission sources covered in GLEAM

Source of emissions		Description
Feed CO_2	field operations	CO_2 emissions arising from the use of fossil fuels during field operations
	fertilizer production	CO_2 emissions from the manufacture and transport of synthetic nitrogenous, phosphate and potash fertilizers
	pesticide production	CO_2 emissions from the manufacture, transport and application of pesticides
	processing and transport	CO_2 generated during the processing of crops for feed and the transport by land and/or sea
	blending and pelleting	CO_2 arising from the blending of concentrate feed
Feed land-use change CO_2	soybean cultivation	CO_2 emission due to LUC associated with the expansion of soybean
	palm kernel cake	CO_2 emission due to LUC associated with the expansion of palm oil plantations
	pasture expansion	CO_2 emission due to LUC associated with the expansion of pastures
Feed N_2O		Direct and indirect N_2O emissions from manure deposited on the fields and used as organic fertilizer and from applied synthetic nitrogenous fertilizer and crop residues decomposition
Feed CH_4	Rice production	CH_4 emissions arising from the cultivation of rice used as feed
Enteric fermentation CH_4		CH_4 emissions caused by enteric fermentation
Manure management CH_4		CH_4 emissions arising from manure storage and management
Manure management N_2O		N_2O emissions arising from manure storage and management
Direct energy use CO_2		CO_2 emissions arising from energy use on-farm for ventilation, heating, etc.
Embedded energy use CO_2		CO_2 emissions arising from energy use during the construction of farm buildings and equipment
Postfarm CO_2		CO_2 emissions from the processing and transport of livestock products

1.4 – DATA RESOLUTION

Data availability, quality vary greatly for differnet regions and depending on the parameters. Basic input data such as animal numbers, herd parameters, mineral fertilizer application rates, temperature, are typically taken from the literature and specific surveys. Intermediate calculations generate outputs and are used in subsequent calculations in GLEAM. They include data on growth rates, animal cohort (or groups), feed rations, animal energy requirements, and others. In some cases, these data sets are available at high level of details for small administrative units, in other cases only at regional level. The spatial resolution of the main input variables in GLEAM is summarized in Table 1.3.

Table 1.3 Spatial resolution of the main GLEAM input variables

Parameters	Cell[1]	Sub-national	National	Regional[2]	Global
Herd					
Animal numbers	X				
Live weights		X	X	X	
Mortality, fertility and replacement data		X	X	X	
Manure					
Nitrogen losses rates				X	X
Management system data		X	X	X	
Leaching rates				X	
Feed					
Crop yields	X				
Harvested area	X				
N, P and K fertilizer application rate			X		
Pesticides application rate			X		
Mechanization level			X		
Nitrogen crop residues	X				
Feed ration	X		X	X	
Digestibility and energy content of feedstuffs			X	X	X
Nitrogen content of feedstuffs				X	X
Energy in field operations and transport					X
Transport distances			X		X
Land-use change					
Soybean		X	X		
Palm kernel cake			X		
Pasture			X		
Animal productivity					
Yield (milk, eggs, fibers)			X	X	
Dressing percentage			X	X	
Fat and protein content			X	X	X
Postfarm					
Transport distances of animals or products			X		
Emission factors					X
Annual average temperature	X				
Climatic zones	X				
Direct and indirect energy		X	X	X	

The spatial resolution varies geographically and depends on the data availability. For each input, the spatial resolution of a given area is defined at the finest level possible.

[1] Approximately 10 km × 10 km at the equator.

[2] Geographic regions or climatic zones, or groups of countries

1.5 – LIVESTOCK DISTRIBUTION AND PRODUCTION SYSTEMS

1.5.1 – Animal populations and spatial distribution

National inventory for all major livestock species (cattle, buffaloes, sheep, goats, pigs and chickens) are aligned with FAOSTAT data for 2015. The geographic distribution is based on the Gridded Livestock of the World (GLW) model Version 4 (modified from Gilbert et al., 2018). Density maps from GLW are built on observed densities and explanatory variables such as climatic data, land cover and demographic parameters.

1.5.2 – Livestock production systems

GLEAM distinguishes between three production systems for cattle (grassland based, mixed farming systems and feedlots), two for buffaloes, sheep and goats (grassland based and mixed farming systems) (Table 1.4). For monogastric species, the model distinguishes three production systems for pigs (backyard, intermediate and industrial) and three for chickens (backyard, layers and broilers; the last two being industrial) (Table 1.5). Livestock production systems are further classified according to the agroecological zones as defined by Seré and Steinfeld (1996):

- **Temperate** includes temperate regions, where at least one or two months a year the temperature falls below 5°C; and tropical highlands, where the daily mean temperature in the growing season ranges from 5 °C to 20 °C.
- **Arid** includes arid and semi-arid tropics and subtropics, with a growing period of less than 75 days and 75–180 days, respectively.
- **Humid** includes humid tropics and sub-humid tropics where the length of the growing period ranges from 181–270 days or exceeds 271 days, respectively

Table 1.4 Characteristics of livestock production systems for ruminant species used in GLEAM

Production system	Characteristics
Ruminant species	
Grassland based (or grazing) systems	Livestock production systems found in areas dominated by pastures and rangelands with short growing period (<60 days) or very low human density (<20 people per km^2), in which more than 10% of the dry matter fed to animals is farm-produced and in which annual average stocking rates are less than 10 livestock units per hectare of agricultural land.
Mixed farming systems	Livestock production systems found in areas dominated by cropland or areas with growing period >60 days and human density >20 people per km^2, in which more than 10% of the dry matter fed to animals comes from crop by-products and/or stubble or more than 10% of the value of production comes from non-livestock farming activities.
Feedlots	Specialized, fully market-oriented operations where animals are fed with a specialized diet that is intended to stimulate weight gain. This period typically lasts for six to nine months, depending on the starting and targeted live weight (for some countries it lasts 3–4 months). Diets are generally composed of highly energetic and protein-rich feedstuffs, such as corn and cakes, respectively. Although it can vary among different operations, animals are kept in fully enclosed areas to facilitate the fattening process.

Source: authors based on Seré and Steinfeld (1996) and Robinson et al. (2011).

Table 1.5 Characteristics of livestock production systems for monogastric species used in GLEAM

Production system	Characteristics	Housing
Pigs		
Backyard	Mainly subsistence driven or for local markets; level of capital inputs reduced to the minimum; herd performance lower than commercial systems; feed contains maximum 20% of purchased non-local feed; high shares of swill, scavenging and locally-sourced feeds.	Partially enclosed: no concrete floor, or if any pavement is present, made with local material. Roof and support made of local materials (e.g. mud bricks, thatch or timber).
Intermediate	Fully market-oriented; medium capital input requirements; reduced level of overall herd performance (compared with industrial); locally-sourced feed materials constitute 30% to 50% of the ration.	Partially enclosed: no walls (or made of a local material if present), solid concrete floor, steel roof and support.
Industrial	Fully market-oriented; high capital input requirements (including infrastructure, buildings, equipment); high level of overall herd performance; purchased non-local feed in diet or on-farm intensively produced feed.	Fully enclosed: slatted concrete floor, steel roof and support, brick, concrete, steel or wood walls.
Chicken		
Backyard	Animals producing meat and eggs for the owner and local market, living freely. Diet consists of swill and scavenging (20% to 40%) while locally-produced feed constitutes the rest.	Simple housing using local wood, bamboo, clay, leaf material and handmade construction resources for supports plus scarp wire netting walls and scrap iron for roof.
Layers	Fully market-oriented; high capital input requirements; high level of overall flock productivity; purchased non-local feed or on-farm intensively produced feed.	Layers housed in a variety of cage, barn and free-range systems, with automatic feed and water provision.

Broilers	Fully market-oriented; high capital input requirements; high level of overall flock productivity; purchased non-local feed or on-farm intensively produced feed.	Broilers assumed to be primarily loosely housed on litter, with automatic feed and water provision.

Source: authors based on Seré and Steinfeld (1996) and Robinson et al. (2011).

1.5.2.1 – Ruminant systems

The distinction between grazing and mixed systems was updated following the methodology developed by Robinson et al. (2011), using the above-mentioned predictors: hybrid coverage agriculture (Fritz et al., 2012), Global length of growing period (Wint, 2018) and Climate Change Initiative (CCI) Land Cover (ESA, 2017).

The further classification of feedlot systems was based on the existence of such systems in the countries as reported in the literature and in national census. Input data were collected through literature reviews and expert opinion and, depending on the availability, at national or sub-national level. Sources of information include national statistics (USDA, 2012; EUROSTAT, 2010; MLA, 2011), literature research (Agribenchmark, 2013; Scholtz et al., 2008) and direct consultations with national experts.

The countries, for which data on feedlots system were collected, are 17: Argentina, Brazil, Uruguay, Mexico, United States of America, Canada, South Africa, Botswana, Namibia, Australia, Spain, Ireland, China, Indonesia, Philippines, Thailand, and Japan. The system is included in the beef sector, except for few countries, in particular Japan, Namibia, South Africa, and Botswana, for which part of the animals fattened come from the dairy sector.

1.5.2.2 – Pigs

The distinction of production systems for pigs was performed using the methodology described in Gilbert et al. (2015). The authors developed a model based on national reported data on the share of 'backyard' pigs and data on gross domestic product (GDP) per capita (in purchase power parity for 2015; PPP_{2010}). This model was then used to estimate the proportion of backyard pigs in countries where this proportion was unavailable. Finally, the estimated numbers of backyard animals were spatially distributed according to the distribution of the human rural population, with areas of high rural population corresponding to higher density of backyard pigs. The distinction between 'intermediate' and 'industrial' systems was done on the basis of reported data supplemented by expert opinion.

1.5.2.3 – Chickens

The same procedure based on Gilbert et al. (2015) was followed for chickens to distinguish between 'backyard' and 'industrial' systems. Animals in the industrial systems were further subdivided into layers and broilers, in three steps combining production data of meat and eggs from FAOSTAT and productivity figures from GLEAM (Box 1). Then, adjustments to the resulting fractions were done so that the proportions of meat and egg protein production in GLEAM correspond as close as possible to those reported by FAOSTAT.

BOX 1 – DISAGGREGATION OF INDUSTRIAL CHICKENS INTO LAYERS AND BROILER SYSTEMS

The procedure to disaggregate industrial systems (CHK_{IND}) into layers (CHK_{LYR}) and broilers (CHK_{BRL}) was done in three steps:

STEP 1. Average yields for eggs and meat were calculated for all chicken in each country, using the backyard and industrial yields calculated from GLEAM parameters and weighting the averages by the shares of backyard and i ndustrial animals from Gilbert et al. (2015).

$$\overline{EGG}yield = (CHK_{BCK} \times EGGyield_{BCK} + CHK_{IND} \times EGGyield_{LYR})$$
$$\overline{MEAT}yield = (CHK_{BCK} \times MEATyield_{BCK} + CHK_{IND} \times MEATyield_{BRL})$$

Where:

$\overline{EGG}yield$ = flock's weighted average egg yield, kg eggs × head^{-1}
$\overline{MEAT}yield$ = flock's weighted average meat yield, kg CW × head^{-1}
CHK_{BCK} = share of backyard systems taken from Gilbert *et al.*, fraction
CHK_{IND} = share of industrial systems taken from Gilbert *et al.*, fraction
$EGGyield_{BCK}$ = egg yield for backyard animals calculated from GLEAM parameters, kg eggs × head^{-1}
$EGGyield_{LYR}$ = egg yield for layer animals calculated from GLEAM parameters, kg eggs × hen^{-1}
$MEATyield_{BCK}$ = meat yield for backyard animals calculated from GLEAM parameters, kg CW × head^{-1}
$MEATyield_{BRL}$ = meat yield for broiler animals calculated from GLEAM parameters, kg CW × head^{-1}

STEP 2. The average yields were combined with production data from FAOSTAT to calculate the share of animals producing meat in the total flock.

$$MEAT_{share} = \frac{FAOSTAT_{meat}/\overline{MEAT}yield}{(FAOSTAT_{meat}/\overline{MEAT}yield) + (FAOSTAT_{eggs}/\overline{EGG}yield)}$$

Where:

$MEAT_{share}$ = share of animals producing meat in the flock, fraction
$FAOSTAT_{meat}$ = chicken meat production from FAOSTAT, kg CW
$\overline{MEAT}yield$ = flock's weighted average meat yield, kg CW × head^{-1}
$FAOSTAT_{eggs}$ = eggs production from FASOTAT, kg eggs
$\overline{EGG}yield$ = flock's weighted average egg yield, kg eggs × head^{-1}

STEP 3. The share of meat producing animals was applied to the industrial animals to estimate the number of "broilers", while the shar eof "layers" was calculated as the difference.

$$CHK_{BRL} = CHK_{IND} \times MEAT_{share} \quad CHK_{LYR} = CHK_{IND} - CHK_{BRL}$$

Where:

CHK_{BRL} = share of broiler animals in the flock, fraction
CHK_{IND} = share of industrial systems taken from Gilbert *et al.*, fraction
$MEAT_{share}$ = share of animals producing meat in the flock, fraction
CHK_{LYR} = share of layer animals in the flock, fraction

2 CHAPTER 2 – HERD MODULE

The first step towards the estimation of production and impacts of livestock supply chains is the characterization of animal populations, which is the function of the herd module.

In particular, the use of the IPCC (2019) Tier 2 methodology requires animal populations to be categorized into distinct cohorts based on animal type, weight, phase of production and feeding situation. This characterization supports the calculation of country-specific age structure, animal performance, feed intake and related emissions. Table 2.1 summarizes the cohorts used in GLEAM, their definition and the sections of the model description where they are calculated. For the schematic representation of the herd dynamics, see *Figure 2.1* to *Figure 2.3*.

Table 2.1 Summary of cohorts in GLEAM

Cohort	Description	Section
CATTLE		**2.1.2**
AF	Adult females, producing milk and calves	
RF	Replacement females, to replace culled and dead adult females	
AM	Adult males, used for reproduction and draught power	
RM	Replacement males, to replace culled and dead adult males	
MF	Meat female animals not fattened in feedlots	
MM	Meat male animals not fattened in feedlots	
MFr	Meat female animals from weaning to age at fattening in feedlots	
MMr	Meat male animals from weaning to age at fattening in feedlots	
MFf	Meat females, surplus animals fattened for meat production in feedlots	
MMf	Meat males, surplus animals fattened for meat production in feedlots	
BUFFALOES, SHEEP, GOATS		**2.1.2, 2.2.2, 2.2.2**
AF	Adult females, producing milk and calves/lambs/kids	
RF	Replacement females, to replace culled and dead adult females	
AM	Adult males, used for reproduction and draught power (buffaloes only)	
RM	Replacement males, to replace culled and dead adult males	
MF	Meat female animals	
MM	Meat male animals	
PIGS		**2.3.2**
AF	Adult females, producing piglets	
RF	Replacement females, to replace culled and dead adult females	
AM	Adult males, used for reproduction	
RM	Replacement males, to replace culled and dead adult males	
M2	Meat animals, female and male fattening animals for meat production	
CHICKENS		
BACKYARD SYSTEMS		**2.4.2**
AF	Adult females, used for reproduction	
AM	Adult males, used for reproduction	
RF	Replacement females, to replace culled and dead adult females	
RM	Replacement males, to replace culled and dead adult males	
MF1, MF2	Growing and adult surplus females	
MM	Surplus males, sold for meat	
LAYERS		**2.4.3**
AF	Adult females, used for reproduction	
AM	Adult males, used for reproduction	
RF	Replacement females, to replace culled and dead adult females	
RM	Replacement males, to replace culled and dead adult males	
MF1	Growing laying females	
MF2	Adult laying females during the first laying period	
MF3	Adult laying females during the molting period	
MF4	Adult laying females during the second laying period	
MM	Surplus males, sold for meat	
BROILERS		**2.4.4**
AF	Adult females, used for reproduction	
AM	Adult males, used for reproduction	
RF	Replacement females, to replace culled and dead adult females	
RM	Replacement males, to replace culled and dead adult males	
M2	Adult female and male broiler animals	

Figure 2.1 Schematic representation of the herd dynamics for ruminants

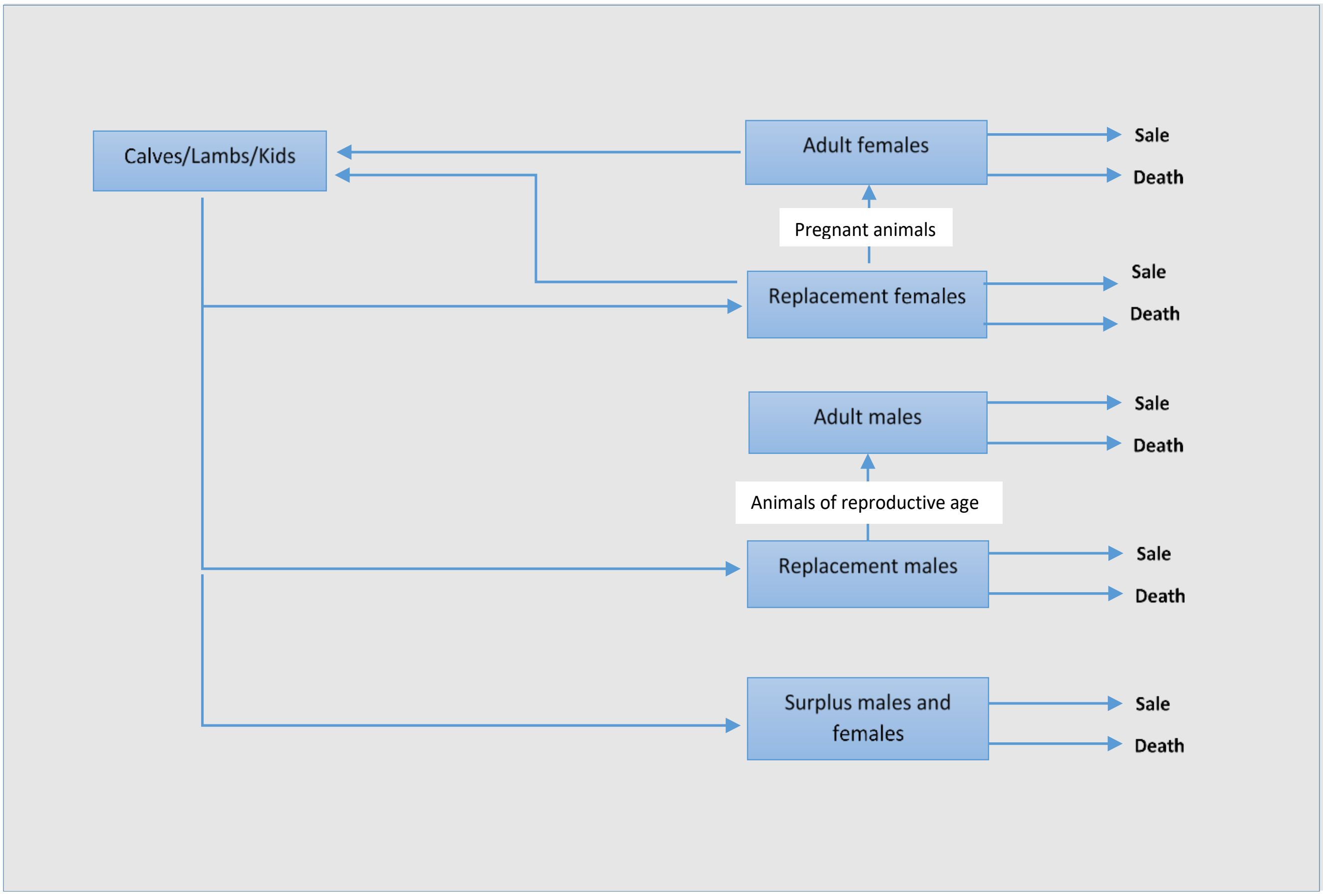


Figure 2.2 Schematic representation of the herd dynamics for pigs and broiler chickens

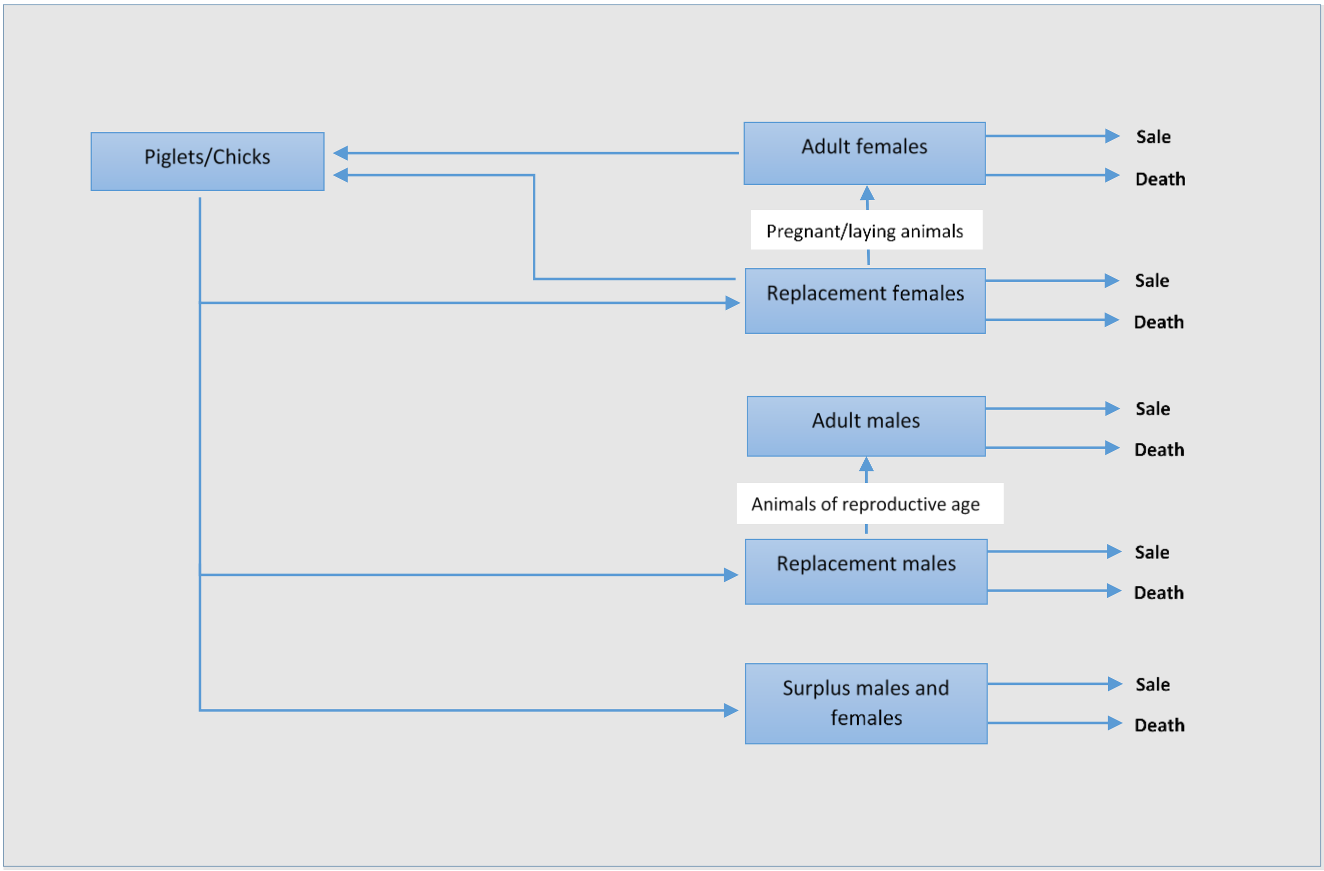
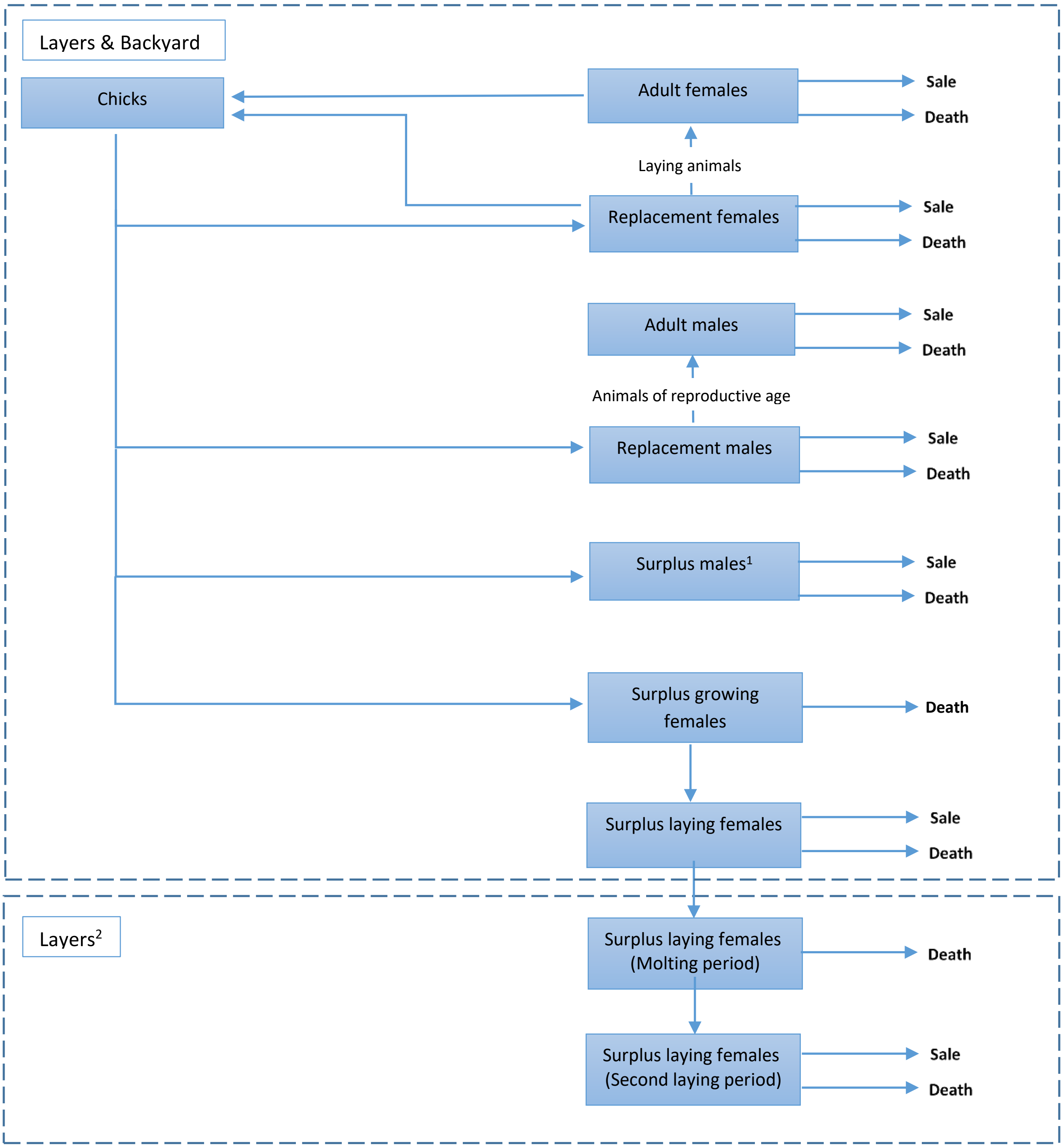


Figure 2.3 Schematic representation of the herd dynamics for backyard and layer chickens



[1] In some countries, the surplus males of the Layers system are killed immediately. Where this is the case, all values for this cohort are null.

[2] In some countries, the laying females of the Layers system are kept for a second laying period after a molting phase. Where this is not the case, they are sold after the first laying period and all values for this section are null.

2.1 – HERD MODULE: LARGE RUMINANTS

This section provides the description of parameters and equations for cattle and buffaloes. Input data and parameters are described in Section 2.1.1. Equations are provided in Section 2.1.2.

2.1.1 – Input and output data and variables

Table 2.2 and Table 2.3 provide the list of input data and parameters and output variables, respectively. Regional values for selected variables are provided on the GLEAM dashboard (https://www.fao.org/gleam/dashboard/).

Table 2.2 Cattle and buffaloes input data and parameters

Variable	Description	Unit
INITIAL AGGREGATED ANIMAL NUMBERS		
NCOWS	Total number of cattle per cell from GLW	heads
NBUFF	Total number of buffaloes per cell from GLW	heads
FNUM	National animal numbers that go into feedlots in a year	heads
LIVE WEIGHTS		
Ckg	Live weight of calves at birth	kg
AFkg	Live weight of adult cows	kg
AMkg	Live weight of bulls	kg
MFSkg	Live weight of female fattening animals at slaughter	kg
MMSkg	Live weight of male fattening animals at slaughter	kg
LWSTARTF, LWENDF	Live weight of feedlot female fattening animals at the beginning and at the end of the fattening period, respectively	kg
LWSTARTM, LWENDM	Live weight of feedlot male fattening animals at the beginning and at the end of the fattening period, respectively	kg
DEATH, FERTILITY AND REPLACEMENT RATES		
DR1	Death rate female calves	percentage
DR1M	Death rate male calves	percentage
DR2	Death rate other animals than calves	percentage
DRf	Death rate animals in feedlots	percentage
FR	Fertility rate of adult female animals	percentage
FRRF	Rate of fertile replacement females. **Note**: a default value of 0.95 is used in all situations	fraction
RRF	Replacement of adult cows	percentage
OTHER INPUT VARIABLES		
AFC	Age at first calving	year
FATTDAY	Length of fattening period in feedlot operations	days
DCR	Dairy cow to total stock of population ratio	fraction
MFR	Bull to cow ratio	fraction

Table 2.3 Cattle and buffaloes output variables

Variable	Description	Unit
COHORTS IN ALL SYSTEMS		
AF	Adult females, producing milk and calves	heads×year^{-1}
RF	Replacement females, to replace culled and dead adult females	heads×year^{-1}
AM	Adult males, used for reproduction and draught power	heads×year^{-1}
RM	Replacement males, to replace culled and dead adult males	heads×year^{-1}
MF	Meat female animals not fattened in feedlots (cattle) or meat female animals (buffaloes)	heads×year^{-1}
MM	Meat male animals not fattened in feedlots (cattle) or meat male animals (buffaloes)	heads×year^{-1}
CF	Female calves	heads×year^{-1}
CM	Male calves	heads×year^{-1}
COHORTS SPECIFIC TO FEEDLOTS		
MFt	Total meat female animals, both feedlot and non-feedlot (only cattle)	heads×year^{-1}
MFf	Meat females, surplus animals fattened for meat production in feedlots (only cattle)	heads×year^{-1}
MFr	Meat female animals from weaning to age at fattening in feedlots	heads×year^{-1}
MMt	Total meat male animals, both feedlot and non-feedlot (only cattle)	heads×year^{-1}
MMf	Meat males, surplus animals fattened for meat production in feedlots (only cattle)	heads×year^{-1}
MMr	Meat male animals from weaning to age at fattening in feedlots	heads×year^{-1}
COHORT SPECIFIC DATA		
cexit	Number of sold animals for meat production from cohort *c*	heads×year^{-1}
cin	Number of animals entering cohort *c*	heads×year^{-1}

cx	Number of dead animals in cohort *c*	heads×year^{-1}
ckg	Live weight of cohort *c*	kg×head^{-1}
ANIMAL NUMBERS SUBTOTALS		
DCATTLE	Total animal numbers in the cattle dairy herd	heads×year^{-1}
DBUFFALO	Total animal numbers in the buffalo dairy herd	heads×year^{-1}
M_HERD	Total fattening animals from dairy and beef herds	heads×year^{-1}
DAILY WEIGHT GAINS		
DWGF	Average daily weight gain of female animals from calf to adult weight	kg×head^{-1}×day^{-1}
DWGM	Average daily weight gain of male animals from calf to adult weight	kg×head^{-1}×day^{-1}
DWGFF	Average daily weight gain of female animals in feedlots (only cattle)	kg×head^{-1}×day^{-1}
DWGMF	Average daily weight gain of male animals in feedlots (only cattle)	kg×head^{-1}×day^{-1}
OTHER VARIABLES		
ASF	Age at slaughter of non-feedlot female animals	year
ASM	Age at slaughter of non-feedlot male animals	year
AFD	Adult female animals from dairy herd	heads×year^{-1}

2.1.2 – Herd equations – Large ruminants

2.1.2.1 – Dairy herd - Female section

AF = DCR × NCOWS or DCR × NBUFF[1]

AFin = AF × (RRF / 100)

AFx = AF × (DR2 / 100)

AFexit = AF × (RRF / 100) – AFx

CFin = AF × ((1 – (DR2 / 100)) × (FR / 100) + (RRF / 100)) × 0.5 × (1 – (DR1 / 100))

CMin = AF × ((1 – (DR2 / 100)) × (FR / 100) + (RRF / 100)) × 0.5 × (1 – (DR1M / 100))

RFin = $((AF \times (RRF / 100)) / FRRF) / (1 - (DR2 / 100))^{AFC}$

RFexit = ((AF × (RRF / 100)) / FRRF) – AFin

RFx = RFin – (AFin + RFexit)

RF = (RFin + AFin) / 2 × AFC

MFin = CFin – Rfin

Unit: *heads × year^{-1}*

ASF = AFC × (MFSkg – Ckg) / (AFkg – Ckg)

Unit: *year*

Equations for cattle

MFtexit = $MFin \times (1 - (DR2 / 100))^{ASF}$

MFtx = MFin – MFtexit

MFt = (MFin + MFtexit) / 2 × (AFC × (MFSkg – Ckg) / (AFkg – Ckg))

MFtd = MFt

MFtin = MFin

---

[1] Use NCOWS or NBUFF for cattle and buffalo respectively

Unit: *heads* × *year*$^{-1}$

Equations for buffaloes

MFexit = $MFin \times (1 - (DR2 / 100))^{ASF}$

MFx = $MFin - MFexit$

MF = $(MFin + MFexit) / 2 \times (AFC \times (MFSkg - Ckg) / (AFkg - Ckg))$

Unit: *heads*×*year*$^{-1}$

2.1.2.2 – *Dairy herd - Male section*

AM = $AF \times MFR$

AMx = $AM \times (DR2 / 100)$

AMexit = $AM / AFC - AMx$

AMin = AM / AFC[2]

RMin = $AMin / (1 - (DR2 / 100))^{AFC}$

RMx = $RMin - AMin$

RM = $(RMin + AMin) / 2 \times AFC$

MMin = $CMin - RMin$

Unit: *heads*×*year*$^{-1}$

ASM = $AFC \times (MMSkg - Ckg) / (AMkg - Ckg)$

Unit: *year*

Equations for cattle

MMtexit = $MMin \times (1 - (DR2 / 100))^{ASM}$

MMtx = $MMin - MMtexit$

MMt = $(MMin + MMtexit) / 2 \times (AFC \times (MMSkg - Ckg) / (AMkg - Ckg))$

MMtd = MMt

MMtin = MMin

DCATTLE = $AF + RF + MFt + AM + RM + MMt$

AFD = AF

Unit: *heads*×*year*$^{-1}$

Equations for buffaloes

MMexit = $MMin \times (1 - (DR2 / 100))^{ASM}$

MMx = $MMin - MMexit$

MM = $(MMin + MMexit) / 2 \times (AFC \times (MMSkg - Ckg) / (AMkg - Ckg))$

DBUFFALO = $AF + RF + MF + AM + RM + MM$

AFD = AF

Unit: *heads*×*year*$^{-1}$

2.1.2.3 – *Beef herd*

Equations for cattle

BCATTLE = $NCOWS - DCATTLE$

IF DCATTLE = 0

AF = $NCOWS \times (1 - MFR)$

ELSE

[2] For cattle and buffalos, bulls are replaced in relation to the age at first calving. This is done to prevent inbreeding, that is, bulls serving their own daughters.

AF = (AFD / DCATTLE) × BCATTLE

Unit: *heads×year⁻¹*

Equations for buffaloes

BBUFFALO = NBUFF – DBUFFALO

IF DBUFFALO = 0

AF = NBUFF × (1 – MFR)

ELSE

AF = (AFD / DBUFFALO) × BBUFFALO

Unit: *heads×year⁻¹*

Once AF in non-dairy herd is estimated, the model follows the same equations shown in Section 2.1.2.1 and Section 2.1.2.2.

2.1.2.4 – Feedlot animals

In the feedlot system, there are 2 phases:

- Rearing phase that includes animals born and grown outside of feedlots from weaning to age at fattening in feedlots. The animals in this phase are indicated by the suffix r.
- Fattening phase during which the animals entered the feedlots are fattened there for a certain number of days. The animals in this phase are indicated by the suffix f.

The animals not included in the feedlots system do not have a suffix. The calculation starts in the beef herd and, only if necessary, the same has been done for the dairy herd.

MFtb = Female fattening animals from beef herd

MMtb = Male fattening animals from beef herd

M_HERD = MFtb + MFtb

Unit: *heads×year⁻¹*

BMFfrac = MFtb / M_HERD

BMMfrac = MMtb / M_HERD

Unit: *fraction*

MFfb = FNUM × BMFfrac

MMfb = FNUM × BMMfrac

Unit: *heads×year⁻¹*

AFF = (LWSTARTF – Ckg) / (AFkg – Ckg) × AFC

ASFF = AFF + FATTDAY / 365

Unit: *year*

AFM = (LWSTARTM – Ckg) / (AMkg – Ckg) × AFC

ASFM = AFM + FATTDAY / 365

Unit: *year*

For clarity purposes, the suffixes ...b are omitted in all the steps in Female and Male sections below.

Female section

MFfin = MFfb × (365 / FATDAY) $/ ((1 - (DR2\ /\ 100))^{AFF})$

MFin = MFtint – MFfin

MFfexit	=	MFf × (365 / FATDAY) × (1 – DRf /100)
MFexit	=	MFtexit – MFfexit
MFr	=	(MFfin × (365 / FATDAY – 1) / (365 / FATDAY) + MFfexit × (365 / FATDAY – 1)) / 2 × AFF

Unit: *heads×year*$^{-1}$

Male section

MMfin	=	MMfb × (365 / FATDAY) / $((1 - (DR2 / 100))^{AFM})$
MMin	=	MMtin – MMfin
MMfexit	=	MMfb × (365 / FATDAY) × (1 – DRf /100)
MMexit	=	MMtexit – MMfexit
MMr	=	(MMfin × (365 / FATDAY – 1) / (365 / FATDAY) + MMfexit × (365 / FATDAY – 1)) / 2 × AFM

Unit: *heads×year*$^{-1}$

In case the animals in the surplus categories of the beef sector are not enough to fullfill the feedlots' requirements, the share between surplus animals in beef and dairy sectors is calculated and applied to the feedlots animals. Then the calculation above is done for both the sectors.

2.1.2.5 – Average weights and growth rates

RFkg	=	(AFkg – Ckg) / 2 + Ckg
RMkg	=	(AMkg – Ckg) / 2 + Ckg
MFkg	=	(MFSkg – Ckg) / 2 + Ckg
MMkg	=	(MMSkg – Ckg) / 2 + Ckg
MFfkg	=	(((LWSTARTF – Ckg) / 2 + Ckg) × AFF + ((LWENDF – LWSTARTF) / 2 + LWSTARTF) × (FATTDAY / 365)) / ASFF
MMfkg	=	(((LWSTARTM – Ckg) / 2 + Ckg) × AFM + ((LWENDM – LWSTARTM) / 2 + LWSTARTM) × (FATTDAY / 365)) / ASFM

Unit: *kg×head*$^{-1}$

DWGF	=	(AFkg – Ckg) / (365 × AFC)
DWGM	=	(AMkg – Ckg) / (365 × AFC)
DWGFF	=	(DWGF × AFF + ((LWENDF – LWSTARTF) / FATTDAY) × (FATTDAY / 365)) / ASFF
DWGFM	=	(DWGM × AFM + ((LWENDM – LWSTARTM) / FATTDAY) × (FATTDAY / 365)) / ASFM

Unit: *kg×animal*$^{-1}$*×day*$^{-1}$

2.2 – HERD MODULE: SMALL RUMINANTS

This section provides the description of parameters and equations for sheep and goats. Input data and parameters are described in Section 2.2.1. Equations are provided in Section 2.2.2.

2.2.1 – Input and output data and variables

Table 2.4 and Table 2.5 provide the list of input data and parameters and output variables, respectively. Regional values for selected variables are provided on the GLEAM dashboard (https://www.fao.org/gleam/dashboard).

Table 2.4 Sheep and goats input data and parameters

Variable	Description	Unit
INITIAL AGGREGATED ANIMAL NUMBERS		
NSHEEP	Total number of sheep, per cell from GLW	heads
NGOAT	Total number of goats, per cell from GLW	heads
LIVE WEIGHTS		
Ckg	Live weight of lambs or kids at birth	kg
AFkg	Live weight of adult female animals	kg
AMkg	Live weight of adult male animals	kg
MFSkg	Live weight of female fattening animals at slaughter	kg
MMSkg	Live weight of male fattening animals at slaughter	kg

DEATH, FERTILITY AND REPLACEMENT RATES		
DR1	Death rate of lambs or kids	percentage
DR2	Death rate other animals than lambs or kids	percentage
FR	Fertility rate of adult female animals	percentage
FRRF	Rate of fertile replacement females. **Note**: a default value of 0.95 is used in all situations	fraction
RRF	Replacement rate female animals	percentage
OTHER INPUT VARIABLES		
AFC	Age at first lambing/kidding	year
DSR	Dairy sheep or goat's ratio, fraction of dairy sheep or goats of the total population	fraction
MFR	Ram to ewe (sheep) or does to bucks (goats) ratio	fraction
LINT	Lambing or kidding interval, period between two parturitions	days
LITSIZE	Litter size, number of lambs or kids per parturition	heads

Table 2.5 Sheep and goats output variables

Variable	Description	Unit
COHORTS		
AF	Adult females, producing milk and lambs or kids	heads×year^{-1}
RF	Replacement females, to replace culled and dead adult females	heads×year^{-1}
AM	Adult males, used for reproduction	heads×year^{-1}
RM	Replacement males, to replace culled and dead adult males	heads×year^{-1}
MF	Meat females <1 year, surplus animals fattened for meat production	heads×year^{-1}
MM	Meat males <1 year, surplus animals fattened for meat production	heads×year^{-1}
C	Lambs or kids	heads×year^{-1}
RF1	Replacement females at the end of first year	heads×year^{-1}
RFA	Replacement females in the midst of first year	heads×year^{-1}
RFB	Replacement females in the midst of the second year	heads×year^{-1}
RM1	Replacement males at the end of first year	heads×year^{-1}
RMA	Replacement males in the midst of first year	heads×year^{-1}
RMB	Replacement males in the midst of the second year	heads×year^{-1}
COHORT SPECIFIC DATA		
***c*exit**	Number of sold animals for meat production from cohort *c*	heads×year^{-1}
***c*in**	Number of animals entering cohort *c*	heads×year^{-1}
***c*x**	Number of dead animals in cohort *c*	heads×year^{-1}
***c*kg**	Live weight of cohort *c*	kg×head^{-1}
ANIMAL NUMBERS SUBTOTALS		
DSHEEP	Total animal numbers in the sheep dairy herd	heads×year^{-1}
DGOAT	Total animal numbers in the goats dairy herd	heads×year^{-1}
DAILY WEIGHT GAINS		
DWGF	Average daily weight gain of female animals from lamb or kid to adult weight	kg×head^{-1}×day^{-1}
DWGM	Average daily weight gain of male animals from lamb or kid to adult weight	kg×head^{-1}×day^{-1}
OTHER VARIABLES		
ASF	Age at slaughter of non-feedlot female animals	year
ASM	Age at slaughter of non-feedlot male animals	year
AFD	Adult female animals from dairy herd	heads×year^{-1}

2.2.2 – *Herd equations – Small ruminants*

2.2.2.1 – *Dairy herd - Female section*

$AF = DSR \times NSHEEP \text{ or } DSR \times NGOAT$

$AFin = AF \times (RRF / 100)$

$AFx = AF \times (DR2 / 100)$

$AFexit = AF \times (RRF / 100) - AFx$

$Cin = AF \times ((1 - (DR2 / 100)) \times (((365 \times FR) / LINT) / 100) \times LITSIZE + (RRF / 100))$

$RFin = ((AF \times (RRF / 100)) / FRRF) / ((1 - (DR1 / 100)) \times (1 - (DR2 / 100))^{(AFC - 1)})$

$RFexit = ((AF \times (RRF / 100)) / FRRF) - AFin$

$RFx = RFin - (AFin + RFexit)$

$RF1 = RFin \times (1 - (DR1 / 100))$

$RFA = (RFin + RF1) / 2$

RFB = $((RF1 + AFin) / 2) \times (AFC - 1)$
RF = $((RFin + RF1) / 2) + (((RF1 + AFin) / 2) \times (AFC - 1))$
MFin = $Cin / 2 - Rfin$
Unit: $heads \times year^{-1}$

ASF = $AFC \times (MFSkg - Ckg) / (AFkg - Ckg)$
Unit: *year*

MFexit = $MFin \times (1 - (DR1 / 100))^{ASF}$
MFx = $MFin - MFexit$
MF = $(MFin + MFexit) / 2 \times ASF$
Unit: $heads \times year^{-1}$

2.2.2.2 – Dairy herd - Male section

AM = $AF \times MFR$
AMx = $AM \times (DR2 / 100)$
AMexit = AM / (3 × AFC[3]) – AMx
AMin = $AM / (3 \times AFC)$
RMin = $AMin / ((1 - (DR1 / 100)) \times (1 - (DR2 / 100))^{(AFC - 1)})$
RM1 = $RMin \times (1 - (DR1 / 100))$
RMA = $(RMin + RM1) / 2$
RMB = $((RM1 + AMin) / 2) \times (AFC - 1)$
RMx = $RMin - AMin$
RM = $((RMin + RM1) / 2) + ((RM1 + AMin) / 2) \times (AFC - 1)$
MMin = $Cin / 2 - RMin$
Unit: $heads \times year^{-1}$

ASM = $AFC \times (MMSkg - Ckg) / (AMkg - Ckg)$
Unit: *year*

MMexit = $MMin \times (1 - (DR1 / 100))^{ASM}$
MMx = $MMin - MMexit$
MM = $(MMin + MMexit) / 2 \times ASM$
Unit: $heads \times year^{-1}$

Equations for sheep

DSHEEP = $AF + RF + MF + AM + RM + MM$
AFD = AF
Unit: $heads \times year^{-1}$

Equations for goats

DGOAT = $AF + RF + MF + AM + RM + MM$
AFD = AF

---

[3] For cattle, bulls are replaced in relation to the age of first calving. This is done to prevent inbreeding, bulls serving their own daughters. In the case of sheep, farmers tend to exchange rams. It is assumed that a ram is exchanged twice, which means that he can serve for three periods, so the replacement rate is only one third of what it would be based on the AFC.

Unit: *heads×year⁻¹*

2.2.2.3 – Non-dairy herd

Equations for sheep

BSHEEP	=	NSHEEP – DSHEEP		
IF	DSHEEP	=	0	
	AF	=	NSHEEP × (1 – MFR)	
ELSE				
	AF	=	(AFD / DSHEEP) × BSHEEP	

Unit: *heads×year^{-1}*

Equations for goats

BGOAT	=	NGOAT – DGOAT	
IF	DGOAT	=	0
	AF	=	NGOAT × (1 – MFR)
ELSE			
	AF	=	(AFD / DGOAT) × BGOAT

Unit: *heads×year^{-1}*

Once AF in non-dairy herd is estimated, the model follows the same equations shown in Section 2.2.2.1 and Section 2.2.2.2.

2.2.2.4 – Average weights and growth rates

RFkg	=	(AFkg + Ckg) / 2
RF1kg	=	Ckg + ((AFkg – Ckg) / AFC)
RFAkg	=	(Ckg + RF1kg) / 2
RFBkg	=	(RF1kg + AFkg) / 2
RMkg	=	(AMkg + Ckg) / 2
RM1kg	=	Ckg + ((AMkg – Ckg) / AFC)
RMAkg	=	(Ckg + RM1kg) / 2
RMBkg	=	(RM1kg + AMkg) / 2
MFkg	=	(MFSkg - Ckg) / 2 + Ckg
MMkg	=	(MMSkg - Ckg) / 2 + Ckg

Unit: *kg×head^{-1}*

DWGF	=	(AFkg – Ckg) / (365 × AFC)
DWGM	=	(AMkg – Ckg) / (365 × AFC)

Unit: *kg×head^{-1}×day^{-1}*

2.3 – HERD MODULE: PIGS

This section provides the description of parameters and equations for pigs. Input and output data and parameters are described in Section 2.3.1. Equations are provided in Section 2.3.2.

2.3.1 – Input and output data and variables

Table 2.6 and Table 2.7 provide the list of input data and parameters and output variables, respectively. Regional values for selected variables are provided on the GLEAM dashoard (https://www.fao.org/gleam/dashboard).

Table 2.6 Pigs input data and parameters

Variable	Description	Unit
INITIAL AGGREGATED ANIMAL NUMBERS		
NPIGS	Total animal number, per cell and production system	heads×year^{-1}
LIVE WEIGHTS		
Ckg	Live weight of piglets at birth	kg
Wkg	Live weight of piglets at weaning age	kg

AFkg	Live weight of adult female animals	kg
AMkg	Live weight of adult male animals	kg
M2Skg	Live weight of fattening animals at slaughter	kg
DEATH, FERTILITY AND REPLACEMENT RATES		
DR1	Death rate of piglets before weaning age	percentage
DRR2A	Death rate of replacement animals between weaning and adult ages	percentage
DRR2B	Death rate of adult animals	percentage
DRF2	Death rate of fattening animals	percentage
FR	Annual parturitions per sow	parturition×year^{-1}
FRRF	Rate of fertile replacement females. **Note**: a default value of 0.95 is used in all situation	fraction
RRF	Replacement rate female animals	percentage
RRM	Replacement rate male animals	percentage
OTHER INPUT VARIABLES		
AF_frac	Sows to total herd ratio.	fraction
WA	Weaning age	days
LITSIZE	Litter size, number of piglets per parturition	heads×parturition^{-1}
MFR	Boar to sow ratio	fraction
DWG2	Average daily weight gain of fattening animals	kg×head^{-1}×day^{-1}

Table 2.7 Pigs output variables

Variable	Description	Unit
PRINCIPAL COHORTS		
AF	Adult females, producing piglets	heads×year^{-1}
RF	Replacement females, to replace culled and dead adult females	heads×year^{-1}
AM	Adult males, used for reproduction	heads×year^{-1}
RM	Replacement males, to replace culled and dead adult males	heads×year^{-1}
M2	Meat animals, female and male fattening animals for meat production	heads×year^{-1}
C	Piglets	heads×year^{-1}
COHORT SPECIFIC DATA		
***c*exit**	Number of sold animals for meat production from cohort *c*	heads×year^{-1}
***c*in**	Number of animals entering cohort *c*	heads×year^{-1}
***c*x**	Number of dead animals in cohort *c*	heads×year^{-1}
***c*kg**	Live weight of cohort *c*	kg×head^{-1}
DAILY WEIGHT GAINS		
DWGF	Average daily weight gain of female young replacement animals	kg×head^{-1}×day^{-1}
DWGM	Average daily weight gain of male young replacement animals	kg×head^{-1}×day^{-1}
OTHER VARIABLES		
AFCF	Age at first parturition calculated in basis of the daily weight gain	year
AFCM	Age at which boars are considered adults in the basis of the daily weight gain	year
A2S	Length of fattening period for meat animals	year

2.3.2 – Herd equations – Pigs

2.3.2.1 – Female section

AF = NPIGS × AF_frac

AFin = AF × (RRF / 100)

AFx = AF × (DRR2B / 100)

AFexit = AF × (RRF / 100) – AFx

Cin = AF × ((1 – (DRRB2 / 100)) × FR × LITSIZE + (RRF / 100) × LITSIZE) × (1 – (DR1 / 100))

Unit: *heads×year^{-1}*

DWGF = AFkg / ((AFkg + AMkg) / 2) × DWG2

Unit: *kg×head^{-1}×year^{-1}*

AFCF = (AFkg – Wkg) / (365 × DWGF) + (WA / 365)

Unit: *year*

RFin = ((AF × (RRF / 100)) / FRRF) / (1 – (DRR2A / 100))^{AFCF}

$RFexit = ((AF \times (RRF / 100)) / FRRF) - AFin$

$RFx = RFin - (AFin + RFexit)$

$RF = (RFin + AFin) / 2 \times ((AFkg - Wkg) / (365 \times DWGF) + (WA / 365))$

$MFin = Cin / 2 - RFin$

Unit: $heads \times year^{-1}$

2.3.2.2 – *Male section*

$AM = AF \times MFR$

$AMx = AM \times (DRR2B / 100)$

Unit: $heads \times year^{-1}$

$DWGM = AMkg / ((AFkg + AMkg) / 2) \times DWG2$

Unit: $kg \times head^{-1} \times year^{-1}$

$AFCM = (AMkg - Wkg) / (365 \times DWGM) + (WA / 365)$

Unit: *year*

$AMexit = AM \times RRM / 100 - AMx$

$AMin = AM \times RRM / 100$

$RMin = AMin / (1 - (DRR2A / 100))^{AFCM}$

$RMx = RMin - AMin$

$RM = (RMin + AMin) / 2 \times ((AMkg - Wkg) / (365 \times DWGM) + (WA / 365))$

$MMin = Cin / 2 - RMin$

Unit: $heads \times year^{-1}$

2.3.2.3 – *Fattening section*

$M2in = MFin + MMin$

Unit: $heads \times year^{-1}$

$A2S = (M2Skg - Wkg) / (365 \times DWG2)$

Unit: *year*

$M2exit = M2in \times (1 - (DRF2 / 100))^{A2S}$

$M2x = M2in - M2exit$

$M2 = (M2in + M2exit) / 2 \times ((M2Skg - Wkg) / (365 \times DWG2))$

Unit: $heads \times year^{-1}$

2.3.2.4 – *Average weights*

$RFkg = (AFkg - Wkg) / 2 + Wkg$

$RMkg = (AMkg - Wkg) / 2 + Wkg$

$M2kg = (M2Skg - Wkg) /2 + Wkg$

Unit: $kg \times head^{-1}$

2.4 – HERD MODULE: CHICKENS

This section provides the description of parameters and equations for chicken. Input and output data and parameters are described in Section 2.4.1. Equations are provided in Section 2.4.2 to Section 2.4.4.

2.4.1 – *Input and output data and variables*

Table 2.8 and Table 2.9 provide the list of input data and parameters and output variables, respectively. Regional values for selected variables are provided on the GLEAM dashboard (https://www.fao.org/gleam/dashboard).

Table 2.8 Chickens input data and parameters

Variable	Description	Unit
INITIAL AGGREGATED ANIMAL NUMBERS		
AFC	Age at first laying (hens) or reproduction (roosters)	days
NCHK	Total number of chickens per cell and production system	heads
LIVE WEIGHTS		
ALL SYSTEMS		
Ckg	Live weight of chicks at birth	kg
BACKYARD SYSTEMS		
AF2kg	Live weight of females at the end of the laying period	kg
AM2kg	Live weight of males at the end of the laying period	kg
M2Skg	Live weight of surplus animals at slaughter	kg
LAYERS AND BROILERS		
AF1kg	Live weight of female reproductive animals at the start of the laying period	kg
AF2kg	Live weight of female reproductive animals at the end of the laying period	kg
BROILERS		
M2Skg	Live weight at slaughter of female and male broiler animals	kg
DEATH, FERTILITY AND REPLACEMENT RATES		
ALL SYSTEMS		
DR1	Chick mortality rate during the first 16–17 weeks. Not an annual rate	percentage
FRRF	Fertility rate of replacement female animals. **Note**: a default value of 0.95 is used in all situation	fraction
BACKYARD SYSTEMS		
DR2	Death rate adult females and males	percentage
LAYERS		
DRL2	Death rate during the laying period	percentage
DRM	Death rate during the molting period. **Note**: a default value of 15 is used in all situation	percentage
BROILERS		
DRB2	Death rate of broiler animals	percentage
DRL2	Death rate of laying animals during the laying period	percentage
OTHER INPUT VARIABLES		
ALL SYSTEMS		
MFR	Rooster to hen ratio per production system	fraction
EGGSyear	Annual laid eggs per hen per production system	eggs $\times$year^{-1}
EGGwght	Average egg weight	gr$\times$egg^{-1}
HATCH	Hatchability, fraction of laid eggs that actually give a chick	fraction
BACKYARD SYSTEMS		
AFS	Age at which adult surplus females are slaughtered	days
CYCLE	Number of reproductive laying cycles	cycles
CLTSIZE	Laid eggs per cycle per reproductive hen	eggs $\times$cycle^{-1}
LAYERS		
LAY1weeks	Length of the first laying period	weeks
LAY2weeks	Length of the second laying period. **Note**: a default value of 30 is used in all situation	weeks
MOLTweeks	Length of the molting period. **Note**: a default value of 6 is used in all situation	weeks
BROILERS		
A2S	Age at slaughter for meat animals	days
BIDLE	Idle days between two production cycles. **Note**: a default value of 14 is used in all situation	days
LAYweeks	Length of the laying period	weeks

Table 2.9 Chickens output variables

Variable	Description	Unit
PRINCIPAL COHORTS		
BACKYARD SYSTEMS		
AF	Adult females, used for reproduction	heads×year^{-1}
RF	Replacement females, to replace culled and dead adult females	heads×year^{-1}
AM	Adult males, used for reproduction	heads×year^{-1}
RM	Replacement males, to replace culled and dead adult males	heads×year^{-1}
MF1, MF2	Growing and adult surplus females	heads×year^{-1}
MM	Surplus males, sold for meat	heads×year^{-1}
C	Chicks	heads×year^{-1}
LAYERS		
AF	Adult females, used for reproduction	heads×year^{-1}
RF	Replacement females, to replace culled and dead adult females	heads×year^{-1}
AM	Adult males, used for reproduction	heads×year^{-1}
RM	Replacement males, to replace culled and dead adult males	heads×year^{-1}
MF1	Growing laying females	heads×year^{-1}
MF2	Adult laying females during the first laying period	heads×year^{-1}
MF3	Adult laying females during the molting period	heads×year^{-1}
MF4	Adult laying females during the second laying period	heads×year^{-1}
MM	Surplus males, sold for meat	heads×year^{-1}
C	Chicks	heads×year^{-1}
BROILERS		
AF	Adult females, used for reproduction	heads×year^{-1}
RF	Replacement females, to replace culled and dead adult females	heads×year^{-1}
AM	Adult males, used for reproduction	heads×year^{-1}
RM	Replacement males, to replace culled and dead adult males	heads×year^{-1}
M2	Surplus female and male broiler animals, sold for meat	heads×year^{-1}
C	Chicks	heads×year^{-1}
COHORT SPECIFIC DATA		
***c*exit**	Number of sold animals for meat production from cohort *c*	heads×year^{-1}
***c*in**	Number of animals entering cohort *c*	heads×year^{-1}
***c*x**	Number of dead animals in cohort *c*	heads×year^{-1}
***c*kg**	Live weight of cohort *c*	kg×head^{-1}
DAILY WEIGHT GAINS		
BACKYARD SYSTEMS		
DWGF1	Average daily weight gain of all hens in their youth period	kg×head^{-1}×day^{-1}
DWGF2	Average daily weight gain of reproductive and surplus hens in their laying and fattening period	kg×head^{-1}×day^{-1}
DWGM1	Average daily weight gain of all male chickens in their youth period	kg×head^{-1}×day^{-1}
DWGM2	Average daily weight gain of reproductive roosters in their reproductive period	kg×head^{-1}×day^{-1}
LAYERS		
DWGF1	Average daily weight gain of all hens in their youth period	kg×head^{-1}×day^{-1}
DWGF2	Average daily weight gain of layers and reproductive hens in their laying period	kg×head^{-1}×day^{-1}
DWGM1	Average daily weight gain of all male chickens in their youth period	kg×head^{-1}×day^{-1}
DWGM2	Average daily weight gain of reproductive roosters in their reproductive period	kg×head^{-1}×day^{-1}
BROILERS		
DWGF0	Average daily weight gain of reproductive female animals	kg×head^{-1}×day^{-1}
DWGM0	Average daily weight gain of reproductive male animals	kg×head^{-1}×day^{-1}
DWGB	Average daily weight gain of broiler animals	kg×head^{-1}×day^{-1}
OTHER VARIABLES		
BACKYARD SYSTEMS		
AF1kg, AM1kg	Live weight of female and male reproductive animals at the start of the laying period	kg×head^{-1}
AFkg, AMkg	Average live weight of adult females and males, respectively	kg×head^{-1}
MMSkg	Live weight of male surplus animals at slaughter	kg×head^{-1}
EGGconsAF	Number of eggs used for human consumption by reproductive hen	egg×head^{-1}×year^{-1}
LAYERS		
AF1kg, AM1kg	Live weight of female and male reproductive animals at the start of the laying period	kg×head^{-1}
AF2kg, AM2kg	Live weight of female and male reproductive animals at the end of the laying period	kg×head^{-1}
AFkg, AMkg	Average live weight of adult females and males, respectively	kg×head^{-1}
MF11kg, MF22kg	Average live weight of laying hens during their growing and laying period, respectively	kg×head^{-1}

MMkg	Average live weight of surplus male animals	$kg \times head^{-1}$
Broilers		
AM1kg, AM2kg	Live weight of male reproductive at the start and the end of the reproductive period	$kg \times head^{-1}$

2.4.2 – Herd equations – Backyard chickens

2.4.2.1 – Reproductive female section

AF = NCHK / 100

Unit: *heads×year⁻¹*

RRF = 365 / (AFS – AFC)[4]

Unit: *fraction*

AFin = AF × RRF

AFx = AF × (DR2 / 100)

AFexit = AF × RRF – AFx

Unit: $heads \times year^{-1}$

EGGSrepro = CYCLE × CLTSIZE

Unit: $eggs \times year^{-1}$

IF EGGSrepro > EGGSyear

EGGSrepro = EGGSyear

EGGconsAF = EGGSyear – EGGSrepro

Unit: $eggs \times year^{-1}$

Cin = (AF × (1 – (DR2 / 100)) × EGGSrepro) × HATCH

RFin = ((AF × RRF) / FRRF) / (1 – (DR1 / 100))

RFexit = ((AF × RRF) / FRRF) – AFin

RFx = RFin – (AFin + RFexit)

RF = (RFin + AFin) / 2 × (AFC / 365)

MF1in = Cin / 2 – RFin

Unit: $heads \times year^{-1}$

2.4.2.2 – Reproductive male section

AM = AF × MFR

Unit: $heads \times year^{-1}$

RRM = RRF

Unit: *fraction*

AMx = AM × (DR2 / 100)

AMexit = AM × RRM – AMx

AMin = AM × RRM

[4] The replacement rate is defined as the inverse of the productive lifespan expressed in years. The productive lifespan is the period that goes from the age at which animals are reproductive (AFC) to the age at which they are slaughtered (AFS). It is assumed that replacement rate for roosters (RRM) is the same as for hens (RRF).

RMin	=	AMin / (1 – (DR1 / 100))
RMx	=	RMin – AMin
RM	=	(RMin + AMin) / 2 × (AFC / 365)
MMin	=	Cin / 2 – RMin

Unit: *heads×year*$^{-1}$

2.4.2.3 – Male fattening section

MMexit	=	MMin × (1 – (DR1 / 100))
MMx	=	MMin – MMexit
MM	=	((MMin + MMexit) / 2) × (AFC / 365)

Unit: *heads×year*$^{-1}$

2.4.2.4 – Female fattening and egg production section

Growing period

MF1x	=	MF1in × (DR1 / 100)
MF1exit	=	(MF1in – MF1x) ×(1 – FRRF)
MF2in	=	(MF1in – MF1x) × FRRF
MF1	=	((MF1in + MF2in) / 2) × (AFC / 365)

Unit: *heads×year*$^{-1}$

Laying period

MF2exit	=	MF2in × (1 – (DR2 / 100))$^{(AFS - AFC) / 365}$
MF2x	=	MF2in – MF2exit
MF2	=	((MF2in + MF2exit) / 2) × ((AFS – AFC) / 365)

Unit: *heads×year*$^{-1}$

EGGconsMF	=	EGGSyear

Unit: *eggs×year*$^{-1}$

2.4.2.5 – Average characteristics

AF1kg	=	M2Skg × (AF2kg / ((AF2kg + AM2kg) / 2))
AM1kg	=	M2Skg × (AM2kg / ((AF2kg + AM2kg) / 2))
MF1Skg	=	AF1kg
MF2Skg	=	AF2kg
MMSkg	=	M2Skg × (AM2kg / ((AF2kg + AM2kg) / 2))
RFkg	=	(AF1kg – Ckg) / 2 + Ckg
RMkg	=	(AM1kg – Ckg) / 2 + Ckg
AFkg	=	(AF2kg – AF1kg) / 2 + AF1kg
AMkg	=	(AM2kg – AM1kg) /2 + AM1kg
MF1kg	=	RFkg
MF2kg	=	AFkg
MMkg	=	(MMSkg – Ckg) / 2 + Ckg

Unit: *kg×head*$^{-1}$

DWGF1	=	(AF1kg – Ckg) / AFC
DWGF2	=	(AF2kg – AF1kg) / (AFS – AFC)
DWGM1	=	(AM1kg – Ckg) / AFC
DWGM2	=	(AM2kg – AM1kg) / (AFS – AFC)

Unit: *kg×head*$^{-1}$*×day*$^{-1}$

2.4.3 – Herd equations – Layers

2.4.3.1 – Lay time

IF molting is not done

	LAYtime	= LAY1weeks / 52
IF	molting is done	
	LAYtime	= (LAY1weeks + LAY2weeks + MOLTweeks) / 52

Unit: *year*

2.4.3.2 – Reproductive female section

AF	=	NCHK / 100
AFin	=	AF / LAYtime
AFx	=	AF × ((52 × DRL2 / LAY1weeks) / 100)
AFexit	=	AF / LAYtime – AFx
Cin	=	AF × (1 – (DRL2 / 100)) × EGGSyear × HATCH
RFin	=	((AF / LAYtime) / FRRF) / (1 – (DR1 / 100))
RFexit	=	((AF / LAYtime) / FRRF) – AFin
RFx	=	RFin – (AFin + RFexit)
RF	=	(RFin + AFin) / 2 × (AFC / 365)
MF1in	=	Cin / 2 – RFin

Unit: *heads*×*year*$^{-1}$

2.4.3.3 – Male reproduction section

AM	=	AF × MFR
AMx	=	AM × ((52 × DRL2 / LAY1weeks) / 100)
AMexit	=	AM / LAYtime – AMx
AMin	=	AM / LAYtime
RMin	=	AMin / (1 – (DR1 / 100))
RMx	=	RMin – AMin
RM	=	(RMin + AMin) / 2 × (AFC / 365)
MMin	=	Cin / 2 – RMin

Unit: *heads*×*year*$^{-1}$

2.4.3.4 – Laying section

Growing period

MF2in	=	MF1in × (1 – (DR1 / 100))
MF1x	=	MF1in – MF2in
MF1	=	((MF1in + MF2in) / 2) × (AFC / 365)

Unit: *heads*×*year*$^{-1}$

Laying period

MF2exit	=	MF2in × (1 – (DRL2 / 100))
MF2x	=	MF2in – MF2exit
MF2	=	((MF2in + MF2exit) / 2) × (LAY1weeks / 52)
IF	molting is not done	
MF4exit	=	MF2exit
MF3	=	0
MF4	=	0

Unit: *heads*×*year*$^{-1}$

IF molting is done

MF3exit[5] = MF2exit × (1 – (DRM / 100))
MF3x = MF2exit – MF3exit
MF3 = ((MF2exit + MF3exit) / 2) × (MOLTweeks / 52)
MF4exit = MF3exit × (1 – (DRL2 / 100))
MF4x = MF3exit – MF4exit
MF4 = ((MF3exit + MF4exit) / 2)) × (LAY2weeks / 52)
Unit: $heads \times year^{-1}$

2.4.3.5 – Male meat production section

IF Country is OECD
MMexit = 0
MMx = 0
MM = 0
Unit: $heads \times year^{-1}$

IF Country is not OECD
MMexit = MMin × (1 – (DR1 / 100))
MMx = MMin – MMexit
MM = ((MMin + MMexit) / 2) × (AFC / 365)
Unit: $heads \times year^{-1}$

2.4.3.6 – Average weight and growth rates

AF1kg = MF1kg
AF2kg = MF2kg
AM1kg = 1.3 × MF1kg
AM2kg = 1.3 × MF2kg
MM1kg = 1.3 × MF1kg
MF11kg = (MF1kg – Ckg) / 2 + Ckg
RFkg = MF11kg
MF22kg = (MF2kg – MF1kg) / 2 + MF1kg
AFkg = MF22kg
AMkg = (AM2kg – AM1kg) / 2 + AM1kg
RMkg = (AM1kg – Ckg) / 2 + Ckg
MMkg = (MM1kg – Ckg) / 2 + Ckg
Unit: $kg \times head^{-1}$

DWGF1 = (MF1kg – Ckg) / AFC
DWGF2 = (MF2kg – MF1kg) / (7 × LAY1weeks)
DWGF3 = 0
DWGF4 = 0
DWGM1 = (AM1kg – Ckg) / AFC
DWGM2 = (AM2kg – AM1kg) / (365 × (LAY1weeks / 52))
Unit: $kg \times head^{-1} \times day^{-1}$

[5] If molting is done, the only variable accounting for the number of adult laying females sold for meat production is MF4exit. In these cases, MF2exit and MF3exit represent the number of laying females moving, in one year, from cohort MF2 to MF3 and from cohort M3 to MF4, respectively.

2.4.4 – Herd equations – Broilers

2.4.4.1 – Reproductive female section

AF	=	NCHK / 100
AFin	=	AF / (LAYweeks / 52)
AFx	=	AF × (((52 × DRL2 / LAYweeks)) / 100)
AFexit	=	AF / (LAYweeks / 52) – AFx
Cin	=	AF × (1 – (DRL2 / 100)) × EGGSyear × HATCH
RFin	=	((AF / (LAYweeks / 52)) / FRRF) / (1 – (DR1 / 100))
RFexit	=	((AF / (LAYweeks / 52)) / FRRF) – AFin
RFx	=	RFin – (AFin + RFexit)
RF	=	((RFin + AFin) / 2) × (AFC / 365)
MFin	=	Cin / 2 – RFin

Unit: *heads*×*year*$^{-1}$

2.4.4.2 – Male reproduction section

AM	=	AF × MFR
AMx	=	AM × ((52 × DRL2 / LAYweeks) / 100)
AMexit	=	AM / (LAYweeks / 52) – AMx
AMin	=	AM / (LAYweeks / 52)
RMin	=	AMin / (1 – (DR1 / 100))
RMx	=	RMin – AMin
RM	=	((RMin + AMin) / 2) × (AFC / 365)
MMin	=	Cin / 2 – RMin

Unit: *heads*×*year*$^{-1}$

2.4.4.3 – Broilers section

M2in	=	MFin + MMin
M2exit	=	M2in × (1 – (DRB2 / 100))
M2x	=	M2in – M2exit
M2	=	((M2in + M2exit) / 2) × ((A2S + BIDLE) / 365)

Unit: *heads*×*year*$^{-1}$

2.4.4.4 – Average weight and growth rates

AFkg	=	(AF2kg + AF1kg) / 2
RFkg	=	(AF1kg – Ckg) / 2 + Ckg
AM1kg	=	1.3 × AF1kg
AM2kg	=	1.3 × AF2kg
AMkg	=	1.3 × AFkg
RMkg	=	(AM1kg – Ckg) / 2 + Ckg
M2kg	=	(M2Skg – Ckg) / 2 + Ckg

Unit: *kg*×*head*$^{-1}$

DWGF0	=	(AF1kg – Ckg) / AFC
DWGM0	=	(AM1kg – Ckg) / AFC

Unit: *kg*×*head*$^{-1}$×*day*$^{-1}$

DWG2B	=	(M2Skg - Ckg) / A2S

Unit: kg×*head*$^{-1}$×*day*$^{-1}$

3 CHAPTER 3 – FEED RATION AND INTAKE MODULE

Animal diets are one of the most important aspects of livestock production. They largely determine animal productivity, land use and emissions from enteric fermentation, manure and feed production. Feed intake (kg of dry matter per animal) depends on the energy requirement of animals. Feed intake is calculated for each species and cohort based on the feed ration, its nutritional value and energy requirement of animals.

The functions of the 'Feed ration and intake' module are to:

- Define the **composition** of the ration for each species and production system;
- Calculate the **nutritional values** of the ration per kilogram of dry matter, and;
- Calculate the average **energy requirement** and the related **feed intake** of each animal.

The schematic representation of this chapter is composed of different figure: for ruminants refer to Figure 3.1, Figure 3.2, Figure 3.3 for the composition of the ration and Figure 3.6 for the energy requirement and feed intake calculation; for the monogastrics refer to Figure 3.4 and Figure 3.5 for ration composition, and Figure 3.7 for the energy requirement and feed intake calculation.

3.1 – TRACING IMPACTS THROUGH TRADE MATRICES

Many of the environmental impacts of feed production occur at the place where the feed crop is produced, and not at the place where feed is consumed by the animal. It is therefore necessary to trace all feed crops from the place of consumption (determined by the distribution of animals) to the place of production, using bidirectional trade data for different commodities, to account for yields, inputs and associated impacts in the feed producing countries.

Considering only imports and re-exports of traded commodities is not sufficient. In many countries, raw products are imported, modified, and exported to a third country. For example, a country without any soybean production might import raw soybeans, process them and export soy cakes for feed. In this case, the environmental impacts associated with the production of soybeans must be estimated according to the yield, inputs and production features of the country that produces soybeans and not of the country where the crops are processed. To do this, we used a tracing algorithm method (Kastner et al., 2011) that implicitly solves the problem associated with re-exports and indicates the "actual" origin of a product along entire trading chain. It requires that all commodities are converted to primary equivalents using extraction fractions derived from FAOSTAT commodity balance sheets. Production values were taken from the GAEZ 2015 + Data set (Frolking et al., 2020).

The use of the traded commodities in the receiving country is determined by the allocation to different uses, reported in FAOSTAT commodity balance sheets, expressed in primary equivalents. To smooth out variability, we used a three-year average around the year 2015 for all FAOSTAT data.

The resulting trade matrix for all was then used to calculate weighted average yields, production inputs and emission factors in each consuming countries, from the local average values in the exporting country.

3.2 – CROP YIELDS AND PASTURE PRODUCTIVITY

Crops are used as animal feed in three main forms: 1) as the main crop (e.g. grains or whole crops such as grass or silage); 2) as crop residues (such as straw) or 3) as agro-industrial by-products (e.g. brans and cakes).

Data on fresh matter yields per hectare of main crops and their respective land area were taken from GAEZ 2015+ Data set (Frolking et al., 2020) and data on dry matter productivity modified from Copernicus Global Land Service (2021) to estimate the above-ground net primary productivity for pasture. These data are used for two main purposes: 1) estimating the local availability of feed for livestock (see Section 3.3.1) and 2) allocating the emissions associated with feed production between the crop and the crop co-products (crop residues and by-products) according to the kind of feed materials used by the animals (see Chapter 6, Section 6.1.3).

To this scope, a first step is the conversion of the fresh matter of each crop to dry matter, to allow for comparability between different materials in terms of mass and emission intensity. To do so, default dry matter (DM) contents for each crop are used from existing database, literature review and expert opinion, following Equation 3.1:

Equation 3.1 (Crops)

$$DMYG_{crop} = FMYG_{crop} \times DM_{crop} / 100$$

Where:

$DMYG_{crop}$ = gross dry matter yield of each crop, kg $DM \times ha^{-1}$

$FMYG_{crop}$ = fresh matter yield of each crop, kg $DM \times ha^{-1}$. Input spatial grids from GAEZ 2015+ Data set (Frolking et al., 2020).

DM_{crop} = dry matter content of each crop, percentage. Values are given in Table S.3.1 (Supplement S1).

This equation is not necessary for all the grass items as the data used is already expressed in DM. In those cases where the crop residues are needed, either as feed material or for allocation purposes, the yield is calculated, in a second step, using the IPCC formulae (IPCC, 2019, Chapter 11, Table 11.2), as shown in Equation 3.2:

Equation 3.2 (Crop residues)

$$DMYG_{cr} = DMYG_{crop} \times Slope_{-crop} + Intercept_{-crop}$$

Where:

$DMYG_{cr}$ = gross dry matter yield of the crop residues of each crop, kg $DM \times ha^{-1}$

$DMYG_{crop}$ = gross dry matter yield of each crop, kg $DM \times ha^{-1}$

$Slope_{-crop}$ = slope from IPCC equation for each crop. Values are given in Table S.3.1 (Supplement S1).

$Intercept_{-crop}$ = intercept from IPCC equation for each crop. Values are given in Table S.3.1 (Supplement S1).

For feed items that are internationally traded, weighted average yields are calculated for each country, based on the national yields of the feed producing countries (including domestic production) and the trade matrices described in Section 3.1.

3.3 – RUMINANTS' FEED RATIONS

Typically, for ruminant species, the major feed ingredients include:

- Grass: ranges from natural pasture and roadsides to improved and cultivated grasslands.
- Feed crops: crops specially grown to feed livestock, e.g. maize silage or grains.
- Tree leaves: browsed in forests or collected and carried to livestock.
- Crop residues: plant material left over from food or other crops, such as straw or stover, left over after harvesting the crop.
- Agro-industrial by-products and wastes: by-products from the processing of crops such as oilseeds, cereals, sugarcane, and fruit. Examples include cottonseed cakes, rapeseed cakes and brans.

• Concentrates: Any feed containing relatively low fibre (< 20%) and high total digestible nutrients (> 60%). These are feed materials used with other components, to improve the nutritive balance of the complete feed, and intended to be further diluted and mixed to produce a supplement or a complete feed[6].

The feed ingredients above are grouped in four broad categories: roughages, cereals, by-products and concentrates. Cereals, by products and concentrates are assumed to be internationally traded (see Section 3.1 and Section 3.2). The complete list of feed materials considered in GLEAM is shown in Table 3.1.

In all livestock production systems, the feed materials, present in the ration, depend on the presence of pasture and fodder, the crops grown and their respective yields. The fraction of concentrates in the ration varies widely, according to the need to complement locally available feed, the purchasing power of farmers, and access to markets. The balance of forage, crops and by-products must be reasonable in order to match animal performance. The proportion of each feed material is determined differently for industrialized and developing regions, for two main reasons. First, while in the industrialized countries, based on literature review and expert consultation, it was possible to completely define the feed ration composition, in terms of the proportions of each feed material, this was not the case for the rest of the world. Second, we assume that the feed ration composition, at least the forage part, is strictly related to what is available on the ground. For further details see Section 3.3.2 and Section 3.3.3.

For ruminant species, three feeding groups of animals are defined due to their distinctive feeding necessities: adult females (AF), replacement animals (RF, RM) and adult males (AM), and surplus males and female animals (MF, MM). A specific group is also defined for animals raised in feedlot (Table 3.2).

To help the reader in understanding the GLEAM methodology for estimating the feed ration composition, a schematic representation with hypothetical figures has been drawn for ruminant species in Figure 3.1, Figure 3.2 and Figure 3.3.

Average values for the feed rations for ruminant species at regional level are available on the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/)

[6] A complete feed is a nutritionally adequate feed for animals, compounded by a specific formula to be fed as the sole ration and capable of maintaining life and promoting production without any additional substance being consumed except water.

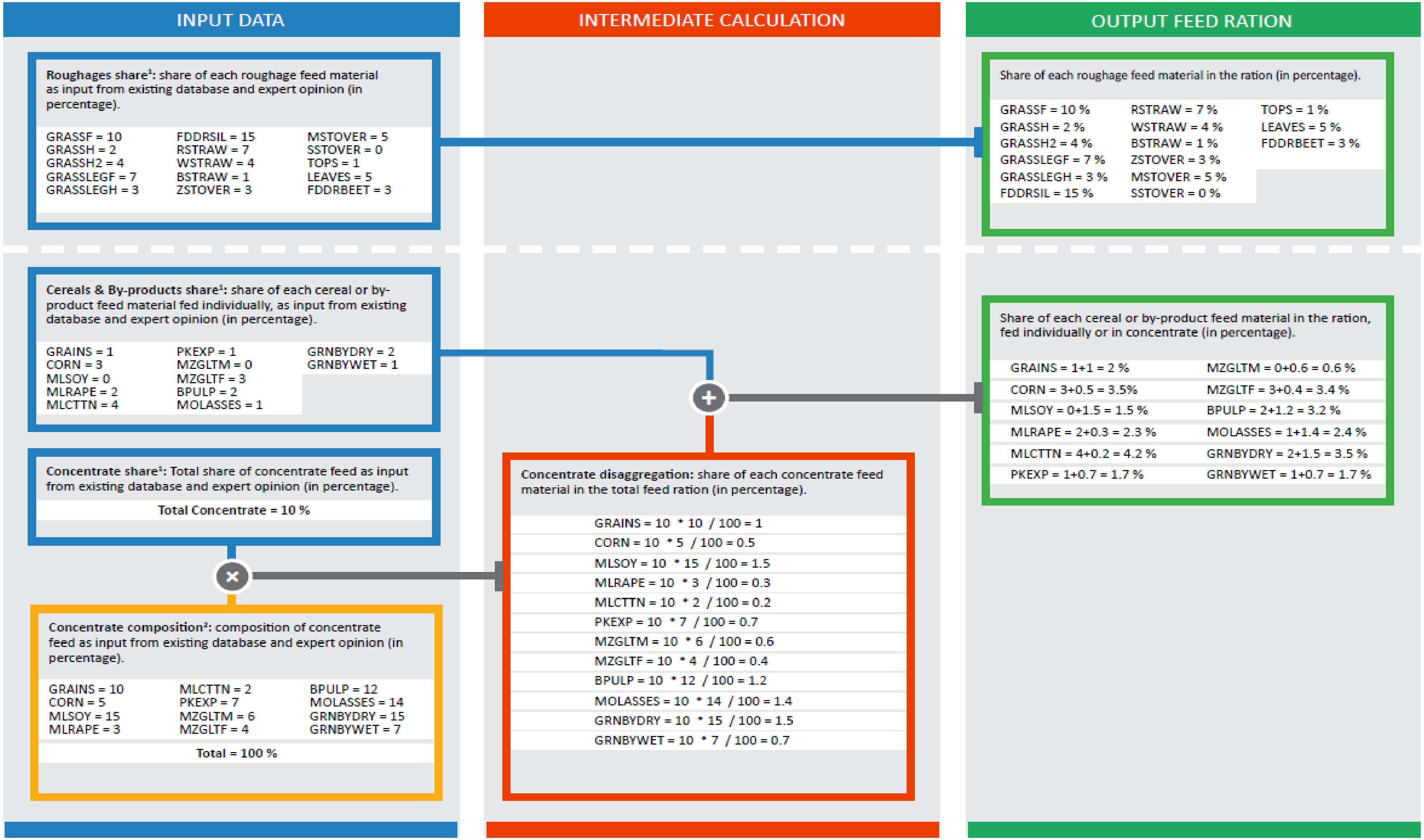
Table 3.1 List of feed materials for ruminant species

Number	Material	Description
Roughages		
1	GRASSF	Any type of natural or cultivated fresh grass grazed or fed to the animals.
2	GRASSH	Hay (grass is cut, dried and stored) or silage (grass is cut and fermented) from any natural or cultivated grass.
3	GRASSH2	Hay from adjacent areas.
4	GRASSLEGF	Fresh mixture of any type of grass and leguminous plants that is fed to the animals.
5	GRASSLEGH	Hay or silage produced from a mixture of any type of grass and leguminous plants.
6	FDDRSIL	Hay or silage from alfalfa (*Medicago sativa*). Silage from whole barley (*Hordeum vulgare*), oat (*Avena sativa*), buckwheat (*Fagopyrum esculentum*), fonio (*Digitaria* spp.) plants and whole maize (*Zea mays*) plants.
7	RSTRAW	Fibrous residual plant material such as straw, brans, leaves, etc. from rice (*Oryza* spp.) cultivation.
8	WSTRAW	Fibrous residual plant material such as straw, brans, leaves, etc. from wheat (*Triticum* spp.) cultivation.
9	BSTRAW	Fibrous residual plant material such as straw, brans, leaves, etc. from barley (*Hordeum vulgare*), rye (*Secale cereale*) or oat (*Avena sativa*) cultivation.
10	ZSTOVER	Fibrous residual plant material such as straw, brans, leaves, etc. from maize (*Zea mays*) cultivation.
11	MSTOVER	Fibrous residual plant material such as straw, brans, leaves, etc. from millet (*Pennisetum glaucum, Eleusine coracana, Panicum miliaceum, etc*) cultivation.
12	SSTOVER	Fibrous residual plant material such as straw, brans, leaves, etc. from sorghum (*Sorghum* spp.) cultivation.
13	TOPS	Top portion of sugarcane (*Saccharum* spp.) plants, consisting of green leaves, bundle sheath and variable proportions of immature cane.
14	LEAVES	Leaves from natural, uncultivated vegetation found in trees, forest, lanes etc.
15	FDDRBEET	Fodder beet (*Beta vulgaris*), also known as mangel beet or field beet, used as animal feed.
Cereals		
16	GRAINS	Grains from barley (*Hordeum vulgare*), oat (*Avena sativa*), buckwheat (*Fagopyrum esculentum*) and fonio (*Digitaria* spp.).
17	CORN	Grains from maize (*Zea* mays) plant.
By-products		
18	MLSOY	By-product from soy (*Glycine max*) oil production, commonly referred to as 'soy cakes' or 'soybean meal'.
19	MLRAPE	By-product from rape (*Brassica napus*) oil production, commonly referred to as 'rape cakes' or 'rapeseed meal'.
20	MLCTTN	By-product from cottonseed (*Gossypium* spp.) oil production, commonly referred to as 'cottonseed meal'.
21	PKEXP	By-products from the production of kernel palm oil (*Elaeis guineensis*), commonly referred to as 'kernel cake'.
22	MZGLTM	By-product from maize processing. It is a protein-rich feed, with about 65% crude protein content.
23	MZGLTF	By-product from maize processing. Unlike the gluten meal, its protein content is lower, of about 25% crude protein content.
24	BPULP	Also known as 'beet pulp', is the remaining material after the juice extraction for sugar production from the sugar beet (*Beta vulgaris*).
25	MOLASSES	By-product from the sugarcane sugar extraction.
26	GRNBYDRY	'Dry' by-products of grain industries such as brans, middlings, etc.
27	GRNBYWET	'Wet' by-products of grain industries such as biofuels, distilleries, breweries, etc.
Concentrates		
28	CONC	Concentrate feed from feed mills.

Table 3.2 Feeding groups for ruminant species

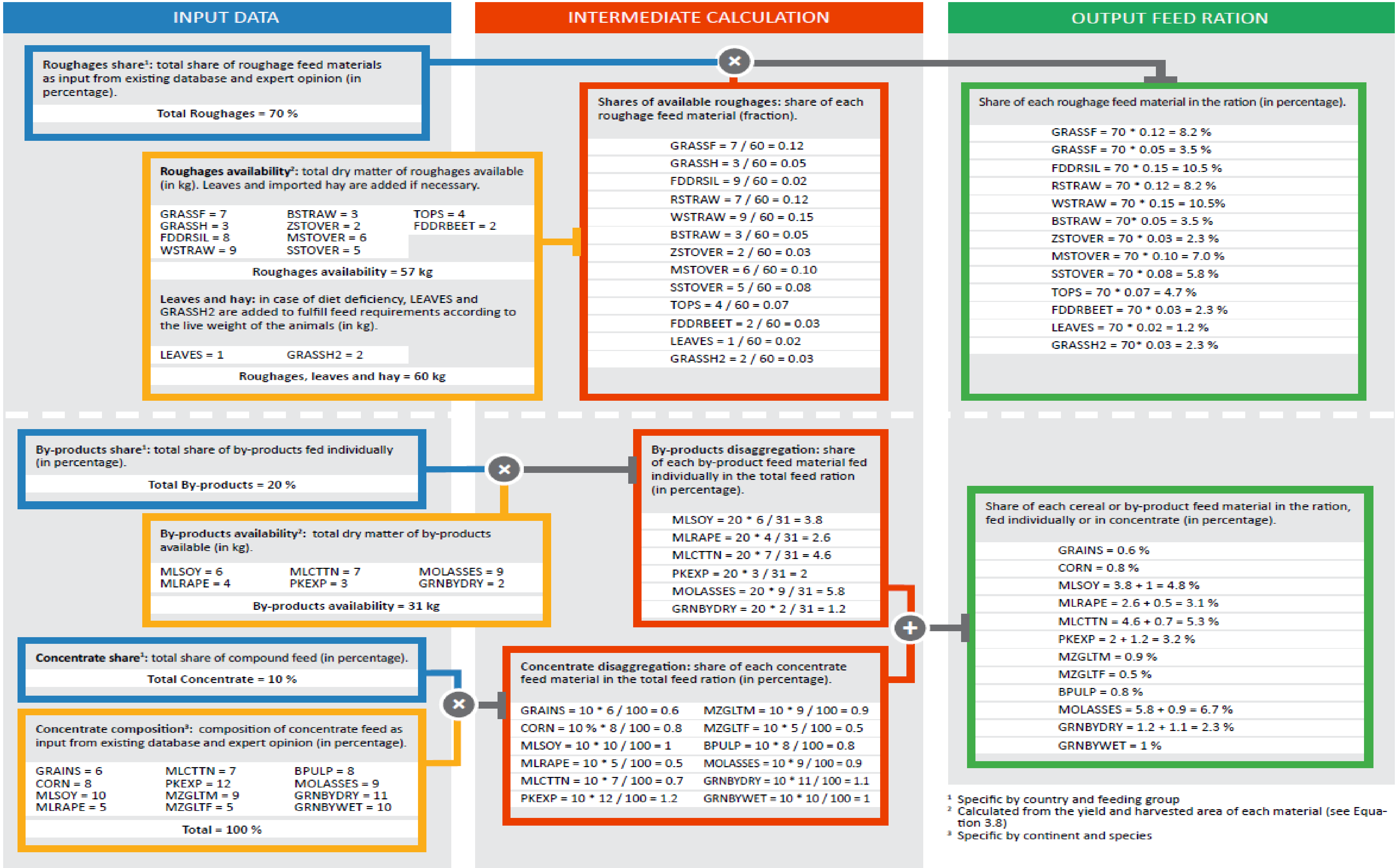
Animal category	GLEAM cohorts
Cattle and Buffaloes	
Group 1	AF
Group 2	AM, RF, RM
Group 3	MF, MM
Group f	MFf, MMf (applies to feedlot animals only)
Small ruminants	
Group 1	AF
Group 2	AM, RF, RM, RFA, RFB, RMA, RMB
Group 3	MF, MM

Figure 3.1 Representation of a hypothetical example of feed ration estimation for ruminant species in industrialized countries



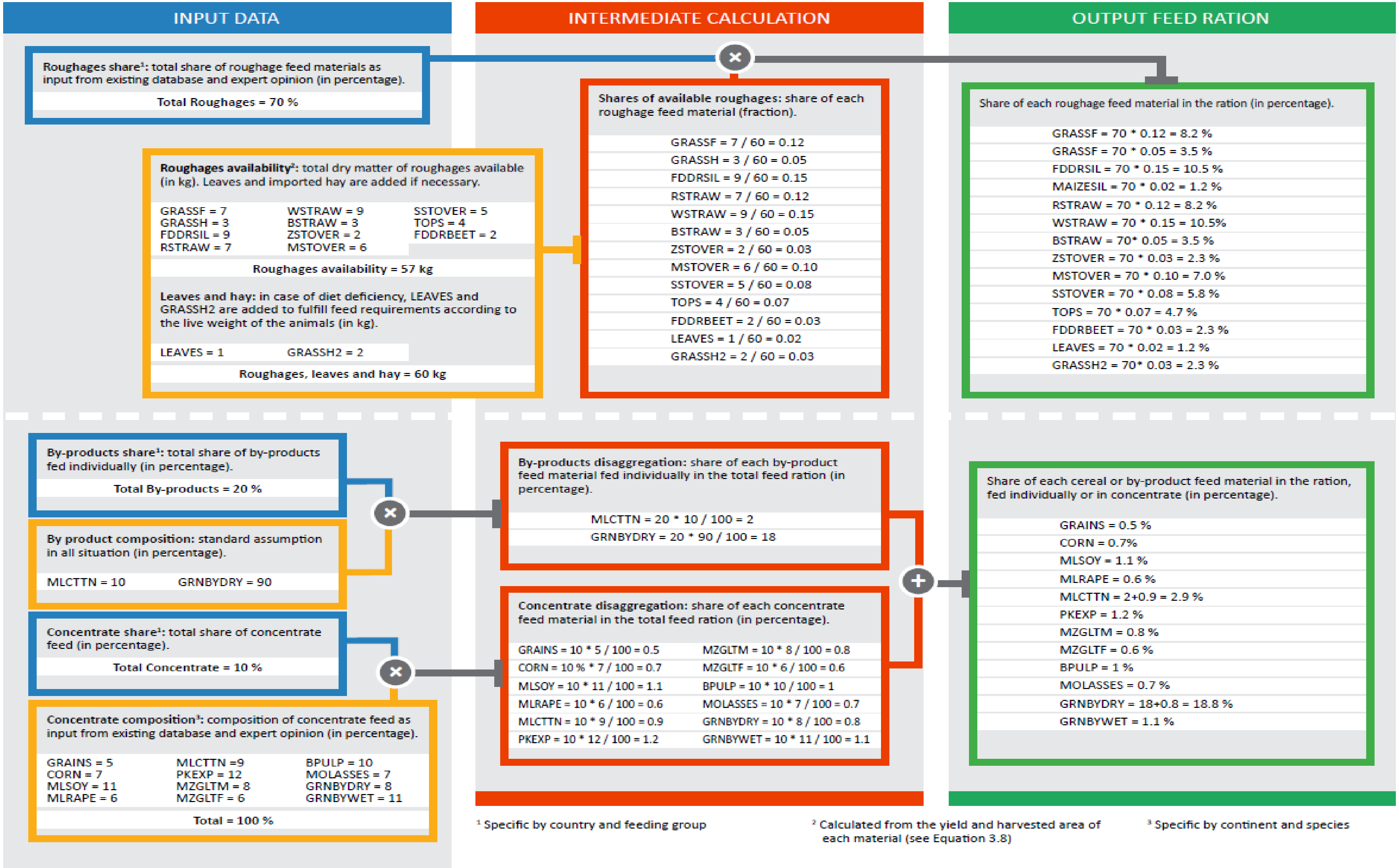
[1] Specific by country and feeding group
[2] Specific by continent and species

Figure 3.2 Representation of a hypothetical example of feed ration estimation for cattle in developing countries



[1] Specific by country and feeding group
[2] Calculated from the yield and harvested area of each material (see Equation 3.8)
[3] Specific by continent and species

Figure 3.3 Representation of a hypothetical example of feed ration estimation for buffaloes and small ruminants in developing countries



3.3.1 – Calculation of the net dry matter yields

The net dry matter yield of each feed material in a given area defines the yield that is available as feed for the animals. For the purpose of estimating the animal ration it is used as a main input in those cases where the calculation of the local availability of feed is required, that is in the developing regions and, therefore, it is calculated only for the roughages and by-products (see Section 3.3.2).

In general, the gross dry matter yield (of the crop or crop residues, depending on the feed material; Equation 3.2) is corrected by the Feed Use Efficiency (FUE), which is the fraction of the yield that is effectively ingested and used as feed by the animals. For silages produced by cereals, it is assumed that the total above-ground biomass production is used, so both the crop and crop residues yields must be considered. Moreover, for some feed materials, the yield of the respective parental crop is also multiplied by the Mass Fraction Allocation (MFA) factor of the material. The latter is a default factor accounting for the feed material mass as a fraction of the total mass of the crop.

Calculations are shown in Equation 3.3. Table 3.3 summarizes the specific equation and input used for each feed material for the calculation of the net dry matter yield.

Equation 3.3

$DMYN_i$ = $DMYG_i \times FUE_i \times MFA_i$

for i = 1, 6 to 13, 15, 18 to 21, 25, 26

Where:

$DMYN_i$ = net dry matter yield of feed material *i*, kg DM×ha^{-1}

$DMYG_i$ = crop gross dry matter yield for feed material *i*, kg DM×ha^{-1}. It can either be the yield of the crop, crop residues or, for feed materials 7 and 8, the sum of both. See Table 3.3

FUE_i = feed use efficiency for feed material *i*, i.e. fraction of the gross yield that is effectively used as feed, fraction. See Table 3.3

MFA_i = mass fraction allocation of feed material *i*, i.e. feed material mass as a fraction of the total mass of the crop, fraction. Values are given in Table 3.3. It is not used for feed materials 9 to 15.

Table 3.3 Net yield equations, gross yields, FUE and MFA for each feed material for ruminant species

Number	Material	Gross dry matter yields	Net yield equation	FUE	MFA
Roughages					
1	GRASSF	Grass	Equation 3.3	Table S.3.2 (Supplement S1)[a]	1
2	GRASSH	Grass	Same as GRASSF	Table S.3.2 (Supplement S1)[a]	1
3	GRASSH2	Grass	Same as GRASSF	Table S.3.2 (Supplement S1)[a]	1
4	GRASSLEGF	Grass	Same as GRASSF	Table S.3.2 (Supplement S1)[a]	1
5	GRASSLEGH	Grass	Same as GRASSF	Table S.3.2 (Supplement S1)[a]	1
6	FDDRSIL	Fodder crops	Equation 3.3	1	1
7	RSTRAW	Rice (crop residues) – Equation 3.2	Equation 3.3	Table S.3.2 (Supplement S1)[a]	Equation 6.10a[c]
8	WSTRAW	Wheat (crop residues) – Equation 3.2	Equation 3.3	Table S.3.2 (Supplement S1)[a]	Equation 6.10a[c]
9	BSTRAW	Barley (crop residues) – Equation 3.2	Equation 3.3	Table S.3.2 (Supplement S1)[a]	Equation 6.10a[c]
10	ZSTOVER	Maize (crop residues) – Equation 3.2	Equation 3.3	Table S.3.2 (Supplement S1)[a]	Equation 6.10a[c]
11	MSTOVER	Millet (crop residues) – Equation 3.2	Equation 3.3	Table S.3.2 (Supplement S1)[a]	Equation 6.10a[c]
12	SSTOVER	Sorghum (crop residues) – Equation 3.2	Equation 3.3	Table S.3.2 (Supplement S1)[a]	Equation 6.10a[c]
13	TOPS	Sugarcane (crop residues) – Equation 3.2	Equation 3.3	Table S.3.2 (Supplement S1)[a]	Equation 6.10a[c]
14	LEAVES	NA	NA	1	1
15	FDDRBEET	Sugar beet	Equation 3.3	1	1
Cereals[d]					
16	GRAINS	Barley and other cereals[b]	NA	1	1
17	CORN	Maize	NA	1	1
By-products[d]					
18	MLSOY	Soybean	Equation 3.3	1	0.80
19	MLRAPE	Rapeseed	Equation 3.3	1	0.58
20	MLCTTN	Cotton	Equation 3.3	1	0.45
21	PKEXP	Oil palm fruit	Equation 3.3	1	0.03
22	MZGLTM	Maize	NA	1	0.05
23	MZGLTF	Maize	NA	1	0.21
24	BPULP	Sugar beet	NA	1	0.19
25	MOLASSES	Sugarcane	Equation 3.3	1	0.13
26	GRNBYDRY	Grains average yield[e]	Equation 3.3	1	0.17
27	GRNBYWET	Barley	NA	1	1

[a] For these feed materials the FUE is spatially explicit.
[b] Average yield of barley and other cereals, excluding wheat, maize, millet, sorghum and rice.
[c] For these feed materials, the MFA is only used for the allocation of the emissions from feed production (see Chapter 6, Section 6.5) and is calculated with a specific equation.
[d] To account for the high level of international trade of these feed materials, average country specific yields were calculated based on trade matrices, as described in Section 3.1 and Section 3.2.
[e] Average yield of wheat, maize, barley, millet, sorghum, rice and other cereals.

3.3.2 – Feed rations in industrialized countries

The feed rations in industrialized countries are taken from country national inventory reports, literature and targeted surveys. The share of each individual feed material is calculated using Equation 3.4.

Equation 3.4

$FEED_{i,fg,T}$ = $FEEDIND_{i,fg,T}$
for i = 1 to 15

$FEED_{i,fg,T}$ = $FEEDIND_{i,fg,T} + CONC_{fg,T} \times CF_{i,T}$
for i = 16 to 27

Where:

$FEED_{i,fg,T}$ = fraction of feed material *i* in the ration for feeding group *fg*, species and system *T*, fraction

$FEEDIND_{i,fg,T}$	=	share of a feed material *i* fed as a separate product in the ration of feeding group *fg* of species and system *T*, fraction
$CONC_{fg,T}$	=	fraction of concentrates in the diet for the feeding group *fg*, species and system *T*, fraction
$CF_{i,T}$	=	fraction of feed material *i* in the composition of concentrate feed for species and system *T*, fraction

3.3.3 – Feed rations in developing countries

The ration in developing countries is based on the proportion of by-products and concentrates in the ration, which are defined through surveys, literature and expert knowledge, and the availability of roughages in a given cell.

3.3.3.1 – Proportion and availability of roughages

First, the total proportion of roughages in the diet for all ruminant species in a given area (Equation 3.5) is calculated based on the average 'by-products' and 'concentrate' fractions (Equation 3.6 and Equation 3.7, respectively).

Equation 3.5

$$RFRAC_{avg,T} = 1 - (BY_{avg,T} + CONC_{avg,T})$$

Where:

$RFRAC_{avg,T}$	=	weighted average fraction of roughages in the diet for ruminant species *T*, fraction
$BY_{avg,T}$	=	weighted average fraction of by-products in the diet for species *T*, fraction. BY_{avg} is calculated in Equation 3.6.
$CONC_{avg,T}$	=	weighted average fraction of concentrates in the diet for species *T*, fraction. $CONC_{avg}$ is calculated in Equation 3.7.

Equation 3.6

$$\begin{aligned} BY_{avg,T} = {} & (BY_{1,T} \times (AF_T \times AFkg_T) \\ & + BY_{2,T} \times (RF_T \times RFkg_T + RM_T \times RMkg_T + AM_T \times AMkg_T) \\ & + BY_{3,T} \times (MF_T \times MFkg_T + MM_T \times MMkg_T)) \\ & / (AF_T \times AFkg_T + RF_T \times RFkg_T + MF_T \times MFkg_T + AM_T \times AMkg_T + RM_T \times RMkg_T + MM_T \times MMkg_T) \end{aligned}$$

Where:

$BY_{avg,T}$	=	weighted average fraction of by-products in the diet for species *T*, fraction
$BY_{1,T}$	=	fraction of by-products in the diet for the feeding group *1,* species and system *T*, fraction
$BY_{2,T}$	=	fraction of by-products in the diet for the feeding group *2,*species and system *T*, fraction
$BY_{3,T}$	=	fraction of by-products in the diet for the feeding group *3,*species and system *T*, fraction
AF_T, RF_T,…	=	animal numbers from the different cohorts as calculated in the herd module for species and system *T*, heads $\times$ year^{-1}
$AFkg_T$, $RFkg_T$,…	=	average live weights for animals within each cohort as calculated in the herd module for species and system *T*, kg $\times$ head^{-1}

The fraction of by-products for each feeding group (BY_1, BY_2 and BY_3) are defined for each species and system based on literature reviews, expert opinion and surveys.

Equation 3.7

$$\begin{aligned} CONC_{avg,T} = {} & (CONC_{1,T} \times (AF_T \times AFkg_T) \\ & + CONC_{2,T} \times (RF_T \times RFkg_T + RM_T \times RMkg_T + AM_T \times AMkg_T) \\ & + CONC_{3,T} \times (MF_T \times MFkg_T + MM_T \times MMkg_T)) \\ & / (AF_T \times AFkg_T + RF_T \times RFkg_T + MF_T \times MFkg_T + AM_T \times AMkg_T + RM_T \times RMkg_T + MM_T \times MMkg_T) \end{aligned}$$

Where:

$CONC_{avg,T}$	=	weighted average fraction of concentrates in the diet for ruminant species *T*, fraction
$CONC_{1,T}$	=	fraction of concentrates in the diet for the feeding group *1,* species and system *T*, fraction
$CONC_{2,T}$	=	fraction of concentrates in the diet for the feeding group *2,* species and system *T*, fraction
$CONC_{3,T}$	=	fraction of concentrates in the diet for the feeding group *3,* species and system *T*, fraction

AF_T, RF_T, …	=	animal numbers from the different cohorts as calculated in the herd module for species and system *T*, heads × $year^{-1}$
$AFkg_T$, $RFkg_T$, …	=	average live weights for animals within each cohort as calculated in the herd module for species and system *T*, kg × $head^{-1}$

The fraction of concentrate for each feeding group ($CONC_1$, $CONC_2$ and $CONC_3$) is defined for each species and system based on literature reviews, expert opinion and surveys.

Once the total proportion of roughages in the diet for a given cell is calculated, GLEAM estimates the total available dry matter of roughages from the total dry matter yields and harvested areas of pasture, fodder and crop residues (Equation 3.8).

Equation 3.8

$$RFEEDKG = \sum_i (DMYN_i \times Area_i)$$
$$\text{for } i = 1, 6 \text{ to } 13, 15$$

Where:

RFEEDKG	=	total dry matter of roughages available per cell, kg
$DMYN_i$	=	net dry matter yield of feed material *i*, kg × ha^{-1}
$Area_i$	=	harvested area of feed material *i*, ha
i	=	feed material *i* from Table 3.2

In a following step, the available amount of roughages per cell is compared with the animal requirements in that same cell, in order to add leaves and hay in case of feed deficiency. Following IPCC guidelines, GLEAM assumes that daily feed intake, expressed in terms of dry matter, must be between 2% and 3% of live weight. Two conditions are defined based on this criterion and the fraction of roughages in the diet calculated in Equation 3.5: sufficient (when roughages are sufficient to sustain a ratio of daily feed intake to bodyweight equal or higher than 2%) and deficiency conditions (when roughages are only sufficient to sustain a ratio of daily feed intake to bodyweight below 2%).

Sufficiency conditions

$$RFEEDKG / LWTOT \geq (0.02 \times 365) \times RFRAC_{avg,T}$$

Deficiency conditions

$$RFEEDKG / LWTOT < (0.02 \times 365) \times RFRAC_{avg,T}$$

Where:

RFEEDKG	=	total dry matter of roughages available per cell, kg
LWTOT	=	total live weight of ruminant species, kg. Calculated in Equation 3.9.
$RFRAC_{avg,T}$	=	weighted average fraction of roughages in the diet for ruminant species *T*, fraction
0.02	=	daily intake as fraction of body weight.

Equation 3.9

$$LWTOT = \sum_T [\sum_c (N_{T,c} \times LW_{T,c})]$$

Where:

LWTOT	=	total live weight of ruminant species, kg
$N_{T,c}$	=	number of animals of species *T* and cohort *c*, heads
$LW_{T,c}$	=	average live weights of animals of species *T* and cohort *c*, kg × $heads^{-1}$

In situations of deficiency, leaves and hay from adjacent areas are included in the ration in two subsequent steps (Equation 3.10). First, leaves are added to an equivalent of 0.3% of daily intake. Second, hay from adjacent areas is added until reaching the 2% bodyweight equivalent defined previously.

Equation 3.10

$LEAVES_T$ = $(0.003 \times 365) \times LWTOT$

IF $(RFEEDKG + LEAVES_T) / LWTOT > (0.02 \times 365) \times RFRAC_{avg,T}$

No extra material is needed and the ration is completed following step 5.

IF $(RFEEDKG + LEAVES_T) / LWTOT < (0.02 \times 365) \times RFRAC_{avg,T}$

Hay from adjacent areas is added as:

$GRASSH2_T$ = $LWTOT \times ((0.02 \times 365) \times RFRAC_{avg,T} - ((RFEEDKG + LEAVES) / LWTOT))$

Where:

$LEAVES_T$ = total dry matter of 'leaves' available for species and system *T*, kg

$GRASSH2_T$ = total dry matter of 'hay from adjacent areas' available for species and system *T*, kg

The final amount of available roughages is calculated as:

Equation 3.11

$RFEEDKGFINAL_T$ = $RFEEDKG + LEAVES_T + GRASSH2_T$

Where:

$RFEEDKGFINAL_T$ = total dry matter of roughages available per cell for species and system *T*, kg

RFEEDKG = total dry matter available from roughages per cell, kg

$LEAVES_T$ = total dry matter of 'leaves' available for species and system *T*, kg

$GRASSH2_T$ = total dry matter of 'hay from adjacent areas' available for species and system *T*, kg

3.3.3.2 – Share of individual roughage feed materials

The estimation of individual shares of roughages in animal diets is accomplished in two steps. The first one (from Equation 3.12 to Equation 3.14) calculates the share of each roughage material in the total dry matter of roughages available for each species. The second step (Equation 3.15) determines the share of each material in relation to the overall diet.

The share of grass and the distinction between fresh grass and hay is done as follows:

Equation 3.12

$GRASSfrac_T$ = $DMYN_1 \times Area_1 / RFEEDKGFINAL_T$

Where:

$GRASSfrac_T$ = fraction of grass (both fresh and hay) in the total dry matter of roughages available per cell for species and system *T*, fraction

$DMYN_1$ = net dry matter yield of 'grass', $kg \times ha^{-1}$

$Area_1$ = grazed or harvested area of 'grass', ha

$RFEEDKGFINAL_T$ = total dry matter of roughages available per cell for species and system *T*, kg

The fraction of grass is then divided between fresh and hay depending on the agroecological zone and the grazing time of animals as shown in Table 3.4. The share of 'Pasture' manure management system is used as proxy for the grazing time.

Table 3.4 Partitioning of grass fraction

Agro-ecological zone	Partitioning of grass
Arid and hyper-arid	Fresh grass: $FEEDfrac_{1,T}{}^{a} = GRASSfrac_T$ Grass hay: $FEEDfrac_{2,T}{}^{b} = 0$
Temperate and tropical highlands	Fresh grass: $FEEDfrac_{1,T} = GRASSfrac_T \times MMS_{pasture,T} / 100$ Grass hay: $FEEDfrac_{2,T} = GRASSfrac_T \times (100 - MMS_{pasture,T}) / 100$
Humid	Fresh grass: $FEEDfrac_{1,T} = GRASSfrac_T$ Grass hay: $FEEDfrac_{2,T} = 0$

[a] $FEEDfrac_{1,T}$ = fraction of fresh grass in the total dry matter of roughages available per cell for species and system *T*, fraction

[b] $FEEDfrac_{2,T}$ = fraction of hay grass in the total dry matter of roughages available per cell for species and system *T*, fraction

The share of imported hay and leaves is calculated in Equation 3.13 below:

Equation 3.13

$FEEDfrac_{3,T}$ = $GRASSH2_T$ / $RFEEDKGFINAL_T$

$FEEDfrac_{14,T}$ = $LEAVES_T$ / $RFEEDKGFINAL_T$

Where:

$FEEDfrac_{3,T}$ = fraction of hay imported from adjacent areas in the total dry matter of roughages available per cell for species and system *T*, fraction

$FEEDfrac_{14,T}$ = fraction of leaves in the total dry matter of roughages available per cell for species and system *T*, fraction

$GRASSH2_T$ = total dry matter of 'hay from adjacent areas' available for species and system *T*, kg

$LEAVES_T$ = total dry matter of 'leaves' available for species and system *T*, kg

$RFEEDKGFINAL_T$ = total dry matter of roughages available per cell for species and system *T*, kg

For the rest of "Roughages", the fraction is calculated as shown in Equation 3.14.

Equation 3.14

$FEEDfrac_{i,T}$ = $DMYN_i \times Area_i$ / $RFEEDKGFINAL_T$
for i = 6 to 13, 15

Where:

$FEEDfrac_{i,T}$ = fraction of feed material *i* in the total dry matter of roughages available per cell for species and system *T*, fraction

$DMYN_i$ = net dry matter yield of feed material *i*, $kg \times ha^{-1}$

$Area_i$ = grazed and/or harvested area of feed material *i*, ha

$RFEEDKGFINAL_T$ = total dry matter of roughages available per cell for species and system *T*, kg

i = feed material *i* from Table 3.2

The final step is to estimate the individual shares of roughage materials in the overall animal diet for each feeding group following Equation 3.15.

Equation 3.15

$FEED_{i,fg,T}$ = $FEEDfrac_{i,T} \times (1 - (BY_{fg,T} + CONC_{fg,T}))$
for i = 1 to 15, excluding 4 and 5

Where:

$FEED_{i,fg,T}$ = fraction of feed material *i* in the ration for feeding group *fg*, species and system *T*, fraction

$FEEDfrac_{i,T}$ = fraction of feed material *i* in the total dry matter of roughages available per cell for species and system *T*, fraction

$BY_{fg,T}$ = fraction of by-products in the diet for the feeding group *fg,* species and system *T*, fraction

$CONC_{fg,T}$ = fraction of concentrates in the diet for the feeding group *fg,* species and system *T*, fraction

i = feed material *i* from Table 3.2

3.3.3.3 – Share of individual by-product feed materials

The estimation of individual share of by-products is done by combining the available yields of feed materials and the data on the share of 'by-products' feed category.

Equation 3.16 – Cattle

$BYFEEDKG$ = $\sum_i (DMYN_i \times Area_i)$
for i = 18, 19, 20, 21, 25, 26

$FEED_{BY,i,fg,T}$ = $BY_{fg,T} \times DMYN_i \times Area_i$ / $BYFEEDKG$
for i = 18, 19, 20, 21, 25, 26

Where:

$BYFEEDKG$ = total dry matter of by-products available per cell, kg

$DMYN_i$	=	net dry matter yield of 'by-product' feed material *i*, kg×ha^{-1}
$Area_i$	=	harvested area of feed material *i*, ha
$FEED_{BY,i,fg,T}$	=	fraction of 'by-product' feed material *i* for feeding group *fg*, species and system *T*, fraction
$BY_{fg,T}$	=	fraction of 'by-products' in the diet for the feeding group *fg,* species and system *T*, fraction
i	=	feed material *i* from Table 3.2

Equation 3.17 – Buffaloes and small ruminants

$$FEED_{BY,20,fg,T} = BY_{fg,T} \times 0.1$$
$$FEED_{BY,26,fg,T} = BY_{fg,T} \times 0.9$$

Where:

$FEED_{BY,20,fg,T}$	=	fraction 'cottonseed meal' for feeding group *fg*, species and system *T*, fraction
$FEED_{BY,26,fg,T}$	=	fraction 'dry by-products of grain industries' for feeding group *fg*, species and system *T*, fraction
$BY_{fg,T}$	=	fraction of by-products in the diet for the feeding group *fg,* species and system *T*, fraction

3.3.3.4 – Share of individual concentrate feed materials

Concentrate feed consists of a number of by-products that can be fed as a separate product and as part of a mixed compound feed. The final step, in the estimation of animal diets, is the distribution of that concentrate among individual feed materials.

Equation 3.18

$$FEED_{i,fg,T} = FEED_{i,fg,T} \quad \text{for } i = 1 \text{ to } 15$$
$$FEED_{i,fg,T} = FEED_{BY,i,fg,T} + CONC_{fg,T} \times CF_{i,T} \quad \text{for } i = 16 \text{ to } 27$$

Where:

$FEED_{i,fg,T}$	=	fraction of feed material *i* in the ration for feeding group *fg*, species and system *T*, fraction
$CONC_{fg,T}$	=	fraction of concentrates in the diet for the feeding group *fg*, species and system *T*, fraction
$CF_{i,T}$	=	fraction of feed material *i* in the composition of concentrate feed for species and system *T*, fraction
$FEED_{BY,i,fg,T}$	=	fraction of 'by-product' feed material *i* for feeding group *fg*, species and system *T*, fraction
i	=	feed material *i* from Table 3.2

3.4 – MONOGASTRICS' FEED RATION

Feed materials for monogastric species are divided into three main categories:

- Swill and feed from scavenging: domestic (and commercial) food waste and feed from scavenging, used in backyard pig and chicken systems and, to a lesser extent, in some intermediate pig systems.
- Non-local feed materials: these are concentrated feed materials that are blended at a feed mill. The materials are sourced from various locations, and there is little link between the location where the feed material is produced and where it is utilized by the animal. These materials are therefore assumed to be internationally traded (see Section 3.1 and Section 3.2).
- Locally produced feed materials: feeds that are produced locally and used extensively in intermediate and backyard systems.

Non-local feed materials fall into four categories: **whole feed crops**, where there are no harvested crop residues; **by-products** from brewing, grain milling, processing of oilseeds, and sugar production; **grains**, which have harvested crop-residues; and other **non-crop derived feed materials**.

The locally produced feed materials are more varied and, in addition to containing some of the crops, grains and by-products that are part of the non-local feeds, also include: **second-grade crops** deemed unfit for human consumption or use in concentrate feed; **crop residues**; and **forage** in the form of grass and leaves.

A complete list of the feed materials considered is shown in Table 3.5.

The proportions of swill, non-local feed and local feeds in the rations for each system and country are based on reported data and expert judgment.

One of the major differences between the local feeds and the non-local feeds is that the proportions of the individual local feed materials are not defined, but are based on what is available in the country or agroecological zone where the animals are located. The percentage of each feed material is determined by calculating the total yield of each of the crops within the country or AEZ, then assessing the fraction of that yield that is likely to be available as animal feed. The percentage of each feed material in the ration is then assumed to be equal to the proportion of the total available feed.

Finally, the total amount of local feed available is compared with the estimated local feed requirement within the cell. If the availability is below a defined threshold, small amounts of grass and leaves are added to supplement the ration.

For a schematic representation of the feed ration estimation for monogastric species see Figure 3.4 and Figure 3.5. Average values for feed ration for monogastrics at regional level are avialble on the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/).

Table 3.5 List of feed materials for monogastrics

Number	Material	Description
Swill and scavenging		
1	SWILL	Household food waste and other organic material used as feed.
Locally-produced feed materials[a]		
2	GRASSF	Any type of natural or cultivated fresh grass grazed or fed to the animals.
3	PULSES	Leguminous beans.
4	PSTRAW	Fibrous residual plant material such as straw, from leguminous plants cultivation.
5	CASSAVA	Pellets from cassava (*Manihot esculenta*) roots.
6	WHEAT	Grains from wheat (*Triticum aestivum*).
7	MAIZE	Grains from maize (*Zea mays*).
8	BARLEY	Grains from barley (*Hordeum vulgare*).
9	MILLET	Grains from millet (*P. glaucum, E. coracana, P. miliaceum, and others*).
10	RICE	Grains from rice (*Oryza* spp.).
11	SORGHUM	Grains from sorghum (*Sorghum* spp.).
12	SOY	Beans from soy (*Glicyne max*).
13	TOPS	Fibrous residual plant material from sugarcane (*Saccharum* spp.) cultivation.
14	LEAVES	Leaves from natural, uncultivated vegetation found in trees, forest, lanes etc.
15	BNFRUIT	Fruit from banana trees (*Musa* spp.)
16	BNSTEM	Residual plant material such as stems from banana (*Musa* spp.) cultivation.
17	MLSOY	By-product from soy (*Glycine max*) oil production, commonly referred to as 'soy cakes' or 'soybean meal'.
18	MLCTTN	By-product from cottonseeds (*Gossypium* spp.) oil production, commonly referred to as 'cottonseeds cakes'.
19	MLOILSDS	By-product (cakes, meals) from oil production other than soy, cottonseed or palm oil.
20	GRNBYDRY	'Dry' by-products of grain industries such as brans, middlings, etc.
Non-local feed materials[b]		
21	PULSES	Leguminous beans.
22	CASSAVA	Pellets from cassava (*Manihot esculenta*) roots.
23	WHEAT	Grains from wheat (*Triticum aestivum*).
24	MAIZE	Grains from maize (*Zea mays*).
25	BARLEY	Grains from barley (*Hordeum vulgare*).
26	MILLET	Grains from millet (*P. glaucum, E. coracana, P. miliaceum, and others*).
27	RICE	Grains from rice (*Oryza* spp.).
28	SORGHUM	Grains from sorghum (*Sorghum* spp.).
29	SOY	Beans from soy (*Glicyne max*).
30	RAPESEED	Seeds from rape (*B. napus*).
31	SOYOIL	Oil extracted from soybeans (*Glicyne max*).
32	MLSOY	By-product from soy (*Glycine max*) oil production, commonly referred to as 'soy cakes' or 'soybean meal'.
33	MLCTTN	By-product from cottonseeds (*Gossypium* spp) oil production, commonly referred to as 'cottonseeds cakes'.
34	MLRAPE	By-products from rape oil production, commonly referred to as 'canola cakes'.
35	PKEXP	By-products from the production of kernel palm oil (*Elaeis guineensis*), commonly referred to as 'kernel cake'.
36	MLOILSDS	By-product (cakes, meals) from oil production other than soy, cottonseed, rapeseed or palm oil.
37	FISHMEAL	By-products from the fish industries.
38	MOLASSES	By-product from the sugarcane sugar extraction.
39	GRNBYDRY	'Dry' by-products of grain industries such as brans, middlings, etc.
40	GRNBYWET	'Wet' by-products of grain industries such as biofuels, distilleries, breweries, etc.
41	SYNTHETIC	Synthetic additives such as amino-acids or minerals.
42	LIMESTONE	Used as source of calcium, is given to laying hens to favor the formation of the egg shell.

[a] Feeds that are produced locally and used extensively in intermediate and backyard systems. It is a more varied and complex group of feed materials, including grains, by-products, crop residues or forages.
[b] Feed materials that are blended at a feed mill to produce concentrate feed. The materials are sourced from various locations and there is little link between the production site and location where are consumed by the animals.

Figure 3.4 Representation of a hypothetical example of feed ration estimation for pigs

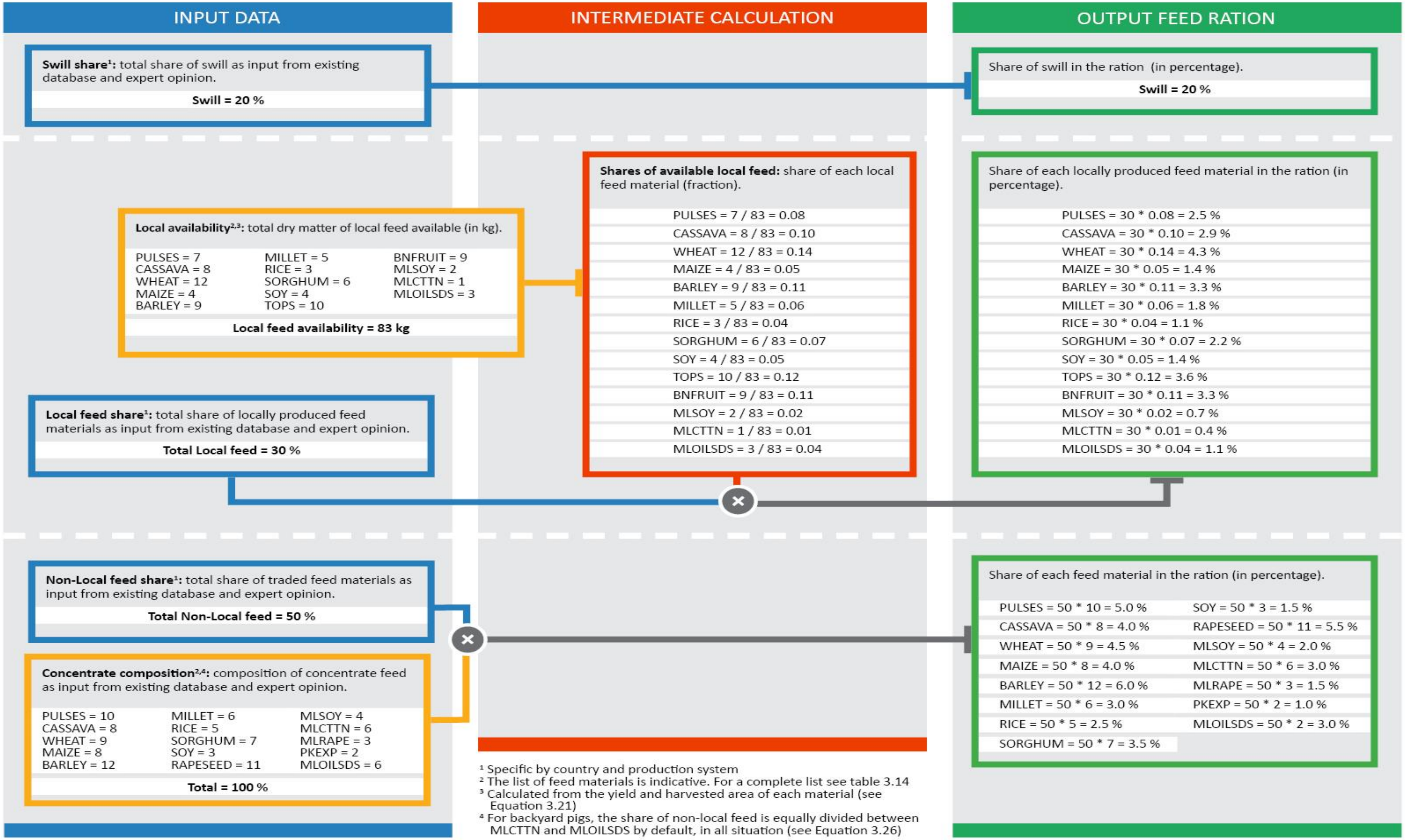
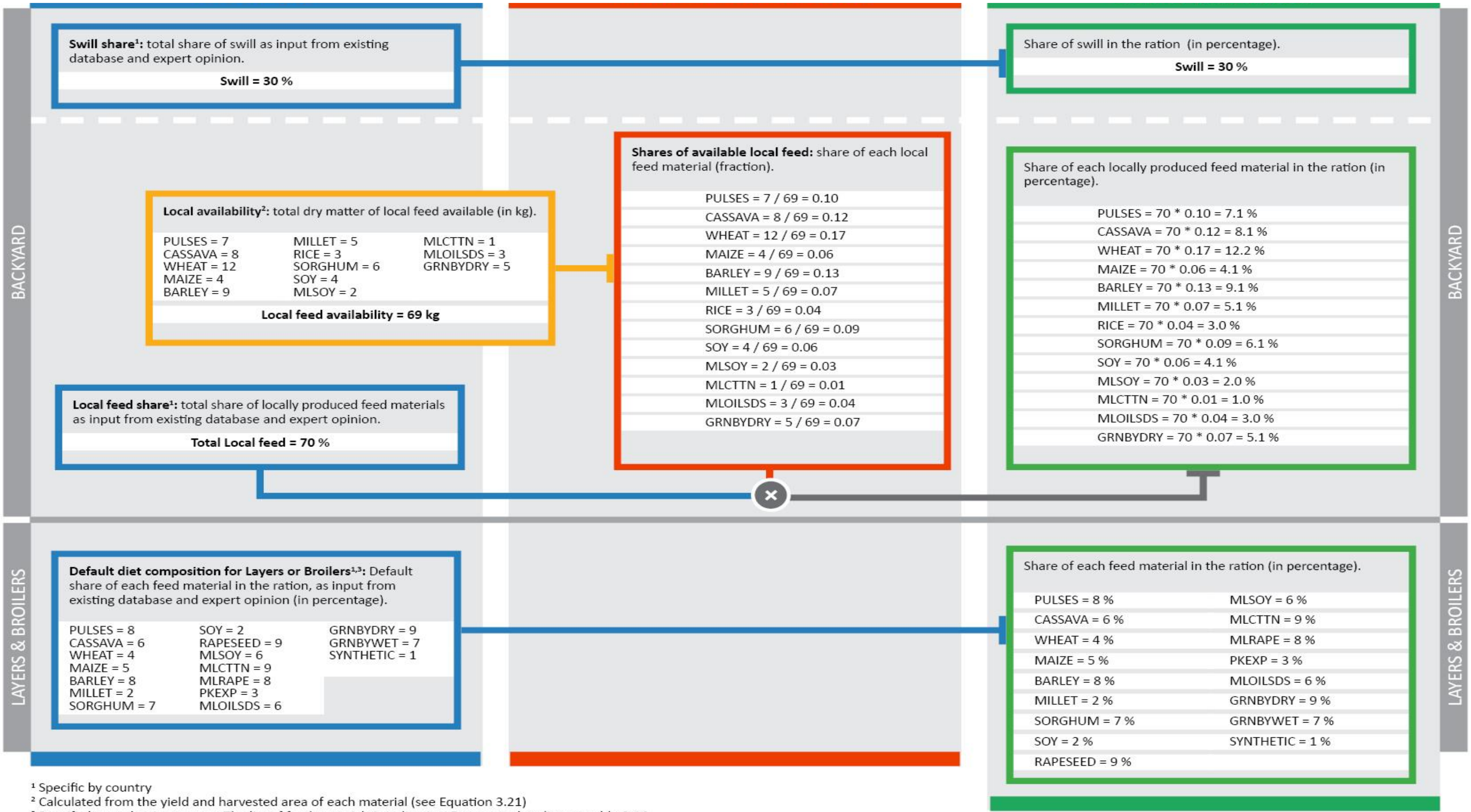


Figure 3.5 Representation of a hypothetical example of feed ration estimation for chickens



[1] Specific by country
[2] Calculated from the yield and harvested area of each material (see Equation 3.21)
[3] Specific by production system. The list of feed materials is indicative. For a complete list see table 3.14

3.4.1 – Calculation of the net dry matter yields

The net dry matter yield of each feed material in a given area defines the yield that is available as feed for the animals. For the purpose of estimating the animal ration it is used as a main input in those cases where the calculation of the local availability of feed is required (see Section 3.3.2 and Section 3.3.4), therefore it is calculated only for the local feed materials. The calculation of the net dry matter yield depends on the type of material considered. In general, the gross dry matter yield (of the crop or crop residues, depending on the feed material; Equation 3.2) is corrected by the FUE, which is the fraction of the yield that is effectively ingested and used as feed by the animals. Moreover, for some feed materials the yield of the respective parental crop is also multiplied by the MFA factor of the material. The latter is a default factor accounting for the feed material mass as a fraction of the total mass of the crop.

Calculations are shown in Equation 3.19. Table 3.6 summarizes the input used for each feed material, for the calculation of the net dry matter yield.

Equation 3.19

$DMYN_i = DMYG_{,i} \times FUE_i \times MFA_i$

for i = 3 to 13, 15 to 20

Where:

$DMYN_i$ = net dry matter yield of feed material *i*, kg DM×ha^{-1}

$DMYG_{,i}$ = gross dry matter yield for feed material *i*, kg DM×ha^{-1}. It can either be the yield of the crop or crop residues. See Table 3.6.

FUE_i = feed use efficiency for feed material *i*, i.e. fraction of the gross yield that is effectively used as feed, fraction. See Table 3.6

MFA_i = mass fraction allocation of feed material *i*, i.e. feed material mass as a fraction of the total mass of the crop, fraction. Values are given in Table 3.6. It is not used for feed materials 3, 4, 6 to 11, 13, 15, 16.

Table 3.6 Net yield equations, gross yields, FUE and MFA for each feed material for monogastric species

Number	Material	Gross dry matter yields	Net yield equation	FUE	MFA
Swill and scavenging					
1	SWILL	NA[a]	NA	1	1
Locally-produced feed materials					
2	GRASSF	Grass	NA	0.95	1
3	PULSES	Pulses	Equation 3.19	1	Equation 6.10b[b]
4	PSTRAW	Pulses (crop residues) – Equation 3.2	Equation 3.19	0.90	Equation 6.10a[b]
5	CASSAVA	Cassava	Equation 3.19	1	1
6	WHEAT	Wheat	Equation 3.19	1	Equation 6.10b[b]
7	MAIZE	Maize	Equation 3.19	1	Equation 6.10b[b,c]
8	BARLEY	Barley	Equation 3.19	1	Equation 6.10b[b]
9	MILLET	Millet	Equation 3.19	1	Equation 6.10b[b]
10	RICE	Rice	Equation 3.19	1	Equation 6.10b[b]
11	SORGHUM	Sorghum	Equation 3.19	1	Equation 6.10b[b]
12	SOY	Soybean	Equation 3.19	1	1
13	TOPS	Sugarcane (crop residues) – Equation 3.2	Equation 3.19	0.70	Equation 6.10a[b]
14	LEAVES	NA[a]	NA	NA	NA
15	BNFRUIT	Banana fruits	Equation 3.19	1	Equation 6.10b[b]
16	BNSTEM	Banana fruits (crop residues) – Equation 3.2	Equation 3.19	0.50	Equation 6.10a[b]
17	MLSOY	Soybean	Equation 3.19	1	0.80
18	MLCTTN	Cotton	Equation 3.19	1	0.45
19	MLOILSDS	Sunflower	Equation 3.19	1	0.60
20	GRNBYDRY	Grains average yield[d]	Equation 3.19	1	0.17
21	GRAINS			1	
Non-local feed materials[d]					
21	PULSES	Pulses	NA	1	Equation 6.10b[b]
22	CASSAVA	Cassava	NA	1	1
23	WHEAT	Wheat	NA	1	Equation 6.10b[b]
24	MAIZE	Maize	NA	1	1
25	BARLEY	Barley	NA	1	Equation 6.10b[b]
26	MILLET	Millet	NA	1	Equation 6.10b[b]
27	RICE	Rice	NA	1	Equation 6.10b[b]
28	SORGHUM	Sorghum	NA	1	Equation 6.10b[b]
29	SOY	Soybean	NA	1	1
30	RAPESEED	Rapeseed	NA	1	1
31	SOYOIL	Soybean	NA	1	0.17
32	MLSOY	Soybean	NA	1	0.80
33	MLCTTN	Cotton	NA	1	0.45
34	MLRAPE	Rapeseed	NA	1	0.58
35	PKEXP	Oil palm fruit	NA	1	0.03
36	MLOILSDS	Sunflower	NA	1	0.58
37	FISHMEAL	NA[a]	NA	NA	NA
38	MOLASSES	Sugarcane	NA	1	0.13
39	GRNBYDRY	Grains average yield[e]	NA	1	0.17
40	GRNBYWET	Barley	NA	1	1
41	SYNTHETIC	NA[a]	NA	NA	NA
42	LIMESTONE	NA[a]	NA	NA	NA

[a] No yield is required for these feed materials: their share in the feed rations and their emission intensities are defined by default values.
[b] For these feed materials, the MFA is only used for the allocation of the emissions from feed production (see Chapter 6, Section 6.1.3) and is calculated with a specific equation.
[c] In industrialized countries, the MFA value of local MAIZE is assumed to be 1, because there is no use for the crop residues.
[d] These materials are sourced from various locations and there is little link between the production site and location where are consumed by the animals. To account for the high level of international trade, average country specific yields were calculated based on trade matrices, as described in Section 3.1 and Section 3.2. Yields, FUE and MFA of these feed materials are used exclusively for the allocation of the emissions from feed production (see Chapter 6, Section 6.1.3).
[e] Average yield of wheat, maize, barley, millet, sorghum, rice and other cereals.

3.4.2 – Proportion of local feed materials

The first step is the calculation of the proportion of locally produced feed materials as shown in Equation 3.20.

Equation 3.20

$LOCALFRAC_T$ = $1 - (SWILLFRAC_T + NONLOCALFRAC_T)$

Where:

$LOCALFRAC_T$ = fraction of locally produced feed materials in the ration of species and system *T*, fraction

$SWILLFRAC_T$ = fraction of swill in the ration of species and system *T*, fraction

$NONLOCALFRAC_T$ = fraction of non-local feed materials in the ration of species and system *T*, fraction

$SWILLFRAC_T$ and $NONLOCALFRAC_T$ are defined base on literature surveys and expert opinion.

3.4.3 – Total locally-produced feed available

The estimation of available local feed is based on the yield and cultivated area of several crops as shown in Equation 3.21.

Equation 3.21

LOCALFEEDKG = $\sum_i(DMYN_i \times Frac_i \times Area_i)$

for i = 3–13, 15–20 (excluding 4, 13–16 for chickens)

Where:

LOCALFEEDKG = total dry matter of locally produced feed materials per cell, kg

$DMYN_i$ = net dry matter yield of feed material *i*, $kg \times ha^{-1}$

$Frac_i$ = fraction of the yield of feed material *i* that is harvested to be used as feed, fraction. The following default values are used: 0.1 for i = 3, 5 to 12; 0.5 for i = 4; 0.15 for i = 16; 1 for other feed materials.

$Area_i$ = harvested area of feed material *i*, ha

i = feed material *i* from Table 3.6

3.4.4 – Comparison with energy requirements and total intake of local feed materials

The total amount of local feed is compared with the animal requirements on an annual basis in the case of pigs. It is assumed that there is sufficient feed when the total available amount in a year represents 10 times the bodyweight.

Deficiency conditions

LOCALFEEDKG / LWTOT < 10

Sufficiency conditions

LOCALFEEDKG / LWTOT ≥ 10

Where:

LOCALFEEDKG = total dry matter of locally produced feed materials per cell, kg

LWTOT = total monogastric species live weight depending on locally produced feed, kg. It is calculated using Equation 3.22.

Equation 3.22

LWTOT = $\sum_T [\sum_c (N_{T,c} \times LW_{T,c}) \times LOCALFRAC_T]$

Where:

LWTOT = total monogastric species live weight depending on locally produced feed, kg

$N_{T,c}$ = number of animals of species and system *T* and cohort *c*, heads

$LW_{T,c}$ = average live weight of animals of species and system *T* and cohort *c*, $kg \times head^{-1}$

$LOCALFRAC_T$ = fraction of locally produced feed materials in the ration of species and system *T*, fraction

In situations of deficiency, grass and leaves are added to the diet. Grass and leaves are added in amounts equivalents to the 10 % and 15% of the total locally produced dry matter.

Equation 3.23

GRASSF = 0.10 × LOCALFEEDKG

LEAVES = 0.15 × LOCALFEEDKG

Where:

GRASSF = total dry matter of 'fresh grass' feed available for monogastric species' consumption, kg

LEAVES = total dry matter of 'leaves' feed available for monogastric species' consumption, kg

LOCALFEEDKG = total dry matter of locally produced feed materials per cell, kg

Therefore, the final amount of local feed materials is calculated as:

Equation 3.24

For pigs:

LOCALFEEDKGFINAL = 1.25 × LOCALFEEDKG

For chickens:

LOCALFEEDKGFINAL = LOCALFEEDKG

Where:

LOCALFEEDKGFINAL = total dry matter of available locally produced feed materials, kg

LOCALFEEDKG = total dry matter of locally produced feed materials per cell, kg

3.4.5 – Individual share of local feed materials

The estimation of individual shares of local feeds is calculated as shown in Equation 3.25.

Equation 3.25

a. $FEED_{i,T}$ = $LOCALFRAC_T$ × GRASSF / LOCALFEEDKGFINAL
for i = 2 (only for pigs)

b. $FEED_{i,T}$ = $LOCALFRAC_T$ × LEAVES / LOCALFEEDKGFINAL
for i = 14 (only for pigs)

c. $FEED_{i,T}$ = $LOCALFRAC_T$ × ($DMYN_i$ × $Frac_i$ × $Area_i$) / LOCALFEEDKGFINAL
for i = 3 to 13, 15 to 20 (excluding 4, 13, 15, 16 for chickens)

Where:

$FEED_{i,T}$ = fraction of feed material *i* in the ration of species and system *T*, fraction

$LOCALFRAC_T$ = fraction of locally produced feed materials in the ration of species and system *T*, fraction

GRASSF = total dry matter of 'fresh grass' feed available for monogastric species' consumption, kg

LEAVES = total dry matter of 'leaves' feed available for monogastric species' consumption, kg

$DMYN_i$ = net dry matter yield of feed material *i*, kg×ha^{-1}

$Frac_i$ = fraction of the yield of feed material *i* that is harvested to be used as feed, fraction. The following default values are used: 0.1 for *i* = 3, 5 to 12; 0.5 for *i* = 4; 0.15 for *i* = 16; 1 for other feed materials.

$Area_i$ = harvested area of feed material *i*, ha

LOCALFEEDKGFINAL = total dry matter of available locally produced feed materials, kg

i = feed material *i* from Table 3.6

3.4.6 – *Individual share of non-local feed materials*

The individual share of non-local materials is calculated in different ways, depending on the particular species and production system. Average feed rations for monogastric species are availalble in the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/).

PIGS – BACKYARD SYSTEMS

The fraction of non-local feed materials in the ration is equally shared between cottonseed cakes and oilseeds cakes.

Equation 3.26

$FEED_i$ = NONLOCALfrac / 2
for i = 33, 36

Where:

$FEED_{i,}$ = fraction of feed material *i* in the ration, fraction
NONLOCALFRAC = fraction of non-local feed materials in the ration, fraction
i = feed material *i* from Table 3.6

PIGS – INTERMEDIATE & INDUSTRIAL SYSTEMS

The non-local feed materials are fed to animals as part of a mixed concentrate feed. Data about the composition of concentrate feed for commercial pigs are based on literature, surveys and expert knowledge. The fraction of each non-local feed material in the total ration is calculated as follows.

Equation 3.27

$FEED_{i,T}$ = $NONLOCALFRAC_T \times CF_i$
for *i* = 21 to 42

Where:

$FEED_{i,T,}$ = fraction of feed material *i* in the ration of system *T*, fraction
$NONLOCALFRAC_T$ = fraction of non-local feed materials in the ration of system *T*, fraction
$CF_{i,T}$ = fraction of feed material *i* in the composition of concentrate feed, fraction
i = feed material *i* from Table 3.6

CHICKENS

It is assumed that non-local feed materials make no contribution of to the diet of backyard animals. Therefore, the final ration for that system is already defined in Equation 3.25.

Diets for layers and broiler systems are fully characterized based on literature reviews, national consultation and expert knowledge.

3.5 – NUTRITIONAL VALUES

Feed nutritional value in GLEAM are taken from several sources including FEEDEPEDIA, NRC guidelines for pigs and poultry and CVB tables from the Dutch feed board database (Stichting CVB) and are summarized in Table S.3.3 and Table S.3.4 in the supplementary information. Using nutritional information on feedstuffs, average values of digestibility, gross and metabolizable energy and nitrogen content are calculated for each species, production system and feeding group following Equation 3.28.

Equation 3.28

a. $DIET_{DI}$ = $\sum_i(FEED_i \times DI_i)$
b. $DIET_{GE}$ = $\sum_i(FEED_i \times GE_i)$
c. $DIET_{ME}$ = $\sum_i(FEED_i \times ME_i)$
d. $DIET_{Ncont}$ = $\sum_i(FEED_i \times Ncont_i)$

Where:

$DIET_{DI}$	=	average digestibility of ration, percentage
$DIET_{GE}$	=	average gross energy content of ration, $MJ \times kgDM^{-1}$
$DIET_{ME}$	=	average metabolizable energy content of ration, $MJ \times kgDM^{-1}$
$DIET_{Ncont}$	=	average nitrogen content of ration, $gN \times kg\ DM^{-1}$
$FEED_i$	=	fraction of feed material *i* in the ration, fraction
DI_i	=	digestibility of feed material *i*, percentage
GE_i	=	gross energy content of feed material *i*, $MJ \times kgDM^{-1}$
ME_i	=	metabolizable energy content of feed material *i*, $MJ \times kgDM^{-1}$
$Ncont_i$	=	nitrogen content of feed material *i*, $gN \times kg\ DM^{-1}$

3.6 – ENERGY REQUIREMENTS

The gross energy requirement is the sum of the requirements for maintenance, milk production, pregnancy, animal activity, weight gain and production. The method estimates the energy requirement for maintenance as a function of live weight and the energy for activity as the energy expended in walking, grazing or scavenging. Energy requirement for production, instead, depends on the level of productivity (e.g. milk yield, live weight gain, fibre production, egg production). Requirements can also be influenced by the physiological state (pregnancy), ambient temperature and the stage of maturity of the animal. Based on production and management practices, the net energy and feed requirements of all animals are calculated. Data from the herd module (i.e. the number of animals in each category, their average weights, growth rates, fertility rates and yields) were combined with input data on: egg weight, protein/fat fraction of the milk, ambient temperature, and activity levels.

For schematic representation of the energy requirement and feed intake calculation, see Figure 3.6 and Figure 3.7.

Figure 3.6 Schematic representation of the energy requirement and feed intake for ruminants

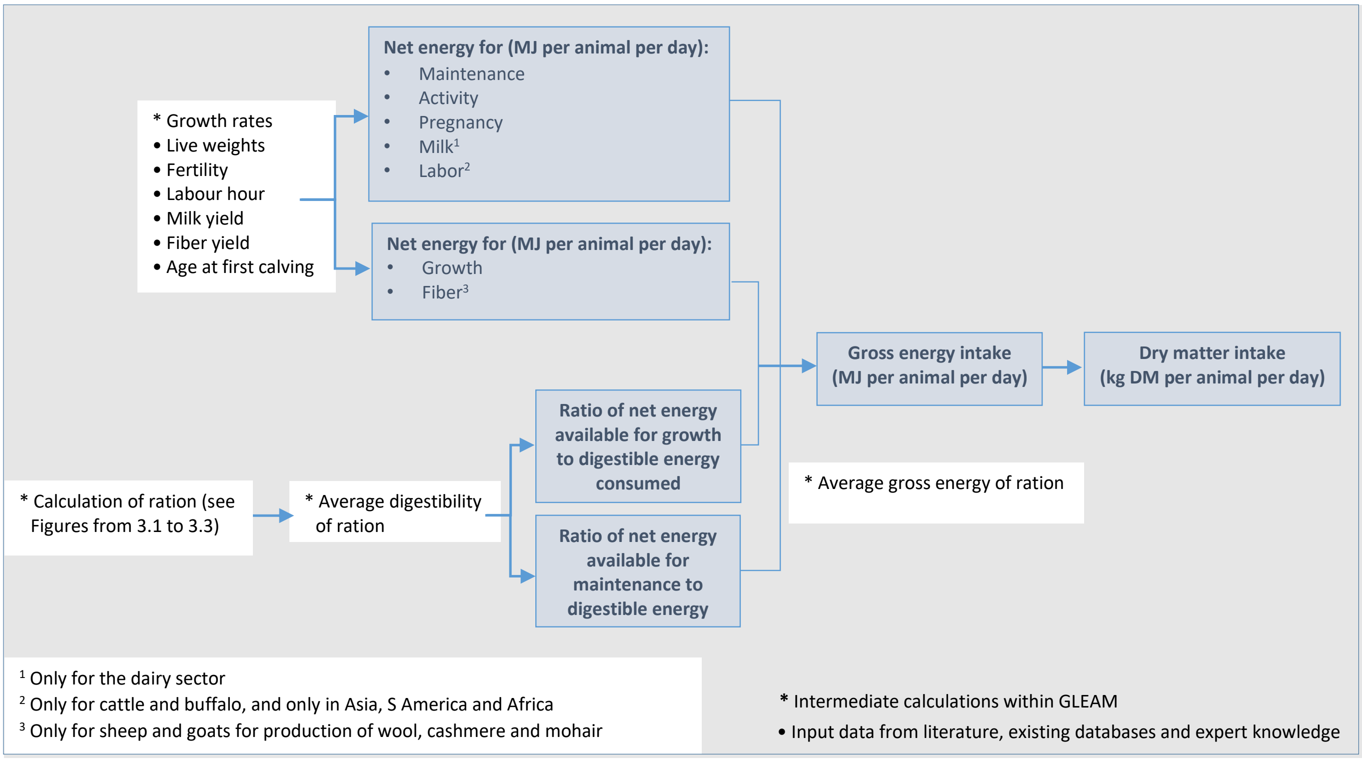
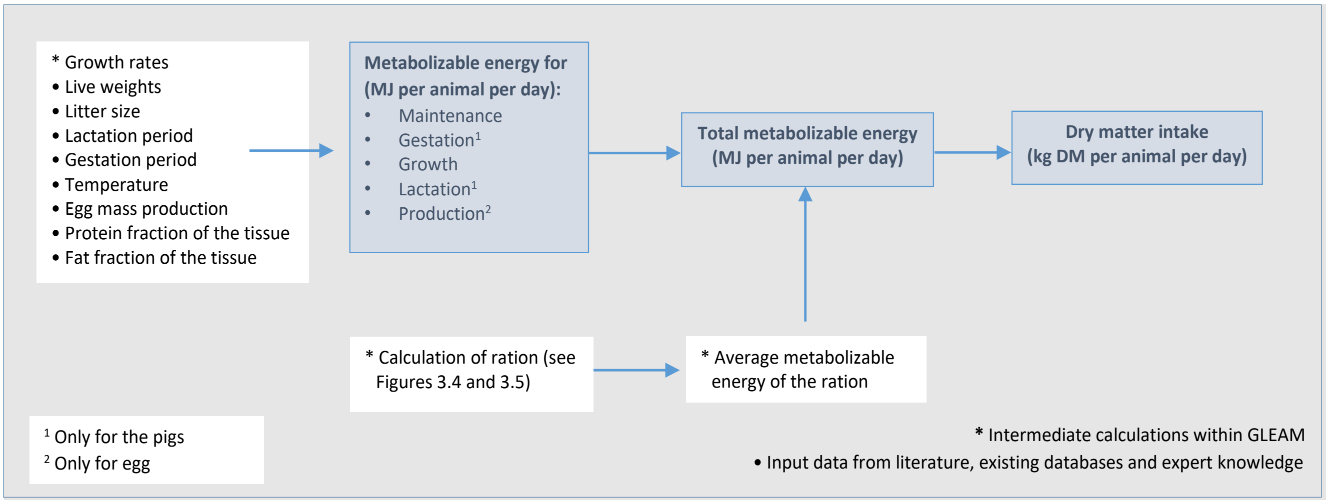


Figure 3.7 Schematic representation of the energy requirement and feed intake for monogastrics



3.6.1 – Energy requirement of ruminants

GLEAM follows the IPCC Tier 2 algorithms and therefore calculates the energy requirements for each cohort individually (IPCC, 2019). Table 3.7 summarizes the equations used to estimate the daily gross energy (GE) needs:

Table 3.7 Equations used to estimate GE for ruminant species

Metabolic function	Abbreviation	Equations for large ruminants	Equations for small ruminants
Maintenance	NE_{main}	Equation 3.29	Equation 3.29
Activity	NE_{act}	Equation 3.30	Equation 3.31
Growth	NE_{gro}	Equation 3.32	Equation 3.33
Milk production	NE_{lact}	Equation 3.34	Equation 3.35
Draught power	NE_{work}	Equation 3.36	Not applicable
Production of fibre	NE_{fiber}	Not applicable	Equation 3.37
Pregnancy	NE_{preg}	Equation 3.38	Equation 3.39
Ratio of net energy available in diet for maintenance to digestible energy consumed	REM	Equation 3.40	Equation 3.40
Ratio of net energy available in diet for growth to digestible energy consumed	REG	Equation 3.41	Equation 3.41
Daily gross energy	GE	Equation 3.42	Equation 3.42

3.6.1.1 – Net energy for maintenance (NE_{main})

NE_{main} is the net energy required for the maintenance of basal metabolic activity. It is estimated as follows:

Equation 3.29

$$NE_{main,c} = C_{main,c} \times LW_c^{\,0.75}$$

Where:

$NE_{main,c}$ = net energy required by animal for maintenance in cohort *c*, $MJ \times head^{-1} \times day^{-1}$

$C_{main,c}$ = coefficient for NE_{main} for each cohort *c*, $MJ \times kg^{-0.75} \times day^{-1}$. Values are given in Table 3.9.

LW_c = average live weight of the animals in cohort *c*, $kg \times head^{-1}$

Table 3.8 Coefficient for calculating NE_{main}

Animal category	GLEAM cohorts	C_{main} ($MJ \times kg^{-0.75} \times day^{-1}$)
Cattle and Buffaloes, lactating cows	AF	0.386
Cattle and Buffaloes, non-lactating cows	RF, MF, MFf	0.322[a]
Cattle and Buffaloes, bulls	AM, RM, MM, MMf	0.370[a]
Goats	AF, AM, MF, MM, RFA, RFB, RMA, RMB	0.315
Sheep lamb to 1 year	RFA, MF	0.236
Sheep intact male lambs to 1 year	RMA, MM	0.271
Sheep older than 1 year	AF, RFB	0.217

Sheep intact males older than 1 year	AM, RMB	0.250

[a] C_{main} of replacement animals is multiplied by 0.974 (except for goats). This prevents an overestimation of NE_{main} resulting from using the average live weight for the entire growing period instead of the average of live weights from each day.

3.6.1.2 – Net energy for activity (NE_{act})

NE_{act} is the net energy required for obtaining food, water and shelter based on the feeding situation and not directly related to the feed quality.

Equation 3.30 – Large ruminants

$NE_{act,c} = C_{act,c} \times NE_{main,c}$

Where:

$NE_{act,c}$ = net energy for animal activity in cohort *c*, $MJ \times head^{-1} \times day^{-1}$

$C_{act,c}$ = coefficient for NE_{act} which depends on the animal feeding condition in cohort *c*, fraction. Values are given in Table 3.9 (IPCC, 2019, Volume 4, Chapter 10, Table 10.5)

$NE_{main,c}$ = net energy required by animal for maintenance in cohort *c*, $MJ \times head^{-1} \times day^{-1}$

Equation 3.31– Small ruminants

$NE_{act,c} = C_{act,c} \times LW_c$

Where:

$NE_{act,c}$ = net energy for animal activity in cohort *c*, $MJ \times head^{-1} \times day^{-1}$

$C_{act,c}$ = coefficient for NE_{act} which depends on the animal feeding condition in cohort *c*, $MJ \times kg^{-1} \times day^{-1}$. Values are given in Table 3.9 (IPCC, 2019, Volume 4, Chapter 10, Table 10.5)

LW_c = average live weight of the animals in cohort *c*, $kg \times head^{-1}$

Table 3.9 Activity coefficients for different feeding situations

Situation	Definition	C_{act}
Cattle and Buffaloes (fraction)		
Stall	Animals are confined to small area with the result of little to none energy expenditure	0.00
Grazing	Animals are confined in areas with sufficient forage requiring modest energy expense to acquire feed	0.17[a]
Rangeland	Animals graze in open range land or hilly terrain and expend significant energy to acquire feed	0.36[a]
Sheep and Goats ($MJ \times kg^{-1} \times day^{-1}$)		
Housed ewes	Animals are confined due to pregnancy in the final trimester (50 days)	0.0096
Grazing flat pasture	Animals walk up to 1 000 meters per day and expend very little energy to acquire feed	0.0107[a]
Grazing hilly pasture	Animals walk up to 5 000 meters per day and expend significant energy to acquire feed	0.0240[a]
Housed fattening lambs	Animals are housed for fattening.	0.0067
Lowland goats	Animals walk and graze in lowland pasture	0.019
Hill and mountain goats	Animals graze in open range land or hilly terrain and expend significant energy to acquire feed.	0.024

[a]In order to reflect the proportion of animals grazing, Cact is multiplied by the share of Pasture/Range/Paddock manure management system (MMSpasture).

3.6.1.3 – Net energy for growth (NE_{gro})

NE_{gro} is the net energy required for growth, that is, for gaining weight. These equations are applied to replacement and fattening animals (both in feedlots and outside feedlots).

Equation 3.32 – Large ruminants

a. $NE_{gro,cf} = 22.02 \times (LW_{cf} / (C_{gro} \times AFkg))^{0.75} \times DWGF^{1.097}$

b. $NE_{gro,cm} = 22.02 \times (LW_{cm} / (C_{gro} \times AMkg))^{0.75} \times DWGM^{1.097}$

c. $NE_{gro,MFf} = 22.02 \times (MFfkg / (C_{gro} \times LWENDF))^{0.75} \times DWGFF^{1.097}$

d. $NE_{gro,MMf} = 22.02 \times (MMfkg / (C_{gro} \times LWENDM))^{0.75} \times DWGFM^{1.097}$

Where:

NE_{gro}	=	net energy required by animal for growth in cohort *c*, MJ×head^{-1}×day^{-1}
LW	=	average live weight of growing animals, kg×head^{-1}
C_{gro}	=	dimensionless coefficient given in Table 3.10
AFkg	=	average live weight of adult female animals, kg×head^{-1}
AMkg	=	average live weight of adult male animals, kg×head^{-1}
DWGF	=	average daily growth rate of female animals from calf to adult animal, kg×head^{-1}×day^{-1}
DWGM	=	average daily growth rate of male animals from calf to adult animal, kg×head^{-1}×day^{-1}
DWGFF	=	average daily growth rate of female animals in feedlots, kg×head^{-1}×day^{-1}
DWGMF	=	average daily growth rate of male animals in feedlots, kg×head^{-1}×day^{-1}
cf	=	cohorts of replacement (RF) or fattening female animals (MF)
cm	=	cohorts of replacement (RM) or fattening male animals (MM)
MFf	=	cohort of feedlot female animals
MMf	=	cohort of feedlot male animals

Table 3.10 Constants for calculating NE_{gro} in large ruminants

Animal category	GLEAM cohorts	C_{gro} (dimensionless)
Cattle and Buffaloes		
Female animals	RF, MF, MFf	0.8
Male animals	RM MM, MMf	1.2 1.0

Equation 3.33 – Small ruminants

$NE_{gro,c}$ = (RF1kg – RFAkg) × [(a + 0.5b(RF1kg – RFAkg)] / 365

Where:

$NE_{gro,c}$	=	net energy required by animal for growth in cohort *c*, MJ×head^{-1}×day^{-1}
RF1kg	=	the live bodyweight at the end of the 1-year-old in cohort *c*, kg×head^{-1}×day^{-1}
RFAkg	=	the live bodyweight in the midst of the 1-year-old in cohort *c*, kg×head^{-1}×day^{-1}
a_c, b_c	=	constants given in Table 3.11 for cohort *c*

Table 3.11 Constants for calculating NE_{gro} in small ruminants

Animal category	GLEAM cohorts	a (MJ×kg^{-1})	b (MJ×kg^{-2})
Sheep and Goats			
Intact males	RM, RMA, RMB	2.5	0.35
Castrates (Sheep)	MM	4.4	0.32
Females (Sheep)	RF, RFA, RFB, MF	2.1	0.45
Goats (all categories)		5.0	0.33

3.6.1.4 – Net energy for milk production (NE_{lact})

NE_{lact} is the net energy required for milk production. These equations are applied to adult females only.

Equation 3.34 – Large ruminants

$NE_{lact,AF}$ = Milk × (1.47 + 0.40 × Fat)

Where:

$NE_{lact,AF}$	=	net energy required by animal for lactation in the adult females cohort *AF*, MJ×head^{-1}×day^{-1}
Milk	=	daily milk production (assumed to be null for the specialized meat herds), kg milk×cow^{-1}×day^{-1}
Fat	=	fat content of milk, percentage by weight

Equation 3.35 – Small ruminants

$NE_{lact,AF}$ = Milk × EV_{milk}

Where:

$NE_{lact,AF}$	=	net energy required by animal for lactation in the adult females cohort *AF*, $MJ \times head^{-1} \times day^{-1}$
Milk	=	daily milk production (assumed to be null for the specialized meat herds), $kg\ milk \times ewe/doe^{-1} \times day^{-1}$
EV_{milk}	=	net energy to produce 1 kg of milk. A default value of 4.6 $MJ \times kg\ milk^{-1}$ is used, assuming a 7% fat content

3.6.1.5 – Net energy for draught power (NE_{work})

NE_{work} is the net energy required for animal work, used to estimate the energy required for draught power from cattle and buffalo bulls. It is estimated that 10% of a day's maintenance energy is used per hour of work. The Equation 3.36 is valid only for the herd with BCR >= 0.10.

Equation 3.36

$$NE_{work,AM} = 0.10 \times NE_{main,AM} \times Hours$$

Where:

$NE_{work,AM}$	=	net energy required by animal for work in the adult males cohort *AM*, $MJ \times head^{-1} \times day^{-1}$
$NE_{main,\ AM}$	=	net energy required by animal for maintenance in the adult males cohort *AM*, $MJ \times head^{-1} \times day^{-1}$
Hours	=	number of hours of work per day, $h \times head^{-1} \times day^{-1}$

3.6.1.6 – Net energy for production of fibre (NE_{fibre})

NE_{fibre} is the net energy required by small ruminants for producing fibre such as wool, cashmere and mohair. These equations are applied to adult and fattening animals.

Equation 3.37

$$NE_{fibre,c} = EV_{fibre} \times Production_{fibre,c}$$

Where:

$NE_{fibre,c}$	=	net energy required by animal for fibre production in cohort *c*, $MJ \times head^{-1} \times day^{-1}$
EV_{fibre}	=	energy value per kilogram of fibre. Default value of 24/365 $MJ \times kg\ fibre^{-1}$ is used
$Production_{fibre,c}$	=	annual production of fibre by animal in cohort *c*, $kg\ fibre \times head^{-1} \times year^{-1}$
c	=	cohorts of adult and fattening animals

3.6.1.7 – Net energy for pregnancy (NE_{preg})

NE_{preg} is the net energy required for pregnancy. For large ruminants, it is estimated that 10% of NE_{main} is needed for a 281-day pregnancy period (Equation 3.38). For small ruminants, this percentage varies depending on the litter size (Equation 3.39). The equation is applied to adult and replacement females only and for goats only to RFB category.

Equation 3.38 – Large ruminants

a. $NE_{preg,AF} = NE_{main,AF} \times 0.1 \times FR / 100$

b. $NE_{preg,RF} = NE_{main,RF} \times 0.1 / (AFC / 2)$

Where:

$NE_{preg,AF}$	=	net energy required by adult females for pregnancy, $MJ \times head^{-1} \times day^{-1}$
$NE_{preg,RF}$	=	net energy required by replacement females for pregnancy, $MJ \times head^{-1} \times day^{-1}$
$NE_{main,AF}$	=	net energy required by adult females for maintenance, $MJ \times head^{-1} \times day^{-1}$
$NE_{main,RF}$	=	net energy required by replacement females for maintenance, $MJ \times head^{-1} \times day^{-1}$
FR	=	fertility rate of adult females, percentage
AFC	=	age at first calving, year

Equation 3.39 – Small ruminants

a. $NE_{preg,AF} = NE_{main,AF} \times (0.077 \times (2 - LITSIZE) + 0.126 \times (LITSIZE - 1)) \times (FR / 100)$

b. $NE_{preg,RF} = NE_{main,RF} \times 0.077$

Where:

$NE_{preg,AF}$	=	net energy required by adult females for pregnancy, $MJ \times head^{-1} \times day^{-1}$
$NE_{preg,RF}$	=	net energy required by replacement females for pregnancy, $MJ \times head^{-1} \times day^{-1}$
$NE_{main,AF}$	=	net energy required by adult females for maintenance, $MJ \times head^{-1} \times day^{-1}$
$NE_{main,RF}$	=	net energy required by replacement females for maintenance, $MJ \times head^{-1} \times day^{-1}$
LITSIZE	=	litter size, number of lambs/kids per parturition, head
FR	=	fertility rate of adult females, percentage

3.6.1.8 – Ratio of net energy in the feed intake for maintenance to digestible energy (REM)

The ratio of net energy available in the feed intake for maintenance to digestible energy consumed (REM) for ruminant species is calculated following Equation 3.40 below:

Equation 3.40

$$REM_{fg} = 1.123 - (4.092 \cdot 10^{-3} \times (DIET_{DI,fg}) + (1.126 \cdot 10^{-5} \times (DIET_{DI,fg} / 100)^2) - (25.4 / (DIET_{DI,fg} / 100))$$

Where:

REM_{fg}	=	ratio of net energy available in the diet for maintenance to digestible energy for the feeding group *fg*, fraction
$DIET_{DI,fg}$	=	average digestibility of ration for the feeding group *fg*, percentage
fg	=	feeding group as shown in Table 3.2

3.6.1.9 – Ratio of net energy available in the feed intake for growth to digestible energy consumed (REG)

The ratio of net energy available in the feed intake for growth to digestible energy consumed (REG) for ruminant species is calculated following Equation 3.41 below:

Equation 3.41

$$REG_{fg} = 1.164 - (5.160 \cdot 10^{-3} \times (DIET_{DI,fg}) + (1.308 \cdot 10^{-5} \times (DIET_{DI,fg} / 100)^2) - (37.4 / (DIET_{DI,fg} / 100))$$

Where:

REG_{fg}	=	ratio of net energy available in the diet for growth to digestible energy consumed for the feeding group *fg*, fraction
$DIET_{DI,fg}$	=	average digestibility of ration for the feeding group *fg*, percentage
fg	=	feeding group as shown in Table 3.2

3.6.1.10 – Total gross energy (GE)

The gross energy requirement is based on the amount of net energy requirements and the energy availability of the feed intake as showed in the equation below, using the relevant terms for each species and animal category:

Equation 3.42

$$GE_{tot,c} = (((NE_{main,c} + NE_{act,c} + NE_{lact,c} + NE_{work,c} + NE_{preg,c}) / REM_{fg}) + ((NE_{gro,c} + NE_{fibre,c}) / REG_{fg})) / (DIET_{DI,fg} / 100)$$

Where:

$GE_{tot,c}$	=	total gross energy requirement by animal in cohort *c*, $MJ \times head^{-1} \times day^{-1}$
$NE_{main,c}$	=	net energy required by animal for maintenance in cohort *c*, $MJ \times head^{-1} \times day^{-1}$
$NE_{act,c}$	=	net energy for animal activity in cohort *c*, $MJ \times head^{-1} \times day^{-1}$
$NE_{gro,c}$	=	net energy required by animal for growth in cohort *c*, $MJ \times head^{-1} \times day^{-1}$
$NE_{lact,c}$	=	net energy required by animal for lactation in cohort *c*, $MJ \times head^{-1} \times day^{-1}$
$NE_{work,c}$	=	net energy required by animal for work in cohort *c*, $MJ \times head^{-1} \times day^{-1}$
$NE_{fibre,c}$	=	net energy required by animal for fibre production in cohort *c*, $MJ \times head^{-1} \times day^{-1-}$
$NE_{preg,c}$	=	net energy required by animal for pregnancy in cohort *c*, $MJ \times head^{-1} \times day^{-1}$
REM_{fg}	=	ratio of net energy available in the diet for maintenance to digestible energy consumed for the feeding group *fg*, fraction
REG_{fg}	=	ratio of net energy available in the diet for growth to digestible energy consumed for the feeding group *fg*, fraction
fg	=	feeding group as shown in Table 3.2

3.6.2 – Energy requirement of pigs

As the 2006 IPCC guidelines do not include equations for calculating the energy requirement of monogastric species, equations for pigs were derived from NRC (1998). The formulas were adjusted in light of recent farm data supplied (P. Bikker, personal communication, 2011). The model distinguishes four groups with respect their nutrition needs: sows, boars, replacement animals and fattening pigs. The table below summarizes the equations used to estimate the energy requirements for pigs.

Table 3.12 Equations used to estimate ME for pigs

Metabolic function	Abbreviation	Equation
Maintenance	ME_{main}	Equation 3.43
Gestation	ME_{gest}	Equation 3.44
Lactation	ME_{lact}	Equation 3.45
Growth	ME_{prot} / ME_{fat}	Equation 3.46/3.47
Total energy requirement		
Adult females (AF)	ME_{tot}	Equation 3.48a
Adult males (AM)	ME_{tot}	Equation 3.48b
Replacement females (RF)	ME_{tot}	Equation 3.48c
Replacement males (RM)	ME_{tot}	Equation 3.48d
Fattening animals (M2)	ME_{tot}	Equation 3.48e

3.6.2.1 – Energy requirement for maintenance (ME_{main})

ME_{main} is the metabolizable energy requirement for maintenance.

Equation 3.43

$$ME_{main,c} = C_{main} \times LW_c^{0.75} \times C_{act}$$

Where:

$ME_{main,c}$ = metabolizable energy required by animal for maintenance in cohort *c*, $MJ \times head^{-1} \times day^{-1}$

C_{main} = coefficient for maintenance energy requirement, $MJ \times kg^{-0.75} \times day^{-1}$. Default value of 0.4435 is used

LW_c = average live weight for maintenance energy requirement of the animals in cohort *c*, $kg \times head^{-1}$. Values are given in Table 3.13,

C_{act} = dimensionless coefficient for activity that depends on animal feeding condition, with 1.125 for backyard and 1.0 for intermediate and industrial systems

Table 3.13 Average live weight for maintenance energy requirements for pigs

Animal cohort	Weight ($kg \times animal^{-1}$)
Adult females (idle)	AFkg
Adult females (gestation)	AFkg + (LITSIZE × Ckg + 0.15 × AFkg) / 2
Adult females (lactation)	AFkg + (0.15 × AFkg) / 2
Adult males	AMkg
Replacement females	RFkg
Replacement males	RMkg
Fattening animals	M2kg

Where:

LITSIZE = litter size, number of piglets per parturition, heads×parturition-1

Ckg = live weight of piglets at birth, kg×head-1

AFkg = average live weight of adult females, kg×head-1

AMkg = average live weight of adult males, kg×head-1

RFkg = average live weight of replacement females, kg×head-1

RMkg = average live weight of replacement males, kg×head-1

M2kg = average live weight of meat animals, kg×head-1

3.6.2.2 – Energy requirement for gestation (ME_{gest})

ME_{gest} is the metabolizable energy requirement for gestation. This equation is applied only to adult and replacement females. In the second case, only a part of the animals is at reproductive age. Therefore, the energy requirement for this cohort must be corrected by the age at first farrowing of the animals.

Equation 3.44

$$ME_{gest,c} = C_{gest} \times LITSIZE \times C_{adj,c}$$

Where:

ME_{gest}	=	metabolizable energy required by animal for gestation in cohort *c*, $MJ \times head^{-1} \times day^{-1}$
C_{gest}	=	coefficient for gestation energy requirement, $MJ \times piglet^{-1}$. Default value of 0.14985 is used
LITSIZE	=	litter size, number of piglets per parturition, $heads \times parturition^{-1}$
$C_{adj,c}$	=	coefficient of adjustment to account for the reproductive part of the cohort *c*, year. A value of 1 is used for adult females and a value of 1 / AFCF is used for replacement females (AFCF is the age at parturition based on the daily weight gain, see Section 2.3.2.1).
c	=	cohort of adult or replacement females

3.6.2.3 – Energy requirement for lactation (ME_{lact})

ME_{lact} is the metabolizable energy requirement for lactation. This equation is applied only to adult and replacement females. In the second case, only a part of the animals is at reproductive age. Therefore, the energy requirement for this cohort must be corrected by the age at first farrowing of the animals.

Equation 3.45

$$ME_{lact,c} = LITSIZE \times (1 - 0.5 \times (DR1 / 100)) \times ((C_{lact} \times (Wkg - Ckg) \times 1000 / Lact) - (C_{wloss} / C_{conv})) \times C_{adj,c}$$

Where:

$ME_{lact,c}$	=	metabolizable energy required by animal for lactation in cohort *c*, $MJ \times head^{-1} \times day^{-1}$
LITSIZE	=	litter size, number of lambs/kids per parturition, $heads \times parturition^{-1}$
DR1	=	death rate of piglets, percentage
C_{lact}	=	coefficient for lactation energy requirement, $MJ \times g\ live\ weight^{-1}$. Default value of 0.02059 is used.
Wkg	=	live weight of piglets at weaning age, $kg \times head^{-1}$
Ckg	=	live weight of piglets at birth, $kg \times head^{-1}$
Lact	=	duration of lactation period, days
C_{wloss}	=	coefficient for weight loss from sow due to lactation, $MJ \times head^{-1} \times day^{-11}$. Default value of 0.3766 is used.
C_{conv}	=	efficiency for intake to milk energy conversion, fraction. Default value of 0.67 is used.
$C_{adj,c}$	=	coefficient of adjustment to account for the reproductive part of the cohort *c*, year. A value of 1 is used for adult females and a value of 1 / AFCF is used for replacement females (AFCF is the age at parturition based on the daily weight gain, see Section 2.3.2.1).
c	=	cohort of adult or replacement females

3.6.2.4 – Energy requirement for growth (ME_{prot} and ME_{fat})

ME_{prot} and ME_{fat} are the metabolizable energy requirements for the generation, during growth, of proteins and fat, respectively. It is assumed that all growth is either fat or protein tissue. These equations are applied only to replacement and fattening animals.

Equation 3.46

$$ME_{prot,c} = DWG_c \times PTissue \times Prot \times C_{MEprot}$$

Where:

$ME_{prot,c}$	=	metabolizable energy required for generating new protein in tissues for cohort *c*, $MJ \times head^{-1} \times day^{-1}$
DWG_c	=	daily weight gain by animal in cohort *c*, $kg \times head^{-1} \times day^{-1}$
PTissue	=	fraction of protein tissue in the daily weight gain, fraction. Default values of 0.60, 0.65 and 0.7 for backyard, intermediate and industrial systems are used, respectively.

Prot = fraction of protein in protein tissue, fraction. Default value of 0.23 is used

C_{MEprot} = metabolizable energy required for protein in protein tissue, MJ×kg protein^{-1}. Default value of 54.0 is used.

c = cohort of replacement and fattening animals

Equation 3.47

$$ME_{fat,c} = DWG_c \times (1 - PTissue) \times Fat \times C_{MEfat}$$

Where:

$ME_{fat,c}$ = metabolizable energy required for generating new fat in adipose tissue for cohort *c*, MJ×head^{-1}×day^{-1}

DWG_c = daily weight gain by animal in cohort *c*, kg×head^{-1}×day^{-1}

PTissue = fraction of protein tissue in the daily weight gain, fraction. Default values of 0.60, 0.65 and 0.7 for backyard, intermediate and industrial systems are used, respectively.

Fat = fraction of fat in adipose tissue, fraction. Default value of 0.90 is used

C_{MEfat} = metabolizable energy required for fat in adipose tissue, MJ×kg fat^{-1}. Default value of 52.3 is used.

c = cohort of replacement and fattening animals

3.6.2.5 – Total energy requirement (ME_{tot})

ME_{tot} is the total metabolizable energy requirement for each animal in a given cohort.

Equation 3.48

a. $ME_{tot,AF} = (Gest \times (ME_{main\text{-}gestation,AF} + ME_{gest}) + Lact \times (ME_{main\text{-}lactation,AF} + ME_{lact}) + Idle \times (ME_{main\text{-}idle,AF})) / (Gest + Lact + Idle)$

b. $ME_{tot,AM} = ME_{main,AM}$

c. $ME_{tot,RF} = (Gest \times (ME_{gest,RF}) + Lact \times (ME_{lact,RF}) + 365 \times AFCF \times (ME_{main,RF} + ME_{prot,RF} + ME_{fat,RF})) / (365 \times AFCF)$

d. $ME_{tot,RM} = ME_{main,RM} + ME_{prot,RM} + ME_{fat,RM}$

e. $ME_{tot,M2} = ME_{main,M2} + ME_{prot,M2} + ME_{fat,M2}$

Where:

ME_{tot} = total metabolizable energy required for a given cohort, MJ×head^{-1}×day^{-1}

ME_{main} = metabolizable energy required by animal for maintenance for a given cohort, MJ×head^{-1}×day^{-1}. For adult females, the model distinguishes between idle, gestation and lactation periods (see Equation 3.43)

ME_{gest} = metabolizable energy required by animal for gestation for a given cohort, MJ×head^{-1}×day^{-1}

ME_{lact} = metabolizable energy required by animal for lactation for a given cohort, MJ×head^{-1}×day^{-1}

ME_{prot} = metabolizable energy required by animal for generation of new proteins in protein tissue for a given cohort, MJ×head^{-1}×day^{-1}

ME_{fat} = metabolizable energy required by animal for generation of new fat in adipose tissue for a given cohort, MJ×head^{-1}×day^{-1}

Gest = duration of gestation period, days

Lact = duration of lactation period, days

Idle = duration of idle period, days

AFCF = age at first parturition, year

3.6.3 – Energy requirement of chickens

Equations for chickens were derived from Sakomura (2004). The model partitions the total metabolizable energy intake into maintenance, growth and production. It is assumed that layers and broilers are kept in housing with an ambient temperature that is constant at 20 °C. For backyard systems, the average annual temperature is used in the estimation of energy for maintenance. Table 3.14 summarizes the equations used to estimate the energy requirements for chicken.

Table 3.14 Equations used to estimate ME for chickens

Metabolic function	Abbreviation	Equation
Maintenance	ME_{main}	Equation 3.49
Growth	ME_{gro}	Equation 3.50
Production	ME_{prod}	Equation 3.51
Total energy requirement		
Backyard production systems		
Reproductive hens	ME_{tot}	Equation 3.52a
Reproductive roosters	ME_{tot}	Equation 3.52b
Surplus hens when adults (laying eggs)	ME_{tot}	Equation 3.52a
Growing female and male chicks for replacement	ME_{tot}	Equation 3.52b
Surplus hens when growing (not laying eggs)	ME_{tot}	Equation 3.52b
Surplus roosters	ME_{tot}	Equation 3.52b
Layers production systems		
Reproductive hens	ME_{tot}	Equation 3.52a
Reproductive roosters	ME_{tot}	Equation 3.52b
Growing female and male chicks for replacement	ME_{tot}	Equation 3.52b
Surplus roosters	ME_{tot}	Equation 3.52b
Laying hens (before laying period and during molting period)	ME_{tot}	Equation 3.52b
Laying hens (during laying period)	ME_{tot}	Equation 3.52a
Broiler production system		
Reproductive hens	ME_{tot}	Equation 3.52a
Reproductive roosters	ME_{tot}	Equation 3.52b
Growing female and male chicks for replacement	ME_{tot}	Equation 3.52b
Broiler animals	ME_{tot}	Equation 3.52b

3.6.3.1 – Energy requirement for maintenance (ME_{main})

ME_{main} is the metabolizable energy requirement for maintenance.

Equation 3.49

$$ME_{main,c} = LW_c^{0.75} \times TEMPreg_c \times C_{act}$$

Where:

$ME_{main,c}$ = metabolizable energy required by animal for maintenance in cohort *c*, MJ×head^{-1}×day^{-1}

LW_c = average live weight of the animal in cohort *c*, kg×head^{-1}.

$TEMPreg_c$ = regression function depending on the temperature for cohort *c*, MJ×kg$^{-0.75}$×day^{-1}. Values are given in Table 3.15.

C_{act} = dimensionless coefficient for activity with a value of 1.25 for backyard and 1.0 for layers and broilers.

Table 3.15 Temperature regression function for maintenance energy requirements

Animal cohort	$TEMPreg_c$ ($MJ \times kg^{-0.75} \times day^{-1}$)
Backyard production systems	
Reproductive adults (AF, AM)	$0.693 - 9.9 \cdot 10^{-3} \times T$[a]
Surplus hens when adults (laying eggs) (MF2)	
Growing female and male chicks for replacement (RF, RM)	if $T < LCT$[b]: $0.386 + 0.03 \times (LCT - T)$ if $T \geq LCT$: $0.386 + 3.7 \cdot 10^{-3} \times (T - LCT)$
Surplus hens when growing (not laying eggs) (MF1)	
Surplus roosters (MM)	
Layers production systems	
Reproductive adults (AF, AM)	$0.693 - 9.9 \cdot 10^{-3} \times T$
Growing female and male chicks for replacement (RF, RM)	0.390
Surplus roosters	
Laying hens (before laying period) (MF1)	
Laying hens (during laying period) (MF2, MF3, MF4)	$0.693 - 9.9 \cdot 10^{-3} \times T$
Broiler production system	
Reproductive adults (AF, AM)	$0.806 - 0.026 \times T + 0.5 \cdot 10^{-3} \times T^2$
Growing female and male chicks for replacement (RF, RM)	$0.727 - 7.86 \cdot 10^{-3} \times T$
Broiler animals (M2)	$1.287 - 0.065 \times T + 1.3 \cdot 10^{-3} \times T^2$

[a] Temperature (°C): average annual value for backyard systems; standard value of 20 for industrial Layers and Broilers systems.
[b] Low critic temperature (°C): calculated as $24.54 - 5.65 \times F$, where F is feathering score (0–1). It is assumed a feathering score of 1.

3.6.3.2 – Energy requirement for growth (ME_{gro})

ME_{gro} is the metabolizable energy requirement for growth.

Equation 3.50

$$ME_{gro,c} = DWG_c \times 1000 \times C_{gro,c}$$

Where:

$ME_{gro,c}$ = metabolizable energy required by animal for growth in cohort *c*, $MJ \times head^{-1} \times day^{-1}$

DWG_c = daily weight gain of animals in cohort *c*, $kg \times head^{-1} \times day^{-1}$. The DWG for reproductive adults in Broilers is taken from Layers.

$C_{gro,c}$ = growth coefficient for cohort *c*, $MJ \times kg^{-1}$. Values are given in Table 3.16.

Table 3.16 Growth coefficient for chickens

Animal cohort	C_{gro} ($MJ \cdot g^{-1}$)
Backyard production systems	
Reproductive adults (AF, AM)	0.0279
Surplus hens when adults (laying eggs) (MF2)	
Growing female and male chicks for replacement (RF, RM)	0.02117
Surplus hens when growing (not laying eggs) (MF1)	
Surplus roosters (MM)	
Layers production systems	
Reproductive adults (AF, AM)	0.0279
Growing female and male chicks for replacement (RF, RM)	0.02117
Surplus roosters	
Laying hens (before laying period) (MF1)	
Laying hens (during laying period) (MF2, MF3, MF4)	0.0279
Broiler production system	
Reproductive adults (AF, AM)	0.03185
Growing female and male chicks for replacement (RF, RM)	0.01045
Broiler animals (M2)	0.01655

3.6.3.3 – Energy requirement for egg production (ME_{egg})

ME_{egg} is the metabolizable energy requirement for egg production. It applied only to the laying animals, specifically: reproductive females for all systems (AF), laying surplus females for backyard chickens (MF2) and surplus females during the first and second laying period for layers (MF2, MF3, MF4).

Equation 3.51

$ME_{egg,c}$ = $10^{-3} \times EGG_c \times C_{egg}$

Where:

$ME_{egg,c}$ = metabolizable energy required by animal for egg production in cohort *c*, MJ×head^{-1}×day^{-1}

EGG_c = egg mass production for cohort *c*, g egg×animal^{-1}×day^{-1}

C_{egg} = energy requirement coefficient for egg production, kJ×g egg^{-1}. Default value of 10.03 is used.

c = cohorts of laying females

3.6.3.4 – Total energy requirement (ME_{tot})

ME_{tot} is the total metabolizable energy requirement for each animal in a given cohort.

Equation 3.52

a. $ME_{tot,c}$ = $ME_{main,c} + ME_{gro,c} + ME_{egg,c}$

for c = cohorts of laying females

b. $ME_{tot,c}$ = $ME_{main,c} + ME_{gro,c}$

for c = cohorts other than laying females

Where:

$ME_{tot,c}$ = total metabolizable energy required by the animal in cohort *c*, MJ×head^{-1}×day^{-1}

$ME_{main,c}$ = metabolizable energy required by the animal for maintenance in cohort *c*, MJ×head^{-1}×day^{-1}

$ME_{gro,c}$ = metabolizable energy required by the animal for growth in cohort *c*, MJ×head^{-1}×day^{-1}

$ME_{egg,c}$ = metabolizable energy required by the animal for egg production in cohort *c*, MJ×head^{-1}×day^{-1}

3.7 – FEED INTAKE

For each cohort and each species, the feed intake is calculated by dividing the total animal's energy requirement by the average energy content of the ration following Equation 3.53 and Equation 3.54.

Equation 3.53 - Ruminants

$DMI_{T,c}$ = $GE_{tot,T,c} / DIET_{GE,T,fg}$

Where:

$DMI_{T,c}$ = daily feed intake per animal in cohort *c* for species and system *T*, kg DM×head^{-1}×day^{-1}

$GE_{tot,T,c}$ = total gross energy requirement by animal in cohort *c* for species and system *T*, MJ×head^{-1}×day^{-1}

$DIET_{GE,T,fg}$ = average gross energy content of ration for feeding group *fg* for species and system *T*, MJ×kgDM^{-1}

c = animal cohort *c* for each ruminant species

fg = feeding group as shown in Table 3.2

Equation 3.54 - Monogastrics

$DMI_{T,c}$ = $ME_{tot,T,c} / DIET_{ME}$

Where:

$DMI_{T,c}$ = daily feed intake per animal in cohort *c* for species and system *T*, kg DM×head^{-1}×day^{-1}

$ME_{tot,T,c}$ = total gross energy requirement by animal in cohort *c* for species and system *T*, MJ×head^{-1}×day^{-1}

$DIET_{ME}$ = average metabolizable energy content of ration, MJ×head^{-1}×day^{-1}

c = animal cohort *c* for each monogastric species

4 CHAPTER 4 – ANIMAL EMISSIONS MODULE

This chapter describes how to estimate emissions at herd level associated with animal production, specifically emissions from enteric fermentation and manure management.

The functions of the 'Animal emissions' module are to:

- Calculate the **enteric emissions**.
- Calculate the **methane and the nitrous oxide** (N_2O) emissions, **plus the ammonia** (NH_3), **nitrogen oxides** (NO_x) and **nitrates** (NO_3^-) flows arising from the **manure management**.
- Use the estimates on nitrogen flows to calculate the amount of **nitrogen excreted** by livestock that is **available for recycle on pasture and cropland**, to be used as input in the "Manure module" (Chapter 5).
- Totalize the **feed, enteric** and **manure management** emissions **for the whole herd or flock**.

For a schematic representation of the animal emissions module, see Figure 4.1.

4.1 – MANURE MANAGEMENT SYSTEMS

Manure management systems (MMS) categories used during manure storage and treatment are described in Table 4.1. Moreover, Table 4.2 reports different categories of use or disposal of manure after the storage and treatment phase. The remaining share of manure that is not used or disposed as per categories listed in Table 4.2 is assumed to be apllied to croplands. On a global scale, there is very limited data available on how manure is managed. Consequently, GLEAM relies on various data sources such as national inventory reports, literature and expert knowledge to define the MMS and the share of manure allocated to each system. When possible, data were also gathered at sub-national level, which enhanced the spatial resolution of the data for large countries (Table 4.3). For other countries, existing GLEAM 2.0 data are used. Data on unregulated discharge of manure are obtained from the literature. Regional MMS percentages are summarized in the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/).

Table 4.1 Manure management systems definitions

Manure management system	Description
Aerobic lagoon	A type of liquid, uncovered manure storage with varying lengths of storage (up to a year or greater). Lagoons can both be a tank construction or an earthen basin and are characterized by natural or forced aeration.
Aerobic processing	Manure is treated through natural or forced aeration processes for oxidation of organic and nitrogenous compounds.
Burned	Manure is collected and burned, usually as (cooking) fuel.
Compost	Manure is stored and turned into compost before using it as fertilizer. Often, manure is frequently turned and mixed during composting process.
Confinement	Manure is allowed to lie as deposited on outdoor confinement areas and is not managed.
Daily spread	Manure is routinely removed from a confinement facility and applied to cropland or pasture within 24 hours of excretion.
Deep litter	An in-house system where, as manure accumulates in the stable, bedding material is continuously added to absorb moisture over a production cycle of 6 to 12 months.
Digester	Also called biogas installation, which converts liquid and solid manure into biogas. As a by-product a digestate is formed which can be used as fertilizer.
Drylot	A paved or unpaved open confinement without any cover and where manure is stored for several months (up to a year or more) and may be removed periodically.
Lagoon	A liquid storage system designed to combine waste stabilization and storage. Lagoons can both be a covered tank construction or an earthen basin and are characterized by the creation of an anaerobic environment.
Liquid	A system where manure as excreted (slurry) is stored in tanks or earthen ponds, sometimes with some addition of water and storage periods of usually less than a year.
Liquid crust	Same storage as *'Liquid'*, but with a naturally or artificially formed crust on the top, which reduces gas emissions.
Manure with litter (poultry)	As manure accumulates in the barn, bedding material is added to absorb the moisture over an entire production cycle. Typically used for poultry breeder flocks and meat type chickens.

Manure without litter (poultry)	Manure is dried as it accumulates and can be similar to an open confinement storage system.
Outdoor Confinement Area	Manure is allowed to lie as deposited on outdoor confinement areas and is not managed.
Pasture + paddock	Manure that is deposited on pasture, grazing land and outdoor confinement areas and not managed.
Pit 1	Manure is collected and stored below a slatted floor in enclosed animal confinement for less than 2 months.
Pit 2	Manure is collected and stored below a slatted floor in enclosed animal confinement for 2 months or more.
Solid storage	Manure is stored, typically for several months, in unconfined piles or stacks.
Thermal drying	Manure (solid) is treated through a drying process and is commonly used to remove volatile contaminants from livestock manure.

Table 4.2 ***Categories of use or disposal of manure after the storage and treatment phase***

Manure use or disposal	Description
Discharge	Manure is discharged in the environment. This is done after a period of storage and activities are often not recorded as many regions do not allow for such practices.
Dumping	Manure is dumped in an (often nearby) river. This can be done after a period of storage and activities are often not recorded as many regions do not allow for such practices.
Fishpond	Manure is used as fertilizer to increase production of food organisms that are eaten by the fish.
Incineration	Manure is burned in a controlled incinerator after a certain period of storage.
Public sewage	Manure enters the public sewage system and further processed at a treatment plant.
Sold	Solid manure is sold as fertilizer or fuel, usually after a period of storage.

Table 4.3 Updated manure management systems

Source	Country	Administrative units	Livestock species	Production system	Reference
Survey	EU	NUTS21	All species	Mixed	Bioteau et al.
GHG inventory	Australia	State	Cattle, pigs, poultry	Mixed	Australian Government
	Brazil	State	Cattle, pigs	Grassland, mixed	De Lima et al.
	Japan	Country	Cattle, pigs, poultry	Mixed Grassland	NIES
	New Zealand	Country	Cattle, pigs, poultry	Mixed	NZ Government
	Switzerland	Country	All species	Grassland, mixed, feedlot	FOEN
NH3 inventory	US	State	Cattle, pigs, poultry	Grassland, mixed, feedlot	EPA
National statistics	Canada	State	Cattle, pigs	Grassland, mixed	Statistics Canada
Literature	Argentina	Country	All species	Grassland, mixed	Hilbert et al., Methane to Markets
	China	Country	Cattle, poultry	Mixed	Bai et al.; Gao et al.
	India	Country	Dairy	Mixed	Gupta et al.
	Mexico	Country	Ruminants, pigs	Mixed	Mink et al.
	Vietnam	Country	Pigs	Mixed	Thu et al.; Dan et al.

MMSs during the storage and treatment phase can be considered as solid or liquid (Table 4.4). This distinction is required for the estimation of nitrogen flows and emissions through different kinds of compounds during manure management. A special case is constituted by categories “Confinement”, “Daily Spread”, “Pit 1” and “Pit 2”, which can be liquid or solid depending on the species or production system. Table 4.5 shows how to classify these categories in GLEAM.

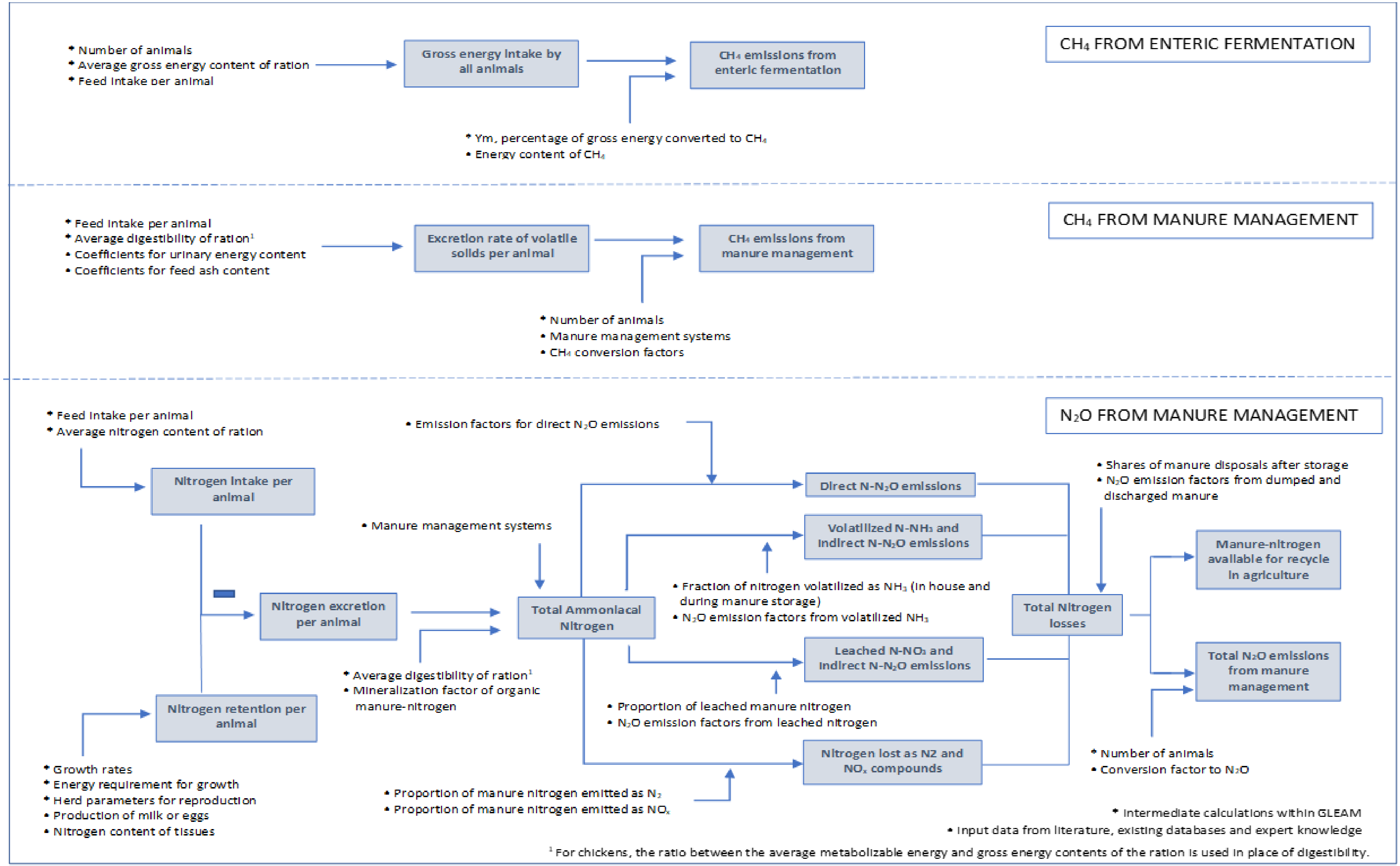
Table 4.4 Solid or liquid manure management systems

Manure management system	Manure type	Manure management system	Manure type
Aerobic lagoon	Liquid	Liquid crust	Liquid
Aerobic processing	Liquid	Manure with litter (poultry)	Solid
Burned	Solid	Manure withou litter (poultry)	Solid
Compost	Solid	Outdoor Confinement Area	Solid
Confinement	Table 4.5	Pasture + paddock	Solid
Daily spread	Table 4.5	Pit 1	Table 4.5
Deep litter	Solid	Pit 2	Table 4.5
Digester	Liquid	Solid storage	Solid
Dry lot	Solid	Thermal drying	Solid
Lagoon	Liquid		
Liquid	Liquid		

Table 4.5 Classification of confinement, daily spread and pit storage categories of MMS

Manure management system	Liquid	Solid
Confinement	Cattle (feedlot)	Other cattle, buffalo, small ruminants, pigs, chickens
Daily spread	Dairy cattle (mixed), pig	Other cattle (beef), buffalo, small ruminant, poultry
Pit 1, Pit 2	Cattle, buffalo, small ruminants, pigs,	Chickens

Figure 4.1 Schematic representation of the animal emissions module



4.2 – METHANE EMISSIONS FROM ENTERIC FERMENTATION

Methane is produced during the digestive process in ruminant species and pigs. Emissions from chickens, although present, are negligible. Enteric emissions are closely related to the composition of the diet, particularly to the energy content. An enteric methane conversion factor, Y_m (percentage of gross energy converted to methane) is used to calculate the methane emissions from enteric fermentation. A Tier 2 approach (IPCC, 2019) is applied for the calculation of enteric CH_4 emissions due to the sensitivity of emissions to diet composition and the relative importance of enteric CH_4 to the overall GHG emissions profile.

Enteric emissions were calculated as follows:

Equation 4.1

$$CH_{4\text{-}Enteric,T,c} = N_{T,c} \times 365 \times DIET_{GE,T} \times DMI_{T,c} \times (Y_{mT,c} / 100) / 55.65$$

Where:

$CH_{4\text{-}Enteric,T,c}$ = methane emissions from enteric fermentation for cohort *c*, species and system *T*, kg $CH_4 \times year^{-1}$

$N_{T,c}$ = number of animals in cohort *c*, species and system *T*, heads

$DIET_{GE,T}$ = average gross energy content of ration for species and system *T*, $MJ \times kgDM^{-1}$

$DMI_{T,c}$ = daily feed intake per animal in cohort *c* for species and system *T*, kg $DM \times head^{-1} \times day^{-1}$

$Y_{mT,c}$ = methane conversion factor for cohort *c*, species and system *T*, percentage of energy in feed converted into methane. Values are given in Table 4.6

55.65 = energy content of methane, $MJ \times kg\ CH_4^{-1}$

Table 4.6 . Methane conversion factors for different species and cohorts

Animal cohort	Y_m (% of energy converted into CH_4)
Cattle and Buffaloes	
Cattle (non-feedlot animals)	$9.75 - 0.05 \times (DIET_{DI,fg})$
Feedlot animals	4
Buffaloes	$9.75 - 0.05 \times (DIET_{DI,fg})$
Sheep and Goats	
Adult reproductive animals	$9.75 - 0.05 \times (DIET_{DI,fg})$
Young replacement and fattening animals	$7.75 - 0.05 \times (DIET_{DI,fg})$
Pigs	
Adult reproductive animals	1.01
Replacement and fattening animals	0.39

Where:
$DIET_{DI}$ = average digestibility of ration for the feeding group *fg* (See Table 3.2), percentage

4.3 – METHANE EMISSIONS FROM MANURE MANAGEMENT

Methane emissions from manure management were calculated using the IPCC Tier 2 method, which requires the estimation of the excretion rate of volatile solids (VS) per animal and the estimation of the proportion of VS that are converted to CH_4. Methane emissions are calculated following Equation 4.2:

Equation 4.2

$$CH_{4\text{-}Manure,T,c} = N_{T,c} \times [(365 \times VS_{T,c}) \times (B_{o,T} \times 0.67 \times \sum_S((MCF_S / 100) \times MMS_{S,T,c}))]$$

Where:

$CH_{4\text{-}Manure,T,c}$ = total methane emissions from manure management for cohort *c*, species and system *T*, kg $CH_4 \times year^{-1}$

$N_{T,c}$ = number of animals in cohort *c*, species and system *T*, heads

$VS_{T,c}$ = daily volatile solid excreted by animal in cohort *c*, species and system *T*, kg $VS \times head^{-1} \times day^{-1}$

$B_{o,T}$ = maximum methane producing capacity for manure for species and system *T*, $m^3\ CH_4 \times kg\ VS^{-1}$. Values are taken from updated Table 10.16 of the new IPCC guidelines (IPCC, 2019, Volume 4, Chapter 10).

MCF_S = methane conversion factor for each manure management system *S*, percentage. Values are taken from updated Table 10.17 of the new IPCC guidelines (IPCC, 2019, Volume 4, Chapter 10). Pit storage management for chickens's manure is assumed to have the same MCF used for poultry manure without litter.

$MMS_{S,T,c}$ = share of manure handled by manure management system S for species and system T, for cohort *c*, fraction

0.67 = conversion factor from volume of methane into kg of gas, kg $CH_4 \times m^{-3}$

GLEAM calculates the VS excretion rate using Equation 4.3 for ruminants, Equation 4.4 for pigs and Equation 4.5 for chicken. All three are based on Equation 10.24 from IPCC (2019).

Equation 4.3 - Ruminants

$$VS_{T,c} = DMI_{T,c} \times (1.04 - (DIET_{DI,fg} / 100)) \times 0.92$$

Where:

$VS_{T,c}$ = daily volatile solid excreted by animal in cohort *c*, species and system *T*, kg $VS \times head^{-1} \times day^{-1}$

$DMI_{T,c}$ = daily feed intake per animal in cohort *c* for species and system *T*, kg $DM \times head^{-1} \times day^{-1}$

$DIET_{DI}$ = average digestibility of ration for feeding group *fg*, percentage

fg = feeding group as shown in Table 3.2

The formula is a modification of the original IPCC equation. First, the average gross energy content of the ration is used instead of a fixed value of 18.45 MJ×kg DM^{-1}. Thus, GE / $DIET_{GE}$ equals the daily intake, DMI. Second, it is assumed that Urinary energy is 4% and the Ash content in feed is 8%. Therefore, GE × (GE + UE) becomes 1.04 and 1 – ASH becomes 0.92.

Equation 4.4 - Pigs

$$VS_{T,c} = DMI_{T,c} \times (1.02 - (DIET_{DI,T} / 100)) \times 0.94$$

Where:

$VS_{T,c}$ = daily volatile solid excreted by animal in cohort *c*, species and system *T*, kg $VS \times head^{-1} \times day^{-1}$

$DMI_{T,c}$ = daily feed intake per animal in cohort *c* for species and system *T*, kg $DM \times head^{-1} \times day^{-1}$

$DIET_{DI}$ = average digestibility of ration for system *T*, percentage

It is assumed that urinary energy is 2% and the ash content in feed is 6% (based on IPCC, 2019; Dämmgen et al., 2011). Therefore, GE × (GE + UE) becomes 1.02 and 1 – ASH becomes 0.94.

Equation 4.5a – Chickens (Backyard and Layers)

$$VS_{T,c} = DMI_{T,c} \times (1.0 - DIET_{ME,T} / DIET_{GE,T}) \times 0.89$$

Where:

$VS_{T,c}$ = daily volatile solid excreted by animal in cohort *c*, species and system *T*, kg $VS \times head^{-1} \times day^{-1}$

$DMI_{T,c}$ = daily feed intake per animal in cohort *c* for species and system *T*, kg $DM \times head^{-1} \times day^{-1}$

$DIET_{ME,T}$ = average metabolizable energy content of ration for system *T*, MJ×kg DM^{-1}

$DIET_{GE,T}$ = average gross energy content of ration for system *T*, MJ×kg DM^{-1}

It is assumed that Urinary energy is 0% and the Ash content in feed is 11% (Davies, 2016). Therefore, GE × (GE + UE) becomes 1 and 1 – ASH becomes 0.89.

Equation 4.5b – Chickens (Broilers)

$$VS_{T,c} = DMI_{T,c} \times (1.0 - DIET_{ME,T} / DIET_{GE,T}) \times 0.95$$

Where:

$VS_{T,c}$ = daily volatile solid excreted by animal in cohort *c*, species and system *T*, kg $VS \times head^{-1} \times day^{-1}$

$DMI_{T,c}$ = daily feed intake per animal in cohort *c* for species and system *T*, kg $DM \times head^{-1} \times day^{-1}$

$DIET_{ME,T}$ = average metabolizable energy content of ration for system *T*, MJ×kg DM^{-1}

$DIET_{GE,T}$ = average gross energy content of ration for system *T*, MJ×kg DM^{-1}

It is assumed that Urinary energy is 0% and the Ash content in feed is 5% (Vakili et al., 2015). Therefore, GE × (GE + UE) becomes 1 and 1 – ASH becomes 0.95.

4.4 – NITROGEN FLOWS FROM MANURE MANAGEMENT

The calculation of the flows of NH_3, N_2O, NO_x^- and N_2 is based on the EEA (2016). The emissions are calculated based on the fraction of the total ammoniacal nitrogen (TAN) using the framework developed in (Vonk et al., 2018).

Emissions from manure management are estimated at two levels: NH_3 from nitrogen deposited in house or yard (the latter referring to confinement area in the USA), and emissions of nitrogen compounds (NH_3, N_2O, NO_X, N_2) during manure storage and treatment. Total emissions of N_2O includes both direct emissions and indirect ones arising from volatilization of NH_3, leaching and disposals of manure other than application to cropland. Moreover, all estimated N flows and losses are then used to calculate the total nitrogen available for application to cropland, to be used as input for the Manure module (see Chapter 5).

4.4.1 – Emission factors

The following tables report the emissions factors used to estimate nitrogen lost as NH_3 (Table 4.7), through direct emissions of N_2O (Table 4.8) or as N_2 and NO_x compounds (Table 4.9). Most of the emission factors are defined by different animal categories, manure types and phases of manure management, and they are all expressed as a proportion of the TAN excreted by animals (see section 4.4.2).

Table 4.7 N-NH_3 emissions factors from manure management systems, proportion of TAN.

Livestock	Manure type	EF_{yard}	EF_{house}	$EF_{storage}$	$EF_{spreading}$	$EF_{grazing}$
Dairy cattle	Slurry	0.30	0.20	0.20	0.55	0.10
	Solid	0.30	0.19	0.27	0.79	0.10
Non-dairy cattle (young cattle, beef, suckling cows)	Slurry	0.53	0.20	0.20	0.55	0.06
	Solid	0.53	0.19	0.27	0.79	0.06
Sheep	Solid	0.75	0.22	0.28	0.90	0.09
Buffalo	Slurry	NA	0.20	0.17	0.55	0.13
	Solid	0.75	0.22	0.28	0.90	0.09
Goats	Slurry	NA	0.20	0.17	0.55	0.13
	Solid	0.75	0.22	0.28	0.90	0.09
Pigs (fattening)	Slurry	0.28	0.28	0.14	0.40	
	Solid	0.28	0.27	0.45	0.81	
Pigs (sows and piglets)	Slurry	NA	0.22	0.14	0.29	
	Solid	NA	0.25	0.45	0.81	
	Pasture (outdoor)	NA				0.25
Laying hens	Slurry	NA	0.41	0.14	0.69	
	Solid	NA	0.41	0.14	0.69	
Broilers	Solid	NA	0.28	0.17	0.66	

Note: For a country (e.g. USA) with a MMS category of confinement area, in house NH3 emissions for $MMS_{confinment}$ are calculated using emissions factors from the yard (EF_{yard}). EF_{house} is used where EF_{yard} is NA.

Table 4.8 Emission factors for direct N-N_2O emissions by animal species

Manure type	Species	EF N-N_2O
Liquid manure without natural crust & Lagoon	Cattle/Buffalo/Pig	0
Liquid manure with natural crust	Cattle/Buffalo	0.01
	Pig	0.01 (pit1/pit2/liqcrust)
Solid manure	Cattle/goats/sheep/Buffalo	0.02
	Broilers/Layers	0.002
	Pig	0.01

Table 4.9 Emission factors for N-N_2 and N-NO_x by manure type

Manure type	EF N-N_2	EF N-NOx
Liquid manure (slurry)	0.003	0.0001
Solid manure	0.30	0.01

4.4.2 – Nitrogen exctretion and calculation of total ammoniacal nitrogen (TAN)

The sum of the amount of nitrogen in ammonia (NH_3) and ammonium (NH_4^+) is called total ammoniacal nitrogen (TAN). Gaseous emissions are calculated based on TAN, which depends on the amount of nitrogen excreted by animals, either through uring and faeces.

4.4.2.1 – Nitrogen excretion rate

GLEAM calculates nitrogen excretion rates following Equations 4.6, which is based on Equation 10.31 to Equation 10.33 from IPCC (2019), as depicted below:

Equation 4.6

$N_{excretion,T,c} = 365 \times ((DMI_{T,c} \times DIET_{Ncont,T}) - N_{retentionT,c})$

Where:

$N_{excretion,T,c}$ = nitrogen excretion per animal in cohort *c*, species and system *T*, kg nitrogen animal^{-1} year^{-1}

$DMI_{T,c}$ = daily feed intake per animal in cohort *c*, for species and system *T*, kg DM×head^{-1}×day^{-1}

$DIET_{Ncont,T}$ = average nitrogen content of ration for species and system *T*, kg N×kg DM diet^{-1}

$N_{retention,T,c}$ = daily nitrogen retention per animal in cohort *c*, species and system *T*, kg N×head^{-1}×day^{-1}. See Table 4.10.

Table 4.10 Nitrogen retention formulas for species and cohorts

Livestock category/cohort	Nitrogen retention
Ruminant species: adult females (AF)	Equation 4.7a
Ruminant species: adult males (AM)	N retention is assumed to be null
Ruminant species: other cohorts (RF, RM, MF, MM)	Equation 4.7b
Pigs: adult females (AF)	Equation 4.8a
Pigs: adult males (AM)	N retention is assumed to be null
Pigs: replacement females (RF)	Equation 4.8b
Pigs: other cohorts (RM, M2)	Equation 4.8c
Chickens: laying hens (AF, MF2, MF4)	Equation 4.9a
Chickens: laying hens during the molting period (MF3)	N retention is assumed to be null
Chickens: other cohorts (AM, RF, RM,MF1, MM, M2)	Equation 4.9b

Equation 4.7 - Ruminants

a. $N_{retention,AF} = (Milk \times Milk_{prot} / 6.38) + (Ckg/365 \times (268 - (7.03 \times NE_{gro,RF} / DWG_{RF})) \times 10^{-3} / 6.25)$

b. $N_{retention,c} = (DWG_c \times (268 - (7.03 \times NE_{gro,c} / DWG_c)) \times 10^{-3} / 6.25)$

Where:

$N_{retention,AF}$ = daily nitrogen retention by animal in cohort *AF*, kg N×head^{-1}×day^{-1}

$N_{retention,c}$ = daily nitrogen retention by animal in cohort *c*, other than cohort *AF*, kg N×head^{-1}×day^{-1}

Milk = average daily production of milk, applicable only to milking animals, kg milk×head^{-1}×day^{-1}

$Milk_{prot}$ = average fraction of protein in milk, fraction

6.38 = conversion from milk protein to milk nitrogen, kg protein×kg N^{-1}

Ckg = average live weight of calves, kg×head^{-1}×day^{-1}

DWG_{RF} = average daily weight gain for cohort *RF*, kg×head^{-1}×day^{-1}

DWG_c = average daily weight gain for cohort *c*, kg×head^{-1}×day^{-1}

268 and 7.03 = constants from the new IPCC 2019 refinement.

$NE_{gro,RF}$ = net energy required by animal for growth in cohort *RF*, MJ×head^{-1}×day^{-1}

$NE_{gro,c}$ = net energy required by animal for growth in cohort *c*, MJ×head^{-1}×day^{-1}

6.25 = conversion from dietary protein to dietary nitrogen, kg protein×kg N^{-1}

AFC = age at first calving, years

c = cohort for animals other than adult males (See Table 4.10).

Equation 4.8 - Pigs

a. $N_{retention,AF} = ((N_{LW} \times LITSIZE \times FR \times (Wkg - Ckg) / 0.98) + (N_{LW} \times LITSIZE \times FR \times Ckg)) / 365$

b. $N_{retention,RF} = N_{LW} \times DWG_c + AFCF^{-1} \times (((N_{LW} \times LITSIZE \times FR \times (Wkg - Ckg) / 0.98) + (N_{LW} \times LITSIZE \times FR \times Ckg)) / 365)$

c. $N_{retention,c}$ = $N_{LW} \times DWG_c$

Where:

$N_{retention,AF}$ = daily nitrogen retention by animal in cohort *AF*, kg N×head^{-1}×day^{-1}

$N_{retention,RF}$ = daily nitrogen retention by animal in cohort *RF*, kg N×head^{-1}×day^{-1}

$N_{retention,c}$ = daily nitrogen retention by animal in cohort *c*, other than cohort *AF* and *RF*, kg N×head^{-1}×day^{-1}

N_{LW} = average content of nitrogen in live weight, kg N×kg live weight^{-1}. Default value of 0.025 is used.

LITSIZE = litter size, heads

FR = fertility rate of sows, parturitions×year^{-1}

Wkg = live weight of piglet at weaning age, kg×head^{-1}

Ckg = live weight of piglets at birth, kg×head^{-1}

0.98 = protein digestibility as fraction, fraction

DWG_c = average daily weight gain for cohort *c*, kg×head^{-1}×day^{-1}

AFCF = age at first parturition, year

c = cohort for animals other than adult males (See Table 4.10).

Equation 4.9 - Chickens

a. $N_{retention,c}$ = $N_{LW} \times DWG + N_{EGG} \times 10^{-3} \times EGG$

for c = cohorts of laying females

b. $N_{retention,c}$ = $N_{LW} \times DWG$

for c = cohorts other than laying and molting females (see table 4.10).

Where:

$N_{retention,c}$ = daily nitrogen retention by animal in cohort *c*, kg N×head^{-1}×day^{-1}

N_{LW} = average content of nitrogen in live weight, kg N×kg live weight^{-1}. Default value of 0.028 is used.

DWG = average daily weight gain for cohort *c*, kg×head^{-1}×day^{-1}

N_{EGG} = average content of nitrogen in eggs, kg N×kg egg^{-1}. Default value of 0.0185 is used.

EGG = egg mass production, g egg×head^{-1}×day^{-1}

4.4.2.2 – Total Ammoniacal Nitrogen (TAN)

The excretion of TAN is calculated as the sum of excretion of urine nitrogen and net mineralized organically bound nitrogen in faeces. The net mineralized organically bound nitrogen is used since TAN can also be immobilized and become organic nitrogen.

Equation 4.10 - Nitrogen in the dung

$N_{dung,T,c}$ = $(DMI_{T,c} \times DIET_{Ncont,T}) \times (1 - DIET_{DI,T,c} / 100)$

Where:

$N_{dung,T,c}$ = nitrogen in dung per animal in cohort *c*, species and system *T,* kg N animal^{-1} year^{-1}

$DMI_{T,c}$ = daily feed intake per animal in cohort *c,* for species and system *T*, kg DM×head^{-1}×day^{-1}

$DIET_{Ncont,T}$ = average nitrogen content of ration for species and system *T*, kg N×kg DM diet^{-1}

$DIET_{DI,T,c}$ = average feed ration digestibility per animal in cohort *c*, species and system *T,* percentage

Equation 4.11 - Nitrogen in the dung mineralized

a. $N_{dung\_liquid,T,c}$ = $N_{dung,T,c} \times Share_{liquid\_manure,T,c}$

b. $N_{dung\_solid,T,c}$ = $N_{dung,T,c} \times Share_{solid\_manure,T,c}$

c. $N_{dung\_mobilized (organic),T,c} = (N_{dung\_liquid,T,c} \times N_{mineralization-liquid}) + (N_{dung\_solid,T,c} \times N_{mineralization-solid})$

Where:

$N_{dung\_liquid,T,c}$ = nitrogen in liquid dung per animal in cohort *c*, species and system *T,* kg N animal^{-1} year^{-1}

$N_{dung\_solid,T,c}$ = nitrogen in solid dung per animal in cohort *c*, species and system *T,* kg N animal^{-1} year^{-1}

$N_{dung\_mobilized\ (organic),\ T,c}$ = mineralized nitrogen from organically bound nitrogen in manure per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$N_{dung,\ T,c}$ = nitrogen in dung per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$Share_{liquid\_manure,\ T,c}$ = share of manure stored in liquid MMSs for cohort *c*, species and system *T*, as calculated based on the classification of the MMSs provided in Table 4.4, fraction

$Share_{solid\_manure,\ T,c}$ = share of manure stored in solid MMSs for cohort *c*, species and system *T*, as calculated based on the classification of the MMSs provided in Table 4.4, fraction

$N_{mineralization}$ = proportion of mineralization of organically bound nitrogen in manure stored in the animal house in liquid manure management system, as reported by Vonk et al. (2018) and in the Table 4.11.

Note: The $MMS_{pasture}$ is excluded from the calculation of TAN in animal housing as well as from the calculation of emissions during animal housing and manure storage.

Table 4.11 The proportion of mineralization of organically bound nitrogen in manure

Nmineralization	
Liquid	**Solid**
0.10	0.25

Equation 4.12 - Nitrogen in the urine

$$N_{urine,T,c} = N_{excretion,T,c} - N_{dung,T,c}$$

Where:

$N_{urine,T,c}$ = nitrogen excreted in urine per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$N_{excretion,T,c}$ = nitrogen excretion per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$N_{dung,T,c}$ = nitrogen in dung per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

Equation 4.13 - TAN

$$N_{TAN,T,c} = N_{urine,T,c} + N_{dung\_mobilized\ (organic),T,c}$$

Where:

$N_{TAN,T,c}$ = total ammoniacal nitrogen excreted per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$N_{urine,T,c}$ = nitrogen excreted in urine per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$N_{dung\_mobilized\ (organic),T,c}$ = mineralized nitrogen from organically bound nitrogen in manure per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

4.4.3 – NH_3 emissions from manure management systems (First step)

The first step in the estimation of nitrogen volatilized as NH_3 from manure management needs to account for two different phases: emissions in the animal housing, before manure collection (Section 4.4.3.1) and emissions during manure storage and treatment (Section 4.4.3.2). The two flows of nitrogen are then summed together (Section 4.4.3.3) to estimate the direct volatilization of nitrogen as NH_3 from manure management. A calculation apart is done for NH_3 emissions from manure that is daily spread on croplands after collection from animal housing (Section 4.4.3.4), as they need to be included in the nitrogen losses but are properly accounted as emissions allocated to crop production.

4.4.3.1 – NH_3 emissions from animal house

The estimation of nitrogen emitted as NH_3 from animal housing is based on the emission factors EF_{yard} and EF_{house} reported in Table 4.7 and the following equations. It requires separate estimates for liquid (Equation 4.14) and solid (Equation 4.15) manure, before summing them together (Equation 4.16)

Equation 4.14

For Feedlots production systems

a. $N_{NH3\_house\ (liquid)} = N_{TAN} \times ((Share_{liquid\_manure} - MMS_{confinement}) \times EF\_NH3_{\_house\ (liquid)} + MMS_{confinement} \times EF\_NH3_{\_yard\ (liquid)})$

Where:

$N_{NH3\_house\ (liquid)}$ = nitrogen emitted as NH_3 from manure deposited in house or yard and managed in liquid MMSs per animal in feedlots, kg N-NH_3 animal^{-1} year^{-1}

N_{TAN} = total ammoniacal nitrogen excreted per animal in feedlots, kg N animal^{-1} year^{-1}

$Share_{liquid\_manure}$ = share of manure stored in liquid MMSs, fraction

$MMS_{confinement}$ = share of manure managed as Confinement, fraction

$EF\_NH3_{\_house\ (liquid)}$ = emission factor of N-NH_3 from manure deposited in house and managed in liquid MMSs, as defined in Table 4.7, kg N-NH_3 kg N^{-1}.

$EF\_NH3_{\_yard\ (liquid)}$ = emission factor of N-NH_3 from manure deposited in the yard and managed in liquid MMSs, as defined in Table 4.7, kg N-NH_3 kg N^{-1}.

For other production systems

b. $N_{NH3\_house\ (liquid),T,c} = N_{TAN,T,c} \times Share_{liquid\_manure,T,c} \times EF\_NH3_{\_house\ (liquid)}$

Where:

$N_{NH3\_house\ (liquid),T,c}$ = nitrogen emitted as NH_3 from manure deposited in house or yard and managed in liquid MMSs per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}

$N_{TAN,T,c}$ = total ammoniacal nitrogen excreted per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$Share_{liquid\_manure,T,c}$ = share of manure stored in liquid MMSs in cohort *c*, species and system *T*, fraction

$EF\_NH3_{\_house\ (liquid)}$ = emission factor of N-NH_3 from manure deposited in house and managed in liquid MMSs, as defined in Table 4.7, kg N-NH_3 kg N^{-1}.

Equation 4.15

For feedlots production systems

a. $N_{NH3\_house\ (solid)}) = N_{TAN} \times (Share_{solid\_manure} - MMS_{pasture}) \times EF\_NH3_{\_house\ (solid)}$

Where:

$N_{NH3\_house\ (solid)}$ = nitrogen emitted as NH_3 from manure deposited in house or yard and managed in solid MMSs per animal in feedlots, kg N-NH_3 animal^{-1} year^{-1}

N_{TAN} = total ammoniacal nitrogen excreted per animal in feedlots, kg N animal^{-1} year^{-1}

$Share_{solid\_manure}$ = share of manure stored in solid MMSs, fraction

$MMS_{pasture}$ = share of manure managed as pasture, fraction

$EF\_NH3_{\_house\ (solid)}$ = emission factor of N-NH_3 from manure deposited in house and managed in solid MMSs, as defined in Table 4.7, kg N-NH_3 kg N^{-1}.

For other production systems

b. $N_{NH3\_house\ (solid)\ ),T,c} = N_{TAN,T,c} \times ((Share_{solid\_manure,T,c} - MMS_{pasture,T,c} - MMS_{confinement,T,c}) \times EF\_NH3_{\_house\ (solid)} + MMS_{confinement,T,c} \times EF\_NH3_{\_yard\ (solid)})$

Where:

$N_{NH3\_house\ (solid),T,c}$ = nitrogen emitted as NH_3 from manure deposited in house or yard and managed in solid MMSs per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}

$N_{TAN,T,c}$ = total ammoniacal nitrogen excreted per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$Share_{solid\_manure,T,c}$ = share of manure stored in solid MMSs in cohort *c*, species and system *T*, fraction

$MMS_{pasture,T,c}$ = share of manure managed as Pasture in cohort *c*, species and system *T*, fraction

$MMS_{confinement,T,c}$ = share of manure managed as Confinement in cohort *c*, species and system *T*, fraction

$EF\_NH3_{\_house\ (solid)}$ = emission factor of N-NH_3 from manure deposited in house and managed in solid MMSs, as defined in Table 4.7, kg N-NH_3 kg N^{-1}.

$EF\_NH3_{\_yard\ (solid)}$ = emission factor of N-NH_3 from manure deposited in the yard and managed in solid MMSs, as defined in Table 4.7, kg N-NH_3 kg N^{-1}.

Equation 4.16

$N_{NH3\_house,T,c} = N_{NH3\_house\,(liquid),T,c} + N_{NH3\_house\,(solid),T,c}$

Where:

$N_{NH3\_house,T,c}$	=	nitrogen emitted as NH_3 from manure deposited in house or yard per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}
$N_{NH3\_house\,(liquid),T,c}$	=	nitrogen emitted as NH_3 from manure deposited in house or yard and managed in liquid MMSs per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}
$N_{NH3\_house\,(solid),T,c}$	=	nitrogen emitted as NH_3 from manure deposited in house or yard and managed in solid MMSs per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}

4.4.3.2 – NH_3 emissions from manure storage

The estimation of nitrogen emitted as NH_3 from manure storage and treatment is based on the emission factors $EF_{storage}$ reported in Table 4.7 and Equation 4.17. The proper emission factor is assigned according to the liquid or solid nature of manure in each MMS, as reported in Table 4.4 and Table 4.5.

Equation 4.17

$N_{NH3\_ms,T,c} = \Sigma_S\left((N_{TAN,T,c} - N_{NH3\_house,T,c}) \times MMS_{S,T,c} \times EF\_NH3_{\_storage,S}\right)$

Where:

$N_{NH3\_ms,T,c}$	=	nitrogen emitted as NH_3 from manure storage per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}
$N_{TAN,T,c}$	=	total ammoniacal nitrogen excreted per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}
$N_{NH3\_house,T,c}$	=	nitrogen emitted as NH_3 from manure deposited in house or yard per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}
$MMS_{S,T,c}$	=	For each manure management system category *S* in cohort *c*, species and system *T*, except for MMS_{daily}, $MMS_{pasture}$ and MMS_{burned}, fraction.
$EF\_NH3_{\_storage,S}$	=	emission factor of N-NH_3 from manure managed in manure management system category *S*, as defined in Table 4.7, kg N-NH_3 kg N^{-1} .

4.4.3.3 – NH_3 emissions from animal house and manure storage

The total nitrogen initially emitted as NH_3 from animal housing facilities and from manure storage and treatment is calculated following equation 4.18.

Equation 4.18

$N_{NH3,T,c} = N_{NH3\_house,T,c} + N_{NH3\_ms,T,c}$

Where:

$N_{NH3,T,c}$	=	nitrogen emitted as NH_3 per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}
$N_{NH3\_house,T,c}$	=	nitrogen emitted as NH_3 from manure deposited in house or yard per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}
$N_{NH3\_ms,T,c}$	=	nitrogen emitted as NH_3 from manure storage per animal in cohort *c*, kg N-NH_3 animal^{-1} year

(See Table 4.5).

4.4.3.4 – NH_3 emissions from daily spread

When the manure is collected from the housing facilities to storage, a part of it is directly spread on agricultural land (cropland or grassland), without any further storage. Thus, the NH_3 emissions of daily spread are only considered "in house", whereas the NH_3 emissions occurring after the spreading are allocated to feed or crop production. NH_3 emissions occurring during the spreading are calculated in the animal emissions module and reported separately.

Equation 4.19

$N_{NH3\_daily\_spread,T,c} = (N_{TAN,T,c} - N_{NH3\_house,T,c}) \times MMS_{daily,T,c} \times EF\_NH3_{\_spreading}$

Where:

$N_{NH3\_daily\_spread,T,c}$ = nitrogen emitted as NH_3 from manure applied to croplands or pastures within 24 hours from excretion, per animal in cohort *c*, species and system *T,* kg N-NH_3 animal^{-1} year^{-1}

$N_{TAN,T,c}$ = total ammoniacal nitrogen excreted per animal in cohort *c*, species and system *T* , kg N animal^{-1} year^{-1}

$N_{NH3\_house,T,c}$ = nitrogen emitted as NH_3 from manure deposited in house or yard per animal in cohort *c*, species and system *T,* kg N-NH_3 animal^{-1} year^{-1}

$MMS_{daily,T,c}$ = share of manure managed as Daily spread in cohort *c*, species and system *T*, fraction

$EF\_NH3_{\_spreading}$ = emission factor of N-NH_3 from manure applied to croplands or pastures within 24 hours from excretion, as defined in Table 4.7, kg N-NH_3 kg N^{-1} .

4.4.4 – N_2O emissions from manure management systems

Part of the losses of nitrogen as N_2O emissions from manure storage and treatment follows two separate pathways: 1) the direct emission of N_2O from manure during storage and treatment (Section 4.4.4.1), and 2) the conversion of part of the volatilized NH_3 (estimated in section 4.4.3.3) to N_2O (Section 4.4.4.2). The two nitrogen flows are then summed togheter in Section 4.4.4.3. The proper emission factor from Table 4.8 is assigned according to the liquid or solid nature of manure in each MMS, as reported in Table 4.4 and Table 4.5.

4.4.4.1 – Direct N_2O emissions

Equation 4.20

$$N_{direct\_N2O,T,c} = N_{TAN,T,c} \times \Sigma_S (MMS_{S,T,c} \times EF\_N_2O_{direct,S,T})$$

Where:

$N_{direct\_N2O,T,c}$ = direct N_2O emissions from manure per animal in cohort *c*, species and system *T*, kg N-N_2O animal^{-1} year^{-1}

$N_{TAN,T,c}$ = total ammoniacal nitrogen excreted per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$MMS_{S,T,c}$ = For each manure management system category *S* in cohort *c*, species and system *T*, except for MMS_{daily}, $MMS_{pasture}$ and MMS_{burned},, fraction.

$EF\_N_2O_{direct,S,T}$ = emission factor for direct N-N_2O emissions from manure managed in MMS category *S* for species and system *T*, as defined in Table 4.1 and Table 4.8, kg N-N_2O kg N^{-1}.

4.4.4.2 – Indirect N_2O emissions

Equation 4.21

$$N_{indirect\_N2O,T,c} = N_{NH3,T,c} \times EF\_N_2O_{indirect}$$

Where:

$N_{indirect\_N2O,T,c}$ = nitrogen emitted as indirect N_2O emissions from manure following atmospheric deposition of NH_3 per animal in cohort *c*, species and system *T*, kg N-N_2O animal^{-1} year^{-1}

$N_{NH3,T,c}$ = nitrogen emitted as NH_3 per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}

$EF\_N_2O_{indirect}$ = emission factor for indirect N-N_2O emissions following atmospheric deposition of NH_3 and NOx, 0.014 kg N-N_2O/kg N in Wet climates and 0.005 kg N-N_2O/kg N in Dry climates, kg N-N_2O kg N^{-1}.

4.4.4.3 – Direct and indirect N_2O emissions

Equation 4.22

$$N_{N2O,T,c} = N_{direct\_N2O,T,c} + N_{indirect\_N2O,T,c}$$

Where:

$N_{N2O,T,c}$ = nitrogen emitted as N_2O from manure storage per animal in cohort *c*, species and system *T,* kg N-N_2O animal^{-1} year^{-1}

$N_{direct\_N2O,T,c}$ = direct N_2O emissions from manure per animal in cohort *c*, species and system *T,* kg N-N_2O animal^{-1} year^{-1}

$N_{indirect\_N2O,T,c}$ = nitrogen emitted as indirect N_2O emissions from manure following atmospheric deposition of NH_3 per animal in cohort *c*, species and system *T,* kg N-N_2O animal^{-1} year^{-1}

4.4.5 – NH_3 emissions from manure (Second step)

The final amount of nitrogen emitted as NH_3 net of indirect N_2O emissions in calculated in Equation 4.23.

Equation 4.23

$$N_{NH3\_final,T,c} = N_{NH3,T,c} - N_{indirect\_N2O,T,c}$$

Where:

$N_{NH3\_final,T,c}$	=	nitrogen emitted as NH_3 net of indirect N_2O emissions per animal in cohort *c*, species and system *T*, kg NNH_3 animal^{-1} year^{-1}
$N_{NH3,T,c}$	=	nitrogen emitted as NH_3 per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}
$N_{indirect\_N2O,T,c}$	=	nitrogen emitted as indirect N_2O emissions from manure following atmospheric deposition of NH_3 per animal in cohort *c*, species and system *T*, kg N-N_2O animal^{-1} year^{-1}

4.4.6 – NO_x emissions from manure management

Part of the nitrogen is lost during manure storage and treatment in the form of NO_x compounds, as calculated in Equation 4.24. The proper emission factor from Table 4.9 is assigned according to the liquid or solid nature of manure in each MMS, as reported in Table 4.4 and Table 4.5.

Equation 4.24

$$N_{NOx,T,c} = N_{TAN,T,c} \times \Sigma_S (MMS_{S,T,c} \times EF\_NO_{x,j})$$

Where:

$N_{NOx,T,c}$	=	nitrogen emitted as NO_x per animal in cohort *c*, species and system *T*, kg N-NO_x animal^{-1} year^{-1}
$N_{TAN,T,c}$	=	total ammoniacal nitrogen excreted per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}
$MMS_{S,T,c}$	=	for each manure management system category *S*, in cohort *c*, species and system *T*, except for MMS_{daily}, $MMS_{pasture}$ and MMS_{burned},.
$EF\_NO_{x,S}$	=	emission factor of N-NO_x from manure managed in MMS category *S*, as defined in Table 4.9, kg N-NO_x kg N^{-1}.

Note: for MMS_{burned}, all nitrogen is lost as NO_x emissions, however, these flows are allocated to energy production (see N_{NOx_energy}, Section 4.4.15).

4.4.7 – NO_x emissions from manure burned as fuel

All nitrogen in manure burned as fuel, net of the fraction volitilized as NH_3 in the animal housing facilities, is lost as NO_x emissions. These emissions need to be accounted to estimate total nitrogen losses but are allocated to energy production (see Section 4.4.15).

Equation 4.25

$$N_{NOx\_burned,T,c} = N_{excretion,T,c} \times MMS_{burned,T,c} - N_{TAN,T,c} \times MMS_{burned,T,c} \times EF\_NH3_{\_house\ (solid)}$$

Where:

$N_{NOx\_burned,T,c}$	=	nitrogen emitted as NO_x per animal in cohort *c*, species and system *T*, kg N-NO_x animal^{-1} year^{-1}
$N_{excretion,T,c}$	=	nitrogen excretion per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}
$MMS_{burned,T,c}$	=	share of manure managed as Burned in cohort *c*, species and system *T*, fraction
$N_{TAN,T,c}$	=	total ammoniacal nitrogen excreted per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}
$EF\_NH3_{\_house\ (solid)}$	=	emission factor of N-NH_3 from manure deposited in house and managed in solid MMSs, as defined in Table 4.7, kg N-NH_3 kg N^{-1}.

4.4.8 – N_2 emissions from manure management

Part of the nitrogen is lost during manure storage and treatment in the form of NO_x compounds, as calculated in equation 4.26. The proper emission factor from Table 4.9 is assigned according to the liquid or solid nature of manure in each MMS, as reported in Table 4.4 and Table 4.5.

Equation 4.26

$N_{N2,T,c} = N_{TAN,T,c} \times \Sigma_S (MMS_{S,T,c} \times EF\_N_{2,S})$

Where:

$N_{N2,T,c}$	=	total nitrogen emitted as N_2 per animal in cohort *c*, species and system *T*, kg N-N_2 animal^{-1} year^{-1}
$N_{TAN,T,c}$	=	total ammoniacal nitrogen excreted per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}
$MMS_{S,T,c}$	=	for each manure management system category *S* in cohort *c*, species and system *T*, except for MMS_{daily}, $MMS_{pasture}$ and MMS_{burned},, fraction
$EF\_N_{2,S}$	=	emission factor of N-N_2 from manure managed in MMS category *S*, as defined in Table 4.7, kg N-N_2 kg N^{-1}.

4.4.9 – Nitrogen loss from leaching

The amount of nitrogen lost through leachig processes of NO_3 during manure storage and treatment is calculated following Equation 4.27.

Equation 4.27

$N_{leach,T,c} = N_{excretion,T,c} \times \Sigma_S (MMS_{S,T,c} \times Leach_{S,T,c})$

Where:

$N_{leach,T,c}$	=	nitrogen lost as NO_3 trough leaching per animal in cohort *c*, species and system *T*, kg N-NO_3 animal^{-1} year^{-1}
$N_{excretion,T,c}$	=	nitrogen excretion per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}
$MMS_{S,T,c}$	=	for each manure management system category *S* in cohort *c*, species and system *T*, except for MMS_{daily}, $MMS_{pasture}$ and MMS_{burned},, fraction
$Leach_{S,T,c}$	=	proportion of manure nitrogen lost due to leaching from manure management system category *S* in cohort *c*, species and system *T,* based on Table 10.22 (IPCC, 2019, Volume 4, Chapter 10), fraction.

4.4.10 – Total nitrogen losses from animal house and manure storage

The total amount of nitrogen lost trough the emissions of different compounds during the storage and treatment of manure is calculated in Equation 4.28. Emissions of NO_x from manure burned as fueld are not included in this calculation, since they are allocated to energy production together with emissions of NO_x from manure incinerated after storage (see Section 4.4.15).

Equation 4.28

$N_{emissions\_tot,T,c} = N_{N2O,T,c} + N_{NH3\_final,T,c} + N_{NOx,T,c} + N_{N2,T,c} + N_{leach,T,c} + N_{NH3\_daily\_spread,T,c}$

Where:

$N_{emissions\_tot,T,c}$	=	total nitrogen emissions from manure management per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}
$N_{N2O,T,c}$	=	nitrogen emitted as N_2O from manure storage per animal in cohort *c*, species and system *T*, kg N-N_2O animal^{-1} year^{-1}
$N_{NH3\_final,T,c}$	=	nitrogen emitted as NH_3 net of indirect N_2O emissions per animal in cohort *c,* species and system *T*, kg NNH_3 animal^{-1} year^{-1}
$N_{NOx,T,c}$	=	nitrogen emitted as NO_x per animal in cohort *c*, species and system *T*, kg N-NO_x animal^{-1} year^{-1}
$N_{N2,T,c}$	=	nitrogen emitted as N_2 per animal in cohort *c*, species and system *T*, kg N-N_2 animal^{-1} year^{-1}

$N_{leach,T,c}$ = nitrogen lost as NO_3 trough leaching per animal in cohort *c*, species and system *T*, kg N-NO_3 animal^{-1} year^{-1}

$N_{NH3\_daily\_spread,T,c}$ = nitrogen emitted as NH_3 from manure applied to croplands or pastures within 24 hours from excretion, per animal in cohort *c*, species and system *T*, kg N-NH_3 animal^{-1} year^{-1}

4.4.11 – Organic nitrogen losses from manure discharge

The amount of organic nitrogen lost through discarge of manure into waterbodies after storage and treatment is calculated in Equation 4.29, based on the share of discarged manure, as defined in Table 4.2. These losses of nitrogen are net of emissions arising in animal housing facilities and during manure management.

Equation 4.29

$$N_{discharge,T,c} = (N_{excretion,T,c} - N_{emissions\_tot,T,c}) \times (1 - MMS_{pasture,T,c} - MMS_{confined,T,c} - MMS_{daily,T,c} - MMS_{burned,T,c}) \times Fraction_{Discharge,T,c}$$

Where:

$N_{discharge,T,c}$ = organic nitrogen lost through manure discharge per animal in cohort *c*, species and system *T*, kg N-NO_3 animal^{-1} year^{-1}

$N_{excretion,T,c}$ = nitrogen excretion per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$N_{emissions\_tot,T,c}$ = total nitrogen emissions from manure management per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$MMS_{pasture,T,c}$ = share of manure managed as Pasture in cohort *c*, species and system *T*, fraction

$MMS_{confined,T,c}$ = share of manure managed as Confinement in cohort *c*, species and system *T*, fraction

$MMS_{daily,T,c}$ = share of manure managed as Daily spread in cohort *c*, species and system *T*, fraction

$MMS_{burned,T,c}$ = share of manure managed as Burned in cohort *c*, species and system *T*, fraction

$Fraction_{Discharge,T,c}$ = proportion of manure discharged into water bodies for cohort *c*, species and system *T*, fraction.

4.4.12 – NO_x loss from incineration

The amount of nitrogen lost as NO_x compounds through incineration of manure after storage and treatment is calculated in Equation 4.30, based on the share of incinerated manure, as defined in Table 4.2. These losses of nitrogen are net of emissions arising in animal housing facilities and during manure management.

Equation 4.30

$$N_{NOx\_incineration,T,c} = (N_{excretion,T,c} - N_{emissions\_tot,T,c}) \times (1 - MMS_{pasture,T,c} - MMS_{confined,T,c} - MMS_{daily,T,c} - MMS_{burned,T,c}) \times Fraction_{Inceneration,T,c}$$

Where:

$N_{NOx\_incineration,T,c}$ = nitrogen emitted as NO_x from manure incineration per animal in cohort *c*, species and system *T*, kg N-NO_x animal^{-1} year^{-1}

$N_{excretion,T,c}$ = nitrogen excretion per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$N_{emissions\_tot,T,c}$ = total nitrogen emissions from manure management per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$MMS_{pasture,T,c}$ = share of manure managed as Pasture in cohort *c*, species and system *T*, fraction

$MMS_{confined,T,c}$ = share of manure managed as Confinement in cohort *c*, species and system *T*, fraction

$MMS_{daily,T,c}$ = share of manure managed as Daily spread in cohort *c*, species and system *T*, fraction

$MMS_{burned,T,c}$ = share of manure managed as Burned in cohort *c*, species and system *T*, fraction

$Fraction_{Inceneration,T,c}$ = fraction of manure incinerated for cohort *c*, species and system *T*, fraction.

Note: most of manure incinerated is used as energy source, thus NO_x emissions from the incineration are allocated to the energy sector.

4.4.13 – Manure nitrogen disposed of in public sewage

The amount of nitrogen lost through disposal of manure in public sewages after storage and treatment is calculated in Equation 4.31, based on the share of manure disposed as such, as defined in Table 4.2. These losses of nitrogen are net of emissions arising in animal housing facilities and during manure management.

Equation 4.31

$$N_{pubbsewage,T,c} = (N_{excretion,T,c} - N_{emissions\_tot,T,c}) \times (1 - MMS_{pasture,T,c} - MMS_{confined,T,c} - MMS_{daily,T,c} - MMS_{burned,T,c}) \times Fraction_{pubbsewage,T,c}$$

Where:

$N_{pubbsewage,T,c}$ = nitrogen emitted as indirect N_2O emissions from manure disposed of in public sewage per animal in cohort *c*, species and system *T*, kg N-N_2O animal^{-1} year^{-1}

$N_{excretion,T,c}$ = nitrogen excretion per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$N_{emissions\_tot,T,c}$ = total nitrogen emissions from manure management per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$MMS_{pasture,T,c}$ = share of manure managed as Pasture in cohort *c*, species and system *T*, fraction

$MMS_{confined,T,c}$ = share of manure managed as Confinement in cohort *c*, species and system *T*, fraction

$MMS_{daily,T,c}$ = share of manure managed as Daily spread in cohort *c*, species and system *T*, fraction

$MMS_{burned,T,c}$ = share of manure managed as Burned in cohort *c*, species and system *T*, fraction

$Fraction_{pubbsewage,T,c}$ = share of manure disposed of in public sewage for cohort *c*, species and system *T*, fraction.

4.4.14 – Manure nitrogen disposed of in dumping

The amount of nitrogen lost through manure dunping after storage and treatment is calculated in Equation 4.32, based on the share of dumped manure, as defined in Table 4.2. These losses of nitrogen are net of emissions arising in animal housing facilities and during manure management.

Equation 4.32

$$N_{dumping,T,c} = (N_{excretion,T,c} - N_{emissions\_tot,T,c}) \times (1 - MMS_{pasture,T,c} - MMS_{confined,T,c} - MMS_{daily,T,c} - MMS_{burned,T,c}) \times Fraction_{dumping,T,c}$$

Where:

$N_{dumping,T,c}$ = manure nitrogen disposed of through dumping per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$N_{excretion,T,c}$ = nitrogen excretion per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$N_{emissions\_tot,T,c}$ = total nitrogen emissions from manure management per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

$MMS_{pasture,T,c}$ = share of manure managed as Pasture in cohort *c*, species and system *T*, fraction

$MMS_{confined,T,c}$ = share of manure managed as Confinement in cohort *c*, species and system *T*, fraction

$MMS_{daily,T,c}$ = share of manure managed as Daily spread in cohort *c*, species and system *T*, fraction

$MMS_{burned,T,c}$ = share of manure managed as Burned in cohort *c*, species and system *T*, fraction

$Fraction_{dumping,T,c}$ = share of manure disposed of in dumping in cohort *c*, species and system *T*, fraction.

4.4.15 – NO_x loss from energy

The amounts of manure nitrogen emitted as NO_x compounds from the buring of manure as fuel (Section 4.4.7) or from its incineration after storage and treatment can be used to estimate the total manure nitrogen lost in this form for energy production, following Equation 4.33.

Equation 4.33

$$N_{NOx\_energy,T,c} = N_{NOx\_burned,T,c} + N_{NOx\_incineration,T,c}$$

Where:

$N_{NOx\_energy,T,c}$ = nitrogen emitted as NO_x through energy production from manure per animal in cohort *c*, species and system *T*, kg N-NO_x animal^{-1} year^{-1}

$N_{NOx\_burned,T,c}$	=	nitrogen excretion per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}
$N_{NOx\_incineration,T,c}$	=	nitrogen emitted as NO_x from manure incineration per animal in cohort *c*, species and system *T*, kg N-NO_x animal^{-1} year^{-1}

4.4.16 – Additional indirect N_2O emissions

Additional indirect emissions od N_2O are produced from nitrogen lost through processes of leaching and dumping or discharge of manure in the environmento or in public sewages. These emissions are calculated using the emission factors reported in IPCC (2000, 2019).

4.4.16.1 – N_2O emissions from nitrogen leaching

The amount of nitrogen lost throug leaching (calculated in Section 4.4.9) is used to estimate indirect N_2O emissions using Equation 4.34.

Equation 4.34

$$N_{N2O\_leaching,T,c} = N_{leach,T,c} \times EF_{\_N2O\_leaching}$$

Where:

$N_{N2O\_leaching,T,c}$	=	nitrogen emitted as indirect N_2O emissions from manure nitrogen lost through leaching per animal in cohort *c*, species and system *T*, kg N-N_2O animal^{-1} year^{-1}
$N_{leach,T,c}$	=	nitrogen lost as NO_3 trough leaching per animal in cohort *c*, species and system *T*, kg N-NO_3 animal^{-1} year^{-1}
$EF_{\_N2O\_leaching}$	=	emission factor for N-N_2O emissions from manure nitrogen lost through leaching, 0.011 kg N-N_2O kg N^{-1}

4.4.16.2 – N_2O emissions from discharged manure

The amount of nitrogen lost throug dischage of maure in the environment (calculated in Section 4.4.11) is used to estimate indirect N_2O emissions using Equation 4.35.

Equation 4.35

$$N_{N2O\_discharge,T,c} = N_{discharge,T,c} \times EF_{\_N2O\_discharge}$$

Where:

$N_{N2O\_discharge,T,c}$	=	nitrogen emitted as indirect N_2O emissions from manure discharged per animal in cohort *c*, species and system *T*, kg N-N_2O animal^{-1} year^{-1}
$N_{discharge,T,c}$	=	organic nitrogen lost through manure discharge per animal in cohort *c*, species and system *T*, kg N-NO_3 animal^{-1} year^{-1}
$EF_{\_N2O\_discharge}$	=	emission factor for N-N2O emissions from manure nitrogen discharged, 0.01 kg N-N2O-N kg N-1. This is equivalent to the sum of the emission factors for rivers (0.0075) and estuaries (0.0025), from IPCC (2000).

4.4.16.3 – N_2O emissions from public sewage

The amount of nitrogen lost throug dischage of maure in public sewages (calculated in Section 4.4.13) is used to estimate indirect N_2O emissions using Equation 4.36.

Equation 4.36

$$N_{N2O\_PublicSewage,T,c} = N_{pubbsewage,T,c} \times EF_{\_N2O\_sewage}$$

Where:

$N_{N2O\_PublicSewage,T,c}$	=	nitrogen emitted as indirect N_2O emissions from manure disposed of in public sewage per animal in cohort *c*, species and system *T*, kg N-N_2O animal^{-1} year^{-1}
$N_{pubbsewage,T,c}$	=	manure nitrogen disposed of in public sewage per animal in cohort *c*, species and system *T*, kg N animal^{-1} year^{-1}

EF_{N2O_sewage} = emission factor for indirect $N\text{-}N_2O$ emissions from manure disposed of in public sewage, 0.01 kg $N\text{-}N_2O$ kg N^{-1}, from IPCC (2000)

4.4.16.4 – N_2O emissions from dumping

The amount of nitrogen lost throug dumping of maure (calculated in Section 4.4.14) is used to estimate indirect N_2O emissions using Equation 4.37.

Equation 4.37

$$N_{N2O\_dumping,T,c} = N_{dumping,T,c} \times EF\_{N2O\_dumping}$$

Where:

$N_{N2O\_dumping,T,c}$ = nitrogen emitted as indirect N2O emissions from manure disposed of through dumping per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2O$ $animal^{-1}$ $year^{-1}$

$N_{dumping,T,c}$ = manure nitrogen disposed of through dumping per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

$EF\_{N2O\_dumping}$ = emission factor for $N\text{-}N_2O$ emissions from manure disposed of through dumping, 0.2 kg $N\text{-}N_2O$ kg N^{-1}, from IPCC (2000)

4.4.17 – Final manure nitrogen losses

The final amount of nitrogen losses from manure management is calculated summing the emissions of different compounds in house and during manure storage and treatment with the the losses from manure burned for energy production, dumped and discharged in public sewages or the environement, following Equation 4.38.

Equation 4.38

$$N_{losses,T,c} = N_{emissions\_tot,T,c} + N_{discharge,T,c} + N_{NOx\_energy,T,c} + N_{pubbsewage,T,c} + N_{dumping,T,c}$$

Where:

$N_{losses,T,c}$ = total manure nitrogen losses per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

$N_{emissions\_tot,T,c}$ = total nitrogen emissions from manure management per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

$N_{discharge,T,c}$ = organic nitrogen lost through manure discharge per animal in cohort *c*, species and system *T*, kg $N\text{-}NO_3$ $animal^{-1}$ $year^{-1}$

$N_{NOx\_energy,T,c}$ = nitrogen emitted as NOx through energy production from manure per animal in cohort *c*, species and system *T*, kg $N\text{-}NO_x$ $animal^{-1}$ $year^{-1}$

$N_{pubbsewage,T,c}$ = manure nitrogen disposed of in public sewage per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

$N_{dumping,T,c}$ = manure nitrogen disposed of through dumping per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

4.4.18 – Manure nitrogen not collected

The nitrogen in manure, net of NH_3 emission, that is not collected from animal housing facilieties may not be lost in the environment. However, since it's not recycled, it has to be considered in any analysis of nitrogen use efficiency. It is also required to calculate the amount of manure-nitrogen that is recyvled (Section 4.4.19). GLEAM estimate this amount of nitrogen based on Equation 4.39. The proper emission factors are assigned according to the liquid or solid nature of manure in MMS category "Confinment", as reported in Table 4.5.

Equation 4.39

$$N_{not\text{-}collected,T,c} = N_{excretion,T,c} \times MMS_{confinement,T,c} - N_{TAN,T,c} \times MMS_{confinement,T,c} \times (EF\_NH_{3\_yard} + EF\_NH_{3\_storage,confinment} + EF\_N_2O_{direct,confinment,T} + EF\_NO_{x,confinement} + EF\_N_{2,confinment} + Leach_{confinment,T,c})$$

Where:

$N_{not\text{-}collected,T,c}$ = not collected manure nitrogen per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

$N_{excretion,T,c}$ = nitrogen excretion per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

$MMS_{confinement,T,c}$ = share of manure managed as Confinement in cohort *c*, species and system *T*, fraction

$N_{TAN,T,c}$ = total ammoniacal nitrogen excreted per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

$EF\_NH_{3\_yard}$ = emission factor of N-NH_3 from manure deposited in the yard and managed in liquid MMSs, as defined in Table 4.1, kg N-NH_3 kg N^{-1}.

$EF\_NH_{3\_storage,\ confinment}$ = emission factor of N-NH_3 from manure managed as Confinement, as defined in Table 4.6, kg N-NH_3 kg N^{-1}.

$EF\_N_2O_{direct,confinment,T}$ = emission factor for direct N-N_2O emissions from manure managed as Confinement, for species and system *T*, as defined in Table 4.1, Table 4.5 and Table 4.7, kg N-N_2O kg N^{-1}.

$EF\_NO_{x,confinement}$ = emission factor of N-NO_x from manure managed as Confinement, as defined in Table 4.1, Table 4.5 and Table 4.8, kg N-NO_x kg N^{-1}.

$EF\_N_{2,confinment}$ = emission factor of N-N_2 from manure managed as Confinement, as defined in Table 4.1, Table 4.5 and Table 4.8, kg N-N_2 kg N^{-1}.

$Leach_{confinment,T,c}$ = proportion of manure nitrogen lost due to leaching from manure management as Confinement in cohort *c*, species and system *T*, based on Table 10.22 (IPCC, 2019, Volume 4, Chapter 10), fraction.

4.4.19 – Manure nitrogen for recycling

The amount of manure-nitrogen available for recycle, net of losses, is calculated following equation 4.39.

Equation 4.39

$$N_{recycled,T,c} = N_{excretion,T,c} - N_{losses,T,c} - N_{not\text{-}collected,T,c}$$

Where:

$N_{recycled,T,c}$ = manure nitrogen available for recycling per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ year

$N_{excretion,T,c}$ = nitrogen excretion per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

$N_{losses,T,c}$ = total manure nitrogen losses per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

$N_{not\text{-}collected,T,c}$ = not collected manure nitrogen per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

4.4.20 – Manure nitrogen for recycling in agriculture

The amount of manure-nitrogen available for application to croplands is calculated removing the share of manure-nitrogen used in aquaculture from the total available for recycle that is calculated in Section 4.4.19, following Equation 4.40.

Equation 4.40

$$N_{recycled\_agr,T,c} = N_{recycled,T,c} - N_{recycled,T,c} \times Fraction_{fishpond,T,c}$$

Where:

$N_{recycled\_agr,T,c}$ = manure nitrogen available for recycling in agriculture per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ $year^{-1}$

$N_{recycled,T,c}$ = manure nitrogen available for recycling per animal in cohort *c*, species and system *T*, kg N $animal^{-1}$ year

$Fraction_{fishpond,T,c}$ = proportion of recycled manure used in fishponds from cohort *c*, species and system *T*, fraction.

4.4.21 – Summary of manure nitrogen compounds

The following equations summarise the amount of manure nitrogen emitted through several compounds during manure management, specifically N_2O (Equation 4.41), NH_3 (Equation 4.42), NO_x (Equation 4.43), NO_3 (Equation 4.44) and N_2 (Equation 4.45). While only N-N2O is required to estimate GHG emissions, the calculation of the nitrogen lost through other compounds can be used for nitrogen use efficiency analysis and the estimation of other impacts on ecosystems and human health.

Equation 4.41

$N\text{-}N_2O_{,T,c} = N_{N2O,T,c} + N_{N2O\_leaching,T,c} + N_{N2O\_Discharge,T,c} + N_{N2O\_PublicSewage,T,c} + N_{N2O\_Dumping,T,c}$

Where:

$N\text{-}N_2O_{,T,c}$	=	total nitrogen emitted as N_2O from manure management per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2O$ $animal^{-1}$ $year^{-1}$
$N_{N2O,T,c}$	=	nitrogen emitted as N_2O from manure storage per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2O$ $animal^{-1}$ $year^{-1}$
$N_{N2O\_leaching,T,c}$	=	nitrogen emitted as indirect N_2O emissions from manure nitrogen lost through leaching per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2O$ $animal^{-1}$ $year^{-1}$
$N_{N2O\_discharge,T,c}$	=	nitrogen emitted as indirect N_2O emissions from manure discharged per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2O$ $animal^{-1}$ $year^{-1}$
$N_{N2O\_PublicSewage,T,c}$	=	nitrogen emitted as indirect N_2O emissions from manure disposed of in public sewage per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2O$ $animal^{-1}$ $year^{-1}$
$N_{N2O\_dumping,T,c}$	=	nitrogen emitted as indirect N_2O emissions from manure disposed of through dumping per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2O$ $animal^{-1}$ $year^{-1}$

Equation 4.42

$N\text{-}NH_{3,T,c} = N_{NH3\_final,T,c}$

Where:

$N\text{-}NH_{3,T,c}$	=	total nitrogen emitted as NH_3 from manure management per animal in cohort *c*, species and system *T*, kg $N\text{-}NH_3$ $animal^{-1}$ $year^{-1}$
$N_{NH3\_final,T,c}$	=	nitrogen emitted as NH_3 net of indirect N_2O emissions per animal in cohort *c*, species and system *T*, kg NNH_3 $animal^{-1}$ $year^{-1}$

Equation 4.43

$N\text{-}NO_{x,T,c} = N_{NOx,T,c} + N_{NOx\_energy,T,c}$

Where:

$N\text{-}NO_{x,T,c}$	=	total nitrogen emitted as NO_x from manure management per animal in cohort *c*, species and system *T*, kg $N\text{-}NO_x$ $animal^{-1}$ $year^{-1}$
$N_{NOx,T,c}$	=	nitrogen emitted as NOx per animal in cohort *c*, species and system *T*, kg N-NOx $animal^{-1}$ $year^{-1}$
$N_{NOx\_energy,T,c}$	=	nitrogen emitted as NOx through energy production from manure per animal in cohort *c*, species and system *T*, kg $N\text{-}NO_x$ $animal^{-1}$ $year^{-1}$

Equation 4.44

$N\text{-}NO_{3,T,c} = Nleach_{,T,c} + N_{discharge,T,c} - N_{N2O\_Discharge,T,c} - N_{N2O\_leaching,T,c}$

Where:

$N\text{-}NO_{3,T,c}$	=	total nitrogen emitted as NO_3 from manure management per animal in cohort *c*, species and system *T*, kg $N\text{-}NO_x$ $animal^{-1}$ $year^{-1}$
$N_{leach,T,c}$	=	nitrogen lost as NO_3 trough leaching per animal in cohort *c*, species and system *T*, kg $N\text{-}NO_3$ $animal^{-1}$ $year^{-1}$
$N_{discharge,T,c}$	=	organic nitrogen lost through manure discharge per animal in cohort *c*, species and system *T*, kg $N\text{-}NO_3$ $animal^{-1}$ $year^{-1}$
$N_{N2O\_discharge,T,c}$	=	nitrogen emitted as indirect N_2O emissions from manure discharged per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2O$ $animal^{-1}$ $year^{-1}$
$N_{N2O\_leaching,T,c}$	=	nitrogen emitted as indirect N_2O emissions from manure nitrogen lost through leaching per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2O$ $animal^{-1}$ $year^{-1}$

Equation 4.45

$N\text{-}N_{2,T,c} = N_{N2,T,c}$

Where:

$N\text{-}N_{2,T,c}$	=	total nitrogen emitted as N_2 from manure management per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2$ animal^{-1} year^{-1}
$N_{N2,T,c}$	=	total nitrogen emitted as N_2 per animal in cohort *c*, species and system *T*, kg $N\text{-}N_2$ animal^{-1} year^{-1}

4.5 – AGGREGATING GREENHOUSE GAS AT HERD OR FLOCK LEVEL

The last step of the animal emissions module is to totalize, for the entire herd or flock, the methane emissions related to animal production, both from enteric fermentation (Equation 4.46) and manure management (Equation 4.47) and the nitrous oxide emissions related to manure management (Equation 4.48).

Equation 4.46

$$CH_{4\text{-Enteric},T} = \sum_c (CH_{4\text{-Enteric},T,c})$$

Where:

$CH_{4\text{-Enteric},T}$	=	total methane emissions from enteric fermentation for species and system *T*, kg CH_4×year^{-1}
$CH_{4\text{-Enteric},T,c}$	=	methane emissions from enteric fermentation for species and system *T* and cohort *c*, kg CH_4×year^{-1}

Equation 4.47

$$CH_{4\text{-Manure},T} = \sum_c (CH_{4\text{-Manure},T,c})$$

Where:

$CH_{4\text{-Manure},T}$	=	total methane emissions from manure management for species and system *T*, kg CH_4×year^{-1}
$CH_{4\text{-Manure},T,c}$	=	methane emissions from manure management for species and system *T* and cohort *c*, kg CH_4×year^{-1}

Equation 4.48

$$N_2O_{manure,T} = 44/28 \times \Sigma_c (N_{T,c} \times N\text{-}N_2O_{T,c})$$

Where:

$N_2O_{manure,T}$	=	total N_2O emitted for species and system *T*, kg N_2O year^{-1}
44 / 28	=	conversion factor from $N\text{-}N_2O$ to N_2O emissions.
$N_{T,c}$	=	number of animals in cohort *c*, species and system *T*, heads
$N\text{-}N_2O_{T,c}$	=	total nitrogen emitted as N_2O per animal in cohort *c* for species and system *T*, kg $N\text{-}N_2O$ animal^{-1} year^{-1}

5 CHAPTER 5 – MANURE MODULE

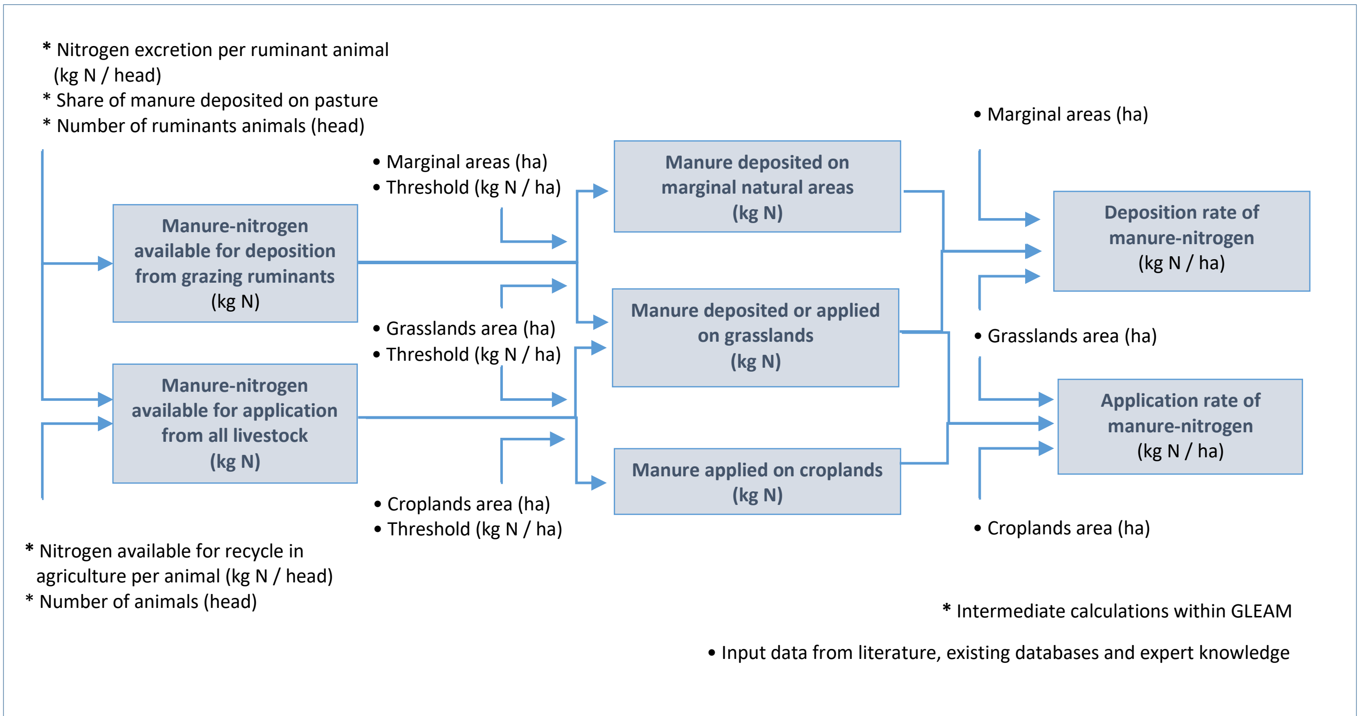
Manure management and application is a key component of crop and livestock production systems. Manure contributes to soil fertility and to nutrient and energy cycles. It is also responsible for emissions of N_2O and CH_4. GLEAM estimates GHG emissions from manure storage and management, and from its application on crops used as livestock feed and on pastures.

The function of the 'Manure' module is to calculate the rate at which excreted nitrogen is applied and deposited in feed crops' fields and pastures. Such application and deposition rates are required to estimate N_2O emissions arising from feed production and consumption by the sector, as calculated by the Feed emissions module (Chapter 6). Actual emissions of N_2O (and CH_4) prior to application are calculated in the Animal emissions module (Chapter 4).

We assumed that manure is applied and deposited in the cell where it is produced. At cell level, manure deposited on grazing areas from ruminants is distributed to grasslands and marginal lands. The marginal lands are defined as areas covered by bare soils, sparse or herbaceous vegetation and shrubland. Manure stored in other MMSs prior to its application is distributed at first on available arable lands and the excess is applied on grassland. We define the maximum threshold for manure nitrogen application or deposition as 700 kg N×ha^{-1} (Gerber et al., 2016). Manure nitrogen in excess is assumed to be a surplus amount that is either lost or not recycled in the reference modelled year.

For a schematic representation of the manure module, see Figure 5.1.

Figure 5.1 Schematic representation of the manure module



Three main surfaces need to be defined for manure application or deposition: 1) cropland, used for the nitrogen available for application from ruminants and monogastrics; 2) grassland, used for the application of the surplus manure not applied on cropland from ruminants and monogastrics and for part of the deposited manure from ruminants; 3) other natural areas, used for part of the deposited manure from ruminants, including bare areas, shrublands and areas with herbaceous or sparse vegetation. The required spatial data of land cover were obtained from ESA (2017).

5.1 – TOTALIZATION OF THE NITROGEN AVAILABLE

The first step is the estimation of the total manure nitrogen available for deposition on pastures by grazing ruminants (Section 5.1.1) and for application to croplands by both ruminant and monogastric species (Section 5.1.2).

5.1.1 – Nitrogen available for deposition by ruminant herd

The amount of manure nitrogen deposited on pastures by grazing ruminants is calculated following Equation 5.1, based on the nitrogen excreted by animals (Section 4.4.2) and the share of manure deposited on pastures.

Equation 5.1

$Navailable_{dep,T} = \Sigma_c ((N_{T,c} \times N_{excretion,T,c} \times MMS_{pasture,T,c})$

Where:

$Navailable_{dep,T}$ = manure nitrogen available for deposition from grazing animals for each ruminant species and system *T*, kg N

$N_{T,c}$ = number of animals in cohort *c*, for each ruminant species and system *T*, heads

$N_{excretion,T,c}$ = nitrogen excretion per animal in cohort *c*, for each ruminant species and system *T*, kg N N animal^{-1} year^{-1}

$MMS_{pasture,T,c}$ = proportion of manure deposited on pasture per animal in cohort *c*, for each ruminant species and system *T*, fraction

5.1.2 – Nitrogen available for application by herd

The amount of manure nitrogen available for application to croplands is calculated following Equation 5.2, based one the manure nitrogen available for recycle in agriculture that is calculated in Section 4.4.20. For ruminants, this amount of nitrogen is net of that deposited on pasture by grazing animals, as calculated in Section 5.1.1.

Equation 5.2

a. Monogastrics

$Navailable_{appl,T} = \Sigma_c(N_{T,c} \times N_{recycled\_agr,T,c})$

Where:

$Navailable_{appl,T}$ = manure nitrogen available for application for each monogastric species and system *T*, kg N

$N_{T,c}$ = number of animals in cohort *c*, for each monogastric species and system *T*, heads

$N_{recycled\_agr,T,c}$ = manure nitrogen available for recycling in agriculture per animal in cohort *c*, for each monogastric species and system T, kg N animal^{-1} year^{-1}

b. Ruminants

$Navailable_{appl,T} = \Sigma_c(N_{T,c} \times N_{recycled\_agr,T,c}) - Navailable_{dep,T}$

Where:

$Navailable_{appl,T}$ = manure nitrogen available for application for each ruminant species and system *T*, kg N

$N_{T,c}$ = number of animals in cohort *c*, for each ruminant species and system *T*, heads

$N_{recycled\_agr,T,c}$ = manure nitrogen available for recycling in agriculture per animal in cohort *c*, for each ruminant species and system T, kg N animal^{-1} year^{-1}

$Navailable_{dep,T}$ = manure nitrogen available for deposition from grazing animals for each ruminant ruminant species and system *T*, kg N

5.1.3 – Total nitrogen available for application or deposition

The total manure nitrogen available for application on croplands or deposition on pastures from all modelled livestock species and systems is calculated following Equation 5.3 and Equation 5.4, respectively.

Equation 5.3

$Navailable_{appl} = \mathbf{\Sigma}_T (Navailable_{appl,T})$

Where:

$Navailable_{appl}$ = total manure nitrogen available for application, kg N

$Navailable_{appl,T}$ = manure nitrogen available for application for each species and system *T*, kg N

Equation 5.4

$Navailable_{dep} = \Sigma_T (Navailable_{dep,T})$

Where:

$Navailable_{dep}$ = total manure nitorgen available for deposition from grazing animals, kg N

$Navailable_{dep,T}$ = manure nitrogen available for deposition from grazing animals for each ruminant species and system *T*, kg N

Nitrogen available for deposition from ruminants needs to be allocated to grassland (Equation 5.5) and other natural areas (Equation 5.6), according to the proportion of available hectares from the two categories. This allocation excludes the nitrogen available for deposition in areas (mostly woodlands) where there is no cover of neither grassland nor the other natural areas considered as marginal lands and that, therefore, remains unassigned and is assumed to be surplus manure nitrogen from deposition.

Equation 5.5

$Navailable_{dep\_grass} = Navailable_{dep} \times (Grassland\_ha / (Grassland\_ha + OthNat\_ha))$

Where:

$Navailable_{dep\_grass}$ = total manure nitrogen available for deposition on grassland from grazing animals, kg N

$Navailable_{dep}$ = total manure nitrogen available for deposition from grazing animals, kg N

Grassland_ha = surface of grassland, calculated from GLC share layers, ha

OthNat_ha = surface of natural areas other than grassland, ha

Equation 5.6

$Navailable_{dep\_othnat} = Navailable_{dep} \times (OthNat\_ha / (Grassland\_ha + OthNat\_ha))$

Where:

$Navailable_{dep\_othnat}$ = total manure nitrogen deposited on natural areas other than grassland from grazing animals, kg N

$Navailable_{dep}$ = total manure nitrogen available for deposition from grazing animals, kg N

OthNat_ha = surface of natural areas other than grassland, ha

Grassland_ha = surface of grassland, ha

5.2 – MANURE-N DEPOSITED ON OTHER NATURAL AREAS FROM RUMINANTS

Estimation of the maximum manure nitrogen deposition allowed on marginal natural areas other than grasslands is based on the assumed maximum thresholds of 700 kg $N \times ha^{-1}$ (Gerber et al., 2016), and is calculated following Equation 5.7. This is then used to estimate the actual amount of manure nitrogen deposited, based on the respective availability, following Equation 5.8.

Equation 5.7

$Nmax\_{othnat} = OthNat\_ha \times Threshold$

Equation 5.8

IF:

$Navailable_{dep\_othnat} \leq Nmax\_{othnat}$

THEN:

$Ndeposited_{othnat} = Navailable_{dep\_othnat}$

ELSE:

$Ndeposited_{othnat} = Nmax\_{othnat}$

Where:

$Nmax\_{othnat}$ = maximum amount of manure nitrogen that can be deposited on natural areas other than grassland, kg N

OthNat_ha = surface of natural areas other than grassland, ha.

Threshold = maximum amount of nitrogen that can be deposited or applied per hectare, 700 kg N×ha^{-1}; (Gerber et al., 2016)

$Navailable_{dep\_othnat}$= total manure nitrogen available for deposition on natural areas other than grassland from grazing animals, kg N

$Ndeposited_{othnat}$ = total manure nitrogen deposited on natural areas other than grassland from grazing animals, kg N

5.3 – MANURE-N APPLIED ON CROPLANDS

At first, all nitrogen available for application from ruminants and monogastrics is used for croplands. Estimation of the maximum manure nitrogen application allowed on croplands is based on the assumed maximum thresholds of 700 kg N×ha^{-1} (Gerber et al., 2016), and is calculated following Equation 5.9. This is then used to estimate the actual amount of manure nitrogen deposited, based on the respective availability, following Equation 5.10.

Equation 5.9

$Nmax\_{}_{cropland} = Croplands\_ha \times Threshold$

Equation 5.10

IF:

$Navailable_{appl} \leq Nmax\_{}_{cropland}$

THEN:

$Napplied_{cropland} = Navailable_{appl}$

ELSE:

$Napplied_{cropland} = Nmax\_{}_{cropland}$

Where:

$Nmax\_{}_{cropland}$ = maximum amount of manure nitrogen that can be applied on cropland, kg N

Cropland_ha = surface of croplands, calculated from GLC share layers, ha

Threshold = maximum amount of nitrogen that can be deposited or applied per hectare, 700 kg N/ha; (Gerber et al., 2016)

$Navailable_{appl}$ = total manure nitrogen available for application, kg N

$Napplied_{cropland}$ = total manure nitrogen applied on cropland, kg N

5.4 – MANURE-N APPLIED OR DEPOSITED ON GRASSLANDS

Estimation of the maximum manure nitrogen application or deposition allowed on croplands is based on the assumed maximum thresholds of 700 kg N×ha^{-1} (Gerber et al., 2016), and is calculated following Equation 5.11.

Equation 5.11

$Nmax\_{}_{grass} = Grassland\_ha \times Threshold$

Where:

$Nmax\_{}_{grass}$ = maximum amount of manure nitrogen that can be deposited or applied on grassland, kg N

Grassland _ha = surface of grassland, calculated from GLC share layers, ha

Threshold = maximum amount of nitrogen that can be deposited or applied per hectare, 700 kg N/ha; (Gerber et al., 2016)

Manure nitrogen in excess from the initial application on croplands (Section 5.3) is available for application on grasslands and is calculated following Equation 5.12.

Equation 5.12

$Navailalbe_{appl\_grass} = Navailable_{appl} - Napplied_{cropland}$

Where:

$Navailable_{appl\_grass}$= total manure nitrogen available for application on grassland, kg N

$Navailable_{appl}$ = total manure nitrogen available for application, kg N

$Napplied_{croplannd}$ = total manure nitrogen applied on cropland, kg N

In order to keep track of the amount of nitrogen applied or deposited, the maximum amount of nitrogen allowed on grasslands must be allocated to nitrogen deposited (Equation 5.13) or applied (Equation 5.14), according to the proportion of nitrogen available from the two sources for grasslands.

Equation 5.13

$$Nmax\_{grass\_dep} = Nmax\_{grass} \times (Navailable_{dep\_grass} / (Navailable_{dep\_grass} + Navailable_{appl\_grass}))$$

Where:

$Nmax\_{grass\_dep}$ = maximum amount of manure nitrogen that can be deposited on grassland from grazing animals, kg N

$Nmax\_{grass}$ = maximum amount of manure nitrogen that can be deposited or applied on grassland, kg N

$Navailable_{dep\_grass}$ = total manure nitrogen available for deposition on grassland from grazing animals, kg N

$Navailable_{appl\_grass}$ = total manure nitrogen available for application on grassland, kg N

Equation 5.14

$$Nmax\_{grass\_appl} = Nmax\_{grass} - Nmax\_{grass\_dep}$$

Where:

$Nmax\_{grass\_appl}$ = maximum amount of manure nitrogen that can be applied on grassland, kg N

$Nmax\_{grass}$ = maximum amount of manure nitrogen that can be deposited or applied on grassland, kg N

$Navailable_{appl\_grass}$ = total manure nitrogen available for application on grassland, kg N

$Navailable_{dep\_grass}$ = total manure nitrogen available for deposition on grassland from grazing animals, kg N

5.4.1 – Nitrogen deposited on grassland

The actual amount of manure nitrogen deposited on grassland is based on the respective maximum deposition allowed (Equation 5.13) and availability (Equation 5.5) and is calculated following Equation 5.15.

Equation 5.15

IF:

$Navailable_{dep\_grass} \leq Nmax\_{grass\_dep}$

THEN:

$Ndeposited_{grass} = Navailable_{dep\_grass}$

ELSE:

$Ndeposited_{grass} = Nmax\_{grass\_dep}$

Where:

$Navailable_{dep\_grass}$ = total manure nitrogen available for deposition on grassland from grazing animals, kg N

$Nmax\_{grass\_dep}$ = maximum amount of manure nitrogen that can be deposited on grassland from grazing animals, kg N

$Ndeposited_{grass}$ = total manure nitrogen deposited on grassland from grazing animals, kg N

5.4.2 – Nitrogen applied on grassland

The actual amount of manure nitrogen applied on grassland is based on the respective maximum application allowed (Equation 5.14) and availability (Equation 5.12) and is calculated following Equation 5.16.

Equation 5.16

IF:

$Navailable_{appl\_grass} \leq Nmax\_{grass\_appl}$

THEN:

$Napplied_{grass} = Navailable_{appl\_grass}$

ELSE:

$Napplied_{grass} = Nmax\_{grass\_appl}$

Where:

$Navailable_{appl\_grass}$ = total manure nitrogen available for application on grassland, kg N
$Nmax_{\_grass\_appl}$ = maximum amount of manure nitrogen that can be applied on grassland, kg N
$Napplied_{grass}$ = total manure nitrogen applied on grassland, kg N

5.5 – MANURE-N APPLICATION OR DEPOSITION RATES

This final section of the Manure module reports the calculation required to estimate the manure nitrogen application and deposition rates, to be used as input parameters for the estimation of feed emissions (Chapter 6).

5.5.1 – Total Manure-Nitrogen deposited or applied

The total amount of manure deposited on both grasslands and other marginal natural areas is calculated following Equation 5.17.

Equation 5.17

$Ndeposited = Ndeposited_{grass} + Ndeposited_{othnat}$

Where:
Ndeposited = total manure nitrogen deposited on grassland or other natural areas from grazing animals, kg N
$Ndeposited_{grass}$ = total manure nitrogen deposited on grassland from grazing animals, kg N
$Ndeposited_{othnat}$ = total manure nitrogen deposited on natural areas other than grassland from grazing animals, kg N

Similarly, Equation 5.18 is used to estimate the total manure nitrogen applied on both grasslands and croplands.

Equation 5.18

$Napplied = Napplied_{grass} + Napplied_{cropland}$

Where:
Napplied = total manure nitrogen deposited on grassland or other natural areas from grazing animals, kg N
$Napplied_{grass}$ = total manure nitrogen applied on grassland, kg N
$Napplied_{croplannd}$ = total manure nitrogen applied on cropland, kg N

5.5.2 – Surfaces

The hectares of agricultural area available for the calculation of deposition and application rates are calculated following Equation 5.21 and Equation 5.22, respectively. To this purpose, however, hectares of grassland need to be allocated between nitrogen deposited and applied, following Equation 5.19 and Equation 5.20, respectively.

Equation 5.19

$Grassland\_ha_{dep} = Grassland\_ha \times (Ndeposited_{grass} / (Ndeposited_{grass} + Napplied_{grass}))$

Where:
$Grassland\_ha_{dep}$ = surface of grassland allocated to manure deposition from grazing animals, ha
Grassland_ha = surface of grassland, calculated from GLC share layers, ha
$Ndeposited_{grass}$ = total manure nitrogen deposited on grassland from grazing animals, kg N
$Napplied_{grass}$ = total manure nitrogen applied on grassland, kg N

Equation 5.20

$Grassland\_ha_{appl} = Grassland\_ha \times (Napplied_{grass} / (Ndeposited_{grass} + Napplied_{grass}))$

Where:
$Grassland\_ha_{appl}$ = surface of grassland allocated to manure application, ha
Grassland_ha = surface of grassland, calculated from GLC share layers, ha
$Napplied_{grass}$ = total manure nitrogen applied on grassland, kg N
$Ndeposited_{grass}$ = total manure nitrogen deposited on grassland from grazing animals, kg N

Equation 5.21

$HA_{dep} = Grassland\_ha_{dep} + OthNat\_ha$

Where:

HA_{dep} = surface of grassland or other natural areas receiving manure nitrogen deposition from grazing animals, ha

$Grassland\_ha_{dep}$ = surface of grassland allocated to manure deposition from grazing animals, ha

$OthNat\_ha$ = surface of natural areas other than grassland, ha

Equation 5.22

$HA_{appl} = Grassland\_ha_{appl} + Cropland\_ha$

Where:

HA_{appl} = surface of grassland or other natural areas receiving manure application, ha

$Grassland\_ha_{appl}$ = surface of grassland allocated to manure application, ha

$Cropland\_ha$ = surface of croplands, calculated from GLC share layers, ha

5.5.3 – Manure-Nitrogen deposition and application rates

Once the total amount of manure nitrogen either deposited during grazing or applied after a phase of storage is calculated, (Section 5.5.1), as well as the respective hectares of agricultural area available (Section 5.5.2), the manure nitrogen deposition and application rates can be calculated, following Equation 5.23 and Equation 5.24, respectively.

Equation 5.23

$Ndepha = Ndeposited / HA_{dep}$

Where:

$Ndepha$ = manure nitrogen deposition rate on grassland or other natural areas from grazing animals, kg N ha^{-1}

$Ndeposited$ = total manure nitrogen deposited on grassland or other natural areas from grazing animals, kg N

HA_{dep} = surface of grassland or other natural areas receiving manure nitrogen deposition from grazing animals, ha

Equation 5.24

$Napplha = Napplied / HA_{appl}$

Where:

$Napplha$ = manure nitrogen application rate on grassland or cropland, kg N ha^{-1}

$Napplied$ = total manure nitrogen deposited on grassland or other natural areas from grazing animals, kg N

HA_{appl} = surface of grassland or other natural areas receiving manure application, ha

6 CHAPTER 6 – FEED EMISSIONS MODULE

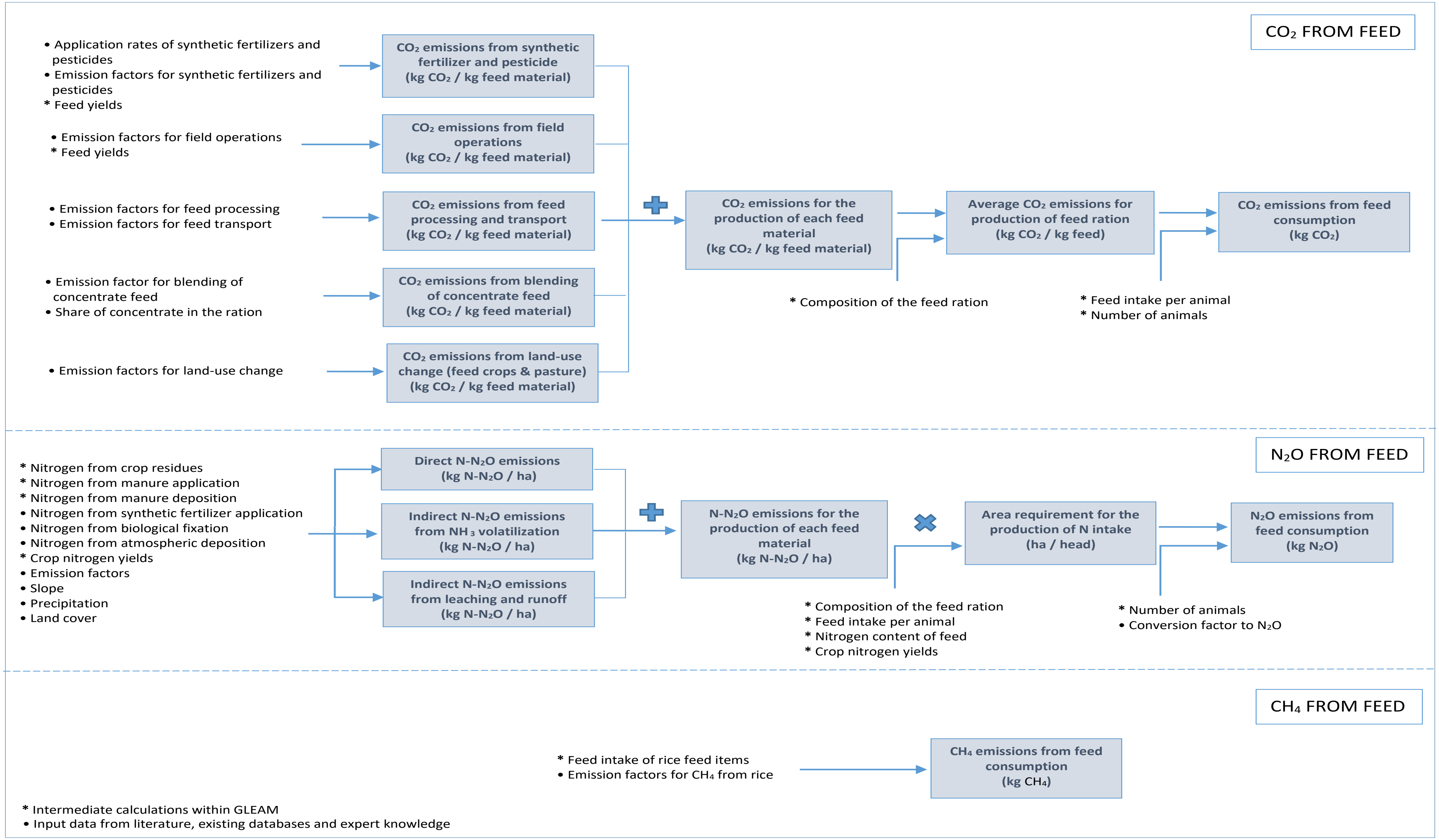
Emissions associated with feed production arise from different sources and include different GHGs. First, emissions of carbon dioxide are associated with the production of synthetic fertilizers and pesticides, energy consumption for tillage, crop management, harvest and storage and, in the case of some feed materials such as by-products, with processing. For some crops emissions include the transport and the energy used in blending and pelleting.

Second, nitrous oxide emissions derive from nitrogen inputs, such as fertilizer application, manure application and deposition, nitrogen from crop residues, biological fixation and natural deposition, in the form of direct and indirect emissions, through volatilization and leaching. Finally, methane emissions can arise from the cultivation of rice used as feed.

The functions of the 'Feed emissions' module are to:

- Calculate the **GHG emissions** related to feed production.
- Calculate the **total emissions** related to the **feed consumption**.
- Totalize the **feed** emissions **for the whole herd or flock**.

Figure 6.1 Schematic representation of the feed emissions module



6.1 – CARBON DIOXIDE AND METHANE EMISSIONS

6.1.1 – Carbone dioxide emissions

6.1.1.1 – Synthetic N, P and K fertilization and pesticides manufacture

Crop-specific data on nitrogen synthetic fertilizer applications at national level were obtained by dividing the total fertilizer consumption for each crop from the International Fertilizer Association (IFA; Heffer et al., 2017) by the harvested area from FAOSTAT for the main fertilizer-consuming countries. Other data on synthetic fertilizer were obtained from the Common Agricultural Policy Regionalised Impact model (CAPRI) for Europe (Leip et al., 2011), and from Swaney et al. (2018) for the United States at a subnational level. For Australia, data were obtained from Navarro et al. (2016). For the rest of the world we used FAOSTAT data. For the nitrogen fertilizer applied to the grassland, we used data from IFA and the literature (Lassaletta et al., 2014). Synthetic phosphorus and potassium fertilizer, as well as pesticides application rates were defined at a national level, based on the LEAP database (LEAP, 2015). CO_2 emissions related to the manufacture and transport of fertilizers and pesticides were calculated using Equation 6.1:

Equation 6.1

a. $CO_2NFERTHA_i = NFERTHA_i \times EF_{NFERT}$

b. $CO_2PFERTHA_i = PFERTHA_i \times EF_{PFERT}$

c. $CO_2KFERTHA_i = KFERTHA_i \times EF_{KFERT}$

d. $CO_2PESTHA_i = PESTHA_i \times EF_{PEST}$

Where:

$CO_2...HA_i$ = carbon dioxide emissions from product ... (N, P, K fertilizer or pesticides) manufacturing for feed material *i*, kg $CO_2 \times ha^{-1}$

$...HA_i$ = application rate of product ... (N, P, K fertilizer or pesticides) for feed material *i*, kg $N \times ha^{-1}$

$EF_{...}$ = regional emission factor of N, P, K fertilizer manufacture or global emission factor for pesticides manufacture, kg $CO_2 \times$kg $product^{-1}$.

For feed items that are internationally traded, weighted average emissions per hectare are calculated for each country, based on the national emissions of the feed producing countries (including domestic production) and the trade matrices described in Section 3.1.

6.1.1.2 – Field operations

Energy is used on-farm for a variety of field operations required for crop cultivation, such as: ploughing, seedbed preparation, sowing, fertilization (lime, organic and synthetic fertilizer application), pesticide spraying, weed control, irrigation and harvesting. Data on the type and amount of energy required and emissions associated per hectare of each feed crop were taken from literature review, existing databases (LEAP, 2015), expert knowledge and surveys (Table S.6.1 and Table S.6.2; Supplement S1). Field operations are undertaken using non-mechanized power sources, i.e. human or animal labour, in some countries. To reflect this variation, the emissions per hectare were adjusted according to the proportion of the field operations undertaken using non-mechanized power sources for each feed material (Table S.6.3 and Table S.6.4; Supplement S1).

6.1.1.3 – Feed transport and processing

Forage, local feeds and swill, by definition, are transported over minimal distances and therefore emissions for transport are set to zero. Non-local feeds for monogastrics and by-products and concentrate for ruminants are assumed to be transported between 100 km and 700 km by road to their place of processing. To account for the distances of sea transport for the international trade for each of these feed items, a weighted sea travel distance was calculated using FAO bilateral trade data (FAOSTAT, 2021) and the sea distance data set from Bertoli et al. (2016). Emissions from processing arise from the energy consumed in activities such as milling, crushing and heating, which are used to process whole crop materials into specific products. For each feed materials, data on energy consumption for processing activities and emissions associated with such activities and transport methods were taken from literature review, existing databases and expert knowledge (Table S.6.5 and Table S.6.6; Supplement S1).

6.1.1.4 – Blending and transport of concentrate feed

In addition, energy is used in feed mills for blending concentrate feed materials, in some cases for transforming the blended materials into pellets, and to transport them to their point of sale. It was assumed that an average of 186 MJ of electricity and 188 MJ of gas were required to blend 1 000 kg of DM, and that the average transport distance was 200 km, which results in an emission factor of **0.0786 kg CO_2-eq×kg concentrate feed^{-1}**. Therefore, emissions from blending and transport of concentrate feed are calculated as follows:

Equation 6.2 - Ruminants

$CO_2kg_{-blend,i.c,T}$ = $EF_{blend} \times CONC_{fg,T} \times CF_{i,T}$

for i = 16 to 27 from Table 3.2

Where:

$CO_2kg_{-blend,i,c,T}$ = total carbon dioxide emissions from blending and transport of concentrate feed per kg of dry matter for feed material *i*, cohort *c*, species and system *T*, kg CO_2×kg DM^{-1}.

EF_{blend} = emission factor for blending and transport of concentrate feed, kg CO_2×kg DM-1. Default value of 0.0786.

$CONC_{fg,T}$ = fraction of concentrates in the diet for the feeding group *fg*, species and system *T*, fraction

$CFi_{,T}$ = fraction of feed material *i* in the composition of concentrate feed for species and system *T*, fraction

Equation 6.3 - Monogastrics

$CO_2kg_{-blend,i.c,T}$ = $EF_{blend} \times FEED_{i,T}$

for i = 21 to 42 from Table 3.6

Where:

$CO_2kg_{-blend,i,c,T}$ = total carbon dioxide emissions from blending and transport of concentrate feed per kg of dry matter for feed material *i*, cohort *c*, species and system *T*, kg CO_2×kg DM^{-1}.

EF_{blend} = emission factor for blending and transport of concentrate feed, kg CO_2×kg DM^{-1}. Default value of 0.0786.

FEEDi,T = fraction of feed material *i* in the ration of species and system *T*, fraction. Described in Section 3.3.5.

6.1.1.5 – GHG emissions arising from the production of non-crop feed materials

Default values of 1.4, 3.6 and 0.08 kg CO_2-eq×kg×feed^{-1} for fishmeal, synthetic additives and limestone were used, respectively. Emissions for leaves and swill were assumed to be null.

6.1.1.6 – Land-use change for feed crops and pasture expansion

Land-use change is a highly complex process. It results from the interaction of multiple drivers which may be direct or indirect and can involve numerous transitions, such as clearing, grazing, cultivation, abandonment and secondary forest re-growth, across scales, from local to global.

The IPCC issued a special report in 2019 on climate and land, highlighting the critical connections between tropical rainforests and global cycles of energy, water, and carbon and it estimates that land-use change contributes a net 1.6 ± 0.8 Gt CO_2 per year to the atmosphere. The debate surrounding the key drivers of deforestation is ongoing and so is the attribution of GHG emissions to these drivers. Many studies have highlighted the magnitude and policy importance of pollution embodied in trade for individual countries or small groups of countries. Furthermore, the flow of pollution through international trade flows has the ability to undermine environmental policies, particularly for global pollutants.

In this version of GLEAM it has been decided to scale up the estimation of emissions associated to land use change adopting the model by Pendrill et al. (2020). It quantified how much and where deforestation occurs from the expansion of croplands and pasture and what products are grown on this converted land.

The expansion of feed crops is focused on pasture, soybean and palm oil production. Indeed, if we look at recent satellite data we find that in 2019, the world lost 5.4 million hectares to deforestation, with Brazil and Indonesia accounting for 52% of it (1.8 million hectares came from Brazil and 1 million hectares from Indonesia). The expansion of pasture for beef production, croplands for soy and palm oil, and increasingly conversion of primary forest to tree plantations for paper and pulp have been the key drivers of this.

The emission factors for each crop for the producer country provided by Pendrill et al. (2020) were then divided by the total production of that crop from FAOSTAT in 2015 obtaining $kgCO_2/kgDM^{-1}$. Land use change emissions from pasture expansion were entirely allocated to beef production.

Furthermore, for Brazil we have decided to follow an even more accurate approach. Thus, net CO_2 emissions from land use change for soybean and pasture in Brazil were calculated following a combined method from Trase (2020) and Pendrill et al. (2020).

In a first step, land use change for soybean and pasture was obtained at the pixel level using classified images (30 m resolution) following Trase (2020) and the data sources listed in Table 6.1, but with a slight adaptation for GLEAM to express emissions from land use change for the year 2015. We used an allocation period of 3 years between a past deforestation event and the new land use together with a lag period of 1 year between deforestation and the establishment of soybean. While we did not include a lag period between deforestation and the pasture land use, we considered that pasture could be used by cattle in the 3 years leading up to 2015 and therefore could account for multiple years of land use change. More specifically:

- If a same pixel classified as “soybean” in 2015 was classified as “deforestation” between 2012 and 2014, then the deforestation event was allocated to soybean in that pixel;
- If a same pixel classified as “pasture” in 2015 was classified as “deforestation” between 2013 and 2015, then the deforestation event was allocated to pasture in that pixel. We then repeated the calculation for pixels classified as “pasture” in 2014 (with deforestation between 2012 and 2014), and 2013 (with deforestation between 2011 and 2013) to account for multiple years of pasture use by cattle.

These per-pixel results were then aggregated at the Brazilian municipality level to provide an estimate of deforestation for soybean in 2015. In the case of deforestation for pasture in 2015, per-pixel results were aggregated both at the Brazilian municipality level and summed across 2013, 2014 and 2015[1].

In a second step, net CO_2 emissions (tonnes CO_2) from land use change for soybean and pasture in 2015 were obtained following Equation using the results obtained above for each Brazilian municipality:

$CO_2net = CO_2gross$ – new vegetation stock + change in soil organic carbon

where CO_2gross (tonnes CO_2) represents the above- and below-ground CO_2 loss from land use change (see above) derived using the carbon stocks from MCTI (2016). The new vegetation stock (tonnes CO_2) is the carbon stock in the new land use (soybean or pasture) obtained by multiplying the total area of the new land use by the factors of 17.23 tonnes CO_2 per hectare (4.7 tonnes C per hectare) for soybean (IPCC, 2019), and 22 tonnes CO_2 per hectare (6 tonnes C per hectare) for pasture (European Union, 2010). Finally, the change in soil organic carbon (tonnes CO_2) is obtained by multiplying the total land area converted to the new land use (soybean or pasture) with factors of 84 tonnes CO_2 per hectare for soybean and 33 tonnes CO_2 per hectare for pasture (respectively 23 and 9 tonnes C per hectare) (Don et al., 2011).

[1] In cases where a pixel was classified both as “soybean” and “pasture” in the same year (due to differences observed in classification methods of the datasets listed in Table 1) we interpreted the pixel as “soybean”.

Table 6.1 List of datasets used to derive deforestation for soybean and pasture in Brazil and associated net CO_2 emissions in 2015.

Dataset	Data Source	Year(s) of interest
Pasture extent	MapBiomas vs. 4.0 — class 15 www.mapbiomas.org/en	2013–2015
Soybean extent	*Global Land Analysis & Discovery (GLAD) University of Maryland: https://glad.umd.edu/	2015
Deforestation	INPE Prodes Amazon	2011–2015
	INPE Prodes Cerrado	2011–2015
	SOS-Mata Atlantica: www.sosma.org.br	2011–2015
	SOS-Pantanal: www.sospantanal.org.br	2011–2015

*Forthcoming publication

Finally, in order to account for the international trade of feed items, average emission factors for LUC associated with the production and import of soy products and palm kernel cake were calculated, for each importing country, based on the emission factors of the exporting ones and the trade matrices described in Section 3.1.

6.1.2 – Methane emissions from rice used for feed

Rice differs from all the other feed crops in that it produces significant amounts of CH_4. These emissions per hectare are highly variable and depend on the water regime during and prior to cultivation, and the nature of the organic amendments. The average CH_4 flux per hectare of rice was calculated for each country using the IPCC Tier 1 methodology (IPCC, 2019, Volume 4, Chapter 5.5).

6.1.3 – Allocation of carbone dioxide and methane emissions between crop and crop co-products

In order to calculate the emission intensity of each feed material, emissions need to be allocated between the crop and crop co-products, such as crop residues or agro-industrial by-products. To this purpose, three allocation factors are used: 1) the MFA (see Section 3.2.1 and Section 3.3.1), defining the crop or co-product mass as a fraction of the total mass, 2) the Economic Fraction Allocation (EFA), which defines the crop or co-product value as a fraction of the total value and 3) the second-grade allocation (A2), to account for the low economic value of second-grade crops (feed materials 3, 6 to 14 and 17 from Table 3.2). The general equations used are as follows:

Equation 6.4

a. $CO_2kg_{-Nfert,i} = CO_2NFERTHA_i \,/\, (DMYG_{crop,i} \times FUE_{crop,i} + DMGY_{cr,i} \times FUE_{cr,i}) \times EFA_i \,/\, MFA_i \times A2_i$

b. $CO_2kg_{-Pfert,i} = CO_2PFERTHA_i \,/\, (DMYG_{crop,i} \times FUE_{crop,i} + DMGY_{cr,i} \times FUE_{cr,i}) \times EFA_i \,/\, MFA_i \times A2_i$

c. $CO_2kg_{-Kfert,i} = CO_2KFERTHA_i \,/\, (DMYG_{crop,i} \times FUE_{crop,i} + DMGY_{cr,i} \times FUE_{cr,i}) \times EFA_i \,/\, MFA_i \times A2_i$

d. $CO_2kg_{-pest,i} = CO_2PESTHA_i \,/\, (DMYG_{crop,i} \times FUE_{crop,i} + DMGY_{cr,i} \times FUE_{cr,i}) \times EFA_i \,/\, MFA_i \times A2_i$

e. $CO_2kg_{-crop,i} = CO_2CROPha_i \,/\, (DMYG_{crop,i} \times FUE_{crop,i} + DMGY_{cr,i} \times FUE_{cr,i}) \times EFA_i \,/\, MFA_i \times A2_i$

f. $CO_2kg_{-proc,i} = CO_2PROCkg_i \times EFA_i \,/\, MFA_i \times A2_i$

g. $CO_2kg_{-LUC,i} = CO_2LUCkg_i \times EFA_i \,/\, MFA_i$

h. $CH_4kg_i = CH_4ha_i \,/\, (DMYG_{crop,i} \times FUE_{crop,i} + DMGY_{cr,i} \times FUE_{cr,i}) \times EFA_i \,/\, MFA_i \times A2_i$

Where:

$CO_2kg_{i\text{-}Nfert,i}$ = total carbon dioxide emissions from nitrogen fertilizer manufacturing per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{-Pfert,i}$ = total carbon dioxide emissions from P fertilizer manufacturing per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{-Kfert,i}$ = total carbon dioxide emissions from K fertilizer manufacturing per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{-pest,i}$ = total carbon dioxide emissions from pesticides manufacturing per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{-crop,i}$ = total carbon dioxide emissions from field operations per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{-proc,i}$ = total carbon dioxide emissions from transport and processing per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{-LUC,i}$ = total carbon dioxide emissions from land-use change per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

CH_4kg_i = total methane emissions per kilogram of dry matter of feed material *i*, kg $CH_4 \times kg\ DM^{-1}$

$CO_2NFERTHA_i$ = carbon dioxide emissions from nitrogen fertilizer manufacturing per hectare of feed material *i*, kg $CO_2 \times ha^{-1}$. Described in Section 6.1.1.1

$CO_2PFERTHA_i$ = carbon dioxide emissions from P fertilizer manufacturing per hectare of feed material *i*, kg $CO_2 \times ha^{-1}$. Described in Section 6.1.1.1

$CO_2KFERTHA_i$ = carbon dioxide emissions from K fertilizer manufacturing per hectare of feed material *i*, kg $CO_2 \times ha^{-1}$. Described in Section 6.1.1.1

$CO_2PESTHA_i$ = carbon dioxide emissions from pesticides manufacturing per hectare of feed material *i*, kg $CO_2 \times ha^{-1}$. Described in Section 6.1.1.1

$CO_2CROPha_i$ = carbon dioxide emissions from field operations per hectare of feed material *i*, kg $CO_2 \times ha^{-1}$. Described in Section 6.1.1.2

$CO_2PROCkg_i$	=	carbon dioxide emissions from transport and processing per kg of parental crop of feed material *i*, kg CO_2×kg DM $^{-1}$. Described in Section 6.1.1.3
CO_2LUCkg_i	=	carbon dioxide emissions from land-use change kg of parental crop of feed material *i*, kg CO_2×ha^{-1}. Described in Section 6.1.1.6
CH_4ha_i	=	total methane emissions per hectare of feed material *i*, kg CH_4×ha^{-1}. Described in Section 6.3
$DMYG_{crop,i}$	=	crop gross dry matter yield for feed material *i*, kg DM×ha^{-1}
$DMGY_{cr,i}$	=	crop residues gross dry matter yield for feed material *i*, kg DM×ha^{-1}
$FUE_{crop,i}$	=	crop feed use efficiency for feed material *i*, i.e. fraction of the gross yield of the crop that is effectively used as feed, fraction. Values are given in Table 6.2 and Table 6.3 for ruminant and monogastric species, respectively.
$FUE_{cr,i}$	=	crop residues feed use efficiency for feed material *i*, i.e. fraction of the gross yield of the crop residues that is effectively used as feed, fraction. Values are given in Table 6.2 and Table 6.3 for ruminant and monogastric species, respectively.
EFA_i	=	economic fraction allocation, i.e. crop or co-product value as a fraction of the total value (of the crop and co-product) for feed material *i*, fraction. Values are given in Table 6.2 and Table 6.3 for ruminant and monogastric species, respectively.
MFA_i	=	mass fraction allocation, i.e. crop or co-product mass as a fraction of the total mass (crop and co-product) for feed material *i*, fraction. Values are given in Table 3.3 and Table 3.6 for ruminant and monogastric species, respectively.
$A2_i$	=	second-grade allocation, i.e. ratio of the economic value of second-grade crop to the economic value of its first-grade equivalent for feed material *i* (applied only in backyard systems for monogastric species to feed materials 3, 6 to 14 and 17 from Table 3.6), fraction. Default value of 0.2 is used.

For most of the feed materials, the default MFA factors are shown in Tables 3.4 (for ruminant species) and Table 3.7 (for monogastric species). For crop residues or grains (whose crop residues are used either as feed or for bedding), dry matter yields and FUE are used to determine the MFA factors, as shown in Equation 6.10.a (for crop residues) and Equation 6.10.b (for grains):

Equation 6.5

a. $MFA_{,i}$ = $(DMGY_{cr,i} \times FUE_{cr,i})/(DMYG_{crop,i} \times FUE_{crop,i} + DMGY_{cr,i} \times FUE_{cr,i})$
for i = 9 to 15 from Table 3.2 (for ruminant species)
for i = 4, 13 and 16 from Table 3.14 (for monogastric species)

b. $MFA_{,i}$ = $(DMGY_{crop,i} \times FUE_{crop,i})/(DMYG_{crop,i} \times FUE_{crop,i} + DMGY_{cr,i} \times FUE_{cr,i})$
for i = 3, 6 to 11, 15, 21, 23, and 25 to 28 from Table 3.14

Where:

MFAi	=	mass fraction allocation, i.e. crop or crop residues mass as a fraction of the total mass (crop and crop residues) for feed material *i*, fraction
$DMYG_{crop,i}$	=	crop gross dry matter yield for feed material *i*, kg DM×ha^{-1}
$DMGY_{cr,i}$	=	crop residues gross dry matter yield for feed material *i*, kg DM×ha^{-1}
$FUE_{crop,i}$	=	crop feed use efficiency for feed material *i*, i.e. fraction of the gross yield of the crop that is effectively used as feed, fraction. Values are given in Table 6.2 and Table 6.3 for ruminant and monogastric species, respectively.
$FUE_{cr,i}$	=	crop residues feed use efficiency for feed material *i*, i.e. fraction of the gross yield of the crop residues that is effectively used as feed, fraction. Values are given in Table 6.2 and Table 6.3 for ruminant and monogastric species, respectively.

If no crop residues are used for feed or bedding, dry matter yield and mass fraction allocation of the residues are assumed to be zero, effectively allocating 100% of the emissions to the crop. As for MFA, the EFA factors are default values for many feed materials (Table 6.2 and Table 6.3 for ruminant and monogastric species, respectively), but for grains and crop residues they are calculated as follows:

Equation 6.6

a. $EFA_{,i}$ = $(DMGY_{cr,i} \times FUE_{cr,i} \times VR_{cr,i}) / (DMYG_{crop,i} \times FUE_{crop,i} \times VR_{crop,i} + DMGY_{cr,i} \times FUE_{cr,i} \times VR_{cr,i})$

for i = 9 to 15 from Table 3.2 (for ruminant species)

for i = 4, 13 and 16 from Table 3. 14 (for monogastric species)

b. $EFA_{,i}$ = $(DMGY_{crop,i} \times FUE_{crop,i} \times VR_{crop,i}) / (DMYG_{crop,i} \times FUE_{crop,i} \times VR_{crop,i} + DMGY_{cr,i} \times FUE_{cr,i} \times VR_{cr,i})$

for i = 3, 6 to 11, 15, 21, 23, and 25 to 28 from Table 3.14

Where:

EFAi = economic fraction allocation, i.e. crop or crop residues value as a fraction of the total value (of the crop and crop residues) for feed material *i*, fraction

$DMYG_{crop,i}$ = crop gross dry matter yield for feed material *i*, kg $DM \times ha^{-1}$

$DMGY_{cr,i}$ = crop residues gross dry matter yield for feed material *i*, kg $DM \times ha^{-1}$

$FUE_{crop,i}$ = crop feed use efficiency for feed material *i*, i.e. fraction of the gross yield of the crop that is effectively used as feed, fraction. Values are given in Table 6.2 and Table 6.3 for ruminant and monogastric species, respectively.

$FUE_{cr,i}$ = crop residues feed use efficiency for feed material *i*, i.e. fraction of the gross yield of the crop residues that is effectively used as feed, fraction. Values are given in Table 6.2 and Table 6.3 for ruminant and monogastric species, respectively.

$VR_{crop,i}$ = value ratio of the crop per mass unit of crop and crop residues for feed material *i*, fraction. The price ratio can be used, if available. Otherwise, the digestibility of crop and crop residues can be used as a proxy of their respective value. Values are given in Table 6.2 and Table 6.3 for ruminant and monogastric species, respectively.

$VR_{cr,i}$ = value ratio of the crop residues per mass unit of crop and crop residues for feed material *i*, fraction. The price ratio can be used, if available. Otherwise, the digestibility of crop and crop residues can be used as a proxy of their respective value. Values are given in Table 6.2 and Table 6.3 for ruminant and monogastric species, respectively.

An allocation factor of 0.2 (A2 in Equation 6.4) is used for second-grade crops, effectively reducing the emissions associated to their production in a roughly proportionate way to their economic value. Clearly, the relative value could potentially vary for different crops and locations depending on supply and demand, or the extent to which there is a market for second-grade crops and the price of alternative feedstuffs.

Table 6.2 Parameters for allocation of emissions to feed materials of ruminant species

Number	Material	FUE_{crop}	FUE_{cr}	EFA	VR_{crop}	VR_{cr}
Roughages						
1	GRASSF	Table S.3.2 (Supplement S1)[a]	NA	1	NA	NA
2	GRASSH	Table S.3.2 (Supplement S1)[a]	NA	1	NA	NA
3	GRASSH2	Table S.3.2 (Supplement S1)[a]	NA	1	NA	NA
4	GRASSLEGF	Table S.3.2 (Supplement S1)[a]	NA	1	NA	NA
5	GRASSLEGH	Table S.3.2 (Supplement S1)[a]	NA	1	NA	NA
6	ALFALFAH	Table S.3.2 (Supplement S1)[a]	NA	1	NA	NA
7	GRAINSIL	1	NA	1	NA	NA
8	MAIZESIL	1	NA	1	NA	NA
9	RSTRAW	1	Table S.3.2 (Supplement S1)[a]	Equation 6.6a	0.66	0.34
10	WSTRAW	1	Table S.3.2 (Supplement S1)[a]	Equation 6.6a	0.67	0.33
11	BSTRAW	1	Table S.3.2 (Supplement S1)[a]	Equation 6.6a	0.67	0.33
12	ZSTOVER	1	Table S.3.2 (Supplement S1)[a]	Equation 6.6a	0.61	0.39
13	MSTOVER	1	Table S.3.2 (Supplement S1)[a]	Equation 6.6a	0.63	0.37
14	SSTOVER	1	Table S.3.2 (Supplement S1)[a]	Equation 6.6a	0.63	0.37
15	TOPS	1	Table S.3.2 (Supplement S1)[a]	Equation 6.6a	0.55	0.45
16	LEAVES	Table 3.3	NA	1	NA	NA
17	FDDRBEET	Table 3.3	NA	1	NA	NA
Cereals						
18	GRAINS	Table 3.3	NA	1	NA	NA
19	CORN	Table 3.3	NA	1	NA	NA
By-products						
20	MLSOY	Table 3.3	NA	0.72	NA	NA
21	MLRAPE	Table 3.3	NA	0.28	NA	NA
22	MLCTTN	Table 3.3	NA	0.23	NA	NA
23	PKEXP	Table 3.3	NA	0.01	NA	NA
24	MZGLTM	Table 3.3	NA	0.10	NA	NA
25	MZGLTF	Table 3.3	NA	0.06	NA	NA
26	BPULP	Table 3.3	NA	0.11	NA	NA
27	MOLASSES	Table 3.3	NA	0.06	NA	NA
28	GRNBYDRY	Table 3.3	NA	0.04	NA	NA
29	GRNBYWET	Table 3.3	NA	0.08	NA	NA

[a] For these feed materials the FUE is spatially explicit.

Table 6.3 Parameters for allocation of emissions to feed materials of monogastric species

Number	Material	FUEcrop	FUEcr	EFA	VRcrop	VRcr
Swill and scavenging						
1	SWILL	Table 3.6	NA	1	NA	NA
Locally-produced feed materials						
2	GRASSF	Table 3.6	NA	1	NA	NA
3	PULSES	Table 3.6	0.90	Equation 6.6b	0.67	0.33
4	PSTRAW	1	Table 3.15	Equation 6.6b	0.67	0.33
5	CASSAVA	Table 3.6	NA	1	NA	NA
6	WHEAT	Table 3.6	0.70a	Equation 6.6b	0.67c	0.33d
7	MAIZE	Table 3.6	0.70b	Equation 6.6b	0.62e	0.38f
8	BARLEY	Table 3.6	0.90	Equation 6.6b	0.80	0.20
9	MILLET	Table 3.6	0.70	Equation 6.6b	0.61	0.39
10	RICE	Table 3.6	0.70	Equation 6.6b	0.68	0.32
11	SORGHUM	Table 3.6	0.70	Equation 6.6b	0.61	0.39
12	SOY	Table 3.6	NA	1	NA	NA
13	TOPS	1	Table 3.15	Equation 6.6b	0.52	0.48
14	LEAVES	NA	NA	NA	NA	NA
15	BNFRUIT	Table 3.6	0.50	Equation 6.6b	0.67	0.33
16	BNSTEM	1	Table 3.15	Equation 6.6b	0.67	0.33
17	MLSOY	Table 3.6	NA	0.72	NA	NA
18	MLCTTN	Table 3.6	NA	0.30	NA	NA
19	MLOILSDS	Table 3.6	NA	0.23	NA	NA
20	GRNBYDRY	Table 3.6	NA	0.04	NA	NA
Non-local feed materials						
21	PULSES	Table 3.6	0	Equation 6.6b	0.67	0.33
22	CASSAVA	Table 3.6	NA	1	NA	NA
23	WHEAT	Table 3.6	0.90	Equation 6.6b	0.80	0.20
24	MAIZE	Table 3.6	NA	1	NA	NA
25	BARLEY	Table 3.6	0.90	Equation 6.6b	0.80	0.20
26	MILLET	Table 3.6	0.90	Equation 6.6b	0.80	0.20
27	RICE	Table 3.6	0.90	Equation 6.6b	0.80	0.20
28	SORGHUM	Table 3.6	0.90	Equation 6.6b	0.80	0.20
29	SOY	Table 3.6	NA	1	NA	NA
30	RAPESEED	Table 3.6	NA	1	NA	NA
31	SOYOIL	Table 3.6	NA	0.27	NA	NA
32	MLSOY	Table 3.6	NA	0.72	NA	NA
33	MLCTTN	Table 3.6	NA	0.23	NA	NA
34	MLRAPE	Table 3.6	NA	0.28	NA	NA
35	PKEXP	Table 3.6	NA	0.01	NA	NA
36	MLOILSDS	Table 3.6	NA	0.28	NA	NA
37	FISHMEAL	NA	NA	NA	NA	NA
38	MOLASSES	Table 3.6	NA	0.06	NA	NA
39	GRNBYDRY	Table 3.6	NA	0.04	NA	NA
40	GRNBYWET	Table 3.6	NA	0.08	NA	NA
41	SYNTHETIC	NA	NA	NA	NA	NA
42	LIMESTONE	NA	NA	NA	NA	NA

[a] The value is 0.90 for industrialized countries.
[b] The value is null for industrialized countries.
[c] The value is 0.80 for industrialized countries.
[d] The value is 0.20 for industrialized countries.
[e] The value is 1 for industrialized countries.
[f] The value is null for industrialized countries.

6.1.4 – Carbone dioxide and methane emission from feed consumption

Before totalizing emissions at herd or flock level (see Section 6.1.5), emissions related to feed consumption must be totalized by cohort. This is done by combining the emissions for each feed material (see Section 6.1.3) and the average feed dry matter intake per animal of each cohort (see Section 3.7) as shown in Equation 6.7.

Equation 6.7

a. $CO_{2\text{-Feed},T,c} = 365 \times N_{T,c} \times DMI_{T,c} \times \sum_i (CO_2kg_{\text{-blend},i,c,T} + (CO_2kg_{\text{-Nfert},i} + CO_2kg_{\text{-Pfert},i} + CO_2kg_{\text{-Kfert},i} + CO_2kg_{\text{-pest},i} + CO_2kg_{\text{-crop},i} + CO_2kg_{\text{-proc},i} + CO_2kg_{\text{-non-crop},i}) \times FEED_{i,T,c})$

b. $CO_{2\text{-Feed-LUC},T,c} = 365 \times N_{T,c} \times DMI_{T,c} \times \sum_i (CO_2kg_{\text{-LUC},i} \times FEED_{i,T,c})$

c. $CH_{4\text{-Feed},T,c} = 365 \times N_{T,c} \times DMI_{T,c} \times \sum_i (CH_4kg_i \times FEED_{i,T,c})$ [1]

Where:

$CO_{2\text{-Feed},T,c}$ = carbon dioxide emissions from energy use associated with feed consumption of cohort *c*, species and system *T*, kg $CO_2 \times year^{-1}$

$CO_{2\text{-Feed-LUC},T,c}$ = carbon dioxide emissions from land-use change associated with feed consumption of cohort *c*, species and system *T*, kg $CO_2 \times year^{-1}$

$CH_{4\text{-Feed},T,c}$ = methane emissions from feed consumption of cohort *c*, species and system *T*, kg $CO_2 \times year^{-1}$

$N_{T,c}$ = number of animals in cohort *c*, species and system *T*, head

$DMI_{T,c}$ = daily feed intake per animal in cohort *c* for species and system *T*, kg $DM \times head^{-1} \times day^{-1}$

$FEED_{i,T,c}$ = fraction of feed material *i* in the ration of cohort *c*, species and system *T*, fraction

$CO_2kg_{\text{-blend},i,c,T}$ = total carbon dioxide emissions from blending and transport of concentrate feed per kg of dry matter for feed material *i*, cohort *c*, species and system *T,* kg $CO_2 \times kg\ DM^{-1}$. Described in Section 6.1.1.4

$CO_2kg_{i\text{-Nfert},i}$ = total carbon dioxide emissions from nitrogen fertilizer manufacturing per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{\text{-Pfert},i}$ = total carbon dioxide emissions from P fertilizer manufacturing per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{\text{-Kfert},i}$ = total carbon dioxide emissions from K fertilizer manufacturing per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{\text{-pest},i}$ = total carbon dioxide emissions from pesticides manufacturing per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{\text{-crop},i}$ = total carbon dioxide emissions from field operations per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{\text{-proc},i}$ = total carbon dioxide emissions from transport and processing per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

$CO_2kg_{\text{-non-crop},i}$ = total carbon dioxide emissions from the production of non-crop feed material *i* per kg of dry matter, kg $CO_2 \times kg\ DM^{-1}$. Described in Section 6.5

$CO_2kg_{\text{-LUC},i}$ = total carbon dioxide emissions from land-use change per kilogram of dry matter of feed material *i*, kg $CO_2 \times kg\ DM^{-1}$

---

[1] Methane emissions related to feed (due to emission from paddy rice cultivation) are only applicable to monogastric species.

CH_4kg_i = total methane emissions per kilogram of dry matter of feed material i, kg $CH_4 \times$kg DM^{-1}

6.1.5 – Totalizing carbone dioxide and methane emissions at herd of flock level

The last step is to totalize, for the entre herd or flock, the emissions related to feed consumption.

Equation 6.8

a. $CO_{2\text{-Feed},T} = \sum_c (CO_{2\text{-Feed},T,c})$

b. $CO_{2\text{-Feed-LUC},T} = \sum_c (CO_{2\text{-Feed-LUC},T,c})$

d. $CH_{4\text{-Feed},T} = \sum_c (CH_{4\text{-Feed},T,c})$ [2]

Where:

$CO_{2\text{-Feed},T}$ = total carbon dioxide emissions from energy use associated with feed consumption of species and system T, kg $CO_2 \times year^{-1}$

$CO_{2\text{-Feed},T,c}$ = carbon dioxide emissions from feed consumption of cohort c, species and system T, kg $CO_2 \times year^{-1}$

$CO_{2\text{-Feed-LUC},T}$ = total carbon dioxide emissions from land-use change associated with feed consumption of species and system T, kg $CO_2 \times year^{-1}$

$CH_{4\text{-Feed},T}$ = total methane emissions from feed consumption of species and system T, kg $CH_4 \times year^{-1}$

$CH_{4\text{-Feed},T,c}$ = methane emissions from feed consumption of cohort c, species and system T, kg $CO_2 \times year^{-1}$

[2] Methane emissions related to feed (due to emission from paddy rice cultivation) are only applicable to monogastric species.

6.2 – NITROUS OXIDE EMISSIONS

The emissions of nitrous oxide from cropping arise from the following main sources of nitrogen inputs: 1) manure applied on crops or deposited on pastures, 2) synthetic fertilizers, 3) crop residues, 4) biological fixation and 5) atmospheric deposition (Uwizeye et al., 2020). From all these nitrogen sources, nitrous oxide can be released through direct emissions and indirect ones from volatilization, runoff and leaching processes. All were calculated using the methodology described in Uwizeye et al. (2020), updated where possible with emissions factors from IPCC (2019). This methodology, which is different than the one used to estimate the emissions of carbon dioxide and methane described in Section 6.1, incorporates of a stepwise approach that takes into account the nitrogen mass balance associated to the production of each feed item, allowing for a purely bio-phisical allocation of emissions to feed materials.

6.2.1 – Total nitrogen output

Equation 6.9 is used to calculate the total output of nitrogen per hectare of each crop used as a source of feed items. This estimate takes into account the nitrogen content of both the above-ground (crop and crop residues) and below-ground biomass of the plant.

Equation 6.9

$total\_output\_ha_i = ((DMYG_{crop,i} \times Ncont_{crop,i} + DMYG_{cr,i} \times Ncont_{cr,i}) + (R_{BG\text{-}BIO,i} \times (DMYG_{crop,i} + DMYG_{cr,i}) \times Ncont_{bg,i}))/1000$

Where:

$total\_output\_ha_i$ = total nitrogen output per hectare associated with the production of feed item i, representing the nitrogen yield of the whole plant, as calculated following the IPCC, kg N ha^{-1}(IPCC, 2019)

$DMYG_{crop,i}$ = crop gross dry matter yield for feed material *i*, kg DM ha^{-1}

$Ncont_{crop,I}$ = nitrogen content of the main crop associated with the production of feed item *i*, g N kg DM^{-1}

$DMYG_{cr,I}$ = crop residue gross dry matter yield associated with the production of feed item *i*, kg DM ha^{-1}

$Ncont_{cr,I}$ = nitrogen content of the crop residue associated with the production of feed item *i*, g N kg DM^{-1}

$R_{BG\text{-}BIO,i}$ = fraction of below-ground residues to above ground biomass ($DMYGcr_i$ + $DMYGcrop_i$) for feed material *i*, fraction. Values are given in Table S.6.7 and Table S.6.8 (Supplement S1).

$Ncont_{bg,I}$ = nitrogen content of the below-ground biomass associated with the production of feed item *i*, g N kg DM^{-1}

6.2.2 – Total nitrogen input

In order to estimate nitrogen losses and emissions associated with feed production, the total nitrogen input per hectare of each required crop is calculated summing several nitrogen inputs.

Nitrogen from **manure deposition or application** per hectare is calculated in the Manure module (Chapter 5), as defined in Section 5.5.3. The deposition rate (Ndepha, Equation 5.23) is used for fresh grass items fed to ruinants, while the application rate (Nappha, Equation 5.24) for all other feed items.

Nitrogen from the **decomposition of crop residues** was calculated using data about crop yields and a modified version of formulae from IPCC (IPCC, 2019, Volume 4, Chapter 11, Table 11.2, Equation 11.6), following Equation 6.10:

Equation 6.10

$Ncr_i = (DMYGcr_i \times N_{AG,i} \times (1 - FracRemove_i)) + (R_{BG\text{-}BIO,i} \times (DMYGcr_i + DMYGcrop_i) \times N_{BG,i})$

Where:

Ncr_i = nitrogen input from crop residues per hectare for feed item *i*, kg N×ha^{-1}

$DMYGcr_i$ = crop gross dry matter yield of feed material *i*, kg DM×ha^{-1}

$DMYGcrop_i$ = crop residues gross dry matter yield of feed material *i*, kg DM×ha^{-1}

$N_{AG,i}$ = nitrogen content of above-ground residues for feed material *i*, kg N×kg DM^{-1}. Values are given in Table S.6.7 and Table S.6.8 (Supplement S1).

FracRemove$_i$ = fraction of above-ground residues of feed material *i* removed annually for purpose such as feed, bedding and construction, fraction. A default value of 0.45 is used with the exception of few countries, whose values are given in Table S.6.9 (Supplement S1).

$R_{BG-BIO,i}$ = fraction of below-ground residues to above ground biomass (DMYGcr$_i$ + DMYGcrop$_i$) for feed material *i*, fraction. Values are given in Table S.6.7 and Table S.6.8 (Supplement S1).

$N_{BG,i}$ = nitrogen content of below-ground residues for feed material *i*, kg N×kg DM^{-1}. Values are given in Table S.6.8 (Supplement S1).

Appication rates of nitrogen from **synthetic fertilizer** were defined at national or subnational level, as described in Section 6.1.1.1. Moreover, spatially explicit data about average **atmospheric deposition** of nitrogen were obtained from Dentener (2006).

Biological nitrogen fixation (BNF) for legumes and rapeseed was estimated as a fraction of the total nitrogen output of the plant biomass based on the LEAP guidelines (2018), following Equation 6.11. For other non-legumes crops, default values from Herridge et al. (2008) and Peoples et al. (2009) were used. A summary of the parameters used to estimate BNF is reported in Table 6.4.

Equation 6.11

$$BNF_i = total\_output\_ha_i \times Ndfa_i$$

Where:

BNF_i = nitrogen input per hectare from biological nitrogen fixation for feed item *i*, kg N/ha for feed item *i*, kg N ha^{-1}

$total\_output\_ha_i$ = total nitrogen output per hectare associated with the production of feed item *i*, representing the nitrogen yield of the whole plant, as calculated following Equation 6.9, kg N ha^{-1}

$Ndfa_i$ = fraction of the whole plant nitrogen content derived from the biological nitrogen fixation for feed item *i*, as defined in Table 6.4, fraction

Table 6.4 Parameters for the estimation of biological nitrogen fixation by crop type

Crop type	Ndfa (%)	Default BNF (kg N/ha)
Legumes	80	NA
Pulses	57	NA
Rapeseed	68	NA
Soybean	50-80	NA
Cereals	NA	5
Cotton	NA	5
Grass	NA	10
Oil palm	NA	5
Sugarbeet	NA	5
Sugarcane	NA	25

Finally, the total nitrogen input per hectare associated with the production of each feed item is calculated following Equation 6.12:

Equation 6.12

$$total\_input\_ha_i = NFERTHA_i + Ncr_i + Nmanure_i + Nad_i + BNF_i$$

Where:

$total\_input\_ha_i$ = total nitrogen inputs per hectare associated with the production of feed item *i*, kg N ha^{-1}

$NFERTHA_i$ = nitrogen input from synthetic fertilizers per hectare for feed item *i*, kg N ha^{-1}

Ncr_i = nitrogen input from crop residues per hectare for feed item *i*, kg N ha^{-1}

$Nmanure_i$ = nitrogen input per hectare from manure deposition or application for feed item *i*; values are calculated in the Manure module and correspond to Ndepha (Equation 5.23) for fresh grass items fed to ruminants and Napplha (Equation 5.24) for other feed items, kg N ha^{-1}

Nad_i = nitrogen input per hectare from an atmospheric natural deposition for feed item *i*, kg N ha^{-1}

BNF_i = nitrogen input per hectare from biological nitrogen fixation for feed item *i*, kg N ha^{-1}

6.2.3 – *Nitrogen losses from surface soil*

This section defines the estimate of nitrogen losses from surface soil per hectare associated with each feed material, which occur through three main pathways: 1) direct emissions of N_2O, 2) volatilization of NH_3 and 3) direct runoff of organic nitrogen.

6.2.3.1 – *Direct nitrogen loss as N_2O*

The amount of nitrogen directly emitted as N_2O per hectare of each crop is calculated following Equation 6.13:

Equation 6.13

a. Grass

$$dir\_N\text{-}N_2O\_loss_i = NFERTHA_i \times EF\_dir\_syn + Ncr_i \times EF\_dir\_org + Nmanure_i \times EF\_dir\_grass$$

b. Rice

$$dir\_N\text{-}N_2O\_loss_i = (NFERTHA_i + Ncr_i + Nmanure_i) \times EF\_dir\_rice$$

c. Other Crops

$$dir\_N\text{-}N_2O\_loss_i = NFERTHA_i \times EF\_dir\_syn + (Ncr_i + Nmanure_i) \times EF\_dir\_org$$

Where:

$dir\_N\text{-}N_2O\_loss_i$ = direct N-N_2O emissions per hectare associated with the production of feed item *i*, kg N-N_2O ha^{-1}

$NFERTHA_i$ = nitrogen input from synthetic fertilizers per hectare for feed item *i*, kg N ha^{-1}

EF_dir_syn = direct N_20 emission factor for synthetic nitrogen inputs in crops other than rice: 0.016 in wet climates; 0.005 in dry climates

Ncr_i = nitrogen input from crop residues per hectare for feed item *i*, kg N ha^{-1}

$Nmanure_i$ = nitrogen input per hectare from manure deposition or application for feed item *i*; values are calculated in the Manure module and correspond to Ndepha for fresh grass items fed to ruminants and Napplha for other feed items, kg N ha^{-1}

EF_dir_grass = direct N_2O emission factor for manure nitrogen input in grass: 0.006 in wet climates; 0.002 in dry climate

EF_dir_org = direct N_2O emission factor for organic nitrogen inputs in crops other than grass and rice: 0.006 in wet climates, 0.005 in dry climates

6.2.3.2 – *Nitrogen loss as volitilized NH_3*

The amount of nitrogen volatilized as NH_3 per hectare of each crop is calculated following Equation 6.14:

Equation 6.14

$$vol\_N\text{-}NH_3\_loss_i = NFERTHA_i \times 0.11 + (Nmanure_i + Ncr_i) \times 0.21$$

Where:

$vol\_N\text{-}NH_3\_loss_i$ = volatilized N-NH_3 emissions per hectare associated with the production of feed item *i*, kg N- NH_3 ha^{-1}

$NFERTHA_i$ = nitrogen input from synthetic fertilizers per hectare for feed item *i*, kg N ha^{-1}

$Nmanure_i$ = nitrogen input per hectare from manure deposition or application for feed item *i*; values are calculated in the Manure module and correspond to Ndepha for fresh grass items fed to ruminants and Napplha for other feed items, kg N ha^{-1}

Ncr_i = nitrogen input from crop residues per hectare for feed item *i*, kg N ha^{-1}

6.2.3.3 – *Direct Runoff of organic nitrogen and NO_3*

As a first step, the estimate of the amount of organic nitrogen lost through surface runoff requires the calculation of a *surface runoff fraction*. This is estimated based on Velthof et al. (2009a) and is expressed as a fraction of the nitrogen input on soil from synthetic fertilizers and manure. The fraction is calculated using Equation 6.15 and is based on the following environmental variables:

- Slope (based on Farr et al., 2007)
- Precipitation (Hijmans et al., 2005)
- Land cover (ESA, 2017)

Equation 6.15

$runoff = LF_{surface\ runoff,max} \times f_{lu} \times f_p / 100$

Where:

runoff = runoff fraction of the nitrogen inputs via fertilizer and manure application and deposition

$LF_{surface\ runoff,max}$ = the maximum runoff fraction for different slope classes, based on Reuter et al. (2007) and reported in Table 6.4.

f_{lu} = reduction factor for land cover ($f_{lu\ cropland} = 1$, $f_{lu\ grassland} = 0.25$) obtained from FAO (Latham et al., 2014)

f_p = reduction factor for precipitation based on Harris et al. (2014) reported in Table 6.5.

Table 6.5 Maximum runoff fraction for different slope classes (Reuter et al., 2007)

Slope	$LF_{surface\ runoff,\ max}$
Level (dominant slope ranging from 0 to 8%)	10%
Sloping (dominant slope ranging from 8 to 15%)	20%
Moderately steep (dominant slope ranging from 15 to 25%)	35%
Steep (dominant slope over 25%)	50%

Table 6.6 Reduction factor for different precipitation classes (Harris et al., 2014)

Precipitation surplus, mm	f_p
>300	1
100-300	0.75
50-100	0.50
<50	0.25

Once the fraction of surface runoff is calculated, it can be applied to the nitrogen inputs from synthetic fertilizers and manure application or deposition per hectare associated to the production of each feed item, following Equation 6.16:

Equation 6.16

$n\_runoff_i = (NFERTHA_i + Nmanure_i) \times runoff$

Where:

n_runoff_i = losses of organic nitrogen through runoff per hectare associated with the production of feed item *i*, kg N ha^{-1}

$NFERTHA_i$ = nitrogen input from synthetic fertilizers per hectare for feed item *i*, kg N ha^{-1}

$Nmanure_i$ = nitrogen input per hectare from manure deposition or application for feed item *i*; values are calculated in the Manure module and correspond to Ndepha for fresh grass items fed to ruminants and Napplha for other feed items, kg N ha^{-1}

runoff = runoff fraction of the nitrogen applied via fertilizer and manure (including grazing)

6.2.3.4 – Total nitrogen loss from surface soil

The total amount of nitrogen losses from surface soil per hectare associated with each feed material is calculated following Equation 6.17:

Equation 6.17

$surface\_loss\_crop\_ha_i = dir\_N\text{-}N_2O\_loss_i + vol\_N\text{-}NH_3\_loss_i + n\_runoff_i$

Where:

surface_loss_crop_ha$_i$ = total nitrogen losses from surface soil per hectare associated with the production of feed item *i*, kg N ha^{-1}

dir_N-N_2O_loss_crop$_i$ = direct N-N_2O emissions per hectare associated with the production of feed item *i*, kg N-N_2O ha^{-1}

vol_N-NH_3_loss$_i$ = volatilized N- NH_3emissions per hectare associated with the production of feed item *i*, kg N-NO_3 ha^{-1}

n_runoff$_i$ = losses of organic nitrogen through runoff per hectare associated with the production of feed item *i*, kg N ha^{-1}

6.2.4 – Organic nitrogen stock

The following section reports the calculation used to estimate the stock of organic nitrogen in soil per hectare, net of the surface losses and emissions described in Section 6.2.3 and of mineralization processes. The stock of organic nitrogen is required to calculate any potential surplus in soil (Section 6.2.5), which in turn is required to estimate losses from leaching processes (Section 6.2.6) and their assoicatred indirect emissions of N_2O. The stock of organic nitrogen in soil is calculated separately for nitrogen inputs from manure (Section 6.2.4.1) and crop resisues (Section 6.2.4.2). The following calculation are based on Dollé and Smati (2005) and Velthof et al. (2009b).

6.2.4.1 – Nitrogen stock in manure

The stock of organic nitrogen in soil, originated from manure deposition or application is calculated following Equation 6.18:

Equation 6.18

a. *Grass*

stock_manure$_i$ = (Nmanure$_i$ - (Nmanure$_i$ × runoff + Nmanure$_i$ × (EF_dir_grass + 0.21)))×miner_f_grass

b. *Rice*

stock_manure$_i$ = (Nmanure$_i$ - (Nmanure$_i$ × runoff + Nmanure$_i$ × (0.004 + 0.21)))×miner_f_crop

Other crops

c. stock_manure$_i$ = (Nmanure$_i$ - (Nmanure$_i$ × runoff + Nmanure$_i$ ×(EF_dir_org + 0.21)))×miner_f_crop

Where:

stock_manure$_i$ = nitrogen stock in manure inputs per hectare associated with the production of feed item *i*, kg N ha^{-1}

Nmanure$_i$ = nitrogen input per hectare from manure deposition or application for feed item *i*; values are calculated in the Manure module and correspond to Ndepha for fresh grass items fed to ruminants and Napplha for other feed items, kg N ha^{-1}

runoff = runoff fraction of the nitrogen applied via fertilizer and manure (including grazing)

EF_dir_gras = direct N_2O emission factor for manure nitrogen input in grass: 0.006 in wet climates and 0.002 in dry climate (IPCC, 2019)

miner_f_grass = share of non-mineralized organic nitrogen in grasslands, 0.1, fraction

miner_f_crop = share of non-mineralized organic nitrogen in cultivated soils, 0.3, fraction

EF_dir_org = direct N_2O emission factor for organic nitrogen inputs in crops other than grass and rice: 0.006 in wet climates, 0.005 in dry climates

6.2.4.2 – Nitrogen stock in residues

The stock of organic nitrogen in soil, originated from crop residues decomposition is calculated following Equation 6.19:

Equation 6.19

a. *Grass*

stock_resid$_i$ = (Ncr$_i$ - Ncr$_i$ × (EF_dir_org + 0.21)) × miner_f_grass

b. *Rice*

stock_resid$_i$ = (Ncr$_i$ - Ncr$_i$ × (0.004 + 0.21)) × miner_f_crop

c. *Other crops*

stock_resid$_i$ = (Ncr$_i$ - Ncr$_i$ × (EF_dir_org + 0.21)) × miner_f_crop

Where:

stock_resid$_i$ = nitrogen stock in inputs from residues per hectare associated with the production of feed item *i*, kg N ha^{-1}

Ncr$_i$ = nitrogen input from crop residues per hectare for feed item *i*, kg N ha^{-1}

runoff = runoff fraction of the nitrogen applied via fertilizer and manure (including grazing)

EF_dir_org = direct N_2O emission factor for organic nitrogen inputs in crops other than grass and rice: 0.006 in wet climates, 0.005 in dry climates

miner_f_grass = share of non-mineralized organic nitrogen in grasslands, 0.1, fraction

miner_f_crop = share of non-mineralized organic nitrogen in cultivated soils, 0.3, fraction

6.2.4.3 – Total organic nitrogen stock

The total stock of organic nitrogen in soil, from both crop reridues decomposition and manure application or deposition is calculated following Equation 6.20:

Equation 6.20

$$organic\_stock_i = stock\_manure_i + stock\_resid_i$$

Where:

organic_stock$_i$ = total organic nitrogen stock in soil per hectare associated with the production of feed item *i*, kg N ha^{-1}

stock_manure$_i$ = nitrogen stock in manure inputs per hectare associated with the production of feed item *i*, kg N ha^{-1}

stock_resid$_i$ = nitrogen stock in inputs from residues per hectare associated with the production of feed item *i*, kg N ha^{-1}

6.2.5 – Nitrogen surplus

Any potential surplus of nitrogen per hectare of soil associated to each feed material can be calculated from the estimates of total inputs to soil (Section 6.2.2), total outputs in the plant biomass (6.2.1), surface nitrogen losses (Section 6.2.3) and stock of organic nitrogen (Section 6.2.4), following Equation 6.21. This surplus of nitrogen is required to calculate the nitrogen losses from leaching processes (Section 6.2.6) and their associated indirect emissions of N_2O.

Equation 6.20

$$surplus_i = total\_input\_ha_i - surface\_loss\_crop\_ha_i - organic\_stock_i - total\_output\_ha_i$$

Where:

surplus$_i$ = nitrogen surplus in soil per hectare associated with the production of feed item *i*, kg N ha^{-1}

total_input_ha$_i$ = total nitrogen inputs per hectare associated with the production of feed item *i*, kg N ha^{-1}

surface_loss_crop_ha$_i$ = total nitrogen losses from surface soil per hectare associated with the production of feed item *i*, kg N ha^{-1}

organic_stock$_i$ = total organic nitrogen stock in soil per hectare associated with the production of feed item *i*, kg N ha^{-1}

total_output_ha$_i$ = total nitrogen output per hectare associated with the production of feed item *i*, representing the nitrogen yield of the whole plant, as calculated following the IPCC guidelines, kg N ha^{-1}

6.2.6 – Leaching in soil and total nitrogen losses

The amount of nitrogen lost through leaching processes depends on the potential availability of a surplus of nitrogen in soil, as calculated in Section 6.2.5, and it can be estimated following Equation 6.22:

Equation 6.22

If <u>$surplus_i > 0$</u>

$$Soil\_leaching_i = surplus_i \times leaching + (surplus_i \times (1 - leaching)) \times 70/100$$

Note: 70% of surplus will be lost via leaching (Velthof et al. 2009b)

If <u>$surplus_i \leq 0$</u>

$$Soil\_leaching_i = 0$$

Where:

soil_leaching$_i$ = nitrogen lost through leaching per hectare associated with the production of feed item *i*, kg N ha^{-1}

surplus$_i$ = nitrogen surplus in soil per hectare associated with the production of feed item *i*, kg N ha^{-1}

leaching = proportion of nitrogen lost through leaching, 0.1, fraction

6.2.7 – Total N-N_2O emissions per hectare

Once the nitrogen lost through leaching processes is calculated, the total amount of nitrogen emitted as N_2O can be estimated. This requires the calculation of indirect N_2O emissions from volatilized NH_3 (Equation 6.23) and from organic nitrogen lost through leaching and runoff (Equation 6.24). Finally, this flows can be summed together with direct N_2O emissions to estimate the total nitrogen emitted as N_2O, per hectare associated with the production of each feed material (Equation 6.25).

Equation 6.23

$$Indirect\_N\text{-}N_20\_vol_i = vol\_N\text{-}NH_3\_loss_i \times EF\_vol$$

Where:

Indirect_N-N_20_vol$_i$= indirect N_2O emission from volatilized NH_3 per hectare associated with the production of feed item *i*, kg N-N_20 ha^{-1}

vol_ N-NH_3_loss$_i$ = volatilized N-NH_3 emissions per hectare associated with the production of feed item *i*, kg N- NH_3 ha^{-1}

EF_vol = indirect N_2O emission factor from volatilized NH_3, 0.014 in Wet climates; 0.005 in dry climates

Equation 6.24

$$Indirect\_N\text{-}N_20\_leaching_i = (soil\_leaching_i + n\_runoff_i) \times 0.011$$

Where:

Indirect_ N-N_20_leaching$_i$=indirect N-N_2O emissions from nitrogen loss through leaching per hectare associated with the production of feed item *i*, kg N-N_2O ha^{-1}

soil_leaching$_i$ = nitrogen lost through leaching per hectare associated with the production of feed item *i*, kg N ha^{-1}

n_runoff$_i$ = losses of organic nitrogen through runoff per hectare associated with the production of feed item *i*, kg N ha^{-1}

Equation 6.25

$$Total\_\ N\text{-}N_2O\_emissions_i = dir\_N\text{-}N_2O\_loss_i + Indirect\_N\text{-}N_20\_vol_i + Indirect\_\ N\text{-}N_20\_leaching_i$$

Where:

Total_N-N_2O_emissions$_i$= total N-N_2O emissions per hectare associated with the production of feed item *i*, kg N-N_2O ha^{-1}

dir_N-N_2O_loss$_i$ = direct N-N_2O emissions per hectare associated with the production of feed item *i*, kg N-N_2O ha^{-1}

Indirect_N-N_20_vol$_i$= indirect N_2O emission from volatilized NH_3 per hectare associated with the production of feed item *i*, kg N-N_20 ha^{-1}

Indirect_ N-N_20_leaching$_i$=indirect N-N_2O emissions from nitrogen loss through leaching per hectare associated with the production of feed item *i*, kg N-N_2O ha^{-1}

6.2.8 – Allocation and total nitrous oxide from feed production

In order to calculate the N_2O emissions associated to the production of feed consumed by livestock, some final steps are still needed. As a first thing, it is necessary to estimate the amount of nitrogen intake consumed by animals from each feed material considered (Section 6.2.8.1), as well as the total surface associated with its production (Section 6.2.8.3). The latter can then be multiplied by the emission per hectare previously calculated, to estimate the total emissions arising from feed production (Section 6.2.8.4). To this purpose, it is also necessary to allocate the estimated emissions to the specific part of the original plant that is consumed as feed by animals. This allocation is based on nitrogen mass fractions, as described in Section 6.2.8.3.

6.2.8.1 – Nitrogen feed intake by feed component

The calculation of the annual nitrogen intake from each feed material per head is calculated based on the feed ration, the nitrogen content of the respective feed item and the daily feed intake previously calculated (see Chapter 3), following Equation 6.26:

Equation 6.26

$$Total\_N\_intake_{i,T,c} = DMI_{T,c} \times 365 \times FEED_{i,T,c} \times Ncont_i / 1000$$

Where:

$Total\_N\_intake_{i,T,c}$ = total nitrogen intake from feed item i by animals in cohort *c* for species and system *T*, kg N head^{-1}

$DMI_{T,c}$ = daily feed intake per animal in cohort *c* for species and system *T*, kg DM×head^{-1}×day^{-1}

$FEED_{i,T,c}$ = fraction of feed material *i* in the ration of animals in cohort *c* for species and system *T*, fraction

$Ncont_i$ = nitrogen content of feed item *i*, g N kg DM^{-1}

6.2.8.2 – Area requirement

Once the total nitrogen intake from each feed material is calculated, it can be used to estimate the agricultural area required for its production, dividing the intake by the respective nitrogen yield in one year, following Equation 6.27. The latter can be calculated multiplying the total nitrogen output of the plant biomass per hectare (Section 6.2.1) by the fraction of said output that is actually consumed as feed. Such nitrogen fraction is calculated following Equation 6.28:

Equation 6.27

$$area_{i,T,c} = Total\_N\_intake_{i,T,c} / (total\_output\_ha_i \times FracN_i)$$

Where:

$area_{i,T,c}$ = area required for the production of the total nitrogen intake from feed item i by animals in chort *c* for species and system *T*, ha×head^{-1}

$Total\_N\_intake_{i,T,c}$ = total nitrogen intake from feed item *i* by animals in chort *c* for species and system *T*, kg N

$Total\_output\_ha_i$ = total nitrogen output per hectare associated with the production of feed item *i*, representing the nitrogen yield of the whole plant, as calculated following Equation 6.9, kg N ha^{-1}

$FracN_i$ = fraction of the total nitrogen output associated with the production of feed item *i* available for consumption as feed, as calculated in Eqaution 6.28, fraction

Equation 6.28

a. *For grass*

$$FracN_{grass} = (Ncont_{grass} \times DMYG_{grass} / 1000) / total\_output\_ha_{grass}$$

Note: for GRASS feed items, FUE is not considered to account for the grazing of different species on the same pastures, avoiding over estimation of the required area in later calculations.

b. *For crops*

$$FracN_i = (Ncont_{crop,i} \times DMYG_{crop,i} \times FUE_i / 1000) / total\_output\_ha_{,i}$$

c. *For crop residues*

$$FracN_i = (Ncont_{cr,i} \times DMYG_{cr,i} \times FUE_i / 1000) / total\_output\_ha_i$$

d. *For by-products*

$$FracN_i = (Ncont_{by\text{-}prod,i} \times DMYG_{crop,i} \times MFA_i \times FUE_i / 1000) / total\_output\_ha_i$$

Where:

$FracN_{grass}$ = fraction of the total nitrogen output of grass available for consumption as feed, fraction

$Ncont_{grass}$ = nitrogen content of the grass feed item, g N kg DM^{-1}

$DMYG_{grass}$ = gross dry matter yield of feed item grass, kg DM ha^{-1}

$output\_ha_{grass}$ = total nitrogen output per hectare associated with feed item grass, representing the nitrogen yield of the whole plant, as calculated following the IPCC guidelines, kg N ha^{-1}

$FracN_i$ = fraction of the total nitrogen output associated with the production of feed item *i* available for consumption as feed, fraction

$Ncont_{crop,i}$ = nitrogen content of the main crop associated with the production of feed item *i*, g N kg DM^{-1}
$DMYG_{crop,i}$ = crop gross dry matter yield associated with the production of feed item *i*, kg DM ha^{-1}
FUE_i = feed use efficiency for feed material *i*, i.e. fraction of the gross yield that is effectively used as feed, fraction
$total\_output\_ha_i$ = total nitrogen output per hectare associated with the production of feed item *i*, representing the nitrogen yield of the whole plant, as calculated following Equation 6.9, kg N ha^{-1}
$Ncont_{cr,I}$ = nitrogen content of the crop residue associated with the production of feed item *i*, g N kg DM^{-1}
$DMYG_{cr,I}$ = crop residue gross dry matter yield associated with the production of feed item *i*, kg DM ha^{-1}
$Ncont_{by\text{-}prod,i}$ = nitrogen content of the main by product associated with the production of feed item *i*, g N kg DM^{-1}

6.2.8.3 – Allocation factors by feed component

Emissions of nitrogen as N_2O per hectare of crop production need to be allocated to the specific feed item consumed by animals. This is done using allocation factors that take into account the amount of nitrogen consumed by animals as actual feed item in respect to the nitrogen output available from the relative crop; similarly to what is done for CO_2 and CH_4, this allocation is needed to avoid double counting of emissions associated with the production of "complementary" feed items when aggregating results (e.g. the same area could be used to produce the grain consumed by monogastrics and the crop residues consumed by ruminants). The allocation factors per feed material are calculated following Equation 6.29:

Equation 6.29

$$ALLOC_{i,T,c} = Total\_N\_intake_{i,T,c} / ((total\_output\_ha_i - Ncr_i) \times area_{i,T,c})$$

Where:

$ALLOC_{i,T,c}$ = allocation factor taking into account the amount of nitrogen consumed as feed by animals in cohort *c*, species and system *T*, in respect to the nitrogen output available from the relative crop for feed item *i*, fraction
$Total\_N\_intake_{i,T,c}$ = total nitrogen intake from feed item *i* by animals in chort *c* for species and system *T*, kg N×$head^{-1}$
$Total\_output\_ha_i$ = total nitrogen output per hectare associated with the production of feed item *i*, representing the nitrogen yield of the whole plant, as calculated following Equation 6.9, kg N ha^{-1}
Ncr_i = nitrogen input from crop residues per hectare for feed item *i*, kg N ha^{-1}
$area_{i,T,c}$ = area required for the production of the total nitrogen intake from feed item *i* by animals in chort *c* for species and system *T*, ha×$head^{-1}$

Note1: allocation is not used (ALLOC = 1) for the following feed items: Ruminants feed items 1, 2, 3, 4, 5, 6 (feed 16 is already excluded from the analysis); Monogastrics feed item 2 (feeds 1, 14, 37, 41 and 42 are already excluded from the analysis).
Note2: for banana fruit and stem and palm cake (monogastric feed items 15, 16 and 32), the nitrogen in crop residues are default global values and are therefore excluded from the equation, resulting in the following: ALLOC = Total nitrogen intake / (total_output_ha × area).
Note3: a correction is required to set the resulting allocation factor for pulses straw (monogastric feed item 4) to a maximum value of 1, to avoid errors related to the combination of yield productivity and fracremoval values.

6.2.8.4 – Total allocated nitrous oxide emissons

Finally, the nitrogen lost as N_2O per hectare of feed production can be used in conjunction with the estimated area requirements and allocation factors to calculate the total N_2O emissions associated to feed consumption at herd or flock level, following Equation 6.30:

Equation 6.30

$$N_2O_{\text{-}Feed,T} = \Sigma_c (\Sigma_i (Total\_N\text{-}N_2O\_emissions_i \times area_{i,T,c} \times ALLOC_{i,T,c} \times N_{T,c})) \times 44/28$$

Where:

$N_2O_{\text{-}Feed,T}$ = total nitrous oxide emissions associated with feed consumption of animals in species and system *T*, kg N_2O×$year^{-1}$
$Total\_N\text{-}N_2O\_emissions_i$ = total N-N_2O emissions per hectare associated with the production of feed item *i*, kg N-N_2O ha^{-1}
$area_{i,T,c}$ = area required for the production of the total nitrogen intake from feed item *i* by animals in chort *c* for species and system *T*, ha×$head^{-1}$

$ALLOC_i$ = allocation factor taking into account the amount of nitrogen consumed as feed by animals in cohort *c*, species and system *T*, in respect to the nitrogen output available from the relative crop for feed item *i*, fraction

$N_{T,c}$ = number of animals in cohort *c*, species and system *T*, head

44 / 28 = conversion factor from N-N_2O to N_2O emissions

7 CHAPTER 7 – EMISSIONS FROM ENERGY USE

This chapter presents the approach and coefficients applied in GLEAM for estimating the GHG emissions from the direct, non-feed related on-farm energy use and embedded energy in farm buildings and equipment.

7.1 – EMISSIONS FROM CAPITAL GOODS – INDIRECT ENERGY USE

Capital goods including machinery, tools and equipment, buildings such animal housing, forage and manure storage are a means of production. Though not often considered in LCAs, capital goods carry with them embodied emissions associated with manufacture and maintenance. These emissions are primarily caused by the energy used to extract and process typical materials that make up capital goods such as steel, concrete or wood. The quantification of embedded energy in capital goods covered in GLEAM includes farm buildings (animal housing, feed and manure storage facilities) and farm equipment such as milking and cooling equipment, tractors and irrigation systems. To determine the effective annual energy requirement, the total embodied energy of the capital energy inputs are discounted and a 20 years straight-line depreciation for buildings, 10 years for machinery and equipment and 30 years for irrigation systems are assumed.

For ruminant species, different levels of housing are defined with varying degrees of quality. In a further step, these types are distributed across the production systems (grassland and mixed), AEZs (arid, humid and temperate), country grouping based on the level of economic development based on literature research, and expert knowledge. Table S.7.1 and Table S.7.2 (Supplement S1) present the average emission factors for ruminant species.

For monogastric species, three different levels of housing were defined with varying degrees of quality. Emissions related to each type were calculated using the embodied energy use from the Swiss Centre for Life Cycle Inventories database – EcoInvent. Table S.7.3 and Table S.7.4 (Supplement S1) present the average emission factors for pigs and chickens, respectively.

7.2 – EMISSIONS RELATED TO ON-FARM ENERGY USE – DIRECT ENERGY USE

Direct on-farm energy includes the emissions arising from energy use on-farm required for livestock production. Energy that is used in feed production and transport is not included, as these emissions are included in the feed category. Energy is required for a variety of purposes such as lighting, ventilation, washing, cooling, heating, milking, and others. Table S.7.5 to Table S.7.7 (Supplement S1) present emission factors from direct energy use based on literature research and existing databases.

8 CHAPTER 8 – POST-FARM EMISSIONS

In addition to the emissions related to the production of primary products (meat, milk and eggs) along the production chain up to the farm gate boundary, GLEAM calculates emissions that are related to post-farm activities. These include a) the emissions related to the transport of raw livestock commodities (meat, milk and eggs) to a processing center, b) emissions related the processing of raw commodities into livestock products, c) emissions related to the packaging of those products.

8.1 – EMISSIONS FROM TRANSPORT TO PROCESSING PLANTS

The food sector is transport-intensive – large quantities of food are transported in large volumes and over long distances. This transport can sometimes be of significance but, in terms of the overall contribution to the life cycle carbon footprint of a product, most LCA studies have found that the contribution of transport is relatively small. The carbon implications of food transport are not only a question of distance. A number of other variables, such as transport mode, efficiency of transport loads and the condition of infrastructure (road quality), fuel type, are important determinants of the carbon intensity of products.

Emissions factors from transporting animal products from the farm to processing plants were based on ECTA (2019) and are calculated following Equation 8.1.

Equation 8.1

$$EFTRANS_{FP} = D_{FP} \times EF_{road}$$

Where:

$EFTRANS_{FP}$ = emission factor for product transport from farm to slaughter/processing plant, kg CO_2-eq×kg CW^{-1} / kg CO_2-eq·kg $milk^{-1}$ / kg CO_2-eq×kg egg^{-1}

D_{FP} = average distance between the farm and the slaughter/processing plant, km. A value of 50 km was assumed as a default distance from places of production to primary processing.

EF_{road} = emission factor for road transport, 0.095 kg CO_2 / (kg × km) as defined in ECTA (2019).

8.2 – PROCESSING AND PACKAGING

To estimate emissions related to processing and packaging of animal products we used emission factors from Poore and Nemecek (2018). These are based on a meta-analysis of 38 700 commercial farms in 119 countries with a median reference year of 2017 and summarize emission factors for 40 food items (including animal products). The relevant emission factors for processing and packaging for different GLEAM commodities are summarized in Table 8.1.

Table 8.1 Post-farm emission factors (kg CO_2/kg product) for packaging and processing for animal products in GLEAM

Product	EFPROC	EFPACK
Bovine Meat (beef herd)	1.269	0.247
Bovine Meat (dairy herd)	1.108	0.268
Lamb & Mutton	1.111	0.251
Pig Meat	0.284	0.296
Poultry Meat	0.440	0.212
Milk	0.149	0.097
Eggs	-	0.161

Not all animals produced are slaughtered in slaughter plants/abattoirs: slaughtering may also take place on-farm or may be carried out by local butchers within the vicinity of production, so that the quantities taken into accont for the above calcuations are reduced. For industrialized countries, it was assumed that 98% of the animals are slaughtered in slaughterhouses. In developing countries, the share of animals transported to slaughter plants varied between 15% and 75% based on the assumption that slaughtering infrastructure is generally lacking and that animals are often slaughtered in closer proximity to where they are raised, with slaughter being carried out by local butchers or household slaughter.

For milk, the fraction of primary products used directly for consumption was estimated from FAOSTAT commodity balance sheets (FAOSTAT, 2018), as the sum of all dairy products over the total milk supply in a country (expressed in milk equivalents). The processing fraction is generally higher in high income countries where milk is processed to other products before consumption.

For eggs, it was assumed that all eggs produced by intensive layers were sent to grading and packaging plants. For Backyard chickens, instead, the share of graded and packaged eggs was assumed to be negligible and set to zero.

8.3 – TOTAL POST-FARM EMISSION FACTORS

Total emission factors from post-farm are calculated using Equation 8.2.

Equation 8.2

$$EFPF_p = (EFTRANS_{FP} + EFPROC_p + EFPACK_p) \times Share\_proc_p$$

Where:

$EFPF_p$ = post-farm emission factor for product *p*, kg CO_2-eq×kg CW^{-1} / kg CO_2-eq×kg $milk^{-1}$/ kg CO_2-eq×kg egg^{-1}

$EFTRANS_{FP}$ = emission factor for product transport, kg CO_2-eq×kg CW^{-1} / kg CO_2-eq×kg $milk^{-1}$/ kg CO_2-eq×kg egg^{-1}

$EFPROC_p$ = emission factor for processing of product *p*, kg CO_2-eq×kg CW^{-1} / kg CO_2-eq×kg $milk^{-1}$/ kg CO_2-eq×kg egg^{-1}

$EFPACK_p$ = emission factor for packaging of product *p*, kg CO_2-eq×kg CW^{-1} / kg CO_2-eq×kg $milk^{-1}$/ kg CO_2-eq×kg egg^{-1}

$Share\_proc_p$ = Share of processed product *p*, fraction

9 CHAPTER 9 – ALLOCATION MODULE

One of the principles of LCA methodology is to allocate emissions among different products and outputs. The approach used in GLEAM to allocate emissions is described in the following sections.

The functions of the 'Allocation' module are:

- Calculate the **total livestock production**;
- Calculate the **total emissions** and the **emission intensity** of each commodity.

For a schematic representation of the allocation module, see Figure 9.1 and Figure 9.2

Figure 9.1 Schematic representation of the allocation module for ruminant species

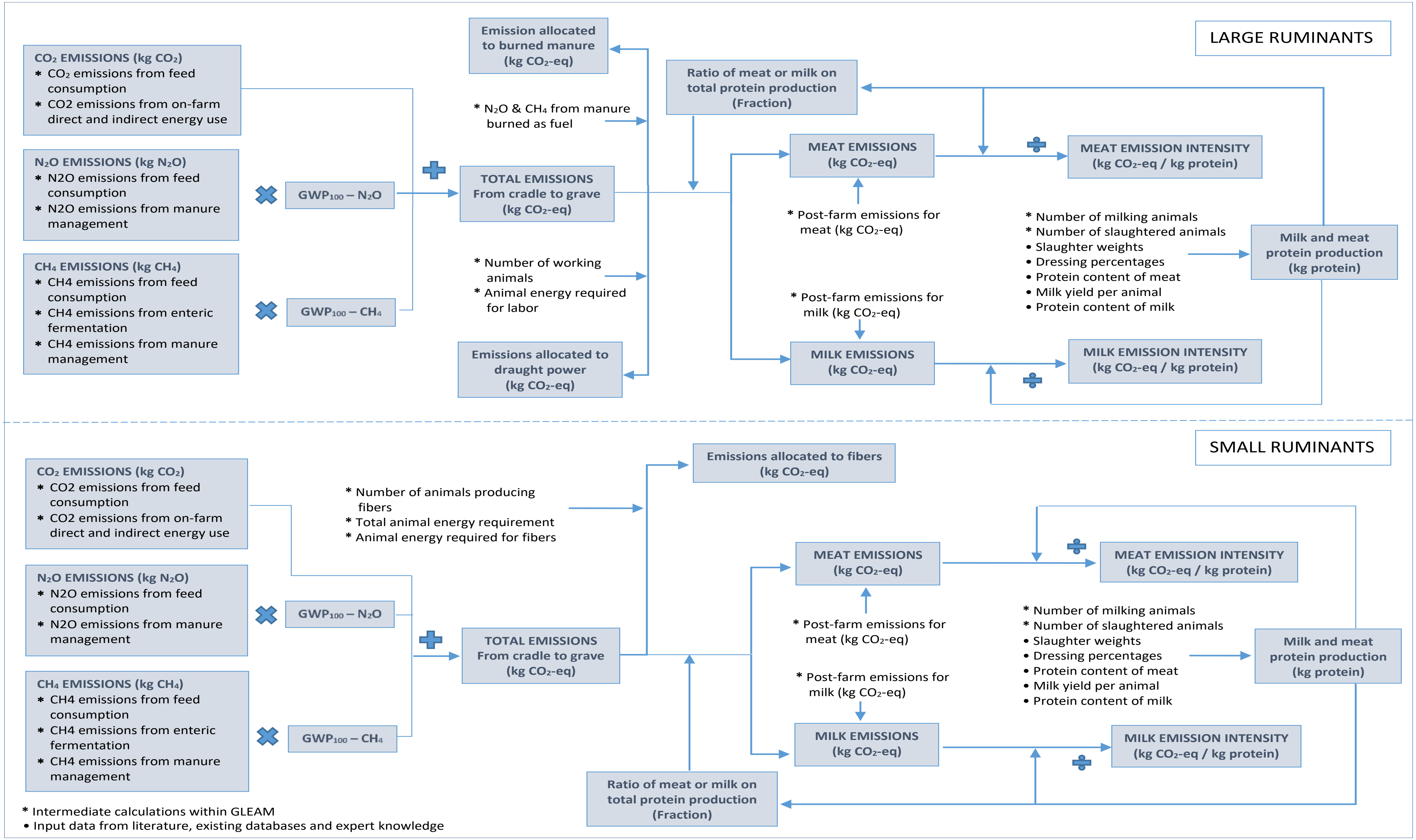
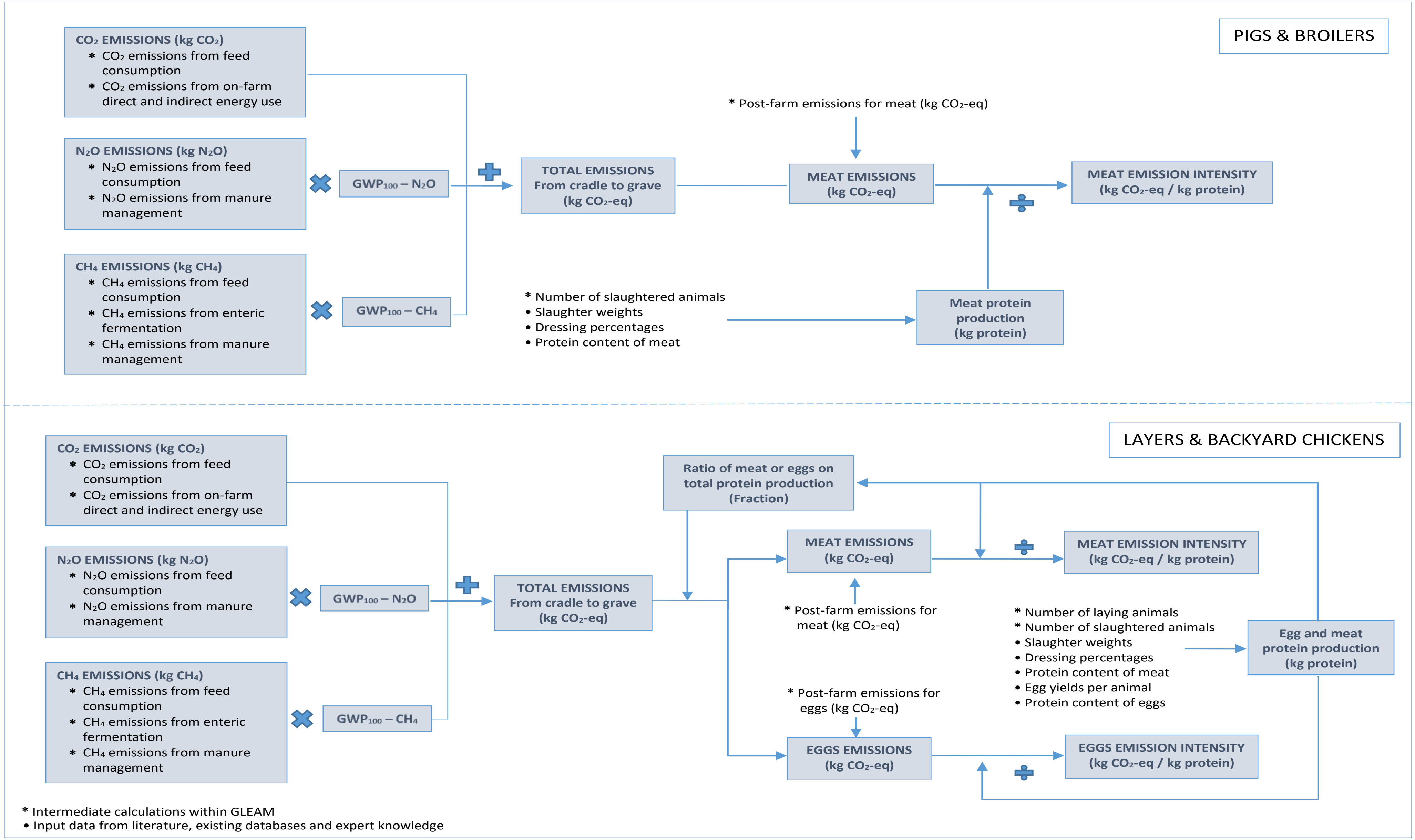


Figure 9.2 Schematic representation of the allocation module for monogastric species



9.1 – TOTAL LIVESTOCK PRODUCTION

This section describes the equations used to calculate the total amount of animal commodities produced by each species and production system, namely meat, milk, eggs, and fibre. All commodities, except fibre, are expressed in terms of protein to allow emission intensities comparison and aggregation between them.

9.1.1 – Production of milk

Total milk production is calculated based on average milk production per animal and number of milking animals. Total milk is then converted into amount of protein.

Equation 9.1

$MILKTOT_{prot,T} = AF_T \times MILK_{yield,T} \times MILK_{prot,T}$

Where:

$MILKTOT_{prot,T}$ = total amount of milk protein produced by species and production system *T*, kg protein×year^{-1}

AF_T = milking animals by species and production system *T*, heads

$MILK_{yield,T}$ = average milk production per milking animal of species and production system *T*, kg milk×head^{-1}×year^{-1}

$MILK_{prot,T}$ = average milk protein content of species and production system *T*, fraction

9.1.2 – Production of meat

Total meat production is calculated from the total number of animals that leave the herd for slaughter and average live weights. Live weight production is then expressed in total amount of protein using dressing percentage data, bone-free-meat to carcass weight ratio and average protein content in meat.

Equation 9.2

$MEATTOT_{prot,T} = BFM_T \times MEAT_{prot,T} \times \sum_c (N_{exit,T,c} \times LW_{,T,c} \times DP_T / 100)$

Where:

$MEATTOT_{prot,T}$ = total amount of meat protein produced by species and production system *T*, kg protein

BFM_T = bone-free-meat to carcass weight ratio for species and production system *T*, fraction. Values are shown in Table 9.1.

$MEAT_{prot,T}$ = average fraction of protein in meat of species and production system *T*, fraction. Values are shown in Table 9.1.

$N_{exit,T,c}$ = number of animals slaughtered by species and production system *T* and cohort *c*, heads

$LW_{,T,c}$ = live weight of slaughtered animals by species and production system *T* and cohort *c*, kg LW×animal^{-1}×year^{-1}

DP_T = dressing percentage of species and production system *T*, percentage. Values are given in Table S.9.1 (Supplement S1).

Table 9.1 Bone-free-meat to carcass weight ratio and protein content

Species	BFM (fraction)	$MEAT_{prot}$ (kg protein×kg meat^{-1})
Large ruminants	0.75	0.2113
Sheep	0.70	0.2013
Goats	0.70	0.1920
Pigs	0.65	0.2020
Chickens	0.75	0.1900

9.1.3 – Production of eggs

Total egg production is calculated from the backyard and layer systems exclusively following Equation 9.3.

Equation 9.3

$EGGTOT_{prot,T}$ = $10^3 \times EGG_{prot} \times EGGwght_T \times EGGSyear_T \times N_{Hens,T}$

Where:

$EGGTOT_{prot,T}$ = total amount of egg protein produced by production system *T*, kg protein×year^{-1}

EGG_{prot} = average protein fraction in eggs, fraction. Default value of 0.1240 was used.

$EGGwght_T$ = average egg weight for production system *T*, g×egg^{-1}

$EGGSyear_T$ = annual laid eggs per hen per production system *T*, eggs×hen^{-1}×year^{-1}. In the case of laying hens used for reproduction (AF) in the Backyard production system, EGGSyear is replaced by the variable EGGconsAF, representing the annual number of laid eggs per hen available for human consumption, as defined in Table 2.18 and Section 2.4.2.1.

$N_{Hens,T}$ = number of laying hens in production system *T*, heads. For the Layers production system, laying hens used for reproduction (AF) are excluded, since it is assumed that all eggs laid by this cohort in industrial systems are used exclusively for reproduction.

9.1.4 – Production of fibre

The production of fibers comprises three fibers: wool for sheep, cashmere and mohair for goats. The total production is calculated combining the number of reproductive and surplus animals producing fibre with the yield of product per animal from FAOSTAT.

It is assumed that all reproductive and surplus animals produce wool, as shown in Equation 9.4.

Equation 9.4 - Wool

$WOOLTOT_{,T}$ = $WOOL_{yield,T} \times \sum_c (N_{T,c})$

Where:

$WOOLTOT_{,T}$ = total amount of wool produced by system *T*, kg×year^{-1}

$WOOL_{yield,T}$ = average wool production per producing animal in system *T*, kg×head^{-1}×year^{-1}

c = cohort of reproductive (AF, AM) or surplus (MF, MM) animals

$N_{,T,C}$ = number of animals in system *T* and cohort *c*, heads

For goats, it is assumed that only a fraction of the animals produce cashmere or mohair. This fraction was obtained at national level from FAOSTAT. Cashmere and mohair production occurs in a few select countries. The total production of cashmere and mohair is calculated as follows:

Equation 9.5 – cashmere and mohair

a. $CSHTOT_{,T}$ = $CSH_{yield,T} \times \sum_c (N_{T,c}) \times CSH_{ratio}$

b. $MHRTOT_{,T}$ = $MHR_{yield,T} \times \sum_c (N_{T,c}) \times MHR_{ratio}$

Where:

$CSHTOT_{,T}$ = total amount of cashmere produced by system *T*, kg×year^{-1}

$MHRTOT_{,T}$ = total amount of mohair produced by system *T*, kg×year^{-1}

$CSH_{yield,T}$ = average cashmere production per producing animal in system *T*, kg×head^{-1}×year^{-1}

$MHR_{yield,T}$ = average mohair production per producing animal in system *T*, kg×head^{-1}vyear^{-1}

$N_{,T,C}$ = number of animals in system *T* and cohort *c*, heads

CSH_{ratio} = ratio of goats producing cashmere, fraction

MHR_{ratio} = ratio of goats producing mohair, fraction

c = cohort of reproductive (AF, AM) or surplus (MF, MM) animals

9.2 – AGGREGATION OF TOTAL EMISSIONS

The total emissions from different stages of the supply chain, calculated with the methods described in the previous chapters are aggregated to estimate the total amount of emissions for each species and production system. These total emissions are then allocated to the different co-products from each supply chain, following the allocation methods described in Section 9.3. Post-farm gate emissions are allocated directly to the respective product in the allocation phase.

Emissions from the three greenhouse gases are summed up. Methane and nitrous oxide emissions are converted into carbon dioxide equivalent (CO_2-eq) using the 100-years Global Warming Potential (GWP_{100}) values from the AR6 IPCC report (Forster et al., 2021). The GWP_{100} is the measure of the ability of a certain gas to trap heat in the atmosphere compared to that of a similar mass of carbon dioxide, over a period of 100 years. Equation 9.6 is used to aggregate the total emissions arising from the whole supply chain of each species and production system.

Equation 9.6

$$GHGTOT_{,T} = CO_{2\text{-Feed},T} + CO_{2\text{-Feed-LUC},T} + (N_2O_{\text{-Feed},T} + N_2O_{\text{-Manure},T}) \times GWP_{100}\text{-}N_2O + (CH_{4\text{-Feed},T} + CH_{4\text{-Enteric},T} + CH_{4\text{-Manure},T}) \times GWP_{100}\text{-}CH_4 + GHG_{nrgd,T} + GHG_{nrge,T}$$

Where:

$GHGTOT_{,T}$ = total emission from species and system *T* (excluding post-farm emissions), kg CO_2-eq×year^{-1}

$CO_{2\text{-Feed},T}$ = total carbon dioxide emissions from energy use associated with feed consumption of species and system *T*, kg CO_2×year^{-1}

$CO_{2\text{-Feed-LUC},T}$ = total carbon dioxide emissions from land-use change associated with feed consumption of species and system *T*, kg CO_2×year^{-1}

$N_2O_{\text{-Feed},T}$ = total nitrous oxide emissions associated with feed consumption of species and system *T*, kg N_2Ovyear^{-1}

$N_2O_{\text{-Manure},T}$ = total nitrous oxide emissions from manure management for species and system *T*, kg N_2O×year^{-1}

$CH_{4\text{-Feed},T}$ = total methane emissions from feed consumption of species and system *T*, kg CH_4×year^{-1}. Monogastric species only.

$CH_{4\text{-Enteric},T}$ = total methane emissions from enteric fermentation for species and system *T*, kg CH_4×year^{-1}

$CH_{4\text{-Manure},T}$ = total methane emissions from manure management for species and system *T*, kg CH_4×year^{-1}

$GHG_{nrgd,T}$ = total emissions from on-farm direct use of energy for species and system *T*, kg CO_2-eq×year^{-1}

$GHG_{nrge,T}$ = total emissions from use of energy embedded in manufacture and maintenance of farm capital goods for species and system *T*, kg CO_2-eq×year^{-1}

GWP_{100}-N_2O = global warming potential of nitrous oxide for 100 years' horizon, kg CO_2-eq×kg N_2O.

GWP_{100}-CH_4 = global warming potential of methane 100 years' horizon, kg CO_2-eq×kg CH_4.

Total post-farm emissions are calculated separately using the emission factors from Section 8.3, following Equation 9.7:

Equation 9.7

a. $GHG_{\text{-PFmeat},T} = EFPF_{meat,T} \times (MEATTOT_{prot,T} \;/\; (BFM_T \times MEAT_{prot,T}))$

b. $GHG_{\text{-PFmilk},T} = EFPF_{milk,T} \times (MILKTOT_{prot,T} \;/\; MILK_{prot,T})$

b. $GHG_{\text{-PFeggs},T} = EFPF_{eggs,T} \times (EGGTOT_{prot,T} \;/\; EGG_{prot})$

Where:

$GHG_{\text{-PFmeat},T}$ = total post-farm emissions for meat of species and system *T*, kg CO_2-eq×year^{-1}

$GHG_{\text{-PFmilk},T}$ = total post-farm emissions for milk of species and system *T*, kg CO_2-eq×year^{-1}

$GHG_{\text{-PFeggs},T}$ = total post-farm emissions for eggs of species and system *T*, kg CO_2-eq×year^{-1}

$EFPF_{meat,T}$ = post-farm emission factor for meat of species and system *T*, kg CO_2-eq×kg CW^{-1}. Emissions for backyard systems of monogastrics are assumed to be null.

$EFPF_{milk,T}$ = post-farm emission factor for milk of species and system *T*, kg CO_2-eq×kg milk^{-1}

$EFPF_{eggs,T}$ = post-farm emission factor for eggs of species and system *T*, kg CO_2-eq×kg egg $^{-1}$. Emissions for backyard chickens are assumed to be null.

$MEATTOT_{prot,T}$ = total amount of meat protein produced by species and production system *T*, kg protein

BFM_T	=	bone-free-meat to carcass weight ratio for species and production system *T*, fraction. Values are shown in Table 9.1.
$MEAT_{prot,T}$	=	average fraction of protein in meat of species and production system *T*, fraction. Values are shown in Table 9.1.
$MILKTOT_{prot,T}$	=	total amount of milk protein produced by species and production system *T*, kg protein×year^{-1}
$MILK_{prot,T}$	=	average milk protein content of species and production system *T*, fraction
$EGGTOT_{prot,T}$	=	total amount of egg protein produced by production system *T*, kg protein×year^{-1}
EGGprot	=	average protein fraction in eggs, fraction. Default value of 0.1240 was used.

9.3 – ALLOCATION OF EMISSIONS AND EMISSION INTENSITIES

9.3.1 – Allocation in ruminant species

Emissions in ruminant herds are allocated between edible commodities, i.e. meat and milk, and non-edible ones, namely manure used as fuel and draught power from large ruminants (cattle and buffaloes) and fibres for small ruminants. Emissions related to non-edible commodities are calculated first and deducted from the total emissions, before these are attributed to meat and milk.

As a first step, CH_4 from manure burned for fuel are calculated applying Equation 4.2 to the manure management system "burned for fuel" only. Therefore, these emissions are deducted from the rest of the manure emissions and allocated to fuel. The remaining emissions from manure are allocated to the other commodities.

To allocate emissions to draught power services, total emissions from draught animals alone are calculated. Then, a fraction of these emissions is allocated to draught power using as allocation factor the ratio of the net energy required for labor to the total net energy required by these animals. The remaining part of the emissions from draught animals is then allocated entirely to meat.

Similarly, the allocation of emissions to fibres is based on the relative share of the net energy required by animals that is used to produce them. The specific energy requirements from animals are calculated following the equations presented in Section 3.6.1. Once part of the emissions is allocated to fibre production, the remaining ones are allocated entirely to edible commodities.

The emissions from pasture expantion are allocated to cattle beef and dairy sector grassland based systems only (with the exclusion of feedlots system), accordingly to the share of animals in each system.

The remaining emissions are allocated between milk and meat using the proportions of proteins production from the two products as allocation factor. Once those emissions are allocated, the respective post-farm emissions are added to the final amount of each commodity. Table 9.2 and Table 9.3 show an example calculation of emission allocation for large and small ruminant herds, respectively.

A specific allocation is also required for feedlot systems of cattle. Emissions from surplus animals in feedlots are, in fact, allocated entirely to meat. However, on a yearly base, animals spend in feedlots only a certain amount of days, during what is called the "finishing" phase, while they spend the rest of the year (the "rearing" phase) outside of feedlots, in the respective native system (either grassland based or mixed, from both dairy and beef specialized herds). Therefore, the specific emission profile associated with feedlot production must be allocated only to the finishing phase, while the emission intensity per head of feedlot animals during the rearing phase is assumed to be equal to that of the surplus animals in the respective system of origin. Specifically, the total emissions from the rearing phase are calculated, at national level, multiplying the average daily emissions per head of surplus animal, in non-feedlot systems, by the number of days of the rearing phase and the number of animals going to feedlots in one year. Similarly, the total emissions from the finishing phase are calculated multiplying the daily emissions from feedlot animals by the number of days that they spend in feedlots. Finally, the emissions from the two phases are summed together to calculate the total emissions from feedlot animals. Table 9.4 shows an example calculation of allocation of emissions from rearing and finishing phases to feedlot systems. The same approach can be used to allocate both the total emissions and those from specific emission sources.

Table 9.2 Example of allocation between products from cattle dairy production

	Animals involved in both meat and milk production (milking cows, reproductive males and replacement animals)	Draught males	Surplus animals
Total emissions – post-farm excluded (kg CO_2-eq)	1 800 000	120 000	255 000
Total emissions from manure burned as fuel (kg CO_2-eq)	100 000	10 000	15 000
Ratio of net energy for labor to the total net energy requirement	-	0.6	-
Total emissions allocated to draught power (kg CO_2-eq)	-	= (120 000 – 10 000) × 0.6 = 66 000	-
Total emission allocated to meat and milk (kg CO_2-eq)	= 1 800 000 – 100,000 = 1 700 000	= 120 000 – 10 000 – 66 000 = 44 000	= 215 000 – 15 000 = 200 000
Total protein (kg)	Milk: 18 000 Meat: 1 500	Meat: 500	Meat: 2 000
Fraction of milk protein	0.92	-	-
Fraction of meat protein	0.08	1	1
Post-farm emissions (kg CO_2-eq)	Milk: 54 000 Meat: 24 000		
Emission intensity of milk (kg CO_2-eq×kg protein^{-1})	= ((1 700 000 × 0.92) + 54 000) / 18 000 = 89.9		
Emission intensity of meat (kg CO_2-eq×kg protein^{-1})	= ((1 700 000 × 0.08) + 44 000 + 200 000 + 24 000) / (1 500 + 500 + 2 000) = 101.0		

Table 9.3 Example of allocation between products from sheep dairy production

	Animals involved in meat, milk and fibre production (reproductive animals)	Animals involved in meat and milk production (replacement animals)	Animals involved in meat and fibre production only (surplus animals)
Total emissions – post-farm excluded (kg CO_2-eq)	50 000	30 000	20 000
Ratio of net energy for wool to the total net energy requirement	0.2	-	0.3
Total protein (kg)	Milk: 500 Meat: 50		Meat: 200
Fraction of milk protein	0.91		-
Fraction of meat protein	0.09		1
Total emission allocated to wool (kg CO_2-eq)	= 50 000 × 0.2 = 10 000	-	= 20 000 × 0.3 = 6 000
Total emission allocated to meat and milk (kg CO_2-eq)	= 50 000 – 10 000 = 40 000	30 000	= 20 000 – 6 000 = 14 000
Post-farm emissions (kg CO_2-eq)	Milk: 1 500 Meat: 1 250		
Emission intensity of milk (kg CO_2-eq×kg protein^{-1})	= (((40 000 + 30 000) × 0.91) + 1 500) / 500 = 130.4		
Emission intensity of meat (kg CO_2-eq×kg protein^{-1})	= (((40 000 + 30 000) × 0.09) + 14 000 + 1 250) / (50 + 200) = 86.2		

Table 9.4 Example of allocation of emissions from rearing and finishing phases to feedlot systems

	Grassland based system	Mixed farming system	Feedlot system
Daily emissions per surplus animal (kg CO_2-eq×head^{-1}×day^{-1})	2.7	2.5	1.6
Number of surplus animals (heads)	50	100	200
Length of the finishing phase (days)	-		120
Length of the rearing phase (days)	= 365 – 120 = 245		-
Total emissions from the rearing phase (kg CO_2-eq)	= (2.7 × 50 + 2.5 × 100) / (50 + 100) × 245 × 200 = 125 767		-
Total emissions from the finishing phase (kg CO_2-eq)	-	-	= 1.6 × 120 × 200 = 38 400
Total emissions allocated to feedlots (kg CO_2-eq)	-	-	= 125 767 + 38 400 = 164 167

9.3.2 – Allocation in monogastric species

Emissions for monogastrics are also allocated between edible products, i.e. meat and eggs, in the case of backyard and layers chickens. For pigs and broilers, all emissions are allocated to meat.

For backyard chickens and layers, the first step is to calculate the specific emissions that are from all animals required for egg production, namely laying hens, reproductive males and replacement animals. In a subsequent step, these emissions are allocated on the basis of the amount of egg and meat protein output, while emissions from the remaining part of the flock are allocated entirely to meat. The respective post-farm emissions are added to the final amount of each commodity. Table 9.5 presents a calculation example.

Table 9.5 Example of allocation between edible products for chickens

	Animals involved in egg and meat production	Animals involved only in meat production
Total emissions (kg CO_2-eq)	50 000	39 000
Total protein (kg)	Eggs: 800 Meat: 200	Meat: 500
Total emission allocated to eggs (kg CO_2-eq)	= 50 000 × (800 / (800 + 200)) = 40 000	-
Total emission allocated to meat (kg CO_2-eq)	= 50 000 × (200 / (800 + 200)) = 10,000	39 000
Post-farm emissions (kg CO_2-eq)	Eggs: 1,200 Meat: 840	
Emission intensity of eggs (kg CO_2-eq×kg protein^{-1})	= (40 000 + 1 200) / 800 = 51.5	
Emission intensity of meat (kg CO_2-eq×kg protein^{-1})	= (10 000 + 39 000 + 840) / (200 + 500) = 71.2	

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APPENDIX A – COUNTRY LISTS

The country grouping used in GLEAM is based on the last available FAO Global Administrative Unit Layers (GAUL). Country groupings were based on Greenhouse Gas Emissions from the Dairy Sector. A Life Cycle Assessment https://www.fao.org/3/k7930e/k7930e00.pdf for Table S.A1 (Supplement S1); and from https://www.fao.org/faostat/en/, https://european-union.europa.eu/principles-countries-history/country-profiles_en, List of OECD Member countries - Ratification of the Convention on the OECD) for Table A2 (Supplement S2).

TABLE A1 – GLEAM country list and classification

Region and country	
LATIN AMERICA AND THE CARIBBEAN (LAC)	
Antigua and Barbuda	Guyana
Argentina	Haiti
Bahamas	Honduras
Barbados	Jamaica
Belize	Martinique
Bolivia (Plurinational State of)	Mexico
Brazil	Nicaragua
Chile	Panama
Colombia	Paraguay
Costa Rica	Peru
Cuba	Puerto Rico
Dominica	Saint Kitts and Nevis
Dominican Republic	Saint Lucia
Ecuador	Saint Vincent and the Grenadines
El Salvador	Suriname
French Guiana	Trinidad and Tobago
Grenada	Uruguay
Guadeloupe	Venezuela
Guatemala	
SUB-SAHARAN AFRICA (SSA)	
Angola	Lesotho
Benin	Liberia
Botswana	Madagascar
Burkina Faso	Malawi
Burundi	Mali
Cabo Verde	Mauritania
Cameroon	Mauritius
Central African Republic	Mozambique
Chad	Namibia
Comoros	Niger
Congo	Nigeria
Côte d'Ivoire	Réunion
Democratic Republic of the Congo	Rwanda
Djibouti	São Tome and Principe
Equatorial Guinea	Senegal
Eritrea	Seychelles
Eswatini	Sierra Leone
Ethiopia	Somalia
Gabon	South Africa
Gambia	Togo
Ghana	Uganda
Guinea-Bissau	United Republic of Tanzania
Guinea	Zambia
Kenya	Zimbabwe
NEAR EAST AND NORTH AFRICA (NENA)	
Algeria	Oman
Armenia	Palestine
Azerbaijan	Qatar

Bahrain	Saudi Arabia
Cyprus	South Sudan
Egypt	Sudan
Georgia	Syrian Arab Republic
Iraq	Tajikistan
Israel	Tunisia
Jordan	Türkiye
Kazakhstan	Turkmenistan
Kuwait	United Arab Emirates
Kyrgyzstan	Uzbekistan
Lebanon	Western Sahara
Libya	Yemen
Morocco	
SOUTH ASIA (SA)	
Afghanistan	Maldives
Bangladesh	Nepal
Bhutan	Pakistan
India	Sri Lanka
Iran, Islamic Republic of	
EASTERN EUROPE (EE)	
Belarus	Poland
Bulgaria	Romania
Czechia	Slovakia
Hungary	Ukraine
Moldova, Republic of	
RUSSIAN FEDERATION (RUS)	
Russian Federation	
EAST ASIA AND SOUTH-EAST ASIA (ESEA)	
Brunei Darussalam	Malaysia
Cambodia	Mongolia
China	Myanmar
China, Hong Kong SAR	Philippines
China, Macao SAR	Republic of Korea
China, Taiwan Province of	Singapore
Democratic People's Republic of Korea	Thailand
Indonesia	Timor-Leste
Japan	Viet Nam
Lao People's Democratic Republic	
OCEANIA (OCE)	
Australia	New Zealand
Cook Islands	Niue
Fiji	Palau
French Polynesia	Papua New Guinea
Kiribati	Samoa
Marshall Islands	Solomon Islands
Micronesia, Federated States of	Tonga
Nauru	Tuvalu
New Caledonia	Vanuatu
WESTERN EUROPE (WE)	
Albania	Liechtenstein
Austria	Lithuania
Belgium	Luxemburg
Bosnia and Herzegovina	Malta
Croatia	Montenegro
Denmark	Netherlands
Estonia	North Macedonia
Faroe Islands	Norway
Finland	Portugal
France	Serbia
Germany	Slovenia
Greece	Spain

Iceland	Sweden
Ireland	Switzerland
Italy	United Kingdom of Great Britain and Northern Ireland
Latvia	
NORTH AMERICA (NA)	
Canada	United States of America

TABLE A2– FAOSTAT country list and classification

Region and country	
AFRICA	
Algeria	Malawi
Angola	Mali
Benin	Mauritania
Botswana	Mauritius
Burkina Faso	Morocco
Burundi	Mozambique
Cabo Verde	Namibia
Cameroon	Niger
Central African Republic	Nigeria
Chad	Réunion
Comoros	Rwanda
Congo	São Tome and Principe
Côte d'Ivoire	Senegal
Democratic Republic of the Congo	Seychelles
Djibouti	Sierra Leone
Egypt	Somalia
Equatorial Guinea	South Africa
Eritrea	South Sudan
Eswatini	Sudan
Ethiopia	Togo
Gabon	Tunisia
Gambia	Uganda
Ghana	United Republic of Tanzania
Guinea	Zambia
Guinea-Bissau	Zimbabwe
Kenya	
Lesotho	
Liberia	
Libya	
Madagascar	
AMERICAS	
Antigua and Barbuda	Guyana
Argentina	Haiti
Bahamas	Honduras
Barbados	Jamaica
Belize	Martinique
Bolivia (Plurinational State of)	Mexico
Brazil	Nicaragua
Canada	Panama
Chile	Paraguay
Colombia	Peru
Costa Rica	Puerto Rico
Cuba	Saint Kitts and Nevis
Dominica	Saint Lucia
Dominican Republic	Saint Vincent and the Grenadines
Ecuador	Suriname
El Salvador	Trinidad and Tobago
French Guyana	United States of America
Grenada	Uruguay
Guadeloupe	Venezuela (Bolivarian Republic of)
Guatemala	
ASIA	

Afghanistan	Lebanon
Armenia	Malaysia
Azerbaijan	Maldives
Bahrain	Mongolia
Bangladesh	Myanmar
Bhutan	Nepal
Brunei Darussalam	Oman
Cambodia	Pakistan
China	Palestine
China, Hong Kong SAR	Philippines
China, Macao SAR	Qatar
China, Taiwan Province of	Republic of Korea
Cyprus	Saudi Arabia
Democratic People's Republic of Korea	Singapore
Georgia	Sri Lanka
India	Syrian Arab Republic
Indonesia	Tajikistan
Iran, Islamic Republic of	Thailand
Iraq	Timor-Leste
Israel	Türkiye
Japan	Turkmenistan
Jordan	United Arab Emirates
Kazakhstan	Uzbekistan
Kuwait	Viet Nam
Kyrgyzstan	Yemen
Lao People's Democratic Republic	
AUSTRALIA and NEW ZEALAND	
Australia	New Zealand
CARIBBEAN	
Antigua and Barbuda	Haiti
Bahamas	Jamaica
Barbados	Martinique
Cuba	Puerto Rico
Dominica	Saint Kitts and Nevis
Dominican Republic	Saint Lucia
Grenada	Saint Vincent and the Grenadines
Guadeloupe	Trinidad and Tobago
CENTRAL AMERICA	
Belize	Honduras
Costa Rica	Mexico
El Salvador	Nicaragua
Guatemala	Panama
CENTRAL ASIA	
Kazakhstan	Turkmenistan
Kyrgyzstan	Uzbekistan
Tajikistan	
EASTERN AFRICA	
Burundi	Mozambique
Comoros	Réunion
Djibouti	Rwanda
Eritrea	Seychelles
Ethiopia	Somalia
Kenya	Uganda
Madagascar	United Republic of Tanzania
Malawi	Zambia
Mauritius	Zimbabwe
EASTERN ASIA	
China	Democratic People's Republic of Korea
China, Hong Kong SAR	Japan
China, Macao SAR	Mongolia
China, Taiwan Province of	Republic of Korea
EASTERN EUROPE	
Belarus	Poland

Bulgaria	Romania
Czechia	Russian Federation
Hungary	Slovakia
Moldova, Republic of	Ukraine
EUROPE	
Albania	Lithuania
Austria	Luxemburg
Belarus	Malta
Belgium	Moldova, Republic of
Bosnia and Herzegovina	Montenegro
Bulgaria	Netherlands
Croatia	North Macedonia
Czechia	Norway
Denmark	Poland
Estonia	Portugal
Faroe Islands	Romania
Finland	Russian Federation
France	Serbia
Germany	Slovakia
Greece	Slovenia
Hungary	Spain
Iceland	Sweden
Ireland	Switzerland
Italy	Ukraine
Latvia	United Kingdom of Great Britain and Northern Ireland
EUROPEAN UNION (EU27)	
Austria	Italy
Belgium	Latvia
Bulgaria	Lithuania
Croatia	Luxemburg
Cyprus	Malta
Czechia	Netherlands
Denmark	Poland
Estonia	Portugal
Finland	Romania
France	Slovakia
Germany	Slovenia
Greece	Spain
Hungary	Sweden
Ireland	
MELANESIA	
Fiji	Solomon Islands
New Caledonia	Vanuatu
Papua New Guinea	
MICRONESIA	
Kiribati	Micronesia (Federated States of)
Marshall Islands	Nauru
MIDDLE AFRICA	
Angola	Democratic Republic of the Congo
Cameroon	Equatorial Guinea
Central African Republic	Gabon
Chad	São Tome and Principe
Congo	
NORTHERN AFRICA	
Algeria	South Sudan
Egypt	Sudan
Libya	Tunisia
Morocco	Western Sahara
NORTHERN AMERICA	
Canada	United States of America
NORTHERN EUROPE	
Denmark	Latvia
Estonia	Lithuania

Faroe Islands	Norway
Finland	Sweden
Iceland	United Kingdom of Great Britain and Northern Ireland
Ireland	
OCEANIA	
Australia	New Zealand
Cook Islands	Niue
Fiji	Papua New Guinea
French Polynesia	Samoa
Kiribati	Solomon Islands
Marshall Islands	Tokelau
Micronesia, Federated States of	Tonga
Nauru	Tuvalu
New Caledonia	Vanuatu
OECD	
Australia	Japan
Austria	Latvia
Belgium	Lithuania
Canada	Luxemburg
Chile	Mexico
Colombia	Netherlands
Comoros	New Zealand
Costa Rica	Norway
Czechia	Poland
Denmark	Portugal
Estonia	Republic of Korea
Finland	Slovakia
France	Slovenia
Germany	Spain
Greece	Sweden
Hungary	Switzerland
Iceland	Türkiye
Ireland	United Kingdom of Great Britain and Northern Ireland
Israel	United States of America
Italy	
POLYNESIA	
Cook Islands	Tokelau
French Polynesia	Tonga
Niue	Tuvalu
Samoa	
SOUTH AMERICA	
Argentina	Guyana
Bolivia (Plurinational State of)	Paraguay
Brazil	Peru
Chile	Suriname
Colombia	Uruguay
Ecuador	Venezuela (Bolivarian Republic of)
French Guyana	
SOUTH EASTERN ASIA	
Brunei Darussalam	Philippines
Cambodia	Singapore
Indonesia	Thailand
Lao People's Democratic Republic Indonesia	Timor-Leste
Malaysia	Viet Nam
Myanmar	
SOUTHERN AFRICA	
Botswana	Namibia
Eswatini	South Africa
Lesotho	
SOUTHERN ASIA	
Afghanistan	Maldives
Bangladesh	Nepal
Bhutan	Pakistan

India	Sri Lanka
Iran, Islamic Republic of	
SOUTHERN EUROPE	
Albania	Montenegro
Bosnia and Herzegovina	North Macedonia
Croatia	Portugal
Greece	Serbia
Italy	Slovenia
Malta	Spain
WESTERN AFRICA	
Benin	Liberia
Burkina Faso	Mali
Cabo Verde	Mauritania
Côte d'Ivoire	Niger
Gambia	Nigeria
Ghana	Senegal
Guinea	Sierra Leone
Guinea-Bissau	Togo
WESTERN ASIA	
Armenia	Lebanon
Azerbaijan	Oman
Bahrain	Palestine
Cyprus	Qatar
Georgia	Saudi Arabia
Iraq	Syrian Arab Republic
Israel	Türkiye
Jordan	United Arab Emirates
Kuwait	Yemen
WESTERN EUROPE	
Austria	Luxemburg
Belgium	Netherlands
France	Switzerland
Germany	