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ClimAg model description

Version 2.0

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1. Introduction

The ClimAg model is a biophysical systems model that calculates the resource use and emissions of greenhouse gases (GHGs) and nitrogen pollutants from food, fiber, and biofuel production. The primary application of ClimAg is to calculate the climate impact of food and biofuel production systems. In addition to recurring GHGs, the model calculates the climate impact of carbon stock changes in plants and soils caused by land use.

ClimAg models all major steps related to agriculture and aquaculture production and use of food, materials, and biofuels, including: i) production of inputs (fertilizer, electricity, etc.); ii) crop, livestock, and seafood production; iii) processing into end-use-ready items; iv) end-use (consumption); and v) transportation between production and use nodes. The model also represents all major co-products and their use; see Figure 1.

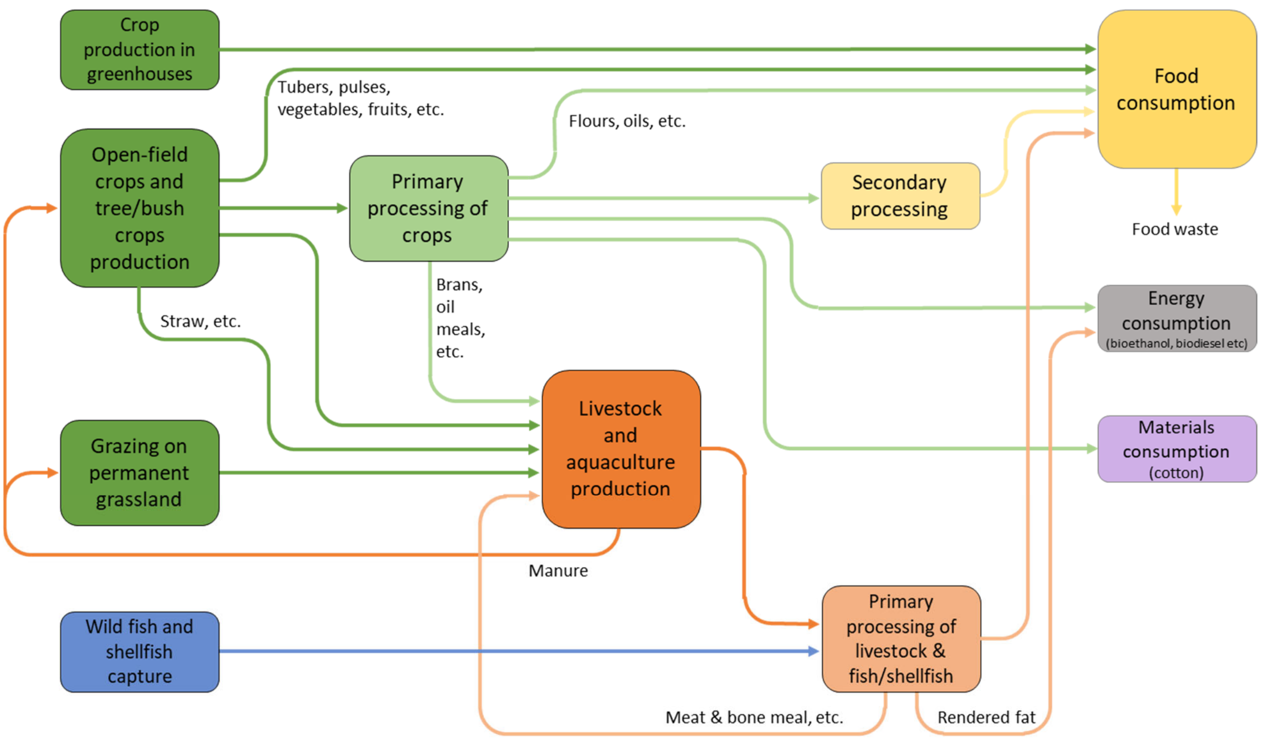

Figure 1 Overview of the ClimAg model system: Sub-systems included and major product and co-product flows. Some flows are indicated for clarity. Emission flows are not shown. Sub-systems not shown are freight transport and production of fuels, electricity, fertilizer, and pesticides.

Key design features of the ClimAg model include:

- **Consistent accounting of upstream resource use and emissions** of all feeds and feedstocks used in production systems. The ClimAg model consistently calculates the land and energy use, and GHG and nitrogen (N) emissions that occur in the supply of all categories of feeds and feedstocks (see Table 23). This applies also to all flows generated as co-products, e.g., cereal brans and oil meals. Such upstream costs are also calculated for co-products, which are often considered free in other models and analyses. For example, straw used for bioenergy or manure used for organic crop production are typically assigned no upstream climate cost.

- **Physically consistent representation of the production and use of co-products** generated in crop and livestock systems, and related processing industries (see Table 16-22 for co-products included). Most co-products are useful as feedstock in other production processes. ClimAg calculates the production of co-products based on mass- and energy-balanced descriptions of the processes in which they originate. This ensures that the availability of co-products is correctly scaled to the production levels in the sub-systems that generate the co-products.
- **Endogenous representation of livestock herds** in terms of number of animals of different functions and ages, and the herd output of milk/egg and slaughter animals. Herd size and structure are calculated using herd dynamics parameters (e.g., reproduction and growth rates, and animal cohort descriptions, mainly age and liveweight); see section 3.1.1. Endogenous representation enables calibration of key herd productivity parameters, such as calving and liveweight gain rates, to country statistics on production per number of livestock.
- **Endogenous estimates of feed energy intake per animal**, calculated with empirically based equations that use various herd characteristics parameters as input data (e.g., liveweight, growth rate, and milk/egg production rate);see 3.2.1. Endogenous calculations of feed energy intake ensure fairly accurate feed use estimates even when feed basket data are incomplete. The benefit of this model feature is particularly important in systems with significant grazing, as the amount of grazed feed is rarely known.
- **Description of nitrogen (N) flows on a mass balance basis**. The ClimAg model includes a highly detailed, mass-balance based representation of N flows in the food and agriculture system (see Figure 3). Mass-balanced descriptions of N flows improve the accuracy of emission estimates for crop and livestock production, from which substantial amounts of N can escape as different gases and nitrate. Most of these losses are expensive to measure directly and rarely known with high certainty. Using mass balance ensures physically consistent results, and more accurate estimates overall of N flows.

The model calculates land and energy use, climate impacts, and N emissions for approximately 400 products and by-products from agriculture, aquaculture, and fisheries (see Table 16-22) and includes most GHG emission sources from agriculture and aquaculture:

- Nitrous oxide (N_2O) from mineral soils, with separate representation of emissions from:
  - Plant residues left in field, including root mass
  - Fertilizer application, specific to crop type
  - Manure application, specific to crop type, manure type, and application technology
  - Manure excreted at grazing
- CO_2 and N_2O from drained organic soils
- Methane (CH_4) from flooded rice fields
- CH_4 from feed digestion ("enteric" fermentation) in ruminants and pigs
- N_2O and CH_4 from livestock manure in animal confinements and storage, respectively
- CH_4 from manure excreted at grazing
- CH_4 and N_2O from aquaculture facilities
- "Indirect" N_2O caused by ammonia and nitrate emissions from agriculture

- CO_2 from fuel and electricity use in crop production (e.g., for land preparation, irrigation, harvesting, and post-harvest crop drying).
- CO_2 from fuel and electricity use in livestock confinements, aquaculture facilities, and capture fisheries
- CO_2 from fuel and electricity use in crop, livestock, and fish/shellfish processing
- CO_2 and N_2O from production of mineral fertilizers and pesticides
- CO_2 from manufacturing of materials used in greenhouse structures
- CO_2 from transportation from production to use and end-use, including inter-regional trade

ClimAg does not include energy use and emissions from manufacturing and construction of machinery, buildings, etc., except for greenhouse structures. In addition, GHG emissions from packaging, retailing or food preparation are not included. Lastly, ClimAg does not include CO_2 emissions from liming, partly because it is a very small source, and partly because the net GHG emissions due to liming are very uncertain and may even be negative (Karlsson Potter et al., 2023).

In addition to the recurring GHG emission sources listed above, ClimAg includes the climate impact of carbon stock changes in plants and soils caused by land use, here referred to as the "carbon opportunity cost" of land use (see 2.5).

When vegetation changes from forest to agricultural land, and vice versa, changes occur in surface albedo and cloud formation which both influence regional and global temperatures. However, due to insufficient understanding and data in the literature, ClimAg does not include these factors.

As mentioned above, production systems included in ClimAg are described on a nitrogen mass-balance basis. The model includes all system inputs of fixed N (fertilizer, biological fixation, and atmospheric deposition), and all potential N losses (emissions). These emissions include:

- Ammonia (NH_3) from soils, with separate representation of emissions from:
  - Fertilizer application on cropland, specific by manure type
  - Manure application on cropland, specific by manure type
  - Manure excreted at grazing, specific by urine and feces, and by species
  - Decomposing crop residues left in field after harvest
- Nitric oxide (NO) from soils
- Dinitrogen (N_2) from soils
- Nitrate (NO_3^-) from soils
- NH_3 from livestock confinements and manure storage facilities
- Runoff of N from livestock confinements and manure storage facilities

2. Crop and pasture production

Agricultural land use for food, fiber, and biofuel production is very diverse. To capture the variation that is relevant to resource and environmental impacts, many types of crops and land use systems have been included in the ClimAg model. In total about 70 different annual and perennial crops on cropland are represented, see Table 16. Between them, these crops account for close to 100% of global cropland use. In addition to crops cultivated in the open field, ClimAg also includes four crops grown in greenhouses: tomatoes, cucumbers, peppers (capsicum), and eggplants.

Pasture production on permanent and semi-permanent grassland is represented by four types, based on the pre-existing native vegetation on the site: originally forest, originally tropical/sub-tropical grassland or woodland, originally temperate grassland, and originally xeric grassland. This distinction helps to facilitate estimates of the climate and environmental impact of permanent and semi-permanent pastures. Semi-permanent grassland refers to grassland that is renewed every 10-15 years by plowing and sowing. This type of grassland is relatively common in, for example, Brazil.

Where applicable, separate representation is done for conventional and organic systems, respectively. The model does not include separate representation of rainfed and irrigated production, except for the calculations of carbon opportunity cost, see 2.5.

Table 1-3 list main exogenous parameters in crop and pasture systems. The sections below provide more details.

2.1 Plant growth and land areas

2.1.1 Plant growth and crop production

Using the parameters in Table 1, the model calculates the total net photosynthetic production per hectare and year and its partition into different plant components (harvestable items, roots etc).

Annual crops

For annual crops on arable land, total net photosynthetic production per hectare is calculated as a function of net harvested mass ('yield'), harvest losses, and allometric relationships of plant organs (harvestable part, non-harvested parts above ground, root mass). For most cereals, oil/protein crops, and starchy root crops, the fraction harvestable part ('harvest index'), α^c, is calculated endogenously as a function of yield, using the equations developed by (García-Condado et al., 2019).

Net plant mass production per hectare and year for crop *c*, P_{net}^{c} (Mg dry matter ha^{-1} yr^{-1}), is thus calculated according to:

$$P_{net}^{c} = \frac{gross\ yield \times dry\ matter\ content\ of\ yield}{\alpha^c} \times \frac{1}{(1 - \%\ root\ mass\ of\ total\ plant\ mass)} \quad \text{Eq. 1}$$

where:

gross yield = *net yield* + *harvest spill/losses* (see Table 1)

Numbers on dry matter content of yield and percentage root mass are given in Table 25.

Table 1 Main exogenous parameters in crop and pasture sub-systems. Parameters describing nitrogen flows are shown in Table 3. Parameters describing plant growth for tree and bush crops are shown in Table 2. Sub-systems are listed in Table 16.

Parameters	Unit/option	Comments
Plant growth and harvest		Applies to field crops, not tree and bush crops
Net harvest of main prod. ('yield')	Mg fresh weight/ha **per harvest**	
Spill/loss during harvest, including discarded product	% of net harvest	Varies from about 2% for cereals to up to 10% for tubers, vegetables, fruits
Number of harvests	per crop rotation	See 2.1 for more details
Length of cultivation cycle	months / years	See 2.1 for more details
Length of growing season	months	
Length of wet/warm v. dry/cold seasons	months	Applies only to grass-legume crops and permanent and semi-permanent grassland
Production in wet/warm and dry/cold seasons	Mg DM/ha per month	Applies only to grass-legume crops and permanent and semi-permanent grassland
Share of harvestable main product ('harvest index'), α^c	% DM of above-ground prod. (total plant mass prod. minus roots for underground crops)	Applies only to annual crops. See Table 25 for numbers
Share of grazed intake	% DM of above-ground production	Applies only to grazed grass-legume crops and permanent and semi-permanent grassland
Share of legumes in grass-leg. mixtures	% DM of total plant mass prod.	Applies only to grass-legume crops
Share of root mass production	% DM of total plant mass prod.	See Table 25 for numbers
Share of harvestable crop by-products (straw, twigs, trunks etc)	% of total produced	
Harvest of crop by-products	% of harvestable	
Inputs other than nitrogen (details on nitrogen inputs are given in 2.2)		
Phosphorus and potassium fertilizer, and pesticides	g / kg yield	
Manure applied – crop farms	Mg/ha land area/yr	Manure purchased from livestock farms
Manure applied – livestock farms	Mg/ha land area/yr	Endogenous parameter. Calculated as a fraction of the manure output from confinements, see 2.2.4
Manure excreted at grazing	Mg/ha land area/yr	Endogenous parameter. Calculated as a function of manure excreted on pastures and the and time spent on pasture, see 3.3.1
Energy use open-field crops		
Diesel for land preparation, tillage, sowing, planting	liter/ha	For tree and bush crops, this includes removal of previous plants
Diesel or electricity for irrigation	liter or GJ per ha irrigated area	
Diesel for fertilizer, pesticide appl.	liter per number of applications	
Diesel for manure application	liter/Mg manure	
Diesel for pruning and removal	liter/ha/year	Tree and bush crops only
Diesel for harvest	liter/ha and liter/Mg harvested	See 2.4.1 for more details
Liquid fuel for post-harvest drying	liter/kg water dried	
Electricity for post-harvest drying	MJ/kg	

Parameters	Unit/option	Comments
Energy and materials use in greenhouses		
Fuel for heating	MJ/m²/year	Fuel options include gas, fuel oil, and wood
Electricity for lighting	MJ/m²/year	
Electricity for irrigation and other	MJ/m²/year	
Materials stock in protective structure	kg/m²	Includes concrete, glass, steel, aluminum, plastics long lifetime, plastics short lifetime
Lifetime of materials in protective structure	years	
CO_2 intensity of materials	kg CO_2/kg	Includes energy use from feedstock extraction and processing into final product
Substrate use	kg/m²	Includes perlite, rockwool, peat, bark
Lifetime of substrates	years	
CO_2 intensity of substrate	kg CO_2/kg	Includes energy use from feedstock extraction and processing into final product
CH_4 emissions from rice production		See 2.4.3 for more details
Baseline emissions	kg CH_4/ha harvested/day	
Cultivation period	days	
Scaling factor – water regime during cultivation	% of baseline emissions	
Scaling factor – water regime *before* cultivation	% of baseline emissions	
Scaling factor – organic inputs	% of baseline emissions	
CO_2 and N_2O emissions from drained organic soils		
Fraction of drained organic soil	% of land area	Specified by crop and pasture type
CO2 emission factor	Mg CO2/ha/yr	Specified by crop, pasture and biome
N2O emission factor	kg N2O/ha/yr	Specified by crop, pasture and biome
Carbon opportunity cost		See 2.5 for details
Plant carbon in potential/native vegetation, $C_p^{plant,nat}$	Mg C/ha	
Soil carbon in potential/native vegetation, $C_p^{soil,nat}$	Mg C/ha	
Plant carbon in crops, $C_p^{plant,prod}$	Mg C/ha	
Soil carbon under crops, $C_p^{soil,prod}$	Mg C/ha	
Fraction of plant matter burnt at deforestation	% of plant carbon in native vegetation	Applies only to the “expansion” metrics
Decay rate of unburnt plant matter, *d*	% decomposed per year	Applies only to the “expansion” metrics
Discounting period, T_{dis}	years	
Discount rate, *r*	% per year	
Amortization period, T_{amort}	years	
Regrowth period, T_{regr}	years	Applies only to the “regrowth” metrics
Soil carbon equilibrium period, T^{soil}	years	The time required for soil carbon to reach a new steady state level

Perennial grasses and legumes

For perennial grasses and/or legumes cultivated on arable land, and permanent and semi-permanent grasslands, growth above ground is stated exogenously. This is done separately for two seasons: the wet and/or warm season, which is the main grazing season, and the dry and/or cold season. Root mass production (including exudates) is calculated as an allometric relationship to above-ground plant mass and a root mass turnover rate.

Perennial trees and bushes

Perennial tree and bush crops are represented in ClimAg by 17 different sub-systems (see list in Table 16). Plantains and bananas are included in this group, although they are not trees nor bushes, and almost all their above-ground plant mass is annual (only the corm and roots are perennial).

The representation of the production cycle includes a separate establishing phase, during which the planted saplings grow but do not yield harvestable products. The establishing phase is typically 2-6 years depending on species. The production phase varies from about 10 to 60 years depending on species.

Plant growth is calculated as the annual turnover of perennial plant mass, and as the annual growth of the harvested part and other annual plant mass, see Table 2 for parameters. Perennial plant mass includes roots, corm, trunk, twigs & branches, and leaves on evergreens (oil palm, coconut, olive, cashew, mango, orange, cocoa, coffee, tea). Annual plant mass other than the product includes leaves on deciduous trees and bushes (almond, grapes, apple) and above-ground growth of banana and plantain. Plant mass stocks of the entire plant are stated exogenously, at the start of the establishing phase and at the end of the production phase, respectively. Exogenous allometric parameters are used to calculate stocks of individual plant components (roots, trunk, twigs/branches/corm, and leaves).

2.1.2 Land areas

In the ClimAg model, a distinction is made between “physical” land area and “harvested” area. The physical area is the land area occupied by a crop, pasture, or other land use (e.g., fallow). On the physical area, one or more harvests can take place during the cultivation cycle (e.g., by double-cropping), with the sum of the harvests being the harvested area.

For permanent/semi-permanent pastures and tree/bush crops, the model calculates the required physical area simply as a function of grazed intake or net harvested yield and the required production on the farm, region, or country, etc.

For arable land, the calculation of the required area is more complex. For arable crops, the physical area of each crop is calculated in a crop-rotation framework, with the number and length of cultivation cycles per rotation cycle as exogenous variables. This allows for the modeling of so-called double cropping rotations, in which a sequence of two crops is grown in the same growing season, for example, rice-rice or soybean-maize. For grass-legume crops on arable land, multiple harvests per year can be modeled.

Table 2 Main exogenous parameters that describe plant growth for tree and bush crops.. Sub-systems are listed in Table 16. Parameter default values are given in Table 24.

Parameters	Unit/option	Comments
Length of production cycle		
Establishing phase	Years	
Production phase	Years	
Age at steady-state plant mass stock	Years	Time when no further net growth of the perennial plant mass occurs
Yield of main product	Mg fresh weight/ha/year	
Pruning/removal of other plant mass		
Pruning and removal of leaves	% of annual growth	
Pruning and removal of twigs/branches	% of annual growth	
Removal of trunks	% of cumulative growth	At end of the production cycle
Plant mass stock		Specified separately for roots, trunk, twigs/branches/corm, and leaves
At start of the establishing phase	Mg DM/ha	
At start of the production phase	Mg DM/ha	Endogenous. Calculated assuming linear growth from start to end of production cycle
At end of the production phase	Mg DM/ha	
Turnover of perennial plant mass stock		
Leaves or fronds	% of stock per year	
Twigs/branches or corm	% of stock per year	
Roots	% of stock per year	
Growth of annual plant mass		
Leaf growth	Mg DM/ha/year	Almond, grape, apple, plantain, and banana
Pseudo stem growth	Mg DM/ha/year	Plantain and banana

2.2 Nitrogen inputs and emissions

In crop and pasture systems, nitrogen (N) flows are described with explicit distinction between inorganic N and organic N. All processes are described on a N mass balance basis.

For inorganic N in the soil-plant system, a further distinction is made between N that potentially can be taken up by the growing plant, here referred to as “up-takeable” N, and N that cannot. For example, the addition of fertilizer-nitrogen during the growth period is considered potentially up-takeable, whereas the atmospheric deposition of N outside the growing season is not.

The representation of the N flows and stocks in the soil-plant system assumes steady-state conditions, i.e., soil N pools are assumed to be constant. This means that the annual amount of soil organic N converted to mineral N equals the annual input to the soil of plant matter and organic manure N.

Table 3 Main exogenous parameters for nitrogen (N) flows in crop and pasture systems.

Parameters	Unit/option	Comments
Nitrogen inputs		
Input from mineral fertilizer, N^{c}_{syn}	kg N/ha land area/year	Endogenous parameter. Calculated as a balance between all other inputs and all outputs (emissions and removals), see 2.2.5
Fertilizer type	Ammonia, ammonium nitrate, ammonium sulphate, urea, urea ammonium nitrate	
Fertilizer application technology	With or without incorporation	
Input from application of stored manure (from pens/confinements), specified by organic and inorganic N: $N^{c}_{st.man,org}$, $N^{c}_{st.man,ino}$	kg N/ha land area/year	Endogenous parameter. Calculated as a fraction of manure output from confinements and its N content, see 2.2.4
Manure application technology	Broad casting, with or without incorporation; Trailing house; Injection	
Manure application time	Spring, Summer, Autumn	
Input from feces and urine excreted at grazing, specified by organic and inorganic N: $N^{c}_{gr.fec,org}$, $N^{c}_{gr.uri,org}$, $N^{c}_{gr.fec,ino}$, $N^{c}_{gr.uri,ino}$	kg N/ha land area/year	Endogenous parameter. Calculated as a function of manure excreted and manure N content, see 2.2.4
Input from decomposing, left-in-field plant matter from preceding crop, N^{c}_{res}	kg N/ha land area/year	Endogenous parameter. See 2.2.2 for more details
Input from biological N fixation, N^{c}_{fix}	kg N/ha land area/year	Endogenous parameter. See 2.2.3 for more details
Input from atmospheric deposition, N^{c}_{dep}	kg N/ha land area/year	
Efficiency of plant uptake of N available for uptake ("up-takeable" N), ε^{c}_{ass}	%, specified by crop	This parameter reflects differences between crops in N uptake related to their varying density and depth of root systems, see 2.2.1
Efficiency of utilization of net N supply to soil as up-takeable N, η^{c}_{f}	%, specified separately by source, and organic and inorganic N	This parameter reflects inefficiencies in N utilization related to mismatches in N supply and uptake, see 2.2.1
Nitrogen removals		
Harvested and/or grazed plant mass, N^{c}_{rem}	kg N/ha land area/year	Calculated as a function of harvested or grazed plant mass times its N content
Ammonia emissions		
Emission factor – decomposing above-ground plant mass	% of N in plant mass left in field or remaining after grazing period	
Emission factors – mineral fertilizer, $\%NH3^{c,t,a}_{syn}$	% of N amount in fertilizer	Specified by fertilizer type and application technology
Emission factors – *in*organic N in applied stored manure, $\%NH3^{c,t,a,s}_{st.man,ino}$	% of *inorganic* N in applied and excreted manure	Specified by manure type, and technology and time of application (season of year)
Emission factors – organic N in applied stored manure, $\%NH3^{c,s}_{st.man,org}$	% of *organic* N in applied and excreted manure	Specified by time of application (season of year)

Parameters	Unit/option	Comments
Emission factors – *in*organic N in excreted manure at grazing, $\%NH3^{c}_{gr.man,ino}$	% of *inorganic* N in applied and excreted manure	
Emission factors – organic N in excreted manure at grazing, $\%NH3^{c}_{gr.man,org}$	% of *organic* N in applied and excreted manure	
Nitrous oxide emissions		
Emission factors – decomposing plant mass, $\%N2O^{c}_{lft}$	% of total N in plant mass left in field or remaining after grazing period minus NH_3 losses	Specified by crop type, and above- and below-ground plant mass
Emission factors – mineral fertilizer, $\%N2O^{c,t}_{syn}$	% of total N amount in fertilizer minus NH_3 losses	Specified by crop and fertilizer type
Emission factors – manure applied, $\%N2O^{c,t,a}_{st.man}$	% of total N amount in applied manure minus NH_3 losses	Specified by crop, manure type, and application technology
Emission factors – manure excreted, $\%N2O^{c,t}_{gr.man}$	% of total N in excreted manure minus NH_3 losses	Specified by livestock type
Nitrate emissions		
Emission factor – nitrate (below root zone)	% of the N surplus in the soil-plant profile, $N^{c}_{soil+pl.bal}$	See 2.2.7 for more details

2.2.1 Nitrogen balance of the soil-plant system

Using the description of total net photosynthetic production (see 2.1.1) as a basis, the model first calculates the *total net nitrogen assimilation* in crop and pasture production, N_{ass} (kg N ha^{-1} yr^{-1}). This is calculated as the growth of different plant components multiplied by their N content (protein content divided by 6.25, see Table 25 for numbers).

Next, the model calculates the *required supply of up-takeable nitrogen* by the growing plant, $N^{c}_{req\ uptakeable}$ (kg N ha^{-1} yr^{-1}). The required supply for up-takeable N of crop *c* is calculated as the total net N assimilation of the crop (N^{c}_{ass}) divided by the efficiency of uptake of N available for uptake, ε^{c}_{ass}:

$$N^{c}_{req\ uptakeable} = \frac{N^{c}_{ass}}{\varepsilon^{c}_{ass}} \qquad \text{Eq. 2}$$

The parameter ε^{c}_{ass} (dimensionless) reflects differences between crop species in the uptake efficiency of soil N related to their varying density and depth of root systems (see Velthof et al. 2009). For example, perennial grasses have very extensive root systems and, therefore, have high uptake efficiencies (close to 100%). However, most other crops have less extensive systems and are therefore unable to take up close to 100% of the plant-available N in the root zone.

Next, the model calculates all inputs. These inputs are i) decomposing organic N in plant matter left in the field from preceding crops, ii) biological fixation, iii) manure, iv) mineral fertilizer, and v) atmospheric deposition. After this, ammonia emissions associated with these inputs are calculated. The remaining nitrogen after ammonia losses is here defined as the *actual net supply* of N, $N^{c}_{net\ sup}$ (kg N ha^{-1} yr^{-1}), to the soil:

$$N^{c}_{net\,sup} = N^{r}_{res} + N^{c}_{fix} + N^{c}_{man} + N^{c}_{syn} + N^{c}_{dep} - N^{c}_{NH3} \qquad \text{Eq. 3}$$

where:

N^{r}_{res} (kg N ha^{-1} yr^{-1}) the total N supply in decomposed plant mass from the previous crop (see 2.2.2)

N^{c}_{fix} (kg N ha^{-1} yr^{-1}) is the total N input through biological fixation (see 2.2.3)

N^{c}_{man} (kg N ha^{-1} yr^{-1}) is the total N in manure excreted or applied on field (see 2.2.4)

N^{c}_{syn} (kg N ha^{-1} yr^{-1}) is the total N input through mineral fertilizer (see 2.2.5)

N^{c}_{dep} (kg N ha^{-1} yr^{-1}) is the total N input through atmospheric deposition

$N^{c}_{NH_3}$ (kg N ha^{-1} yr^{-1}) are the total emissions of ammonia (see 2.2.6)

Then the model calculates how much of this net supply can contribute to the *supply of up-takeable nitrogen* $N^{c}_{sup\,uptakeable}$ (kg N ha^{-1} yr^{-1}), by applying a parameter, here denoted η^{c}_{f} (dimensionless), that reflects inefficiencies in N utilization related to mismatches in supply and uptake:

$$N^{c}_{sup\,uptakeable} = \sum_{f=1}^{n} \eta^{c}_{f} \times N^{c}_{net\,sup\,f} \qquad \text{Eq. 4}$$

where:

η^{c}_{f} (dimensionless) is the fraction of net N supply from source *f* (see Eq. 3) taken up by crop *c*

$N^{c}_{net\,sup\,f}$ (kg N ha^{-1} yr^{-1}) the net N supply from source *f*

For several reasons, in real systems, the net supply is almost always larger than the potential uptake. This is because, for example, the mineralization of organic N and atmospheric deposition both occur during the non-growing season. This parameter is also applicable to the supply of manure and fertilizer, which typically are supplied in excess of the potential uptake. This is partly because of local excess supply, in the form of urine patches and manure being applied outside the growing period. More importantly, it is due to fundamental uncertainties in estimating uptake, because of the impossibility of predicting weather conditions over the entire growing period. Faced with this uncertainty, farmers tend to anticipate higher yields and, accordingly, apply fertilizer and manure at the higher end.

Lastly, the model calculates the net *plant-soil nitrogen balance*, as the sum of all external N inputs minus N removed in harvested or grazed plant mass, N^{c}_{rem} (kg N ha^{-1} yr^{-1}), and all gas outputs except dinitrogen (NH_3, N_2O, NO). In most systems, the balance is positive, i.e., the inputs exceed the outputs. This surplus is assumed to leave the soil as nitrate and dinitrogen (see 2.2.7).

2.2.2 Nitrogen supply from previous crop

The N net supply from decomposing crop residues and other plant matter left in the field from preceding crops is calculated as the N content of plant mass left in the field after harvest or grazing period, minus emissions of ammonia that occur during the decomposition process (less than 5% of total above-ground organic N is typically lost).

It should be noted that the decomposition of plant matter left in the field takes several years to be complete. Here, steady-state conditions are assumed, where the annual amount of plant matter left in the field is the same over several years. In this way, the annual amount of organic N converted to mineral N equals the annual input from decomposing plant matter.

For arable-land crops, the net N supply in decomposed plant mass from the previous crop, N^{r}_{res} (kg N ha^{-1} yr^{-1}), is calculated as an area-weighted average for all crops, $c = 1, 2, \dots n$, in the crop rotation, *r*:

$$N^{r}_{net\ res} = \sum_{c=1}^{n} \left(N^{c}_{lft} \times \beta^{c}_{r} - N^{c}_{lft,abo} \times \%NH3^{c}_{lft,abo} \times \beta^{c}_{r}\right) \qquad \text{Eq. 5}$$

where:

β^{c}_{r} (dimensionless) is the average arable-land area fraction of crop *c* over the *entire crop rotation* cycle.

N^{c}_{lft} (kg N ha^{-1} yr^{-1}) is the total N content of plant mass for crop *c* left in field after harvest or grazing period.

$N^{c}_{lft,abo}$ (kg N ha^{-1} yr^{-1}) is the *above-ground* N content of plant mass for crop *c* left in field after harvest and/or uneaten plant mass at grazed areas.

$\%NH3^{c}_{lft,abo}$ (dimensionless) is the fraction of above-ground N in plant mass for crop *c* lost through ammonia volatilization.

For example, for a 4-yr crop rotation consisting of a 3-yr grass ley and a 1-yr barley crop, α^{ley}_{r} would be 75% and α^{barley}_{r} 25%. Assuming that N^{ley}_{lft}=140 and N^{barley}_{lft}= 40, and $\%NH3^{c}_{lft,abo}$= 0 for simplicity, then N^{r}_{res} = 115 kg N ha^{-1} yr^{-1}. This number, hence, represents the *annual average* pre-crop N supply *at steady state* for all crops in the rotation.

For permanent grasslands, and tree and bush crops, net N supply is simply calculated as the N content in decomposing plant mass left in field from the previous growth cycle, minus ammonia losses.

The up-takeable fraction, η^{c}_{res}, of nitrogen from decomposed plant matter depends on how much of the decomposition occurs under periods with crop uptake of N. As a default, ClimAg uses 70% for annual crops, and 90% for permanent grassland, based on Velthof et al. (2009).

2.2.3 Nitrogen net supply from biological fixation

For crops in symbiosis with nitrogen-fixing bacteria, N addition to the soil by fixation, N^{c}_{fix} (kg N ha^{-1} yr^{-1}), is calculated as a percentage, $\%N_{dfa}$, of the total N in the annual net photosynthetic production, N^{c}_{ass}, plus N transferred to co-growing crops and/or immobilized. This is in line with other models (see, for example, Høgh-Jensen et al., 2004):

$$N^{c}_{fix} = \%N_{dfa} \times N^{c}_{ass} \times (1 + \%N_{trans}) \qquad \text{Eq. 6}$$

where $\%N_{trans}$ (dimensionless) is the fraction of N transferred to co-growing crops and/or immobilized.

For crops with plant-associated but non-symbiotic nitrogen-fixing bacteria, N^{c}_{fix} is simply an exogenously stated quantity.

For symbiotic fixation, no losses are assumed in the uptake by the plant, since the fixed N is fed directly into the plant roots. However, the amount of fixed N deposited in the soil (biologically fixed N transferred and/or immobilized) enters the soil N pool and is, therefore, subject to losses before being taken up by the subsequent crops. Furthermore, N in plant matter from nitrogen-fixing crops left in field is subject to losses described in 2.2.2.

2.2.4 Nitrogen supply from manure

The calculation of the N supply from manure represents the organic and inorganic N fractions in the manure separately. It also calculates the supply separately from the land application of manure excreted in confinements and manure excreted during grazing. For both applied and excreted manure, the N net supply is calculated as the N content of the manure, minus emissions of ammonia that occur after application or excretion.

The amounts and N contents of manure from confinements and manure excreted during grazing are calculated endogenously in ClimAg, see 3.3.1 and 3.3.4. For manure from confinements applied on cropland, the net supply of inorganic and organic N $N^{c}_{net\ st.man,ino}$ and $N^{c}_{net\ st.man,org}$ (kg N ha^{-1} yr^{-1}), is calculated as the amount of manure divided by the area of cropland (ha) receiving manure, minus ammonia losses:

$$N^{c}_{net\ st.man,ino} = \frac{\%\ applied \times N^{l}_{man,sto,ino}}{cropland\ area\ applied} \times \left(1 - \%NH_3{}^{c,t,a,s}_{st.man,ino}\right) \qquad \text{Eq. 7}$$

$$N^{c}_{net\ st.man,org} = \frac{\%\ applied \times N^{l}_{man,sto,ino}}{cropland\ area\ applied} \times \left(1 - \%NH_3{}^{c}_{st.man,org}\right) \qquad \text{Eq. 8}$$

where:

% applied is the fraction of manure produced at the livestock farm applied on cropland at the farm. If not applied, the manure is sold, burnt, or otherwise lost.

$N^{l}_{man,sto,ino}$ (kg N yr^{-1}) is output from manure storage at the livestock farm of inorganic manure N, see Eq. 56.

$N^{l}_{man,sto,org}$ (kg N yr^{-1}) is output from manure storage at the livestock farm of organic manure N, see Eq. 55.

$\%NH_3{}^{c,t,a,s}_{f}$ (dimensionless) is the fraction of N input for crop *c* lost through ammonia volatilization. The index *t* denotes the sub-type of input (different types of manure), the index *a* denotes the sub-set of application technologies, and the index *s* the time (season) of manure application (see Table 3).

The calculation of the N supply from manure excreted during grazing is done in a way similar to that of stored manure. All excreted manure is assumed to be left on the pasture, except in cases of manure collection for use as fuel, etc.

The amount of up-takeable N from inorganic and organic manure N is calculated separately for i) applied manure on cropland, ii) excreted feces on pasture, and iii) excreted urine on pasture, with explicit distinction between inorganic and organic N for all of them.

For organic manure N applied on cropland, default values on the up-takeable fraction, $\eta^{c}_{st.man,org}$, are the same as those for decomposed plant matter (see 2.2.2). For inorganic N, the up-takeable fraction of inorganic N, $\eta^{c}_{st.man,ino}$, depends on the timing of application and the degree of application in excess of uptake. Application outside the crop growth period is associated with a very low up-takeable fraction.

For excreted feces and urine, the fraction is somewhat lower because of the uneven spatial distribution with a high input at urine and feces patches (Velthof et al. (2009).

2.2.5 *Nitrogen supply from fertilizer*

Formally, the input of N fertilizer is calculated as the balance between the required supply by the crop and the net inputs from all other sources. That is, any deficit of up-takeable soil nitrogen in relation to the amount required by the crop is met by supply of fertilizer nitrogen, N_{syn}^{c} (kg N ha^{-1} yr^{-1}):

$$N_{syn}^{c} = \frac{1}{\left(1 - \%NH3_{syn}^{c,t,a}\right) \times \eta_{syn}^{c}} \times \left[N_{req\ uptakeable}^{c} - N_{net\ res}^{r} \times \eta_{res}^{c} - N_{fix}^{c} - N_{dep}^{c} \times \eta_{dep}^{c} - N_{net\ st.man,ino}^{c} \times \eta_{st.man,ino}^{c} - N_{net\ gr.uri,ino}^{c} \times \eta_{gr.uri,ino}^{c} - N_{net\ gr.fec,ino}^{c} \times \eta_{gr.fec,ino}^{c} - N_{net\ st.man,org}^{c} \times \eta_{st.man,org}^{c} - \left(N_{net\ gr.uri,org}^{c} + N_{net\ gr.fec,org}^{c}\right) \times \eta_{gr.man,org}^{c}\right] \quad \text{Eq. 9}$$

where:

$N_{req\ uptakeable}^{c}$ (kg N ha^{-1} yr^{-1}) is the required supply of up-takeable N by crop *c*, see Eq. 2.

$N_{net\ res}^{r}$ (kg N ha^{-1} yr^{-1}) is the net (i.e., after ammonia losses) N supply from decomposed plant matter left in field from the previous crop, see 2.2.2.

N_{fix}^{c} (kg N ha^{-1} yr^{-1}) is the input through biological N fixation, see 2.2.3.

N_{dep}^{c} (kg N ha^{-1} yr^{-1}) is the input through atmospheric deposition.

$N_{net\ st.man,org}^{c}$ and $N_{net\ st.man,ino}^{c}$ (kg N ha^{-1} yr^{-1}) is the net (i.e., after ammonia losses) supply of organic and inorganic N, respectively, in manure from confinements.

$N_{net\ gr.fec,org}^{c}$, $N_{net\ gr.uri,org}^{c}$, $N_{net\ gr.fec,ino}^{c}$ and $N_{net\ gr.uri,ino}^{c}$ (kg N ha^{-1} yr^{-1}) is the net (i.e., after ammonia losses) supply of organic and inorganic N in feces and urine, respectively, excreted during grazing.

η_{f}^{c} (dimensionless) is the fraction of net input *f* that contributes to the supply of up-takeable N for crop *c*, see 2.2.1.

The fraction of up-takeable N from applied fertilizer nitrogen, η_{syn}^{c}, can, in theory, be close to 100%. In practice, however, application in excess of uptake is prevalent, leading to a lower up-takeable fraction and lower efficiency in fertilizer use.

2.2.6 *Emissions of ammonia, nitrogen dioxide, and nitric oxide*

Losses of *ammonia*, $N_{NH_3}^{c}$ (kg N ha^{-1} yr^{-1}), for crop *c*, are calculated according to:

$$N_{NH_3}^{c} = N_{syn}^{c} \times \%NH_{3}{}_{syn}^{c,t,a} + N_{st.man,org}^{c} \times \%NH_{3}{}_{st.man,org}^{c,s} + N_{st.man,ino}^{c} \times \%NH_{3}{}_{st.man,ino}^{c,t,a,s} + \left(N_{gr.fec,org}^{c} + N_{gr.uri,org}^{c}\right) \times \%NH_{3}{}_{gr.man,org}^{c} + N_{gr.fec,ino}^{c} \times \%NH_{3}{}_{gr.fec.man,ino}^{c} + N_{gr.uri,ino}^{c} \times \%NH_{3}{}_{gr.uri.man,ino}^{c} + N_{lft,abo}^{c} \times \%NH_{3}{}_{lft,abo}^{c} \quad \text{Eq. 10}$$

where:

N_{syn}^{c} (kg N ha^{-1} yr^{-1}) is the input through mineral fertilizer.

$N^c_{st.man,org}$ and $N^c_{st.man,ino}$ (kg N ha^{-1} yr^{-1}) are the organic and inorganic N, respectively, in stored manure (from pens/confinements) applied to crop *c*.

$N^c_{gr.fec,org}$, $N^c_{gr.uri,org}$, $N^c_{gr.fec,ino}$ and $N^c_{gr.uri,ino}$ (kg N ha^{-1} yr^{-1}) are the organic and inorganic N in feces and urine, respectively, excreted during grazing.

$N^c_{lft,abo}$ (kg N ha^{-1} yr^{-1}) is the above-ground N content of plant mass left in field after harvest and/or uneaten plant mass at grazed areas.

$\%NH_3{}^{c,t,a,s}_{f}$ (dimensionless) is the fraction of N input *f* for crop *c* lost through ammonia volatilization. The index *t* denotes the sub-type of input (different types of fertilizer or stored manure), the index *a* denotes the sub-set of application technologies, and the index *s* denotes the time (season) of manure application (see Table 3).

For the emission factor for fertilizer, $\%NH_3{}^{c,t,a}_{syn}$, there are separate entries for each of the five types of mineral fertilizer *t* included in the model. In addition, there are separate values for the case where the fertilizer is incorporated in the soil and the case where it is not. Hence, there are ten different $\%NH_3{}^{c}_{syn}$ in the model.

Similarly, for the emission factors for *inorganic* N in *stored* manure (from pens/confinements), i.e. $\%NH_3{}^{c,t,a,s}_{st.man,ino}$, there are separate entries depending on manure type *t* (see Table 6), application technology *a* (see Table 1) and time of application *s*. For each manure type, there are 12 different $\%NH_3{}^{c}_{st.man,ino}$ in the model.

Emissions of *nitrous oxide*, N^c_{N2O} (kg N ha^{-1} yr^{-1}), for crop *c*, are calculated according to:

$$N^c_{N_2O} = N^c_{net\ syn} \times \%N_2O^{c,t}_{syn} + N^c_{net\ st.man} \times \%N2O^{c,t,a}_{st.man} + N^c_{net\ gr.man} \times \%N_2O^{c,t}_{gr.man} + N^c_{lft,abo} \times \left(1 - \%NH_3{}^{c}_{lft,abo}\right) \times \%N_2O^c_{lft,abo} + N^c_{lft,bel} \times \%N_2O^c_{lft,bel} \quad \text{Eq. 11}$$

where:

$N^c_{net\ syn}$ (kg N ha^{-1} yr^{-1}) is the net (i.e., after ammonia losses) supply through mineral fertilizer.

$N^c_{net\ st.man}$ kg N ha^{-1} yr^{-1}) is the net (i.e., after ammonia losses) supply of N in manure from confinements.

$N^c_{net\ gr.man}$ (kg N ha^{-1} yr^{-1}) is the net (i.e., after ammonia losses) supply of N in feces and urine excreted during grazing.

$N^c_{lft,abo}$ (kg N ha^{-1} yr^{-1}) is the above-ground N content of plant mass left in field after harvest and/or uneaten plant mass at grazed areas.

$N^c_{lft,bel}$ (kg N ha^{-1} yr^{-1}) is the N content of below-ground (root) plant mass remaining after harvest and/or annual turnover of root mass in perennial crops (grasses or tree and bush crops).

$\%NH_3{}^{c}_{f}$ (dimensionless) is the fraction of N input *f* for crop *c* lost through ammonia volatilization.

$\%N_2O^{c,t,a}_{f}$ (dimensionless) is the fraction of N input *f* for crop *c* emitted as nitrous oxide. The index *t* denotes the sub-type of input (different types of fertilizer or stored manure, or different types of grazing manure), and the index *a* denotes the sub-set of *manure* application technologies

It should be noted that, as described in the equation above, the emission factors $\%N_2O_f^{c,t,a}$ are applied to the *net* supply of each input, i.e., after deducting ammonia losses.

In addition to variation by crop, there are separate entries for $\%N_2O_f^{c,t,a}$ for different types of stored manure (liquid or solid) and different types of manure application technologies (surface application or injection/incorporation).

The calculation of *nitric oxide* emissions, N_{NO}^c (kg N ha^{-1} yr^{-1}), is done in a manner analogous to that of nitrous oxide, but with no differentiation between fertilizer/manure types or application technologies.

2.2.7 Emissions of nitrate and dinitrogen

As mentioned in 2.2.1, plant-soil nitrogen balance, $N_{soil+pl.bal}^c$ (kg N ha^{-1} yr^{-1}), for crop *c* is calculated as the sum of all external N inputs minus N harvested or grazed and all gas outputs except dinitrogen:

$$N_{soil+pl.bal}^c = N_{syn}^c + N_{st.man}^c + N_{gr.man}^c + N_{fix}^c + N_{dep}^c - N_{rem}^c - N_{NH_3}^c - N_{N_2O}^c - N_{NO}^c \quad \text{Eq. 12}$$

where:

N_{syn}^c (kg N ha^{-1} yr^{-1}) is the input through mineral fertilizer.

$N_{st.man}^c$ (kg N ha^{-1} yr^{-1}) is the nitrogen in stored manure (from pens/confinements) applied.

$N_{gr.man}^c$ (kg N ha^{-1} yr^{-1}) is the nitrogen in feces and urine excreted during grazing.

N_{fix}^c (kg N ha^{-1} yr^{-1}) is the input through biological fixation.

N_{dep}^c (kg N ha^{-1} yr^{-1}) is the input through atmospheric deposition.

N_{rem}^c (kg N ha^{-1} yr^{-1}) is the nitrogen in plant mass removed through harvest and/or grazing.

$N_{NH_3}^c$, $N_{N_2O}^c$, N_{NO}^c (kg N ha^{-1} yr^{-1}) are the emissions of ammonia, nitrous oxide and nitric oxide, respectively.

Typically, the sum of external N inputs is larger than the sum of harvested N and ammonia (and N_2O and NO) emissions. As in (Velthof et al., 2009), this N surplus is partitioned in the model between leaching of nitrate below the root zone and denitrification to dinitrogen.

2.3 Phosphorus, potassium, and pesticide inputs

The use of pesticides and phosphorus and potassium fertilizer is calculated as the harvested (or grazed) yield of the crop multiplied by a crop-specific usage factor in *g input per kg* of yield.

2.4 Greenhouse gas emissions from on-farm energy use, rice, and drained organic soils

This section covers CO_2 emissions from energy use, methane emissions from rice cultivation, and CO_2 and nitrous oxide emissions from drained organic soils. For nitrous oxide emissions from mineral soils, see 2.2.6, and for methane emission from manure excreted at grazing, see 3.3.3.

2.4.1 CO_2 emissions from on-farm energy use in crop production

In ClimAg, CO_2 emissions from on-farm diesel and electricity use for crop production include:

- Land preparation (leveling, plowing, tilling etc.), sowing and planting
- Fertilizer and pesticide application
- Manure application
- Irrigation
- Pruning of tree crops
- Harvesting and transportation to storage
- Post-harvest drying before storage

For land preparation, diesel use is calculated as a crop-specific fuel use rate per physical area. For crops on arable land, the use of diesel for tillage and sowing is calculated as a fuel use factor in *liters per ha* multiplied by the area tilled and sowed. In the case of tree crops, the energy used for establishing the plantation is apportioned over its estimated lifetime.

For the application of fertilizer and pesticides, ClimAg calculates diesel use as a fuel use rate per number of applications. Diesel use for manure application is calculated as a fuel use factor in *liter per Mg* manure multiplied by the weight of manure applied.

Energy use for irrigation includes both diesel and electricity and is calculated as a crop-specific diesel and/or electricity use rate per irrigated area.

The use of diesel for harvest (and transport to on-farm storage) is influenced by both the area covered and the weight of the harvested plant mass. Thus, diesel use is calculated as a fuel use factor in *liter per ha* multiplied by the area harvested plus two fuel use factors in *liter per Mg* multiplied by the weight of harvested products and by-products (e.g. straw), respectively. For straw not harvested, i.e., left in field, there is additional diesel use in liter per Mg for chopping of straw.

The use of fuel oil for drying harvested cereal and other grain crops is calculated as a fuel use factor in *liter per kg of water evaporated* multiplied by the amount of water evaporated in the crop. As a default, the model uses a factor of 0.15 liter oil per kg of water, based on (Edström et al., 2005).

2.4.2 CO_2 emissions from energy and materials use in greenhouse crop production

To estimate the resource use and environmental impact of crop production in greenhouses, ClimAg calculates the energy use not only for operating the greenhouse but also for producing the greenhouse structures.

Energy use for operating the greenhouse includes heating, lighting, and irrigation/miscellaneous, see Table 1. To calculate the impact of the use of protective structures, ClimAg represents six different types of materials, with the specification of stocks (in kg m^{-2}), lifetime, and energy and CO_2 intensity in their production.

ClimAg also represents the use of four different types of substrates in a similar way to that of protective structures.

2.4.3 Methane emissions from rice cultivation

The calculation of methane emissions from rice cultivation follows the methodology set out by (IPCC, 2019). Methane emissions, in kg CH_4 per *harvested* area per year, are calculated as a climate-specific default emission rate multiplied by three different scaling factors that reflect variations in management. These scaling factors reflect differences in i) water regime *during* the cultivation cycle, ii) water regime *before* the cultivation cycle, and iii) amount and type of organic matter added (e.g. manure) or left in the field (e.g. straw).

2.4.4 CO_2 and nitrous oxide emissions from drained organic soils

Emissions of CO_2 and nitrous oxide from drained organic soils are calculated as the drained land area multiplied by climate-specific emission factors in kg N_2O per ha and Mg CO_2 per ha, respectively.

2.5 Carbon stock changes

2.5.1 Introduction

Since agricultural production mainly takes place on land that supports plant growth, most agricultural land use occurs at the expense of reduced carbon stored in forests and other native, carbon-rich vegetation. Therefore, agricultural land use has an inherent climate impact in the form of reduced land carbon stocks and, hence, higher atmospheric CO_2 levels. Conceptually, this effect can be described as the "carbon opportunity cost" (COC) of land: when we use a parcel of land for agricultural production, we forego the opportunity to store carbon in the native vegetation and soils that otherwise could exist on that land. (Note, however, that irrigating dry lands may, in contrast, increase carbon storage.)

Reductions (or increases) in land carbon stocks resulting from converting natural lands to agriculture and aquaculture are one-off fluxes. For example, when forests, grasslands, and other native vegetation are cleared for agriculture or aquaculture, most of the carbon stored in the vegetation is converted to CO_2 almost instantly, mainly via burning, representing a one-off pulse emission of CO_2. In contrast, if agricultural land spared from use regains its native vegetation, reaching a steady-state carbon stock will take decades or more. Yet, despite the longer time horizon, the total carbon stock increase following restoration is still a one-off change in a carbon stock: after a certain time period, there is no additional growth in the carbon stock.

In contrast to these carbon stock changes, the use of cleared land for the production of agricultural goods can proceed, in theory, indefinitely. This distinction presents a non-trivial calculation problem in apportioning the climate impact from the one-off carbon stock change (decrease or increase) over a recurring, indefinite output of agricultural goods.

The ClimAg model includes two primary approaches for addressing this calculation problem. The first approach, here called the "expansion" metric, estimates the CO_2 emissions that occur because of agricultural expansion (i.e. deforestation). This one-off emission can be understood conceptually as the investment cost, in units of carbon dioxide, of creating new agricultural land. The second approach, here called the “regrowth” metric, estimates the uptake of CO_2 that would occur if land currently in agricultural use were spared and native vegetation allowed to regrow.

For both metrics, ClimAg calculates the difference between the plant and soil carbon stored in potential native vegetation and the carbon stored in agricultural vegetation. This difference is the foregone carbon storage due to agricultural land use and represents the amount of carbon emitted in the case of the “expansion” metric, and the amount of carbon uptake in the “regrowth” metric. For both metrics the cumulative carbon storage effect from land use is the same; in practice, the only main difference between the metrics is the dynamic of the carbon stock change, as detailed below.

2.5.2 The “expansion” metrics: Quantifying the COC of land as the carbon emissions from converting native vegetation into agricultural land and aquaculture ponds

In the expansion metric, the calculation issue at hand is how to apportion the one-off CO_2 emission from the clearing of a parcel of land (i.e., the carbon “investment cost”) over the future benefits in the form of agricultural (or aquaculture) outputs from that parcel of land. Here, ClimAg uses two different approaches:

A. Discounted expansion metric

Because of the uncertainty regarding tipping points in the climate system (i.e., non-linear, irreversible responses to increased global warming), a low-risk mitigation strategy should value early emission reductions more than later ones. In ClimAg this is accounted for by applying a discount rate to future CO_2 emissions. For consistency, ClimAg also discounts the future production on the land.

As mentioned, in the process of agricultural expansion by the destruction of native vegetation, a major fraction of the plant matter is burnt, leading to instant emissions of carbon. However, a substantial amount of plant carbon is not completely burnt but instead decomposes exponentially at a rate that depends mainly on the climate. Hence, not all of the one-off CO_2 emissions pulse occurs at year 0, but instead takes place over several years. For consistency, these emissions from decay are discounted to calculate an aggregate present value (see Eq. 13). Default numbers on the fraction of plant carbon burnt are shown in Table 4.

Soil carbon stock change following natural land conversion to agriculture also occurs gradually; it may take many decades to reach a new, lower soil carbon equilibrium level. ClimAg calculates soil carbon loss as a percentage loss of native soil carbon (typically 5-20%, depending on crop and climate), which occurs over a specified period (typically 30-60 years, depending on climate). The soil carbon losses are discounted to an aggregate present value assuming a linear change in soil carbon levels (see Eq. 13).

In summary, in the discounted expansion metric, the carbon opportunity cost for product (e.g., crop) p, $COC_p^{exp,dis}$ (kg CO_2 kg^{-1}), equals the aggregate, time-discounted carbon lost from native vegetation on land used in the region to produce the crop, divided by the aggregate, time-discounted annual production in the region for that crop:

$$COC_p^{exp,dis} = \frac{44}{12} \times \frac{C_p^{burnt,nat} + \int_0^{T_{dis}} C_p^{unburnt,nat} \times \left(e^{d}-1\right) \times e^{-(d+r)t} - C_p^{plant,prod} + \int_0^{T_{dis}^{soil}} \frac{C_p^{soil,nat} - C_p^{soil,pr}}{T^{soil}} \times e^{-rt}}{\int_0^{T_{dis}} Y_p \times e^{-rt}} \quad \text{Eq. 13}$$

where:

$C_p^{burnt,nat}$ (Mg C ha^{-1}) is the burned amount of native vegetation plant carbon for product p.

$C_p^{unburnt,nat}$ (Mg C ha^{-1}) is the remaining, unburnt amount of native plant carbon for product p.

$C_p^{plant,prod}$ (Mg C ha^{-1}) is the amount of plant carbon in the production system for product p.

$C_p^{soil,nat}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) under native vegetation for product p.

$C_p^{soil,prod}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) in the production system for product p.

T_{dis} (years) is the discounting period.

T^{soil} (years) is the time required for soil carbon to reach a new steady state level.

T_{dis}^{soil} (years) is the discounting period for soil carbon loss (equals T^{soil} unless $T_{dis}^{soil} > T_{dis}$, then T_{dis}^{soil} is set to the value of T_{dis}).

r (% per year) is the discount rate.

d (% per year) is the decay rate for plant matter remaining after burning.

Y_p (Mg ha^{-1} year^{-1}) is the annual yield of product p (constant value over the calculation period).

The same equation applies to grazing land; in this case, grazed intake of plant matter per hectare is equivalent to yield per hectare. For aquaculture ponds, we assume that all pre-existing plants and half of the soil carbon is lost instantly. In this case, the numerator in Eq. 13 becomes $C_p^{plant,nat} + 0.5 \times C_p^{soil,nat}$.

Table 4 Default burning rates in the expansion COC metrics and parameters in the regrowth COC metrics. Sources: (Anderson-Teixeira and DeLucia, 2011; Cook-Patton et al., 2020).

Biome	Fraction of plant matter burnt at deforestation (at year zero)		Parameter values in Chapman-Richards growth function	
	Of above-ground	Of entire plant including roots	k	m
Tropical moist forest	52%	43%	0,090	0.5
Tropical dry forest	52%	43%	0,080	0.5
Tropical coniferous forest	52%	43%	0,050	0.5
Temperate broadleaf forest	51%	42%	0,070	0.5
Temperate coniferous forest	51%	42%	0,065	0.5
Boreal forest & taiga	59%	52%	0,050	0.5
Tropical grass- & shrubland	75%	36%	0,085	0.5
Temperate grass- & shrubland	83%	44%	0,070	0.5
Flooded grassland	75%	36%	0,075	0.5
Montane grass- & shrubland	59%	40%	0,065	0.5
Mediterranean forest & shrub	75%	40%	0,070	0.5
Deserts	75%	20%	0,060	0.5

B. Amortized expansion metric

A crude but also more straightforward approach is to amortize the total one-off carbon emission, including all cumulative soil carbon losses, evenly over a set period of years. The amortized carbon opportunity cost for product p, $COC_p^{exp,amor}$ (kg CO_2 kg^{-1}), is calculated as:

$$COC_p^{exp,amort} = \frac{44}{12} \times \frac{C_p^{plant,nat} + C_p^{soil,nat} - C_p^{plant,prod} - C_p^{soil,prod}}{T_{amort} \times Y_p} \quad \text{Eq. 14}$$

where:

$C_p^{plant,nat}$ (Mg C ha^{-1}) is the amount of plant carbon in native vegetation for product p.

$C_p^{soil,nat}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) under native vegetation for product p.

$C_p^{plant,prod}$ (Mg C ha^{-1}) is the amount of plant carbon in the production system for product p.

$C_p^{soil,prod}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) in the production system for product p.

T_{amort} (years) is the amortization period.

Y_p (Mg ha^{-1} year^{-1}) is the annual yield of product p (constant value over the calculation period).

This metric is equivalent to straight-line amortization in accounting; it is also the approach recommended for accounting for carbon stock changes in the 2019 IPCC guidelines for National Inventory Reports (IPCC, 2019). It should be noted that, although not explicit, amortization, too, implies a discounting of future costs and benefits, as the discounting metric above also does. After the amortization period, future costs and benefits are assigned zero value.

2.5.3 The "regrowth" metrics: Quantifying the COC of land as the carbon uptake from regrowth of potential native vegetation.

In the regrowth metric, the carbon opportunity cost is measured as the CO_2 uptake that would occur if the land was no longer used, but instead allowed to regain its native vegetation. For a parcel of land, this quantity is divided by the output from the current use of that land. As with the expansion metric, ClimAg calculates two different variants:

A. Discounted regrowth metric

As mentioned above, discounting is appropriate when valuing future emissions and the future uptake of CO_2. As with the expansion metric, ClimAg discounts the CO_2 uptake that would occur over time through the regrowth of vegetation, and the future production that takes place through continued use of the land.

ClimAg calculates the regrowth of native vegetation using the Chapman-Richards growth function, which is widely used in forestry (Burkhart and Tomé, 2012):

$$c(t)_p^{plant,nat} = C_p^{plant,nat} \times \left(1 - e^{-kt}\right)^{\frac{1}{(1-m)}} \quad \text{Eq. 15}$$

where:

$c(t)_p^{plant,nat}$ (Mg C ha^{-1}) is the amount of plant carbon <u>at time *t*</u> in potential native vegetation on land where product p is produced.

$C_p^{plant,nat}$ (Mg C ha^{-1}) is the amount of plant carbon <u>at steady state</u> in potential native vegetation on land where product p is produced (equals $C_p^{plant,nat}$ in Eq. 14).

t is time in years.

k and m (dimensionless) are Chapman-Richards parameters that determine the shape of the growth curve.

Table 4 shows the default numbers on parameters k and m for different biomes, which were derived by fitting the Chapman-Richard growth function to the dataset in (Cook-Patton et al., 2020). ClimAg uses these growth curves to calculate the gain of carbon in the plant component of the regrowing vegetation, as shown in Eq. 15. The gain in plant carbon over time is discounted to an aggregate present value (see Eq. 16).

For soil carbon, carbon gains are calculated in a way that is equivalent to the losses in the expansion metric (see 2.5.2). ClimAg calculates the gain as a linear increase of soil carbon back to the native, steady-state level over a time period that varies depending on the climate. The soil carbon gains are discounted to an aggregate present value (see Eq. 16).

In summary, for the discounted regrowth metric, the carbon opportunity cost for product p, $COC_p^{regr,dis}$ (kg CO_2 kg^{-1}), equals the aggregate, time-discounted carbon gain from the regrowth of native vegetation on land used in the region to produce the crop, divided by the aggregate, time-discounted annual production in the region for that crop:

$$COC_p^{regr,dis} = \frac{44}{12} \times \frac{\int_0^{T_{dis}} \left[c(t)_p^{plant,nat} - c(t-1)_p^{plant,nat}\right] \times e^{-rt} - C_p^{plant,prod} + \int_0^{T_{dis}^{soil}} \frac{C_p^{soil,nat} - C_p^{soil,prod}}{T^{soil}} \times e^{-rt}}{\int_0^{T_{dis}} Y_p \times e^{-rt}} \quad \text{Eq. 16}$$

where:

$c(t)_p^{plant,nat}$ (Mg C ha^{-1}) is the amount of plant carbon at time t in potential native vegetation on land where product p is produced (see Eq. 15).

$C_p^{soil,nat}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) under potential native vegetation on land where product p is produced.

$C_p^{plant,prod}$ (Mg C ha^{-1}) is the amount of plant carbon in the production system for product p.

$C_p^{soil,prod}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) in the production system for product p.

T_{dis} (years) is the discounting period.

T^{soil} (years) is the time required for soil carbon to reach a new steady state level.

T_{dis}^{soil} (years) is the discounting period for soil carbon gain (equals T^{soil} unless $T_{dis}^{soil} > T_{dis}$, then T_{dis}^{soil} is set to the value of T_{dis}).

r (% per year) is the discount rate.

Y_p (Mg ha^{-1} year^{-1}) is the annual yield of product p (constant value over the calculation period).

B. Undiscounted regrowth metric

A more straightforward method is to calculate the cumulative, undiscounted gain in carbon on a parcel of land over a set period, and divide this quantity by the cumulative, undiscounted output from the land over this period. One benefit of this approach is that it is less sensitive to the assumed shape of the growth curve, since only the cumulative growth matters. The formula for calculating the undiscounted regrowth carbon opportunity cost for product p, $COC_p^{regr,undis}$ (kg CO_2 kg^{-1}), can be written as:

$$COC_p^{regr,undis} = \frac{44}{12} \times \frac{c(T_{regr})_p^{plant,nat} - C_p^{plant,prod} + \varepsilon \times \left(C_p^{soil,nat} - C_p^{soil,prod}\right)}{T_{regr} \times Y_p} \qquad \text{Eq. 17}$$

where:

$c(T_{regr})_p^{plant,nat}$ (Mg C ha^{-1}) is the amount of plant carbon at the end of the regrowth period (T_{regr}) in potential native vegetation on land where product p is produced (see Eq. 15).

$C_p^{plant,prod}$ (Mg C ha^{-1}) is the amount of plant carbon in the production system for product p.

$C_p^{soil,nat}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) under potential native vegetation on land where product p is produced.

$C_p^{soil,prod}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) in the production system for product p.

T_{regr} (years) is the regrowth period.

T^{soil} (years) is the time required for soil carbon to reach a new steady state level.

ε (dimensionless) is the fraction of soil carbon gain that occurs during the regrowth period (equals 1 unless $T^{soil} > T_{regr}$, then $\varepsilon = \frac{T_{regr}}{T^{soil}}$).

Y_p (Mg ha^{-1} year^{-1}) is the annual yield of product p (constant value over the calculation period).

3. Livestock production

The ClimAg model represents all major food-related livestock systems; see Table 5. These livestock systems account for approximately 90% of global land use by domestic animals. For all livestock systems, conventional and organic systems are represented separately. For pigs and poultry, free-range systems are also represented. ClimAg representation of cattle systems can be used as fairly accurate proxies for equivalent buffalo systems; similarly, sheep systems can be used as proxies for goat systems. In this way, the land and climate impacts of the vast majority of global food-related livestock production is well represented by the ClimAg model system.

Livestock numbers and their feed intake are calculated endogenously in the ClimAg model, using information that is available in national statistics. In this way, feed intake and feed efficiencies (feed intake per output) can be estimated using basic information specific to a country, region, or individual farm.

First, the model calculates the required number of animals per unit of output for each of the animal categories; see Figure 2, Table 5 and 3.1.1. The main exogenous parameters used here include reproduction rates, liveweight gain rates, and milk/egg yields (see Table 6). By adjusting these herd parameters, the herd productivity can be calibrated against, e.g., country-level statistics on animal numbers and production. Next, the model uses these herd parameters to calculate the required feed energy intake for each animal category, using empirical equations (see 3.2.1). Lastly, taking the calculated energy requirements as an input, feed dry matter intake is calculated with feed baskets and feed energy values as exogenous parameters (see 3.2.2). This endogenous calculation of feed intake ensures fairly accurate feed use estimates even when feed basket data are incomplete. The benefit of this model feature applies particularly to systems with significant amounts of grazing since the grazed feed quantity is rarely known.

Table 6 lists the main exogenous parameters in crop and pasture systems. The sections that follow provide more details for how livestock systems are represented in the model.

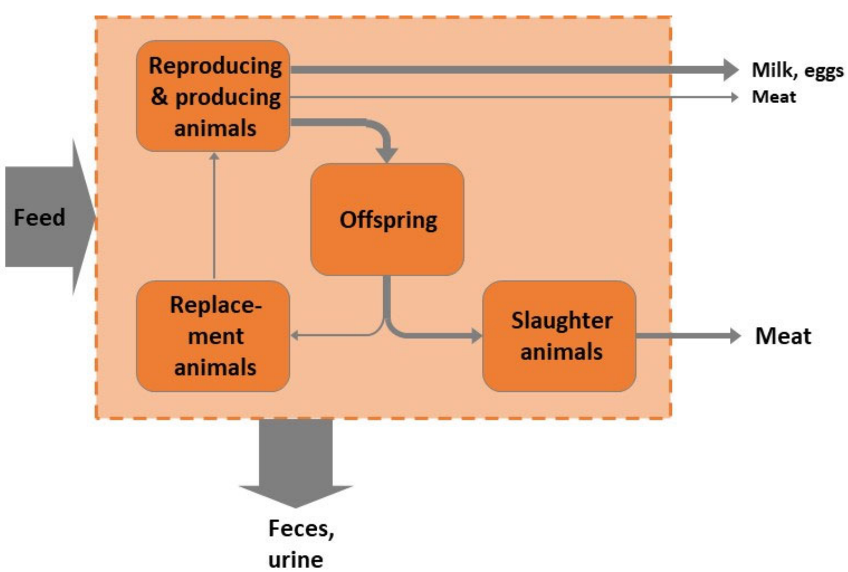

Figure 2 Generic structure of the representation of livestock systems in the ClimAg model.Thickness of flows are roughly proportional to rate.

Table 5 Animal categories (i.e., cohorts) included in livestock sub-systems.

Sub-system	Animal category by functional group				Outputs
	Mature animals	**Young animals**	**Replacement animals**	**Slaughter animals**	
Cattle milk	Dairy cows	Calves, female Calves, male	Heifers	Bulls Steers Heifers	Cattle whole milk Slaughter animals (cow) Weaned calves
Dairy cattle beef				Bulls Steers Heifers	Slaughter animals
Beef cattle beef	Beef cows Breeding bulls	Calves, female Calves, male	Heifers	Bulls Steers Heifers	Slaughter animals
Sheep – dairy herd	Ewes Rams	Lambs, female Lambs, male	Ewe lambs	Ewe lambs Ram lambs	Sheep whole milk Slaughter animals Wool
Sheep – meat herd	Ewes Rams	Lambs, female Lambs, male	Ewe lambs	Ewe lambs Ram lambs	Slaughter animals Wool
Pork	Sows	Piglets Weaners	Gilts	Hogs	Slaughter animals
Eggs	Laying hens		Pullets		Eggs Slaughter animals (hen)
Broiler	Breeding hens		Pullets	Broilers	Slaughter animals

For cattle and sheep systems, most key parameters, such as productivity and feed rations, are represented separately for the two principal seasons of the year: i) the wet and/or warm season when pasture production on natural and human-made grassland is abundant and ii) the dry and/or cold season when pasture production is low or non-existing. During the dry/cold season in temperate regions, animals are typically kept in barns.

3.1 Animals and production

3.1.1 Animal stocks and flows

In a herd/flock module of a livestock system, the model calculates the number of animals in each animal category (cohort; see Table 5) that are required to produce one unit of output (meat, milk, or egg). Mathematically, each animal cohort category in each sub-system is modeled as a stock-flow system. This means that the model calculates the number of animals (stock) in each cohort as a function of the entry rates and exit rates (flows) in to and out of the cohort. Parameters used for setting and/or calculating entry and exit rates include birth/hatching rates, liveweight gain rates, mortality rates, culling rates, and exit ages (e.g., weaning age, slaughter age); see Table 6.

Table 6 Main exogenous parameters in livestock sub-systems. Most parameters are specific to each animal category in the sub-system. For cattle and sheep systems, several parameters are specified separately for wet/warm and dry/cold seasons.

Parameters	Unit/type	Comments
Animals, herd dynamics		
Mature liveweight, MLW	kg	
Current liveweight, LW	kg	Endogenous parameter. Calculated using a daily time step.
Liveweight at birth/hatching	kg	
Liveweight at first birth/egg-laying	kg	
Liveweight at slaughter	kg	
Reproduction rate	Number born/female/year	For poultry, number of eggs laid
Culling rate (of mature animals)	% of stock/year	
Mortality rate – mature	% of stock/year	
Mortality rate – young	% of born	Specified for different growth phases
Milk yield	kg milk/cow or ewe/day	
Milk consumed by offspring	% DM of feed basket	
Wool yield	kg wool/ewe/year	
Egg yield	kg egg/hen/year	
Liveweight gain, LWG	kg/head/day	Specified for different growth phases
Age at first birth/egg-laying	months/days	
Age at slaughter	months/days	
Carcass yield and other animal allometrics		See Table 28 for numbers
Feed, enteric methane		
Maintenance energy adjustment factor for breed, MF_{breed}	% of base maintenance energy requirements	See 3.2.1 for details
Maintenance energy adjustment factor for lactation and animal, MF_{animal}	% of base maintenance energy requirements	See 3.2.1 for details
Maintenance energy adjustment factor for activity $MF_{activity}$	% of base maintenance energy requirements	See 3.2.1 for details
Growth energy adjustment factor for animal type GF_{animal}		See 3.2.1 for details
Feed basket (% of individual feeds)	% DM of each feed of all intake	See 3.2.2 for details
Feeding waste	% of feed offered	
Feed energy content of each feed	MJ NE or ME per kg of feed	See Table 25-26, 29-30 for numbers
Protein content of each feed	% DM	See Table 25-26, 29-30 for numbers
Emission factor enteric methane	% of feed GE intake	Endogenous parameter. See 3.2.4 for details
Feed conservation (silage/hay)		
Tractor diesel – string prep., baling	liter/ha	
Tractor diesel – coating, loading etc	liter/Mg produced	
Losses during processing, storage	% of dry matter	
Confinements, manure		
Bedding materials used in confinement	kg of manure excreted	

Parameters	Unit/type	Comments
Manure retention time in confinement	days	
Manure retention time in storage	days	
Manure systems	Slurry, outdoor storage Slurry, storage beneath animals Semi-solids, storage beneath animals Semi-solids, frequent removal Anaerobic lagoon Separate solid and liquid storage Drylot Deep bedding Daily spread Anaerobic digester (for biogas) Burning as fuel	Semi-solids systems apply only to poultry
Volatile solids (VS) decay in confinement and storage, DF^{a}_{con} and DF^{a}_{sto}	% of VS excreted in confinement, or entering storage	See 3.3.1 for details
Maximum methane production per unit of volatile solids, B	m^3 CH_4/kg VS	See 3.3.1 for details
Emission factor manure methane – confinement phase	% of max methane production	See 3.3.3 for details
Emission factor manure methane – storage phase	% of max methane production	Partly endogenous parameter. See 3.3.3 for details
Emission factor manure ammonia – confinement phase	% of inorganic nitrogen	See 3.3.4 for details
Emission factor manure ammonia – storage	% of inorganic nitrogen	See 3.3.4 for details
Emission factor manure nitrous oxide – confinement phase	% of total nitrogen (including feeding waste and bedding mtrls)	See 3.3.4 for details
Emission factor manure nitrous oxide– storage phase	% of total nitrogen (including feeding waste and bedding mtrls)	See 3.3.4 for details
Nitrogen lost through runoff from confinement, $N^{a}_{run.con}$	% of inorganic and organic nitrogen	
Nitrogen lost through runoff from storage, $N^{a}_{run.sto}$	% of inorganic and organic nitrogen	
Energy use in confinements		
Fuel for heating	MJ/head/year	For ruminant system, the number is applied only to the part of year spent in confinement
Fuel and/or electricity for feeding, ventilation, lighting, manure management etc.	MJ/head/year	
Electricity for milking	MJ/kg milk produced	

Representation of herd/flock dynamics presumes a steady-state situation, so that that herd/flock characteristics are constant from year to year. This also means that the herd/flock structure (i.e., each cohort's share of the entire herd/flock) is represented as steady-state averages, separately for the wet/warm (grazing) and dry/cold (barn) seasons in the case of cattle and sheep.

In contrast to many other herd models, the average liveweight of a cohort is not an exogenous constant but is here an endogenous parameter, LW, calculated using a daily time step. This allows for calculating feed energy requirements for maintenance (see 3.2.1) according to the daily liveweight figure. This approach provides more accurate estimate of energy requirements than using an average liveweight number for a longer time period since maintenance energy requirements are non-linear with respect to liveweight (as illustrated by the equations in 3.2.1).

3.1.2 Production rates of meat, milk, egg, and wool

Production rates of meat per unit of animals in stock are calculated using the herd/flock dynamics parameters in 3.1.1, which enables calculating the exit (production) rate of slaughtered animals. Combining the production rate of slaughter animals and the allometric relationships of animal organs (lean tissue, fatty tissue, bone, non-carcass part, etc.; see Table 28) give the meat production per unit of animals in the herd/flock.

Production rates of milk, egg, and wool are stated exogenously. For cattle and sheep, milk production per unit female animal per day is set separately for each of the two seasons (wet/warm and dry/cold). Egg and wool production rates are set as production per hen/ewe per year; see Table 6.

3.2 Feed and methane emissions from feed digestion

3.2.1 Feed requirements

For each animal category in each system, feed energy requirements are calculated using empirical bio-energetic equations for which. Basic herd parameters, such as liveweight and liveweight gain rate, are set exogenously.

Feed energy requirements represented in ClimAg are those for maintenance, activity, growth, gestation, and milk, egg, and wool production, but exclude draft work, which is of minor importance. Energy requirements are calculated using a *daily* time step and aggregated into total annual requirements (or in the case of cattle and sheep, for each of the two seasons, i.e. wet/warm and dry/cold). For cattle and sheep, the model represents feed energy requirements as net energy systems, and for pigs and poultry, metabolizable energy systems.

Maintenance

The following equations are used to calculate energy requirements for maintenance, specified by species and animal category (parameter definitions follow below the equations):

Cattle – dairy breeds (National Research Council, 2001):

$$NE_l = MF_{breed} \times MF_{animal} \times MF_{activity} \times 0.334 \times LW^{0.75}$$ [MJ NE_l/day] Eq. 18

Cattle – beef breeds (National Research Council, 1996):

$$NE_m = MF_{breed} \times MF_{animal} \times MF_{activity} \times 0.322 \times LW^{0.75}$$ [MJ NE_m/day] Eq. 19

Sheep (National Research Council, 2007):

$$NE_m = MF_{breed} \times MF_{animal} \times MF_{activity} \times 0.234 \times LW^{0.75}$$ [MJ NE_m/day] Eq. 20

Pigs (Kyriazakis and Whittemore, 2006):

$$ME_m = MF_{activity} \times 0.44 \times LW^{0.75} \quad \text{[MJ ME/day]} \quad \text{Eq. 21}$$

Poultry – laying hens (Larbier and Leclercq, 1994):

$$ME_m = MF_{activity} \times 0.565 \times LW^{0.75} \quad \text{[MJ ME/day]} \quad \text{Eq. 22}$$

Poultry – broilers (Larbier and Leclercq, 1994):

$$ME_m = MF_{activity} \times 0.418 \times LW^{0.75} \quad \text{[MJ ME/day]} \quad \text{Eq. 23}$$

where:

NE_l: Net energy for lactation (see 3.2.2)
NE_m: Net energy for maintenance (see 3.2.2)
ME_m: Metabolizable energy for maintenance (see 3.2.2)
LW: Liveweight [kg]
MF_{breed}: Adjustment factor for different breeds
MF_{animal}: Adjustment factor for lactation and animal type
$MF_{activity}$: Adjustment factor for activity

The type of cattle breed is known to influence maintenance requirements. For example, for Simmental breeds, energy needs are about 20% higher than in Eq. 19, whereas for Nelore breeds they are about 10% lower (National Research Council, 1996).

For lactating cattle, the model assumes maintenance energy requirements are 20% higher, based on (National Research Council, 1996). Furthermore, for uncastrated (intact) males of both cattle and sheep, maintenance energy requirements are assumed to be 15% higher (National Research Council, 2007, 1996).

For animals kept in barns or other confinements, additional energy requirements for activity is negligible. In contrast, for grazing animals,energy requirements for activity can be substantial, posing up to a 50% increase in maintenance requirements (National Research Council, 1996). In the ClimAg model, default assumptions are a 10% increase for grazing on cropland and 15-25% increase for grazing on permanent grasslands.

Growth

The following equations are used for calculating the energy requirements for growth (liveweight gain), specified by species and animal category (parameter definitions follow the equations):

Cattle (National Research Council, 1996):

$$NE_g = 22 \times \left[\frac{LW}{GF_{animal} \times MLW}\right]^{0.75} \times LWG^{1.097} \quad \text{[MJ } NE_g\text{/day]} \quad \text{Eq. 24}$$

Sheep (National Research Council, 2007):

$$NE_g = (1.155 - 0.008786 \times (MLW - LW)) \times LW^{0.75} \times LWG \quad \text{[MJ } NE_g\text{/day]} \quad \text{Eq. 25}$$

Pigs (Kyriazakis and Whittemore, 2006):

$$ME_g = 54.6 \times LWG_{protein} + 54.6 \times LWG_{lipid}$$ [MJ ME/day] Eq. 26

Poultry – replacement pullets (Larbier and Leclercq, 1994):

$$ME_g = 59.1 \times LWG_{protein} + 53.5 \times LWG_{lipid}$$ [MJ ME/day] Eq. 27

Poultry – broilers (Larbier and Leclercq, 1994):

$$ME_g = 60.3 \times LWG_{protein} + 46.1 \times LWG_{lipid}$$ [MJ ME/day] Eq. 28

where:

NE_g: Net energy for growth (see 3.2.2)
ME_g: Metabolizable energy for growth (see 3.2.2)
MLW: Liveweight at maturity [kg]
LWG: Liveweight gain [kg/day]
$LWG_{protein}$: Protein content in liveweight gain [kg/day]
LWG_{lipid}: Lipid content in liveweight gain [kg/day]
GF_{animal}: Adjustment factor for animal type

The value of the adjustment factor GF_{animal} for cattle reflects differences in percentage fat in weight gain, which tend to be higher for females than males. In the ClimAg model, this factor is 0.8 for females, 1.0 for castrated males, and 1.2 for intact males (National Research Council, 1996).

Milk, egg, and wool production

Milk – cattle:

$$NE_l = GE_{milk}$$ [MJ NE_l/day] Eq. 29

Milk – sheep:

$$NE_m = GE_{milk}$$ [MJ NE_m/day] Eq. 30

Milk – pigs (Kyriazakis and Whittemore, 2006):

$$ME = 1.43 \times GE_{milk}$$ [MJ ME/day] Eq. 31

Egg (Larbier and Leclercq, 1994):

$$ME = 1.68 \times GE_{egg}$$ [MJ ME/day] Eq. 32

Wool:

$$NE_m = GE_{wool}$$ [MJ NE_m/day] Eq. 33

where:

GE_{milk}: Gross energy content of milk production
GE_{egg}: Gross energy content of egg production
GE_{wool}: Gross energy content of wool production

3.2.2 Feed use

The ClimAg model calculates feed use based on the assumption that the estimated feed energy requirements for each animal category are fully met by feed matter intake. Exogenous parameters for calculating feed matter intake are the feed energy content of individual feeds and feed baskets (the share of individual feedstuff in the ration).

Feed energy value and composition

Data on feed energy content and other feed characteristics are given in Table 25-26, 29-30 in the Appendices.

The metabolizable and net energy value of cattle and sheep feeds from digestible energy (*DE*, in MJ kg dry matter) content is calculated using the following equations:

Cattle – dairy breeds (National Research Council, 2001):

$ME = -1.88 + 1.01 \times DE$	[MJ/kg DM]	Eq. 34
$NE_l = -0.502 + 0.556 \times DE$	[MJ/kg DM]	Eq. 35
$NE_m = -4.69 + 1.12 \times DE - 0.0222 \times DE^2 - 0.000331 \times DE^3$	[MJ/kg DM]	Eq. 36
$NE_g = -6.90 + 1.16 \times DE - 0.0280 \times DE^2 - 0.000384 \times DE^3$	[MJ/kg DM]	Eq. 37

Beef cattle, sheep (National Research Council, 2007, 1996):

$ME = 0.82 \times DE$	[MJ/kg DM]	Eq. 38
$NE_m = -4.69 + 1.12 \times DE - 0.0222 \times DE^2 - 0.000331 \times DE^3$	[MJ/kg DM]	Eq. 39
$NE_g = -6.90 + 1.16 \times DE - 0.0280 \times DE^2 - 0.000384 \times DE^3$	[MJ/kg DM]	Eq. 40

For calculating the metabolizable energy value of pig feeds from digestible energy (*DE*, in MJ kg dry matter) content, this equation is used:

$ME = 0.955 \times DE$	[MJ/kg DM]	Eq. 41

Feed baskets

Table 7 presents the feed items that can be included in the feed basket for each livestock system. Feed baskets are set exogenously as a fraction of total feed intake (in percent dry matter), separately for each animal category (Table 5). For ruminant systems, feed rations are stated separately for the wet/warm (grazing) and dry/cold (barn) seasons. Additionally, feedlot rations are specified separately for farms with finishing in separate confinements (“feedlot”).

Table 7 Feed items included in the representation of feed baskets for livestock sub-systems. Fractions of feeds within the composite categories of co-products and residues are adjustable.

Feed item	Cattle	Sheep	Pigs	Poultry
Cereals				
Wheat grains	x	x	x	x
Maize grains	x	x	x	x
Barley grains	x	x	x	x
Sorghum grains	x	x	x	x
Oat grains	x	x	x	x
Starchy roots				
Cassava	x		x	
White potato	x		x	
Sweet potato			x	
Protein crops				
Soybean (whole)	x		x	x
Faba beans	x		x	x
Peas	x		x	x
Forage products from cropland – fed in confinement				
Grass-legume silage/hay	x	x	x	
Whole-maize silage	x	x		
Whole-sorghum silage	x	x		
Whole-wheat silage	x	x		
Whole-sugarcane silage	x	x		
Forage products from cropland – grazed				
Grass-legume	x	x	x	
Permanent and semi-permanent pastures	x	x		
Herbage and browse from forest grazing	x	x		
Other products				
Milk	x	x	x	
Vegetable oils			x	x
Calcium carbonate				x
Urea	x			
Protein concentrates from co-products				
Oil meals[1]	x	x	x	x
Distillers/brewers grains	x	x	x	x
Other[2]	x	x	x	x
Energy concentrates from co-products				
Cereal brans, etc[3]	x	x	x	x
Molasses/beet pulp	x	x	x	x
Other[4]	x	x	x	
Residues				
Cereal straw	x	x		
Other crop residues	x	x		
Discarded food			x	

[1] Includes meals from soybeans, rapeseed, sunflower, peanut, coconut, oil palm kernel, and cottonseed
[2] Includes wheat gluten, maize gluten meal, starch extraction residue, meat and bone meal, fish meal, and whole cottonseed
[3] Includes broken rice, brans of wheat, rice, millet, rye; maize hominy feed, wheat gluten feed, maize gluten feed and germ meal
[4] Includes whey, buttermilk, and tops and leaves of cassava, potato, yams, and sugar beet

Feeding waste

Some of the feed offered to animals in confinements (and supplemental feeds in grazing paddocks) is not consumed but wasted. For cereals and other concentrate feed, the waste fraction is generally very low (1-2%), but for silage and hay, the waste fraction can be significant (5-10%). These waste streams are accounted for in the ClimAg model. Feed waste from confinements is assumed to be incorporated into the manure stream.

3.2.3 Feed production and supply

Each livestock sub-system in the ClimAg model comprises a land module to enable representation of feed production on land in the vicinity of the animal confinement, as well as grazing on cropland or permanent grassland. Representation of plant growth, nitrogen flows, and fertilizer and energy use in the land modules is described in section 2 above.

All forage feed cultivated on cropland (i.e., grasses, legumes and grass-legume mixtures, and whole cereals), and most of the cereals used as feed are assumed to be produced on the livestock farm. All other feeds, including by-products such as cereal brans, oil meals, etc., are assumed to be purchased and transported to the farm. All upstream resource use and environmental impacts of purchased feed are tracked and added to the on-farm impacts; see Table 23.

Conservation of forage crops by ensiling (or haying) involves additional diesel use and is calculated separately. Diesel use is calculated as an additional fuel use factor in *liter per ha* multiplied by the area harvested, plus a fuel use factor in *liter per Mg* multiplied by the weight of conserved plant mass (Table 6). In addition, the model accounts for dry matter losses that occur during the conservation process, typically on the order of 5 to 15%.

3.2.4 Methane emissions from feed digestion

Methane emissions from feed digestion ("enteric fermentation") in ruminants and pigs are calculated as a fraction of gross energy intake. In contrast to many other livestock models, for cattle and sheep, this fraction is not an exogenous constant, but here an endogenous parameter calculated as a function of feed quality, daily feed intake, and animal liveweight. For cattle, the model uses equations developed by (Moraes et al., 2014) based on their statistical analysis of a dataset of c. 2,600 energy balance trials. For sheep, the model uses equations developed by (Van Lingen et al., 2019), who analyzed a database containing 270 measurements.

3.3 Manure and methane, nitrous oxide, and ammonia emissions

3.3.1 Manure production

For each animal category, the ClimAg model calculates the quantities of manure produced as a function of the energy and protein content of the feed intake, in combination with exogenous parameters on energy and ash content of feces and urine.

For cattle, sheep and pigs, the amount of feces energy produced can, by definition, be calculated as the difference between the feed intake's gross energy and digestible energy content. Similarly, the amount of urine energy can be calculated as the difference between the digestible energy content and metabolizable energy content, minus the energy in produced methane. For poultry, the difference between gross energy and metabolizable energy gives the manure energy produced.

The corresponding amount of "volatile solids" in manure (dry matter minus ash), which determines the potential production of methane (see 3.3.3), is calculated using assumed values on gross energy and ash content per kg of manure; see Table 8.

The amount of N in manure is calculated as the difference between feed N intake and N retained in animal mass. Feed N intake, $N_{int}^{a,s}$ (Mg N yr^{-1}), for animal cohort *a* and season *s*, is calculated from the feed basket and the protein content (divided by 6.25) of each feed component in the basket (for protein contents, see Table 25-26, 29-30). N retained in animal mass, $N_{ret}^{a,s}$ (Mg N yr^{-1}), is calculated from the protein content (divided by 6.4) of liveweight gain and milk/egg/wool production (for protein contents, see Table 28).

The partition of excess N intake into feces and urine is calculated according to the relationship developed by (Scholefield et al., 1991):

$$N_{uri}^{a,s} = \left(N_{int}^{a,s} - N_{ret}^{a,s}\right) \times \left(14 \times NC_{rat}^{a,s} + 0.24\right) \quad \text{Eq. 42}$$

$$N_{fec}^{a,s} = \left(N_{int}^{a,s} - N_{ret}^{a,s} - N_{uri}^{a,s}\right) \quad \text{Eq. 43}$$

where $N_{uri}^{a,s}$ (kg N yr^{-1}) and $N_{fec}^{a,s}$ (kg N yr^{-1}) are the amounts of N excreted in urine and feces, respectively, and $NC_{rat}^{a,s}$ (dimensionless) is the N concentration (on a dry matter basis) in the feed basket.

Table 8 Composition of manure fractions (as excreted) in livestock sub-systems. For sources, see table footnotes.

System and manure stream	Dry matter (% fresh)	Ash (% DM)	Ammonium, uric acid and urea nitrogen (% of **total** N)	Gross energy[1] (HHV, MJ/ kg DM)
Cattle[2]				
Feces	15%	15%	20%	17.8
Urine	5.0%	50%	85%	5.5
Sheep[3]				
Feces	15%	15%	20%	17.8
Urine	5.0%	50%	85%	5.5
Pigs[4]				
Feces	30%	20%	35%	16.8
Urine	2.5%	50%	90%	5.5
Poultry[5]				
Layer	25%	24%	70%	14.8
Broiler	25%	27%	70%	14.2

[1] Calculated assuming an ash free gross energy content of 21.0 MJ/kg DM for cattle and pig feces (Font-Palma, 2019; Wnetrzak et al., 2015) and 19.5 for poultry manure (Quiroga et al., 2010), and 11 MJ/kg DM for urine (close to urea, 10.5 MJ/kg DM).
[2] Based on (Hansen et al., 2008; Mathot et al., 2020, 2012; Petersen et al., 2016)
[3] Same numbers as for cattle assumed
[4] Based on (Hansen et al., 2008; Petersen et al., 2016; Sanchez and González, 2005; Vu et al., 2009)
[5] Based on (Ashworth et al., 2020; Nahm, 2003)

The fraction of feces and urine excreted on pastures is assumed to equal the fraction of time spent on pastures. The fraction of time spent on pastures is estimated as the fraction of grazed feed intake of total feed intake.

Feed waste and bedding materials are added to the manure excreted in confinements. The amount of volatile solids and N in these streams are included in the calculations of methane and N emissions from manure; see 3.3.3 and 3.3.4.

3.3.2 Type of confinements and manure storage

The type of animal confinement and manure storage technology influence the emission rates of methane, nitrous oxide, and ammonia from manure. In the ClimAg model, confinements and storage are represented by ten different manure management system types; see Table 6.

Emissions of methane, nitrous oxide, and ammonia are calculated separately for each of these confinement and storage technologies to reflect how their different inherent conditions influence emission rates.

3.3.3 Methane emissions and manure decay

Soon after excretion, the volatile solids (VS) in manure are subjected to decomposition by microbes. The ClimAg model represents this decomposition by setting exogenously a fraction of VS decay, DF^m, that occurs in the confinement and subsequent storage (if any).

Decomposition of manure leads to production of methane and CO_2, as well as conversion of organic N into ammonium (inorganic N), of which some is converted to ammonia and emitted (see next section). Rate of methane production is calculated as a function of the excreted quantity of VS, multiplied by an animal- and feed-specific factor that reflects the maximum potential methane production per unit of VS (denoted B) and a climate- and management-specific methane conversion factor (often denoted MCF) that reflects to what extent the maximum methane production is realized. The part of the fraction of VS decay that does not cause methane production is assumed to be lost as CO_2.

These calculations are done separately for the emissions that occur in animal confinements and emissions that occur during subsequent manure storage, if any. Apart from the methane generated from the manure itself, calculations are also done of methane produced from substrates added to the manure stream in confinements, mainly bedding materials and feeding waste.

Confinement

Methane emissions in confinements increase with longer manure retention times. Therefore, methane emissions are calculated as a function of retention time.

Emissions of methane, $C^a_{CH4,con}$ (kg yr^{-1}), for animal cohort a, is calculated according to the following equation:

$$C^a_{CH_4,con} = 0.67 \times \left(VS^a_{con,fec} \times B^a_{fec} + VS^a_{con,uri} \times B^a_{uri} + VS^a_{bed} \times B^a_{bed} + VS^a_{wst} \times B^a_{wst}\right) \times EF^m_{CH4,con} \times \tau^m_{con} \quad \text{Eq. 44}$$

where:

$VS^a_{con,fec}$ and $VS^a_{con,uri}$ (kg DM yr^{-1}) is the volatile solids content, in feces and urine, respectively, excreted in confinement by animal a.

VS^a_{bed} and VS^a_{wst} (kg DM yr^{-1}) is the volatile solids content of used bedding materials (on-farm supplied or purchased) and feed waste (uneaten feed in confinement) for animal a.

B^a (m^3 CH_4 (kg VS)$^{-1}$) is the maximum CH_4 production potential per unit of volatile solids in the substrate.

$EF^m_{CH_4,con}$ (dimensionless) is the *daily* methane production in confinement as a fraction of the maximum CH_4 production potential of the substrate in manure system m.

τ^m_{con} (days) is the retention time in the confinement of substrate (excreted manure, bedding material, and feed waste) for manure system m.

Calculation of the output of substrate with methane-production potential that leaves the confinement (i..e, which equals input to storage), considers the losses of VS that occur in the confinement due to decay. Hence, the "maximum CH_4 production potential" in the substrate leaving the confinement as output, $maxCH4^a_{man,stl}$ (kg yr^{-1})t, for animal cohort a is given by:

$$maxCH_4{}^a_{man,con} = 0.67 \times \left(VS^a_{st.fec} \times B^a_{st.fec} + VS^a_{st.uri} \times B^a_{st.uri} + VS^a_{bed} \times B^a_{bed} + VS^a_{wst} \times B^a_{wst}\right) \times \left(1 - EF^m_{CH_4,con} - DF^a_{con}\right) \quad \text{Eq. 45}$$

where:

DF^a_{con} (dimensionless) is the fraction VS being decomposed in the confinement, of the amount VS excreted in confinement by animal a.

Storage

To calculate methane emissions during manure storage, the ClimAg model uses different approaches for solid and liquid manure types.

For solid manure types (feces, deep litter, poultry manure, etc.), methane production rates are generally low, and therefore a simple approach is used. Emissions of methane from manure storage, $C^a_{CH4,sto}$ (kg yr^{-1}), are calculated according to:

$$C^a_{CH_4,sto} = maxCH_4{}^a_{man,con} \times EF^{m,s}_{CH_4,sto} \quad \text{Eq. 46}$$

where:

$EF^{m,s}_{CH4,sto}$ (dimensionless) is the total production of methane during storage as a fraction of the maximum CH4 production potential of the substrate in manure system *m, s* (*s* as in solid manure). The emission factor here equals the commonly used MCF parameter and is an exogenous fixed number for the annual amount of manure entering storage, although specific to climate zone and manure type.

For liquid manure types (slurry, urine, etc.), methane production rates can be very high, and a more detailed approach is used to reflect the large regional variation in methane emissions due to climatic differences. Here, the ClimAg model calculates the methane emission factor $EF_{CH4,sto}^{m,l}$ during the storage period using *monthly* average temperatures as input, in contrast to most other models which use annual average temperature. Here, methane production calculations are based on the predictive model presented in (IPCC, 2019), which is itself based on a model developed by (Mangino et al., 2001).

Since methane production is non-linearly related to temperature, calculating methane emissions using average temperatures over a long time period (e.g., a year) is likely to underestimate emissions. In general, modeled estimates based on shorter time steps will provide more accurate emission estimates. This is particularly true in cool regions where most annual methane production occurs during a few warm months when temperatures exceed 15 °C.

In addition to using monthly temperature data, the calculation also factors in the timing and frequency of removal (emptying) of manure from storage for application on land. The resulting emission factor $EF_{CH4,sto}^{m,l}$ is used to calculate annual methane emissions in the same way as in Eq. 46:

$$C_{CH4,sto}^{a} = maxCH_{4man,con}^{a} \times EF_{CH4,sto}^{m,l} \qquad \text{Eq. 47}$$

Grazing

Methane emissions from manure excreted on pastures, $C_{CH4,graz}^{a}$ (kg yr^{-1}), are generally very small, and are calculated in a simple way:

$$C_{CH_4,graz}^{a} = 0.67 \times \left(VS_{graz,fec}^{a} \times B_{fec}^{a} + VS_{graz,uri}^{a} \times B_{uri}^{a}\right) \times EF_{CH_4,graz}^{m} \qquad \text{Eq. 48}$$

where:

$VS_{con,fec}^{a}$ and $VS_{con,uri}^{a}$ (kg DM yr^{-1}) is the volatile solids content, in feces and urine, respectively, excreted at grazing by animal *a*.

B^{a} (m^3 CH_4 (kg VS)$^{-1}$) is the maximum CH_4 production potential per unit of volatile solids in substrate.

$EF_{CH4,graz}^{m}$ (dimensionless) is the total production of methane as a fraction of maximum CH_4 production potential of substrate.

3.3.4 Nitrogen emissions and output

In the ClimAg model, descriptions of inputs, losses, and outputs of N in animal confinements and manure storage facilities are made on a mass-balance basis, with explicit distinction between inorganic and organic N. Input flows represented include feces, urine, bedding material and feed waste, separately by animal cohort.

Ammonia and nitrous oxide emissions in confinement

Most of the N in excreted manure is in inorganic form, i.e., ammonium (see Table 8). Decomposition of manure leads to conversion of the organic N in the manure into ammonium, increasing the supply of inorganic N.

Following common practice, in the ClimAg model, manure ammonia emissions are calculated as a fraction (emission factor) of the amount of ammonium in the manure. In the confinement phase, the emission factor is applied to the amount of ammonium *when excreted*. The emissions of ammonia from confinement, $N^{a}_{NH_3,con}$ (kg N yr^{-1}), for animal cohort a, is calculated according to:

$$N^{a}_{NH_3,con} = \left(N^{a}_{st.fec,ino} + N^{a}_{st.uri,ino}\right) \times EF^{m}_{NH_3,con} \quad \text{Eq. 49}$$

where:

$N^{a}_{st.fec,ino}$ and $N^{a}_{st.uri,ino}$ (kg N yr^{-1}) is the inorganic N content, in feces and urine, respectively, excreted in confinement by animal a.

$EF^{m}_{NH3,con}$ (dimensionless) is the fraction lost through ammonia volatilization in confinement for manure system m.

Emissions of nitrous oxide from the confinement, $N^{a}_{N2O,con}$ (kg N yr^{-1}), are calculated as an emission factor of the *total* amount of N entering the confinement:

$$N^{a}_{N_2O,con} = \left(N^{a}_{st.fec,ino} + N^{a}_{st.uri,ino} + N^{a}_{st.fec,org} + N^{a}_{st.uri,org} + N^{a}_{bed} + N^{a}_{wst}\right) \times EF^{m}_{N_2O,con} \quad \text{Eq. 50}$$

where:

$EF^{m}_{N2O,con}$ (dimensionless) is the fraction emitted as nitrous oxide in confinement for manure system m.

Output of nitrogen from confinement

The calculation of the output of N from the confinement considers the losses as ammonia and nitrous oxide, and the increase of ammonium and the equivalent decrease in organic N because of decay of volatile solids. It also considers N losses through runoff. Hence, output from the confinement of organic-N, $N^{a}_{man,stl,org}$ (kg N yr^{-1}), and inorganic N, $N^{a}_{man,stl,ino}$ (kg N yr^{-1}), which equal input to storage (or to field, if daily spread), for animal cohort a is given by:

$$N^{a}_{man,con,org} = \left(N^{a}_{st.fec,org} + N^{a}_{st.uri,org} + N^{a}_{bed} + N^{a}_{wst}\right) \times \left(1 - DF^{m}_{con}\right) - N^{a}_{run,org} \quad \text{Eq. 51}$$

$$N^{a}_{man,con,ino} = N^{a}_{st.fec,ino} + N^{a}_{st.uri,ino} + \left(N^{a}_{st.fec,org} + N^{a}_{st.uri,org} + N^{a}_{bed} + N^{a}_{wst}\right) \times DF^{m}_{con} - N^{a}_{NH_3,con} - N^{a}_{N_2O,con} - N^{a}_{run,ino} \quad \text{Eq. 52}$$

where:

DF^{m}_{con} (dimensionless) is the fraction of volatile solids decomposed in the confinement for manure system m.

$N^{a}_{run.con,org}$ and $N^{a}_{run.con,ino}$ are organic-N and inorganic-N content in surface runoff from the confinement

Note that runoff may in some systems be collected in a settling basin and, subsequently, a holding pond, and may be recycled to the field; here, however, it is treated as a lost flow.

Ammonia and nitrous oxide emissions from storage

Emissions of ammonia from storage, $N^{a}_{NH_3,sto}$ (kg N yr^{-1}), are calculated as an emission factor of the amount of ammonium (inorganic nitrogen) entering storage:

$$N^{a}_{NH_3,sto} = N^{a}_{man,con,ino} \times EF^{m}_{NH_3,sto} \qquad \text{Eq. 53}$$

where $EF^{m}_{NH3,sto}$ (dimensionless) is the fraction lost through ammonia volatilization during storage for manure system m.

Emissions of nitrous oxide from storage, $N^{a}_{N2O,sto}$ (kg N yr^{-1}), is calculated as an emission factor of the amount of *total* N entering storage:

$$N^{a}_{N2O,sto} = (N^{a}_{man,con,ino} + N^{a}_{man,con,org)} \times EF^{m}_{N2O,sto} \qquad \text{Eq. 54}$$

where $EF^{m}_{N2O,sto}$ (dimensionless) is the fraction emitted as nitrous oxide during storage for manure system m.

Output of nitrogen from storage

The calculation of the output of N from storage considers the losses as ammonia and nitrous oxide, and the increase of ammonium and the equivalent decrease in organic nitrogen because of the decay of volatile solids. It also considers N losses through runoff. Output from storage of organic-N, $N^{l}_{man,sto,org}$ (kg N yr^{-1}), and inorganic N, $N^{l}_{man,sto,ino}$ (kg N yr^{-1}), for application to field (or other use) is the sum of manure storage output for all animal categories, $a = 1, 2, \ldots n$, in livestock system *l*, and is calculated as:

$$N^{l}_{man,sto,org} = \sum_{a=1}^{n} \left(N^{a}_{man,sto,org} \times (1 - DF^{m}_{sto})\right) \qquad \text{Eq. 55}$$

$$N^{l}_{man,sto,ino} = \sum_{a=1}^{n} \left(N^{a}_{man,sto,ino} + N^{a}_{man,sto,org} \times DF^{m}_{sto} - N^{a}_{NH_3,sto} - N^{a}_{N_2O,sto}\right) \qquad \text{Eq. 56}$$

where:

DF^{m}_{sto} (dimensionless) is the fraction of volatile solids decomposed in during storage for manure system m.

$N^{a}_{run.sto,org}$ and $N^{a}_{run.sto,ino}$ are organic-N and inorganic-N content in surface runoff from storage

Note that N emissions occurring after application of manure on cropland, and after excretion on pastures, are described in 2.2.6.

3.4 CO_2 emissions from on-farm energy use

For livestock farming operations, in addition to those for feed production, ClimAg calculates CO_2 emissions from energy use separately for three categories:

- Fuel oil for heating
- Electricity for milking

- Fuel oil and/or electricity for all other purposes (feeding, ventilation, lighting, manure management, etc.)

Energy use and emissions from heating and general purposes are calculated by assuming systems-specific energy use per animal unit and time spent in confinement. Annual energy use is calculated by multiplying these factors by the percentage time of the year spent in confinement. In this way, the model factors in the differences in energy use due to varying extent of grazing in ruminant systems.

4. Aquaculture production, capture fisheries

Compared to livestock systems, the potential climate and environmental impacts of aquaculture systems are typically less varied. In the ClimAg model, therefore, the representation of aquaculture systems is simpler compared to that of livestock systems. Table 9 presents the main exogenous parameters included in the representation of aquaculture systems.

4.1 Feed and land use in aquaculture

In aquaculture, feed use efficiency is typically quantified according to the "economic feed conversion ratio" (eFCR), which quantifies total feed input per total net output (actual harvest) of product. The ratio factors in losses of the product by death, escapes, etc., and that of non-ingested feed. Because of relatively small variation in feed requirements across aquaculture systems, improvements in model accuracy are less dependent on detailed estimates of feed energy requirements, in contrast to the modeling of livestock systems. Instead, feed use in aquaculture is represented simply in ClimAg using exogenous values for eFCR.

Table 9 Main exogenous parameters in aquaculture sub-systems. Sub-systems are listed in Table 18.

Parameters	Unit/option	Comments
Feed use		
Economic feed conversion ratio	kg feed used/kg product harvested	
Fraction external feed	% of all feed use	
Feed basket (% of individual feeds)	% of each feed of all external feed	See Table 10 for feed items
Land use		
Land use per output	m²/kg product (annually)	Applies only to artificial ponds
Nitrous oxide and methane emissions		
Nitrous oxide emission factor	% of nitrogen in external feed, minus feed nitrogen retained in animal mass	
Methane emission factor	kg methane/hectare water area/year	Applies only to artificial ponds
Energy use		
Gas, fuel oil and electricity for feed production (feed mill)	MJ/kg feed	Energy use is stated separately for the different energy sources
Diesel and electricity for aquaculture facility	MJ/kg product	Energy use is stated separately for the different energy sources

Several common species in aquaculture can feed on organic matter naturally present in the water body, such as plankton and detritus. Some filter-feeding species, such as certain carp (e.g., silver carp) and mollusks, feed exclusively on naturally occurring food, and their production uses no external feed. The ClimAg model represents the use of in-situ feed by a parameter that states the fraction of external feed in each sub-system.

Feed baskets are set exogenously as a fraction of total *external* feed use. Table 10 presents the possible feed items available for the feed basket in the aquaculture system. All external feed is assumed to be transported to aquaculture facilities from crop farms and/or compound feed plants. Upstream resource use and environmental impacts of external feed that occur in crop production and processing are accounted for and added to the on-site impacts; see Table 23.

Table 10 Feed items included in the representation of feed baskets for aquaculture sub-systems. Fractions of feeds within the composite categories are adjustable.

Items
Unprocessed crop products
Wheat grains, Maize grains, Soybean seeds, Faba beans, Pea seeds, Cassava (dried)
Crop starch concentrates
Wheat flour, Wheat starch, Maize starch, Broken rice
Oil
Vegetable oil[1], Fish oil[2]
Crop protein concentrates
Wheat bran, Maize hominy feed, Rice bran, Wheat gluten meal, Maize gluten meal, Oil meals[3]
Animal protein concentrates
Meat and bone meal[4], Fish meal[5]
Pigments etc
Pigments, Amino acids, Minerals/vitamins

[1] Includes oils from all vegetable oil sub-systems included in ClimAg (see Table 19)
[2] Includes oils from all fish sub-systems included in ClimAg (see Table 20)
[3] Includes meals from soybeans, rapeseed, sunflower, peanut, coconut, oil palm kernel, and cottonseed
[4] Includes meals from all livestock sub-systems included in ClimAg (see Table 17)
[5] Includes meals from all fish sub-systems included in ClimAg (see Table 18)

Aquaculture production of crustaceans and freshwater fish mainly occurs in artificial ponds, created at the expense of native vegetation or other land uses. In ClimAg, land use is defined by an exogenous parameter that sets the land requirement per annual output of product. Carbon storage changes due to this land use are calculated in the same way as for agricultural land use (see 2.5).

4.2 Methane and nitrous oxide emissions from aquaculture

Large input of feed to aquaculture ponds, in combination with poor aeration of the water mass, stimulates substantial methane production. Methane production is represented by an exogenous parameter that sets the annual methane emission per hectare of water area.

Because of the large input of N in feed to aquaculture ponds, nitrous oxide (N_2O) production in the water mass is larger than what it would be without the feed input. In ClimAg, nitrous oxide emissions are calculated as an emission factor multiplied by the amount of feed N input to the water mass that is not retained in animal mass, i.e., feed N excreted in feces and feed not ingested. N content retained in animal mass is calculated as the protein content of the aquacultural output (see Table 28) divided by 6.4.

4.3 CO_2 emissions from energy use in aquaculture and capture fisheries

For aquaculture operations, ClimAg calculates CO_2 emissions from energy use separately for:

- Gas, fuel oil, and electricity for production of compound feed
- Diesel and electricity for running the aquaculture facility

For capture fisheries, ClimAg includes CO_2 emissions from the fuel consumed by fishing vessels.

5. Processing of crop, livestock, and aquaculture and fisheries products

5.1 Food products: Crop products and plant-based meat and dairy substitutes

Processing of crop products mainly involves separating plant materials into more homogenous fractions that have a relatively high concentration of either starch, oil, sugar, or protein. This processing is hereafter referred to as "primary" processing. Some of the outputs from primary crop processing are consumed as food (e.g., vegetable oils and white rice), and some are used as feedstock in further processing (e.g., composite products), hereafter referred to as "secondary" processing.

In ClimAg, both primary and secondary processing are described on a mass and energy balance basis, with separate balances for nitrogen (protein). In primary processing, the yield of the main product, as well as that of significant co-products, are represented. Energy use in each process is represented, with separate calculations for process steps with significant energy use, such as drying; see Table 11. Upstream resource use and environmental impacts associated with the production of the feedstocks are accounted for and added to the on-site (i.e., the processing plant) impacts. see Table 23.

Table 11 Main exogenous parameters in primary processing of crop products into food-type items. Sub-systems are listed in Table 19.

Parameters	Unit/option	Comments
Feedstock use		
Yield of main product	% of feedstock (crop product)	
Yield(s) of co-product(s)	% of feedstock (crop product)	
Co-product use for on-site steam production	% of co-product	Option included for oat hulls, shells and fibers from oil palm fruit bunches, sunflower hulls, peanut hulls, coconut husks & shells, olive pomace, and sugarcane bagasse
Energy use		
Gas, fuel oil, electricity, and on-site produced steam for main process steps	MJ/kg feedstock	Energy use is stated separately for the different energy sources
Gas, fuel oil, electricity, and on-site produced steam used for drying of co-product streams	MJ/kg output	Included for sugar beet pulp, brewers' grains, distillers' grains
Emissions		
Methane emissions from treatment of palm oil mill effluent	% methane per dry matter in effluent	

As to secondary processing, the ClimAg model also represents the production of plant-based meat and dairy substitutes, as these products generally have a lower climate cost compared to animal meat and dairy products.

Plant-based meat substitutes are currently marketed in many different forms. Products designed to closely resemble real animal meat are typically made from a combination of protein concentrates (and/or isolates) and vegetable oils, together with additives and other minor ingredients. Among the most used plant protein sources are soybeans and peas. As a fat source, any vegetable oil may be used, except in certain products, such as patties, for which coconut fat is preferred for its high melting point.

For plant-based meat substitutes, ClimAg represents four distinct, but generalized ingredient configurations for plant-based meat products; see Table 21. These configurations use either soybean or peas as a plant protein source, either at a low or high fat content. In the high-fat configurations, coconut fat is used.

For plant-based dairy product substitutes, ClimAg represents the most common types of milk substitutes (soy, oat, almond, rice), and three variants of plant-based butter substitutes based either on soy oil, palm oil or coconut oil, in addition to rapeseed and sunflower oil which are included in all three variants; see Table 21. For cheese and cream substitutes, only one ingredient configuration is included, reflecting the smaller variability within the ingredient composition of currently marketed products.

Exogenous parameters taken to model plant-based meat and dairy sub-processes are feedstock inputs (kg feedstock per kg output) and energy use per output. As in the case of primary processing, upstream resource use and environmental impacts associated with the production of the feedstocks are accounted for and added to the on-site (the processing plant) impacts; see Table 23.

5.2 Food products: Dairy, meat, and fish & shellfish

Primary processing of slaughtered animals and fish/shellfish involves the cutting of body parts to separate non-food (i.e., hides, guts) from food parts and further cutting and/or grinding of food parts to obtain specific meat and fish/shellfish products. Primary processing of whole milk generally represents more diverse processes than that of slaughtered animals. Basic processes involve production of items with a lower or higher milk fat concentration than whole milk, removal of the milk carbohydrate fraction (cheese production), and drying into milk powder products.

Table 12 Main exogenous parameters in primary processing of dairy, meat and fish/shellfish products. Sub-systems are listed in Table 20.

Parameters	Unit/option	Comments
Feedstock use		
Yield of main product	% of feedstock (whole milk, whole animals)	Technically, for dairy, yields are derived from the stated fat content of the outputs.
Yield(s) of co-product(s)	% of feedstock (whole milk, whole animals)	
Energy use		
Gas, fuel oil, and electricity for main process steps	MJ/kg feedstock	Energy use is stated separately for the different energy sources
Gas, fuel oil, and electricity for drying and other additional processing of co-product streams	MJ/kg output	Included for whey, rendered fat and meat and bone meal, and reduction (rendering) of refuse of from fish gutting and filleting

As for crops, the yield of the main product, as well as that of significant co-products, are represented in the primary processing of livestock and fish/shellfish. Also, energy use in each process is represented, with separate calculations for process steps with significant energy use, such as rendering and drying; see Table 12. As in the case of crop processing, upstream resource use and environmental impacts associated with the production of the feedstocks are accounted for and added to the on-site (the processing plant) impacts; see Table 23.

5.3 Materials products: Cotton

Some major global agricultural crops are produced mainly for materials functions. These include seed cotton, linseed, and rubber trees. In ClimAg, representation of seed cotton is included.

The model also includes the processing of seed cotton into cotton lint (the main product, used for textile purposes), and various co-products; see Table 22. Exogenous parameters for seed cotton processing are analogous to those for primary processing of crops to food; see Table 11. As in the case of crop processing, upstream resource use and environmental impacts associated with the production of the feedstocks are accounted for and added to the on-site (the processing plant) impacts; see Table 23.

5.4 Energy products: Liquid fuels, gas

A significant fraction of the global production of agricultural crops is used to produce liquid fuels, destined mainly for the road transportation sector. ClimAg represents nine different types of biodiesel and bioethanol; see Table 22. Exogenous parameters taken in modeling the production of these liquid fuels are analogous to those for primary processing of crops into food; see Table 11. As in the case of crop processing, upstream resource use and environmental impacts associated with the production of the feedstocks are accounted for and added to the on-site (the processing plant) impacts; see Table 23.

Some manure and other biomass streams are currently diverted into anaerobic reactors, which are designed to realize to the greatest extend possible the methane production potential of the inherent substrates. ClimAg includes representation of reactors that use cattle or pig slurry as substrates, with whole-cereal silages and food waste as complementary substrates. Exogenous parameters for reactors are analogous to those for methane production from manure; see 3.3.3.

6. Production of fossil-based fuels, electricity, fertilizers, and pesticides

The ClimAg model represents six different fuels made from fossil carbon feedstocks: coal, oil, gas, diesel, gasoline, and kerosene (jet fuel). These fuels are characterized by their energy and carbon content per unit weight and volume. In addition to fuel-CO_2 released at burning, ClimAg represents emissions associated with the extraction of feedstocks (mainly methane leaks) and processing into ready-to-use fuels (mainly refinery emissions).

For electricity, ClimAg includes one average CO_2 intensity for all electricity use in all sectors. This number represents the average on-site and upstream emissions associated with electricity production in a region.

ClimAg represents seven different fertilizers, mainly of single-nutrient type, and one pesticide type; see Table 13. The representation of phosphorus, potassium, and pesticides in ClimAg is simple due to their relatively low energy intensity or relatively low consumption (pesticides).

Table 13 Fertilizers and pesticides included in ClimAg and feedstocks and parameters represented in their production.

Type	**Feedstocks/energy sources included**	**Parameters** (units in per kg of product)
Nitrogen fertilizers		
Primary feedstocks		
Ammonia	Fossil gas, Fossil oil, Fossil coal, Electricity	Feedstock/energy use (MJ/kg), CO_2 emissions (kg CO_2/kg)
Nitric acid	Ammonia Fossil gas, Fossil oil, Fossil coal, Electricity	Feedstock use (kg NH_3/kg), Energy use (MJ/kg), Nitrous oxide emissions (g N_2O/kg), CO_2 emissions (kg CO_2/kg)
Nitrogen fertilizers		
Ammonia, anhydrous	Ammonia	Feedstock (kg/kg), Energy use (MJ/kg), CO_2 emissions (kg CO_2/kg)
Ammonium nitrate	Ammonia, nitric acid Fossil gas, Electricity	Feedstock (kg/kg), Energy use (MJ/kg), CO_2 emissions (kg CO_2/kg)
Ammonium sulphate	Ammonia Fossil gas, Electricity	Feedstock (kg/kg), Energy use (MJ/kg), CO_2 emissions (kg CO_2/kg)
Urea	Ammonia Fossil gas, Electricity	Feedstock (kg/kg), Energy use (MJ/kg), CO_2 emissions (kg CO_2/kg)
Urea ammonium nitrate	Urea, nitric acid Fossil gas, Electricity	Feedstock (kg/kg), Energy use (MJ/kg), CO_2 emissions (kg CO_2/kg)
Other fertilizers and pesticides		
Phosphorus fertilizers	Energy use modeled as fossil gas only	Energy use (MJ/kg), CO_2 emissions (kg CO_2/kg P)
Potassium fertilizers	Energy use modeled as fossil gas only	Energy use (MJ/kg K), CO_2 emissions (kg CO_2/kg K)
Pesticide	Energy use modeled as fossil gas only	Energy use (MJ/kg active substance), CO_2 emissions (kg CO_2/kg active substance)

7. Trade and transportation

7.1 Trade balances and resource/environmental costs of imports

In any global-scale, multi-regional application of ClimAg, trade between regions is represented for all major items that are traded over longer distances. In the case of crops, this includes, for example, most cereals and other dry crops, but excludes bulky crops, such as forages (silage, etc.) and sugar crops.

Upstream resource use and environmental impacts associated with imports to a region are calculated as the weighted average of the resource use and environmental impacts per kg for the exported quantities from all exporting regions. Energy use and emissions associated with the importation transport (see 7.2) are added to the upstream resource use and emissions. Hence, the resource use and emissions per kg of imported items is the weighted average of upstream resource use and emissions plus that of the importation itself.

7.2 Energy use and CO_2 emissions from freight transport

7.2.1 Transport nodes and cargo characteristics

In the ClimAg model, energy use and emissions from freight transport are included for all routes that significantly add to the total environmental impact:

- Transport of crop products from the farm or greenhouse to either: i) food primary processing plant (to make, e.g., flour or oil); ii) food stores for direct consumption (e.g., vegetables and fruits); iii) livestock and aquaculture farms for use as feed; or iv) other processing plants (e.g., biofuels)
- Transport of whole animals and whole milk to processing plants, and whole eggs to food stores
- Transport of processed food from processing plants to food stores for consumption, or secondary processing plants
- Importation of products to a region

Each route is described in terms of distances, divided into distances for "long" distribution and "short" distribution. "Short" distribution refers to shorter legs from or to the point of departure or arrival of the cargo as part of longer routes that use several modes of transport. In ClimAg, short distribution is done by trucks; for long distribution, there are several possible transport modes (see 7.2.2).

In addition to distances, the cargo is described in terms of its pallet density and whether the cargo needs to be chilled during transport. Pallet density is the weight of the cargo per volume required in its packaged form and determines whether weight or volume is the limiting factor for the mode of transport (in maritime shipping, the inverted concept, the "stowage" factor, is used). Chilled transport creates an additional energy requirement on top of that for the locomotion.

7.2.2 Modes of transport

Table 14 describes the freight transport options included in ClimAg. Ground transport options do not include rail transport because of its small importance for the transport of agricultural goods. Furthermore, only fuel-propelled options are included; no electric options are included. Electric trucks are increasingly being deployed in several regions, but still comprise a small percentage of overall truck fleets.

Table 14 Transport modes and their main exogenous parameters included in ClimAg. For sources, see table footnotes.

Parameters	Weight capacity (Mg)[1]	Maximum pallet density (Mg/m^3)[2]	Fuel use per km (liter/km)[1]	Cold transport surcharge (%)[3]	Fuel use per cargo weight and km, at full capacity used (MJ/Mg/km)	CO_2 emissions per cargo weight and km, at full capacity used (g CO_2/Mg/km)
Long distribution						
Road						
“Bulk”	40	1.0	0.48	not applic.	0.43	38
“Semi-trailer”	26	0.28	0.35	30%	0.48	43
“Trailer”	40	0.30	0.42	30%	0.38	34
Sea						
“Bulk”	80,000 DWT	0.80	70	not applic.	0.033	2.8
“Reefer”	100,000 DWT	0.35	700	included	0.26	22.0
“Container”	100,000 DWT (8,000 TEU)	0.35	240	not applic.	0.091	7.6
Air						
“Continental”	41	0.14	7.9	0%	6.5	580
“Inter-continental”	92	0.14	13.4	0%	4.9	440
Short distribution						
“Small”	5.0	0.10	0.25	30%	1.8	160
“Large”	10	0.17	0.40	30%	1.4	130

DWT: deadweight tonnage; TEU: twenty-foot equivalent (container equivalent)
[1] Based on NTM Calc at https://www.transportmeasures.org/en/
[2] Author estimates based on various industry data.
[3] Based on (Swahn, 2008)

8. Food end-use and food waste

In ClimAg, consumption is referred to as "end-use," to distinguish the use of items for consumption from that as feedstock. Food end-use in ClimAg is represented using about 130 items, of which 45 are items from livestock and fish & seafood; see Table 15.

Food end-use in ClimAg is represented as "apparent" consumption, which is the amount of food delivered to the food retail sector. This quantity is estimated on an annual basis using statistics on production.

ClimAg also represents the actual intake of food, that is, the amount of food ingested. Based on detailed descriptions of the chemical composition of food items (see Table 25-29), ClimAg calculates the daily intake per capita of protein, fat, carbohydrates, alcohol, and crude fiber.

Food waste is calculated as the difference between reported apparent consumption in statistics and estimated actual intake per capita, and includes waste in retail, households, restaurants and other food outlets. ClimAg distinguishes between edible and inedible/unpreferred items in food waste. Inedible/unpreferred items include bones, egg shell, hulls, peelings and similar, and is calculated based on allometric data for each item. Edible waste is calculated as a fraction of apparent consumption and is calculated separately for all items in the food basket, to be able to reflect the varying levels of waste for different types of food.

Based on detailed data on upstream resource use and environmental impacts for each food item (Table 23), ClimAg calculates the per-capita resource use and environmental impacts from food end-use. However, ClimAg does not include energy use in retail, for food storage or food preparation. Additionally, the resource use and environmental impacts of food packaging are not included.

Table 15 Food items included in the representation of food consumption.

Item	Comment
Meat	
Beef, Sheep/goat meat, Pork, Chicken	Retail weight. Each meat category is a composite of several meat cuts with varying bone content, see Table 20 for details
Offal	
Offal	Composite of cattle, sheep/goats, pork, and chicken
Eggs	
Hen eggs	Whole weight including shell
Dairy	
Milk/yogurt, Cheese	Composite of cattle and sheep/goat milk/yogurt
Butter, Cream	
Milk powder	Composite of skim and whole-milk powder
Fish/seafood	
Freshwater fish	Fillet. Composite of captured fish, carp, tilapia, and other farmed freshwater fish
Pelagic fish	Fillet. Composite of captured fish, farmed salmon, and farmed non-freshwater fish
Demersal fish	Fillet
Crustaceans	Peeled meat. Composite of captured and farmed crustaceans
Mollusks	Whole weight. Composite of captured and farmed crustaceans
Vegetable meat &dairy substitutes	

Item	Comment
Meat substitute	Composite of four different types, see Table 21
Milk/yogurt substitute	Composite of four different types, see Table 21
Cheese substitute, Cream substitute	
Butter substitute	Composite of three different types, see Table 21
Cereal products	
Wheat flour, Maize grits & meal, Rice (white), Sorghum meal, Millet flour, Oat groats Rye flour, Other cereals	
Starchy tubers	
Cassava, white potato, sweet potato, yams	Unpeeled tuber
Oils & fats	
Soybean oil, Palm oil, Rapeseed oil, Sunflower oil, Peanut oil, Coconut oil, Olive oil, Palm kernel oil, Maize oil, Cotton oil	
Lard	Composite of cattle, sheep/goats, and pork
Pulses	
Common beans, Faba beans, Cowpeas, Chickpeas, Peas (dried), Pigeon peas, Lentils, Other pulses	
Nuts & seeds	
Soybean seeds, Peanuts, Sunflower seeds, Sesame seed, Cashewnut, Almond, Coconut, Other tree nuts	
Vegetables	
Tomato, Okra, Peas (green), Cabbage, Cucumber, Pepper (capsicum), Eggplant, Cauliflower/broccoli, Onion, Carrot, Other vegetables	Composite of open-field and greenhouse produced for tomato, cucumber, pepper and eggplant
Fruits	
Grape, Mango, Plantain, Banana, Apple, Orange, Other temperate fruits, Other topical fruit	
Sweets, stimulants	
White sugar, Cocoa, Coffee, Tea	Sugar is a composite of cane sugar and beet sugar
Alcoholic beverages	
Beer, Wine, Spirits	

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Appendices

Table 16 Crop/pasture sub-systems included in ClimAg.

Sub-system		**Inputs**	**Outputs**	
Category	Sub-system		Main product	Co-products
Open field crops on arable land	Generic	Land; NPK fertilizer; manure; pesticides; diesel, fuel oil, electricity		
	Cereals			
	Wheat		Wheat grains	Wheat straw
	Maize		Maize grains	Maize stover
	Rice – high input		Rice grains	Rice straw
	Rice – low input		Rice grains	Rice straw
	Barley		Barley grains	Barley straw
	Sorghum		Sorghum grains	Sorghum stover
	Millet		Millet grains	Millet straw
	Oats		Oats grains	Oats straw
	Rye		Rye grains	Rye straw
	Other cereal		Other cereals grains	Other cereals straw
	Oil/protein crops			
	Soybean		Soybean seed	Soybean stalk
	Rapeseed		Rapeseed	Rapeseed stalk
	Peanut		Peanut pod	Peanut stalk
	Sunflower		Sunflower seed	Sunflower stalk
	Sesame		Sesame seed	Sesame stalk
	Common beans		Common bean	Common bean stalk
	Faba beans		Faba bean	Faba bean stalk
	Cowpea		Cowpea bean	Cowpea stalk
	Chickpea		Cowpea bean	Chickpea stalk
	Pea (dried)		Cowpea bean	Pea stalk
	Pigeon pea		Pigeon pea	Pigeon pea stalk
	Lentil		Lentil seed	Lentil stalk
	Other		Other beans/seed	Oth. oil/protein stalk
	Starchy roots			
	Cassava		Cassava tuber	Cassava leaf, stem
	White potato		White potato tuber	White potato top
	Sweet potato		Sweet potato tuber	Sweet potato top
	Yam		Yam tuber	Yam top
	Sugar crops			
	Sugarcane		Sugarcane stem	Sugarcane top/leaf
	Sugar beet		Sugar beet tuber	Sugar beet top
	Vegetables			
	Tomato		Tomato fruit	Tomato stalk
	Okra		Okra fruit	Okra stalk
	Pea (green)		Pea seed	Pea stalk
	Cabbage		Cabbage	Cabbage stalk
	Cucumber		Cucumber fruit	Cucumber stalk
	Pepper (capsicum)		Pepper fruit	Pepper stalk
	Eggplant (aubergine)		Eggplant fruit	Eggplant stalk
	Cauliflower & broccoli		Cauliflower/broccoli	Tomato stalk
	Other above-ground veg.		Oth. above-gr. product	Oth. above-gr. residue
	Onion		Onion	Onion top
	Carrot		Carrot tuber	Carrot top
	Other below-ground veg.		Oth. below-gr. product	Oth. below-gr. top

Sub-system		Inputs	Outputs	
Category	Sub-system		Main product	Co-products
	Perennial grass-legume mixtures			
	For harvest		Harvested mass	
	For grazing		Grazed mass	
	Other forages			
	Whole maize		Harvested mass	
	Whole sorghum		Harvested mass	
	Whole wheat		Harvested mass	
	Whole sugarcane		Harvested mass	
	Fiber crops			
	Cotton		Seed cotton	Cotton stalk
	Other crops			
	Green manure		Green manure	
Greenhouse crops	Generic	Land; NPK fertilizer; pesticides; gas, fuel oil, wood fuel, electricity; materials for protective structure (concrete, glass, steel, aluminum, plastic), substrates (perlite, rockwool, peat, bark)		
	Tomato		Tomato fruit	Tomato stalk
	Cucumber		Cucumber fruit	Cucumber stalk
	Pepper (capsicum)		Pepper fruit	Pepper stalk
	Eggplant (aubergine)		Eggplant fruit	Eggplant stalk
Tree and bush crops	Generic	Land; NPK fertilizer; manure; pesticides; diesel, electricity		
	Oil/protein-rich crops			
	Oil palm		Oil palm fruit bunch	Frond, trunk
	Coconut		Coconut	Frond, trunk
	Olive		Olive fruit	Leaf, twig, trunk
	Cashew		Cashew nut w. apple	Leaf, twig, trunk
	Almond		Almond w. hull & shell	Leaf, twig, trunk
	Other tree nuts		Other tree nuts	Leaf, twig, trunk
	Fruit crops			
	Grapes		Grape fruit	Leaf, twig, trunk
	Mango		Mango fruit	Leaf, twig, trunk
	Plantains		Plantain fruit	Leaf, corm, trunk
	Banana		Banana fruit	Leaf, corm, trunk
	Apple		Apple fruit	Leaf, twig, trunk
	Orange		Orange fruit	Leaf, twig, trunk
	Other temperate fruits		Other temperate fruit	
	Other tropical fruits		Other tropical fruit	
	Stimulant crops			
	Cocoa		Cocoa been	Leaf, twig, trunk
	Cocoa		Coffee bean	Leaf, twig, trunk
	Tea		Tea leaf	Twig, trunk
Permanent/ semi-perm. grasslands	Generic	Land; NPK fertilizer; manure		
	On former forest land		Grazed mass	
	On former tropical/sub-tropical grass/woodland		Grazed mass	
	On former temperate/ montane grassland		Grazed mass	
	On former xeric grassland		Grazed mass	

Table 17 Livestock sub-systems included in ClimAg.

Sub-system		Inputs	Outputs	
Category	Sub-system		Main product	Co-products
All	Generic	Land; NPK fertilizer, pesticides; diesel, fuel oil, electricity; Feed, bedding materials, animals		
	Cattle			
	Cattle milk		Whole cattle milk	Slaughter animal (culled cows), calves, manure
	Dairy bulls/heifers		Slaughter animal	Manure
	Beef cattle		Slaughter animal	Manure
	Sheep			
	Dairy herd		Whole sheep milk	Slaughter animal, wool, manure
	Meat herd		Slaughter animal	Wool, manure
	Pigs			
	Pork		Slaughter animal	Manure
	Poultry			
	Egg		Whole egg	Slaughter animal (culled hens), manure
	Broiler		Slaughter animal	Manure

Table 18 Aquaculture/fisheries sub-systems included in ClimAg.

Sub-system		Inputs	Outputs	
Category	Sub-system		Products	Co-products
Aquaculture	Generic	Land; feed; diesel, gas, electricity		
	Freshwater fish			
	Carp		Whole fish	
	Tilapia		Whole fish	
	Other freshwater fish		Whole fish	
	Non-freshwater fish			
	Salmon		Whole fish	
	Other non-freshwater fish		Whole fish	
	Other			
	Crustaceans		Whole crustacean	
	Mollusks		Whole mollusk	
Fisheries	Generic	Diesel		
	Freshwater fish		Whole fish	
	Pelagic fish		Whole fish	
	Demersal fish		Whole fish	
	Crustaceans		Whole crustacean	
	Mollusks		Whole mollusk	
	Fish for reduction		Whole fish	

Table 19 Sub-systems of crop processing for food-type items included in ClimAg. Feedstock stated when consisting of other than whole crop product.

Sub-system		**Inputs**	**Outputs**	
Category	Sub-system		Products	Co-products
Cereals	Generic	Feedstock; fuel oil, gas, electricity		
	Wheat flour		Wheat flour	Brans/middling, germ
	Maize flour		Maize grits, meal & flour	Oil, hominy feed
	White rice		White rice	Broken rice, bran, hulls
	Sorghum flour		Sorghum flour	Oil, hominy feed
	Millet flour		Milet flour	Bran, hulls
	Oat groats		Oat groats	Hulls
	Rye flour		Rye flour	Bran, hulls
	Other cereals flour		Other cereals flour	Bran
Vegetable oils	Generic	Feedstock; fuel oil, gas, electricity		
	Soybean oil		Soybean oil	Meal
	Palm oil		Palm oil	Kernel oil, kernel meal
	Rapeseed oil		Rapeseed oil	Meal
	Sunflower oil		Sunflower oil	Meal, hulls
	Peanut oil		Peanut oil	Meal, hulls
	Coconut oil		Coconut oil	Meal, husks, shells
	Olive oil		Olive oil	Pomace oil
Sugars	Generic	Feedstock; fuel oil, gas, electricity		
	Cane white sugar		Cane white sugar	Molasses, bagasse
	Beet white sugar		Beet white sugar	Molasses, pulp
Alcoholic beverages	Generic	Feedstock; fuel oil, gas, electricity		
	Barley beer		Beer	Brewers' grains, culms, yeast
	Barley spirits		Spirits	Distillers' grains, culms, pot ale syrup
	Grape wine		Wine	Pomace, spent yeast
Starch	Generic	Feedstock; fuel oil, gas, electricity		
	Maize starch		Maize starch	Oil, gluten feed, gluten meal, germ meal
	Cassava starch		Cassava starch	Pomace
	Wheat starch	Wheat flour	Wheat starch	Gluten feed, gluten
	Potato starch		Potato starch	Protein concentrate, starch residue pulp
Protein concentrates	Generic	Feedstock; fuel oil, gas, electricity		
	Soy protein concentrate	Soymeal	Soybean protein concentrate	Soy carbohydrates
	Soybean protein isolate	Soymeal	Soybean protein isolate	Soy carbohydrates
	Pea protein concentrate		Soybean protein concentrate	Pea carbohydrates
	Pea protein isolate		Soybean protein isolate	Pea carbohydrates

Table 20 Sub-systems of livestock and fish/shellfish processing included in ClimAg

Sub-system		**Inputs**	**Outputs**	
Category	Sub-system		Products	Co-products
Dairy	Generic	Whole milk (except for butter); gas, electricity		
	Cattle milk/yogurt & cream		Cattle milk/yogurt	Cream
	Cattle cheese		Cattle cheese	Whey (dried)
	Cattle butter	Cream	Butter	Buttermilk
	Cattle skim-milk powder		Skim-milk powder	
	Cattle whole-milk powder		Whole-milk powder	
	Sheep milk/yogurt & cream		Sheep milk/yogurt	Cream
	Sheep cheese		Sheep cheese	Whey (dried)
Abattoir	Generic	Whole animal; gas, electricity		
	Beef		Fillet/sirloin, round/chuck roast, diced meat, ground meat. All items are boneless	Offal for human consumption, fat for human consumption; rendered fat, meat & bone meal, blood meal, hide, ingesta
	Sheep/goat meat		Leg/chops (7,5% bone), shoulder/ shank (15% bone), diced meat, ground meat	Offal for human consumption, fat for human consumption; rendered fat, meat & bone meal, blood meal, hide, ingesta
	Pork		Ham, chops/loin (10% bone), shoulder (15% bone), belly (bacon), spare ribs (20% bone), ground meat	Offal for human consumption, fat for human consumption; skin, rendered fat, meat & bone meal, blood meal, ingesta
	Chicken		Breast, thigh (20% bone), drumstick (30% bone), wing (45% bone), other	Offal for human consumption; rendered fat, meat, feather & bone meal, ingesta
Fish/shellfish processing - Farmed		Whole animal; gas, electricity		
	Carp		Carp fillet	Fish oil, fish meal
	Tilapia		Tilapia fillet	Fish oil, fish meal
	Catfish & other freshwater fish		Other freshwater fish fillet	Fish oil, fish meal
	Salmon		Salmon fillet	Fish oil, fish meal
	Other non-freshwater fish		Other non-freshwater fish fillet	Fish oil, fish meal
	Crustaceans		Crustacean meat	Shrimp meal
Fish/shellfish processing - Captured		Whole animal; gas, electricity		
	Freshwater fish		Freshwater fish fillet	Fish oil, fish meal
	Pelagic fish		Pelagic fish fillet	Fish oil, fish meal
	Demersal fish		Demersal fish fillet	Fish oil, fish meal
	Crustaceans		Crustacean meat	Shrimp meal

Sub-system		Inputs	Outputs	
Category	Sub-system		Products	Co-products
	Reduction fish		Fish oil, fish meal	

Table 21 Sub-systems of manufacturing of composite food items included in ClimAg.

Sub-system		Inputs	Outputs
Category	Sub-system		Products
Meat substitutes	Generic	Gas, electricity	
	Soybean based, lean (see Table 27 for composition)	Soy protein concentrate, soy protein isolate, vegetable oil	Soy-based meat substitute
	Soybean based, fat (see Table 27 for composition)	Soy protein concentrate, soy protein isolate, vegetable oil	Soy-based meat substitute
	Pea base lean (see Table 27 for composition)	Pea protein concentrate, pea protein isolate, vegetable oil	Pea-based meat substitute
	Pea based, fat (see Table 27 for composition)	Pea protein concentrate, pea protein isolate, vegetable oil	Pea-based meat substitute
Dairy drink substitutes	Generic	Gas, electricity	
	Soy drink/yogurt	Soybean seeds, white sugar	Soy-based milk substitute
	Oat drink/yogurt	Oat groats, vegetable oil	Oat-based milk substitute
	Almond drink	Almond kernels, white sugar	Almond-based milk substitute
	Rice drink	White rice, vegetable oil	Rice-based milk substitute
Other dairy substitutes	Generic	Gas, electricity	
	Plant-based cheese	Starch, coconut oil	Plant-based cheese substitute
	Plant-based cream	Oat groats, vegetable oil	Plant-based cream substitute
	Plant-based butter – rapeseed/sunflower/soy	25% rapeseed oil, 25% sunflower oil, 20% soy oil (30% water)	Plant-based butter substitute
	Plant-based butter – rapeseed/sunflower/palm	25% rapeseed oil, 25% sunflower oil, 20% palm oil (30% water)	Plant-based butter substitute
	Plant-based butter – rapeseed/sunflower/coconut	25% rapeseed oil, 25% sunflower oil, 20% coconut oil (30% water)	Plant-based butter substitute

Table 22 Sub-systems of manufacturing of materials- and fuel-type items included in ClimAg.

Sub-system		Inputs	Outputs	
Category	Sub-system		Products	Co-products
Materials				
	Cotton lint	Seed cotton; fuel oil, gas, electricity	Cotton lint	Cottonseed; cotton oil, cotton meal, ginning waste, hulls, linters
Fuels	Generic	Fuel oil, gas, electricity		
	Biogas	Manure, silage	Biogas	
	Soybean biodiesel	Soybean oil	Biodiesel	
	Oil palm biodiesel	Palm oil	Biodiesel	
	Rapeseed biodiesel	Rapeseed oil	Biodiesel	
	Sunflower biodiesel	Sunflower oil	Biodiesel	
	Animal fat biodiesel	Rendered fat	Biodiesel	
	Wheat ethanol	Wheat grains	Bioethanol	Distillers' grains (dried)

Sub-system		**Inputs**	**Outputs**	
Category	Sub-system		Products	Co-products
	Maize ethanol	Maize grains	Bioethanol	Distillers' grains (dried)
	Cane ethanol	Sugarcane stems	Bioethanol	Electricity
	Cereal straw ethanol	Cereal straw	Bioethanol	

Table 23 Resource use, emissions and foregone carbon stocks represented for each category of sub-systems.

Category	Resource use, emissions, and carbon stock changes represented						
	On-site **(within sub-system) impact parameters included**			**Inputs to sub-system**	***Up-stream*** **impacts included for inputs**		
	Resource use including inputs	**Emissions**	**Carbon stock changes**	**Item**	**Resource use**	**Emissions**	**Carbon stock changes**
Production of crops – open field	Cropland (arable land and land for tree/bush crops) N, P, K fertilizers Manure Pesticides Diesel Fuel oil Electricity	NH_3, NO, N_2O, N_2, NO_3^- plant cultivation and N runoff soils CO_2 and N_2O drained organic soils CH_4 flooded rice CO_2 fuel use	Soil C changes from changes in management Foregone plant and soil C stocks	Diesel, electricity		CO_2 fuels and electricity production	
				NPK fertilizers, pesticides	Fuel and electricity fertilizer and pesticide production	CO_2, N_2O fertilizer and pesticide production	
				Manure	Cropland, permanent grassland, new fixed nitrogen[1], energy	N_2O[2], CH_4[3], CO_2[4] Ammonia, nitrate	Foregone plant and soil C stocks
Production of crops – greenhouse	Land N, P, K fertilizers Pesticides Gas Fuel oil Electricity Materials for protective structure and substrates (see Table 16)	NH_3, N_2O, N_2, NO_3^- plant cultivation CO_2 fuel use	Foregone plant and soil C stocks	Gas, fuel oil, electricity		CO_2 fuels and electricity production	
				NPK fertilizers, pesticides	Fuel and electricity fertilizer and pesticide production	CO_2, N_2O fertilizer and pesticide production	
				Materials for protective structure		CO_2 materials production	
				Substrates		CO_2 substrate production	
Production of livestock (including on-farm produced crops for feed)	Arable land Permanent and semi-perm. grassland N, P, K fertilizers Pesticides Diesel Fuel oil Electricity Purchased livestock feed and bedding materials	NH_3, NO, N_2O, N_2, NO_3^- plant cultivation and N runoff soils CO_2 and N_2O drained organic soils CH_4 animals CH_4 manure NH_3, N_2O and N runoff from manure CO_2 fuel use	Soil C changes from changes in management Foregone plant and soil C stocks	Diesel, fuel oil, electricity		CO_2 fuels and electricity production	
				NPK fertilizers, pesticides	Fuel and electricity fertilizer and pesticide production	CO_2, N_2O fertilizer and pesticide production	
				Feed (see Table 7), bedding materials	Cropland, permanent grassland, new fixed nitrogen[1], energy	N_2O[2], CH_4[3], CO_2[4] Ammonia, nitrate	Foregone plant and soil C stocks

Category	Resource use, emissions, and carbon stock changes represented						
	On-site **(within sub-system) impact parameters included**			**Inputs to sub-system**	***Up-stream*** **impacts included for inputs**		
	Resource use including inputs	**Emissions**	**Carbon stock changes**	**Item**	**Resource use**	**Emissions**	**Carbon stock changes**
Production of farmed fish/shellfish (aquaculture)	Land (ponds only) Gas Diesel Electricity Aquaculture feed	N_2O water mass CH_4 water mass (ponds only) CO_2 fuel use	Foregone plant and soil C stocks (ponds only)	Gas, diesel, electricity		CO_2 fuels and electricity production	
				Feed (see **Error! Reference source not found.**)	Cropland, permanent grassland, new fixed nitrogen[1], energy	N_2O[2], CH_4[3], CO_2[4] Ammonia, nitrate	Foregone plant and soil C stocks
Primary processing of crops, and livestock and aquaculture outputs	Gas Fuel oil Electricity Feedstock (crop products, animals)	CO_2 fuel use		Gas, diesel, electricity		CO_2 fuels and electricity production	
				Feedstock (crop products, animals)	Cropland, permanent grassland, new fixed nitrogen[1], energy	N_2O[2], CH_4[3], CO_2[4] Ammonia, nitrate	Foregone plant and soil C stocks
Secondary processing of outputs from primary processing (bio-diesel, plant-based, etc.)	Gas Fuel oil Electricity Feedstock	CO_2 fuel use		Gas, diesel, electricity		CO_2 fuels and electricity production	
				Feedstock	Cropland, permanent grassland, new fixed nitrogen[1], energy	N_2O[2], CH_4[3], CO_2[4] Ammonia, nitrate	Foregone plant and soil C stocks
Consumption of food, energy, materials	Food, biofuels, cotton			Food, biofuels, cotton	Cropland, permanent grassland, new fixed nitrogen[1], energy	N_2O[2], CH_4[3], CO_2[4] Ammonia, nitrate	Foregone plant and soil C stocks

[1] Includes nitrogen fertilizer and biologically fixed nitrogen.
[2] Includes all potential upstream sources of N_2O (fertilizer production, soils, manure, aquaculture ponds, "indirect" N_2O). Specified separately for fertilizer production, crop farms, and livestock farms.
[3] Includes all potential upstream sources of CH_4 (flooded rice, animals, manure, aquaculture ponds, crop processing). Specified separately for flooded rice, livestock/aquaculture farms, and crop processing.
[4] Includes all potential upstream sources of CO_2 (organic soils, energy use). Specified separately for organic soils, fertilizer/pesticides production, crop and livestock farm energy use, primary and secondary processing energy use, and transportation energy use.

Table 24 Default values on key parameters that represent plant growth in tree and bush crops. For sources, see table footnotes.

	Length of cycle (years)		**Plant mass stock** at end of production phase					**Turnover rate of perennial plant mass** (% of stock per year**)**		
	Establishing	**Production**	**Total (Mg DM/ha)**	**% leaf or frond**	**% twig/branch or corm**	**% trunk**	**% root**	**Leaf or frond**	**Twig/branch or corm**	**Root**
Oil/protein crops										
Oil palm[1]	2,0	23	85	27%	0%	60%	13%	0,5	not applic.	0,30
Coconut[2]	5,0	60	95	27%	0%	60%	13%	0,5	not applic.	0,30
Olive[3]	5,0	60	32	14%	35%	38%	13%	0,5	0,05	0,30
Cashew[4]	2,0	18	40	10%	20%	55%	15%	0,5	0,05	0,30
Almond[5]	3,0	22	30	14%	35%	38%	13%	not applic.	0,05	0,30
Other tree nuts	3,0	22	35	14%	35%	38%	13%	not applic.	0,05	0,30
Fruit crops										
Grape[6]	3,0	27	30	15%	50%	22%	13%	not applic.	0,05	0,30
Mango[7]	4,0	26	50	18%	30%	39%	13%	0,5	0,05	0,30
Plantain	0,5	8,0	15	15%	25%	48%	12%	not applic.	0,1	0,50
Banana[8]	0,5	8,0	19	15%	25%	48%	12%	not applic.	0,1	0,50
Apple[9]	3,0	22	26	15%	50%	22%	13%	not applic.	0,05	0,30
Orange[10]	3,0	47	31	15%	50%	22%	13%	0,5	0,05	0,30
Other fruit - temperate	3,0	22	19	15%	50%	22%	13%	not applic.	0,05	0,30
Other fruit – tropical	2,0	23	13	15%	50%	22%	13%	0,5	0,05	0,30
Stimulant crops[11]										
Cocoa	5,0	60	31	14%	35%	38%	13%	0,5	0,05	0,30
Coffee	5,0	60	28	14%	35%	38%	13%	0,5	0,05	0,30
Tea	3,0	60	20	27%	40%	20%	13%	0,5	0,05	0,30

[1] Based on (Chase and Henson, 2010; Henson and Dolmat, 2003; Kho and Jepsen, 2015; Schmidt, 2007)
[2] Based on (Bhagya et al., 2017; Lasco, 2002; Nair et al., 2018)
[3] Based on (Proietti et al., 2014; Rodrigues et al., 2012)
[4] Based on (Brito de Figueirêdo et al., 2016; Daouda et al., 2017; Richards, 1992; Victor et al., 2021)
[5] Based on (Bartzas et al., 2017; Kendall et al., 2015)
[6] Based on (Hernández-Montes et al., 2022; Morandé et al., 2017)
[7] Based on (Dao et al., 2021; Naik et al., 2019)
[8] Based on (Ganeshamurthy, 2023; Gonçalves and Kernaghan, 2014; Ortiz-Ulloa et al., 2021; Zhao et al., 2014)
[9] Based on (Zanotelli et al., 2015)
[10] Based on (Iglesias et al., 2013; Sahoo et al., 2021)
[11] Based on (Ehrenbergerová et al., 2016; N'Gbala et al., 2017; Ortiz-Ceballos et al., 2020; Somarriba et al., 2013)

Table 25 Allometrics, composition and energy value of crop components. Allometrics and composition as % of dry matter unless otherwise stated. Energy values in MJ/kg dry matter. For tree and bush crops, percentage of product refers to the annual production of the production divided by the annual turnover of all above ground mass, and percentage of roots refers to the annual turnover of root mass divided by the annual turnover of all plant mass. Numbers shown on crop product as percentage of above-ground mass are example data only, valid for East Asia. For sources, see table footnotes.

	ALLOMETRICS[1]		COMPOSITION AND ENERGY VALUE[2]												
	Of above-ground	Of whole plant	DM (at harvest)	DM (at storage)	Protein	Lipid	Carbo-hydrate	Dietary fiber	NDF	GE-HHV	GE-LHV	Human ME	Rumi-nant DE	Pig DE	Chicken ME
Cereal grains															
Wheat – bread quality	49%		81%	86.8%	13.2%	1.7%	80.6%		14.3%	18.4		16.6			
Wheat – feed quality	49%		81%	86.8%	12.0%	1.7%	81.8%		14.3%	18.3			16.3	16.0	14.0
Maize	37%		79%	86.4%	9.3%	4.3%	82.5%		12.0%	18.8		17.2	16.3	16.4	15.3
Rice (in hull, 20% of grain)	44%		78%	88.0%	6.9%	2.3%	79.5%			17.5		15.5			
Barley	44%		81%	86.7%	11.5%	2.1%	78.5%		21.6%	18.2		16.1	15.5	14.8	12.6
Sorghum	37%		83%	86.5%	10.9%	3.4%	81.4%		10.9%	18.6		16.9	15.1	16.4	15.7
Millet	40%		83%	91.3%	12.0%	4.9%	76.5%			18.7		16.9			
Oats	43%		81%	88.1%	10.8%	5.4%	66.9%		37.2%	18.8		15.2	14.2	12.5	10.8
Rye	35%		81%	87.3%	10.3%	1.4%	84.1%		16.2%	18.1		16.6			
Other cereals	40%		81%	87.3%	10.9%	1.6%	82.7%		14.5%	18.1		16.5			
Oil/protein crops products															
Soybean	26%		82%	88.1%	39.5%	21.4%	27.3%	10.6%	12.5%	23.5		20.1	17.2	18.1	16.1
Rapeseed	27%		86%	92.2%	20.7%	45.5%	20.6%			27.9		23.9			
Peanut (pods)		45%	82%	94.3%	24.7%	38.1%	16.1%	7.1%		26.6		21.6			
Nut (78% of pod)				95%	29.5%	48.0%	15%	9.1%		29.2		26.1			
Hull				92%	7.0%	2.0%	20.0%			17.5	15.7				
Sunflower (in hull)	32%		82%	93.2%	17.3%	47.1%	14.6%	6.7%		28.2		23.4			
Kernel (75% of seed)				94%	21.5%	62.2%	9.0%	9.0%		31.8		28.9			
Hull				91%	5.0%	2.7%	31.0%			17.7	15.9				
Sesame	25%		82%	95.3%	18.6%	52.2%	12.5%	11.5%		29.1		25.5			
Common bean	22%		82%	89.0%	24.7%	1.7%	52.8%	16.9%		18.7		15.2			
Faba bean	27%		81%	86.1%	31.1%	1.3%	44.4%	19.0%	16.1%	18.9		14.8	15.5	15.6	11.1
Cowpea	23%		82%	89.0%	26.7%	2.3%	54.4%	12.0%		18.9		15.6			
Chickpea	29%		82%	92.3%	22.2%	6.5%	54.8%	13.2%		19.7		16.6			
Pea (dry)	25%		81%	85.0%	25.3%	1.2%	57.9%	12.6%	14.1%	18.8		15.6	15.9	15.8	11.3
Pigeon pea	23%		82%	89.4%	24.3%	1.7%	53.4%	16.8%		18.7		15.2			
Lentil	28%		82%	91.7%	26.8%	1.2%	57.0%	11.7%		18.8		15.6			
Other oil/protein field crops	24%		82%	90.5%	24.9%	18.8%	39.8%	12.5%		22.4		19.0			
Oil palm (fruit bunches)	48%		52%	52%	3.5%	45.0%				27.5		15.2			
Coconut (whole)	23%		54%	54%	3.2%	16.6%	5.0%			20.0		7.6			
Kernel (21% of nut)				50%	8.0%	68.0%	16.0%			32.5		29.2			
Husk (58% of nut)				70%	1.4%	1.4%	1.4%			16.1	14.5				
Shell & pairings (19%)				70%	2.9%	5.7%	1.4%			18.2	16.4				

	ALLOMETRICS[1]		COMPOSITION AND ENERGY VALUE[2]												
	Of above-ground	Of whole plant	DM (at harvest)	DM (at storage)	Protein	Lipid	Carbo-hydrate	Dietary fiber	NDF	GE-HHV	GE-LHV	Human ME	Rumi-nant DE	Pig DE	Chicken ME
Olive	21%		49%	49%	3.5%	45.0%	29%			26.0		22.1			
Cashew (in shell, no apple)	18%		94.5%	95%	16.7%	39.7%				26.8					
Kernel (76% of nut)				95%	18.9%	46.3%	22.1%			28.2		24.9			
Shell				90%	3.1%										
Almond (in shell, no hull)	55%		93.0%	93%	10.4%	21.6%				22.4					
Kernel (41% of nut)				96%	21,9%	52,1%	9,9%			29,6		25,7			
Shell				91%	2,4%										
Other tree nuts	35%		90%	90%	9.4%	19.0%	68.2%			21.6		18.2			
Starchy roots products															
Cassava		69%	41%	41.0%	3.2%	0.7%	88.5%	4.4%	8.4%	17.3		16.2	15.7	15.0	
White potato		65%	19%	18.5%	7.0%	0.5%	73.0%	13.0%	7.9%	16.9		14.8	15.7	15.6	
Sweet potato		68%	23%	23.0%	6.8%	0.2%	77.4%	13.0%		17.5		15.4		15.7	
Yam		70%	31%	30.5%	5.0%	0.6%	78.4%	13.4%		17.5		15.5			
Sugar crops products															
Sugar cane stems	68%		30%	30.0%	3.0%	1.5%				17.0		6.7			
Sugar beet tubers		69%	23%	23.0%	3.0%	0.5%				17.4		11.4			
Vegetables products															
Tomato	60%		5.3%		15%	2.5%	49%	25%		17.4		13.8			
Okra	50%		10%		19%	1.8%	41%	31%		17.7		13.3			
Pea (green)	26%		20%		26%	2.0%	36%	33%		18.9		13.9			
Cabbage	50%		9.2%		12%	1.1%	51%	28%		17.1		13.4			
Cucumber	50%		3.5%		23%	1.4%	66%	0%		17.5		15.6			
Pepper (capsicum)	50%		8,0%		15%	1.4%	36%	24%		14.6		11.1			
Eggplant	50%		7.0%		14%	2.1%	37%	37%		17.2		12.5			
Cauliflower & broccoli	24%		9.5%		29%	2.3%	31%	28%		18.2		13.3			
Other veg. above ground	50%		9.5%		12%	1.1%	51%	28%		17.1		13.4			
Onion		75%	11%		10.1%	0.9%	67.0%	17.4%		17.5		14.8			
Carrot		70%	11%		8.6%	1.0%	61.0%	22.9%		17.1		14.0			
Other veg. below ground		70%	11%		8.6%	1.0%	61.0%	22.9%		17.1		14.0			
Fruit crop products															
Grape	34%		18.1%		3.5%	0.8%	86.0%	6.9%		17.4		15.4			
Mango	15%		14.3%		5.5%	4.0%	76.2%	11.8%		18.3		11.3			
Plantain	35%		28.4%		3.9%	2.0%	81.0%	8.2%		17.3		3.69			
Banana	45%		21.4%		5.2%	3.3%	74.9%	10.2%		17.4		11.6			
Apple	35%		13.3%		0.6%	0.6%	78.9%	17.9%		17.3		13.8			
Orange	39%		17.4%		5.8%	1.2%	79.0%	11.1%		17.6		8.5			
Other fruits - temperate	40%		16.2%		3.3%	0.9%	81.3%			15.4		14.7			

	ALLOMETRICS[1]		COMPOSITION AND ENERGY VALUE[2]												
	Of above-ground	**Of whole plant**	**DM (at harvest)**	**DM (at storage)**	**Protein**	**Lipid**	**Carbo-hydrate**	**Dietary fiber**	**NDF**	**GE-HHV**	**GE-LHV**	**Human ME**	**Rumi-nant DE**	**Pig DE**	**Chicken ME**
Other fruits – tropical	45%		21.4%		4.9%	3.1%	77.4%			15.9		15.1			
Stimulant crops products															
Cocoa	8,6%		90%		4.2%	17.0%	0%			7.7		8.5			
Coffee	21%		90%		6.4%	0.0%	0%			1.5		2.9			
Tea	50%		95%		12.3%	0.4%	65.4%	3.9%		15.2		13.7			
Fiber crops products															
Seed cotton	35%		91%		14.1%	11.7%	70.1%			20.2					
Straw, stover & stalks															
Wheat straw			91.4%		3.5%	1.4%			78.9%	16.9			8.3		
Maize stover			90.0%		6.0%	1.8%			69.9%	17.1			8,5		
Rice straw			92.8%		3.5%	1.4%			69.1%	14.9			7.2		
Barley straw			92.8%		3.5%	1.4%			80.5%	16.7			8.0		
Sorghum stover			90.9%		3.5%	1.8%			69.9%	17.1			8,5		
Millet straw			90.0%		6.0%	0.7%			75.0%	16.2			8.5		
Oats straw			93.1%		5.0%	1.5%			76.0%	16.7			8.1		
Rye straw			89.6%		3.5%	1.4%			77.9%	16.7			8.2		
Other cereals straw			92.0%		3.5%	1.5%			75.0%	16.9			8.5		
Soybean stalks & husks			89.1%		7.0%	3.5%			79.7%	17.3			9.4		
Rapeseed stalks & husks			92.1%		5.7%	2.1%			74.2%	17.1			6.9		
Peanut stalks (fresh)			20.0%		15.7%	2.8%			35.2%	16.2			11.7		
Sunfl. stalks & thr. heads			75.0%		5.7%	1.5%			66.9%	16.7			7.8		
Sesame stalks			90.0%		5.0%	1.4%			75.0%	16.9			8.5		
Common bean stalks			88.0%		7.1%	1.1%			69.7%	16.6			9.2		
Faba bean stalks & husks			89.7%		7.4%	1.3%			59.6%	16.7			7.9		
Cowpeas stalks & husks			92.5%		17.1%	1.4%			43.2%	16.1			7.3		
Chickpeas stalks & husks			90.4%		5.4%	1.0%			65.6%	16.8			7.5		
Peas stalks & husks			88.8%		8.2%	2.1%			54.9%	16.7			9.8		
Pigeon peas stalks & husks			90.3%		14.5%	1.9%			78.6%	18.0			10.8		
Lentils stalks & husks			92.1%		7.0%	1.5%			60.6%	16.7			9.2		
Other oil/prot. crops straw			83.2%		8.8%	1.8%			63.6%	16.8			8.8		
Cassava leaves			22.5%		24.9%	6.8%			42.3%	19.2			12.4		
Cassava stalks			30.0%		5.0%	1.0%				17.5					
White potato tops			23.0%		10.0%	4.3%			42.7%	16.7			11.0		
Sweet potato tops			13.0%		16.5%	4.8%			42.7%	18.4			11.0		
Yam tops			24.0%		12.0%	2.3%			42.7%	17.4			11.0		
Sugar cane tops & leaves			27.0%		4.9%	1.5%			68.0%	16.8			10.0		
Sugar beet tops & leaves			25.0%		11.0%	1.5%			35.0%	15.0			11.0		
Tomato leaves & stems			18.0%		17.0%					18.5					
Okra leaves & stems			18.5%		24.0%					19.0					

	ALLOMETRICS[1]		COMPOSITION AND ENERGY VALUE[2]												
	Of above-ground	**Of whole plant**	**DM (at harvest)**	**DM (at storage)**	**Protein**	**Lipid**	**Carbo-hydrate**	**Dietary fiber**	**NDF**	**GE-HHV**	**GE-LHV**	**Human ME**	**Rumi-nant DE**	**Pig DE**	**Chicken ME**
Pea seeds leaves & stems			16.0%		17.7%					18.6					
Cabbage leaves & stems			15.0%		20.0%					18.7					
Cucumber leaves & stems			13.5%		15.0%					18.4					
Pepper leaves & stems			14.0%		20.0%					18.7					
Eggplant leaves & stems			14.0%		20.0%					18.7					
Cauli./broc. stems & leaves			13.5%		30.0%					19.3					
Other above-ground veg.			16.2%		18.7%					18.6					
Onion tops			13.0%		10.0%					18.1					
Carrot tops			16.0%		10.0%					18.1					
Other below-ground veg.			15.0%		10.0%					18.1					
Cotton straw			90%		6.4%					16.9					
Leaves, fronds															
Oil palm fronds			40%		7.5%	2.0%	50%			18.1					
Coconut fronds			40%		7.5%	2.0%	50%			18.1					
Olive leaves			40%		10.0%	2.0%	47%			18.2					
Cashew leaves			40%		10.0%					2.4					
Almond leaves			40%		7.5%	2.0%	50%			11.3					
Other tree nuts leaves			40%		7.5%	2.0%	50%			11.3					
Grape leaves			35%		10.0%	6.0%	71%			17.1					
Mango leaves			40%		7.5%	2.0%	50%			11.3					
Plantain leaves			20%		6.5%	5.6%	77%			17.1					
Banana leaves			20%		14.6%	7.7%	69%			18.5					
Apple leaves			40%		7.5%	2.0%	50%			11.3					
Orange leaves			40%		7.5%	2.0%	50%			11.3					
Other fruits			40%		7.5%	2.0%	50%			11.3					
Twigs, branches, corm															
Olive			50%		2.0%										
Cashew			50%		0.9%										
Almond			50%		2.0%										
Other tree nuts			50%		2.0%										
Grape			50%		2.0%										
Mango			50%		2.0%										
Plantain			20%		3.0%										
Banana			20%		3.0%										
Apple			50%		2.0%										
Orange			50%		2.0%										
Other fruits			50%		2.0%										
Trunks															
Oil palm			50%		1.9%										

	ALLOMETRICS[1]		COMPOSITION AND ENERGY VALUE[2]													
	Of above-ground	Of whole plant	DM (at harvest)	DM (at storage)	Protein	Lipid	Carbo-hydrate	Dietary fiber	NDF	GE-HHV	GE-LHV	Human ME	Rumi-nant DE	Pig DE	Chicken ME
Coconut			50%		1.9%										
Olive			50%		1.1%										
Cashew			50%		0.9%										
Almond			50%		1.3%										
Other tree nuts			50%		1.3%										
Grape			50%		1.3%										
Mango			50%		1.3%										
Plantain			6.9%		3.5%	1.5%	84%								
Banana			7.2%		5.1%	3.5%	76%								
Apple			50%		1.3%										
Orange			50%		1.3%										
Other fruits - temperate			50%		1.3%										
Roots															
Wheat		17%			5.6%										
Maize		17%			4.4%										
Rice		14%			4.5%										
Barley		17%			5.6%										
Sorghum		18%			4.4%										
Millet		20%			4.4%										
Oats		18%			5.0%										
Rye		18%			5.6%										
Other cereals		18%			5.6%										
Soybean		16%			5.0%										
Rapeseed		16%			5.0%										
Peanut		16%			5.0%										
Sunflower		16%			5.0%										
Sesame		20%			5.0%										
Common bean		16%			5.0%										
Faba bean		16%			5.0%										
Cowpea		16%			5.0%										
Chickpea		16%			5.0%										
Pea (dry)		16%			5.0%										
Pigeon pea		16%			5.0%										
Lentil		16%			5.0%										
Other oil/protein field crops		16%			5.0%										
Oil palm		11%			3.1%										
Coconut		16%			3.1%										
Olive		12%			3.1%										
Cashew		14%			3.3%										
Almond		6.1%			3.1%										
Other tree nuts		9.2%			3.1%										

	ALLOMETRICS[1]		COMPOSITION AND ENERGY VALUE[2]												
	Of above-ground	**Of whole plant**	**DM (at harvest)**	**DM (at storage)**	**Protein**	**Lipid**	**Carbo-hydrate**	**Dietary fiber**	**NDF**	**GE-HHV**	**GE-LHV**	**Human ME**	**Rumi-nant DE**	**Pig DE**	**Chicken ME**
Cassava		12%			5.0%										
White potato		12%			8.8%										
Sweet potato		12%			8.8%										
Yam		12%			8.8%										
Sugar cane		8%			6.0%										
Sugar beet		12%			6.0%										
Tomato		5,0%			6.0%										
Okra		10%			6.0%										
Pea (green)		16%			5.0%										
Cabbage		6.0%			10%										
Cucumber		6.0%			6.0%										
Pepper (capsicum)		6.0%			6.0%										
Eggplant		6.0%			6.0%										
Cauliflower & broccoli		5.0%			13%										
Other vegetables		5.0%			6.0%										
Onion		5.0%			6.0%										
Carrot		5.0%			6.0%										
Grape		8.0%			3.1%										
Mango		11%			3.1%										
Plantain		6.8%			3.1%										
Banana		5.8%			3.1%										
Apple		8.1%			3.1%										
Orange		7.9%			3.1%										
Other fruits		7.5%			3.1%										
Cocoa		14%			3.1%										
Coffee		12%			3.1%										
Tea		13%			3.1%										
Cotton		17%			5.0%										
Grass-legume on cropland[3]		45%													
Grasses					7.0%										
Legumes					14%										
Perm. and semi-perm. grass		50%[4]			5.0%										

[1] Based on (Bowen et al., 1999; García-Condado et al., 2019; IPCC, 2019; Kage and Stützel, 1999; Kapur et al., 2013; Lam et al., 2018; Palosuo et al., 2015; Reid and English, 2000; Rodríguez et al., 2020; Taghizadeh-Toosi et al., 2014)

[2] Food item composition based on (Public Health England, 2021; U.S Department of Agriculture, n.d.); feed item composition based and (INRA, n.d.; National Academies of Sciences, 2021, 2016; Sauvant, 2004; Wirsenius, 2000)

[3] Additional composition data is available in Wirsenius et al, The full climate cost of agriculture and aquaculture including foregone land carbon storage, *In preparation*

[4] Amount of root mass is assumed to be twice that of above-ground mass, and that the annual turnover of root mass is 50%

Table 26 Composition and energy value of products and by-products from crop processing into food products. Composition as % of dry matter unless otherwise stated. Energy numbers in MJ/kg dry matter. For sources, see table footnotes.

Items[1]	DM (% of fresh)	Protein	Lipid	Carbo-hydrate	Alcohol	Dietary fiber	NDF	GE-HHV	GE-LHV	Human ME	Rumi-nant DE	Pig DE	Chicken ME
Cereal products													
Wheat flour	86.8%	11.7%	0.8%	86.9%		4.1%		18.3		17.4			
Maize grits & flour	86.4%	8.6%	1.2%	88.7%		5.8%		18.2		17.4			
Rice white	87.1%	7.7%	0.7%	89.8%		1.1%		17.8		16.9			
Sorghum flour	86.5%	10.5%	0.7%	86.8%		5.8%		18.1		17.2			
Millet flour	91.3%	11.3%	3.4%	81.5%		5.0%		18.5		17.4			
Oats groats	88.1%	13.6%	6.9%	71.9%		7.5%		19.4		17.7			
Rye flour	87.3%	9.6%	1.3%	85.7%		4.1%		18.1		17.0			
Other cereals flour	87.3%	8.5%	0.6%	89.6%		4.1%		18.0		17.2			
Vegetable oils	100%		100%					39.3		37.0			
Starches													
Wheat starch	88.5%	0.0%	0.1%	99.4%		0.0%		17.4		16.9			
Maize starch	88.2%	0.0%	0.8%	99.2%		0.0%		17.7					
Cassava starch	88.0%	0.0%	0.1%	99.4%		0.0%		17.4		16.9			
Potato starch	88.0%	0.0%	0.1%	99.4%		0.0%		17.4		16.9			
Protein concentrates/isolates													
Soy protein concentrate	90.0%	65.0%	0.5%	18.0%		13.0%	10.0%	21.0		15.3			
Pea protein concentrate	90.0%	65.0%	0.5%	19.0%		13.0%	10.0%	21.1		15.5			
Soy protein isolate	90.0%	90.0%	0.5%	2.0%		5.0%	10.0%	22.7		16.2			
Pea protein isolate	90.0%	90.0%	0.5%	3.0%		4.0%		22.7		16.3			
Sugars													
Cane sugar	100%			100%				17.5		17.0			
Beet sugar	100%			100%				17.5		17.0			
Alcoholic beverages													
Beer	7.4%	2.7%	0.0%	40.5%	54.1%	0.0%		23.8		23.0			
Wine	11.3%	0.0%	0.0%	8.0%	91.2%			28.6		27.8			
Spirits	32.0%	0.0%	0.0%	0.0%	100%			29.8		29.0			
Cereal by-products													
Wheat bran (excl. germ)	87.0%	17.0%	3.9%	62.8%			45.5%	18.4			13.0	10.7	7.9
Maize hominy feed	86.5%	13.3%	5.8%	65.3%			30.0%	18.7		15.5	16.3	14.2	11.2
Rice bran incl. germ	90.0%	15.6%	17.8%	49.1%			26.7%	20.8		17.6	14.5	13.9	13.0
Rice hull	90.0%	0.0%	0.0%	55.0%				14.0					
Sorghum hominy feed	86.5%	13.9%	2.9%	67.6%			30.0%	18.1		14.9	16.3	14.2	11.2
Millet bran	88.5%	16.9%	11.3%	64.4%			45.5%	20.2		18.0	13.0	10.7	7.9
Millet hull	92.0%	2.5%	0.5%	43.0%				16.2		7.9			
Oat hull	89.0%	5.0%	2.5%	57.0%			75.0%	17.6		11.5	7.5		

Items[1]	DM (% of fresh)	Protein	Lipid	Carbo-hydrate	Alcohol	Dietary fiber	NDF	GE-HHV	GE-LHV	Human ME	Rumi-nant DE	Pig DE	Chicken ME
Rye bran incl. germ	87.0%	17.0%	2.0%	69.5%			45.5%	18.1		15.4	13.0	10.7	7.9
Other cereals bran	87.0%	17.0%	3.9%	62.8%			45.4%	18.4		15.0	13.0	10.7	7.9
Vegetable oil by-products													
Soybean meal	87%	50.2%	1.2%	35%		13.4%	14.0%	19.7			15.9	16.6	10.6
Rapeseed meal	87%	36.8%	3.1%	37.0%			32.0%	19.2			13.0	13.1	6.8
Peanut meal	91%	55%	3.1%	28%			15.9%	20.4			16.9	17.0	11.2
Peanut hull	92.0%	7%	3%	20%				17.5					
Sunflower meal	88%	41%	4.1%	25%			40.0%	19.5			12.1	11.3	6.9
Sunflower hull	91%							17.7					
Oil palm kernel meal	92.0%	18.5%	3.6%	46.4%			73.0%	18.4			13.3	8.5	5.1
Oil palm kernel shell	85.0%	6.3%							19.3				
Oil palm mesocarp fiber	63%	7.0%							17.5				
Oil palm empty bunches	43%	5.0%											
Coconut meal	90%	24%	2.1%	49%			55.0%	18.4			14.5	9.9	5.9
Coconut husk	70%	1.4%	1.4%	1.4%				16.1					
Coconut shell & parings	70%	2.9%	5.7%	1.4%				18.2					
Olive pomace oil	100%									37.0			
Olive pomace meal	88%	6.3%	1.5%	52%				15.6					
Starch by-products													
Wheat gluten feed	88,5%	16,8%	5,2%	33,1%			31,6%	18.8			14.4	13.7	10.0
Wheat gluten	94.0%	80,0%	2,1%	17,3%				22,8		17.3	22.0	21.9	16.8
Maize oil	100%	0.0%	100%	0.0%				39.3		37.0			
Maize gluten feed	88.0%	19.8%	6.5%	55.6%			34.1%	19.2			14.7	13.3	8.6
Maize gluten meal	89.5%	67.0%	5.6%	25.7%			2.2%	22.5			22.0	21.9	16.8
Maize germ meal	88.0%	22.2%	2.6%	69%			45.5%	18.4			15.8	14.6	8.4
Potato protein concentrate	92.0%	84.8%	1.1%	1.1%				21.6		15.4			
Sugar by-products													
Cane molasses	73%	5.5%	1.0%	78.8%			0.0%	15.5			13.8	12.8	12.8
Cane bagasse	50.0%	1.8%	0.6%	45.6%				16.7	15.9				
Cane filter cake (pressed)	26.0%	10.0%	11.0%	43.0%				16.3					
Beet molasses	75%	14.0%	0.2%	73.1%			0.0%	16.2			13.8	13.1	11.9
Beet pulp (dried)	89%	9.0%	1.0%	64.0%			41.0%	17.0			13.8	12.5	7.5
Alcohol by-products													
Beer malt culms	89.3%	25.0%	2.0%	52.5%			44.7%	18.4			12.1	9.9	0.0
Brewer's grains	92.0%	26.5%	7.3%	44.9%			0.0%	20.0			15.5	9.9	8.5
Brewer's yeast	94.0%	49.0%	2.4%	39.8%			8.8%	19.8			15.5	9.9	8.5
Wine pomace	20.0%	12.0%	6.0%	47.6%				18.1					
Wine spent yeast	10.0%	50.0%	2.0%	27.5%				19.9					
Spirits malt culms	89.3%	25.0%	2.0%	52.5%			44.7%	18.4			12.1	9.9	0.0
Distiller's grains	92.0%	20.0%	8.0%	50.7%			0.0%	19.9			14.2	10.0	0.0
Pot ale syrup	90.0%	37.0%	2.4%	51.8%			8.8%	19.1			17.8	18.0	0.0

[1] Food item composition based on (Public Health England, 2021; U.S Department of Agriculture, n.d.); feed item composition based and (INRA, n.d.; National Academies of Sciences, 2021, 2016; Sauvant, 2004; Wirsenius, 2000)

Table 27 Composition and energy value of plant-based meat and dairy substitutes. Composition as % of dry matter unless otherwise stated. Energy numbers in MJ/kg dry matter unless otherwise stated. Based on back-of-package information for a large set of plant-based products currently on the market.

Item	DM (% of fresh)	Total protein	Edible protein (% fresh)	Total lipid	Carbohydrate	Dietary fiber	GE-HHV	Human ME (MJ/ kg fresh)
Plant-based milk/yogurt substitutes								
Soy drink (1.8% fat)	9.8%	36.1%	3.5%	19.7%	35.7%	8.2%	22.7	2.0
Oat drink (1.5% fat)	10.0%	10.0%	1.0%	15.0%	65.0%	6.0%	21.4	2.5
Almond drink (1.0% fat)	3.9%	11.0%	0.4%	26.5%	55.6%	6.4%	22.8	0.8
Rice drink (1.0% fat)	12.1%	5.6%	0.7%	8.9%	85.1%	1.0%	19.7	2.3
Plant-based cheese substitutes								
Cheese substitute (21% fat)	45%	0.0%	0%	46.7%	47.0%	0.0%	26.6	11.4
Plant-based butter substitutes								
Butter substitute (70% fat)	71%	0.0%	0%	98.6%	0.0%	0.0%	38.7%	25.9
Plant-based cream substitutes								
Oat cream (13% fat)	20.6%	4.4%	0.9%	63.4%	29.1%	3.4%	31.0	6.1
Plant-based meat substitutes								
Soy based meat, lean (7% fat)	32.5%	52.3%	17%	21.9%	9.0%	10.5%	22.5	6.3
Pea based meat, lean (7% fat)	32.5%	52.3%	17%	21.9%	9.0%	9.7%	22.5	6.3
Soy based meat, fat (20% fat)	43.0%	37.3%	16%	46.8%	5.0%	6.1%	28.0	10.74
Pea based meat, fat (20% fat)	41.0%	39.1%	16%	49.0%	3.4%	3.9%	29.1	10.53

Table 28 Allometrics, composition and energy value of livestock and fish body components. Allometrics as % of fresh weight. Composition as % of dry weight. Numbers shown on allometrics are example data only, valid for East Asia. For sources, see table footnotes.

	ALLOMETRICS OF WHOLE BODY AND CARCASS[1]									COMPOSITION AND ENERGY VALUE[2]					
	Carcass/ fillet - of *whole* body	**Carcass - of *empty* body**	**Lean tissue (of carcass or cut)**	**Fatty tissue (of carcass or cut)**	**Bone (of carcass or cut)**	**Skin (of carcass)**	**Non-carcass parts (of empty body)**	**Digesta (of whole body)**	**Meat cut (of carcass)**	**DM (% of fresh)**	**Total protein**	**Edible protein (% fresh weight)**	**Total lipid**	**Total ash**	**Human ME (MJ/ kg fresh weight)**
WHOLE BODY															
Cattle															
Dairy cows	47.2%	53.0%					47%	11%		40.6%	37.8%	6.9%	48.1%	11.8%	4.0
Beef cows	49.7%	55.8%					44%	11%		40.1%	38.4%	7.4%	48.0%	11.3%	4.3
Dairy bulls	52.4%	58.9%					41%	11%		39.1%	40.4%	7.9%	44.3%	12.8%	3.8
Beef bulls	55.2%	62.0%					38%	11%		38.0%	42.2%	8.7%	42.8%	12.5%	3.8
Beef steers/heifers	52.4%	58.9%					41%	11%		40.0%	38.6%	7.8%	47.7%	11.3%	4.5
Sheep															
Ewes	37.9%	43.6%					56%	13%		46.4%	36.6%	4.8%	49.9%	11.1%	3.5
Lambs	47.4%	54.5%					46%	13%		45.0%	37.5%	6.3%	48.2%	11.8%	4.1
Pigs															
Sows	63.0%	69.2%					31%	9.0%		45.4%	40.5%	7.4%	46.5%	11.5%	6.2
Hogs	70.0%	76.9%					23%	9.0%		38.9%	48.7%	11.1%	40.8%	8.8%	5.8
Chickens															
Laying hens	70.0%	71.4%					29%	2.0%		36.4%	52.6%	9.4%	36.4%	10.7%	5.1
Broilers	73.0%	74.5%					21%	2.0%		36.4%	52.3%	10.1%	37.0%	6.7%	5.4
Fish, shellfish															
Captured															
Freshwater fish	45.0%						47%	15.0%		30.5%	69.8%	10.7%	21.8%	8.4%	2.74
Pelagic fish	50.0%						41%	15.0%		33.0%	67.3%	14.2%	25.5%	7.3%	4.52
Demersal fish	45.0%						47%	15.0%		30.5%	69.8%	10.8%	21.8%	8.4%	3.30
Crustaceans	50.0%						50%			25.3%	76.0%	9.7%	5.1%	18.9%	1.83
Mollusks	40.0%						60%			44.2%	68.8%	7.0%	5.8%	25.4%	1.41
Reduction Fish	45.0%						47%	15.0%		28.0%	71.4%	9.0%	21.4%	7.1%	2.53
Farmed															
Carp	42.0%						50%	16.0%		27.5%	67.3%	7.6%	24.2%	8.5%	2.16
Tilapia	37.0%						55%	17.0%		27.5%	70.9%	7.4%	20.0%	9.1%	1.53
Other freshwater	40.0%						52%	16.0%		26.5%	66.0%	6.4%	24.5%	9.4%	1.75
Salmon	45.0%						46%	17.0%		34.5%	53.6%	9.1%	39.1%	7.2%	3.89
Other non-freshw.	45.0%						46%	16.0%		30.0%	65.0%	9.0%	26.7%	8.3%	2.53
Crustaceans	57.0%						43%			22.5%	77.0%	10.4%	5.1%	17.9%	1.97
Mollusks	20.0%						80%			83.5%	3.4%	2.8%	0.5%	96.2%	0.62

	ALLOMETRICS OF WHOLE BODY AND CARCASS[1]								COMPOSITION AND ENERGY VALUE[2]						
	Carcass/ fillet - of *whole* body	Carcass - of *empty* body	Lean tissue (of carcass or cut)	Fatty tissue (of carcass or cut)	Bone (of carcass or cut)	Skin (of carcass)	Non-carcass parts (of empty body)	Digesta (of whole body)	Meat cut (of carcass)	DM (% of fresh)	Total protein	Edible protein (% fresh weight)	Total lipid	Total ash	Human ME (MJ/ kg fresh weight)
CARCASS															
Cattle															
Dairy cows			63%	20%	17%					43.3%	41.8%	14.6%	44.6%	13.5%	8.5
Beef cows			65%	20%	15%					42.5%	42.7%	15.0%	44.9%	12.4%	8.6
Dairy bulls			68%	14%	18%					40.7%	46.2%	15.0%	38.6%	15.2%	7.2
Beef bulls			72%	12%	16%					38.9%	49.0%	15.7%	36.6%	14.5%	6.9
Beef steers/heifers			65%	20%	15%					42.5%	42.7%	15.0%	44.9%	12.4%	8.6
Sheep															
Ewes			52%	25%	23%					48.4%	36.3%	12.8%	48.1%	15.6%	9.2
Lambs			56%	22%	22%					46.5%	36.3%	13.3%	45.7%	15.7%	8.7
Pigs															
Sows			47.0%	26.0%	22.5%	4.5%				50.8%	34.6%	11.8%	50.3%	15.1%	9.9
Hogs			69.0%	15.5%	11.0%	4.5%				40.7%	46.8%	15.8%	42.3%	10.9%	8.2
Chickens															
Laying hens			60.0%	15.0%	25.0%					39.7%	46.7%	13.4%	41.0%	12.4%	7.3
Broilers			62.0%	15.0%	23.0%					39.3%	47.2%	13.9%	41.1%	11.7%	7.4
MEAT CUTS															
Cattle															
Fillet, sirloin			95%	5.0%	0%				6.4%	28.5%	69%	20%	27%	3.7%	6.2
Round, chuck roast			90%	10%	0%				30%	31.0%	62%	19%	35%	3.3%	7.3
Diced meat			85%	15%	0%				7.5%	33.5%	55%	19%	42%	2.9%	8.3
Ground meat			83%	17%	0%				31%	34.3%	54%	18%	44%	2.8%	8.8
Sheep															
Leg boneless, chops			75%	18%	7.5%				25%	38.0%	48%	18%	43%	8.2%	8.5
Shoulder, shank			70%	15%	15%				22%	40.0%	47%	19%	40%	13%	7.5
Diced meat			85%	15%	0%				14%	33.5%	55%	19%	42%	2.9%	8.3
Ground meat			67%	33%	0%				15%	42.4%	39%	17%	59%	2.0%	12.5
Pigs															
Hams			99%	1.0%	0%				21%	28.7%	74%	21%	21%	4.9%	5.8
Chops, loin			81%	9.0%	10%				21%	37.0%	54%	20%	34%	11%	7.5
Shoulder bone-in			77%	8.0%	15%				16%	38.8%	52%	20%	33%	15%	7.3
Belly (bacon)			55%	45%	0%				12%	51.0%	29%	15%	69%	2.2%	15.5
Spare ribs			60%	10%	30%				4.1%	45.9%	44%	20%	35%	22%	7.8
Ground meat			78%	22%	0%				8.2%	39.5%	46%	18%	51%	3.2%	10.5

	ALLOMETRICS OF WHOLE BODY AND CARCASS[1]									COMPOSITION AND ENERGY VALUE[2]					
	Carcass/ fillet - of *whole* body	**Carcass - of *empty* body**	**Lean tissue (of carcass or cut)**	**Fatty tissue (of carcass or cut)**	**Bone (of carcass or cut)**	**Skin (of carcass)**	**Non-carcass parts (of empty body)**	**Digesta (of whole body)**	**Meat cut (of carcass)**	**DM (% of fresh)**	**Total protein**	**Edible protein (% fresh weight)**	**Total lipid**	**Total ash**	**Human ME (MJ/ kg fresh weight)**
Chickens															
Breast, skin on			97%	3.0%	0%				28%	27.9%	73%	20%	25%	2.0%	6.0
Thigh			68%	12%	20%				27%	37.1%	51%	19%	38%	11%	8.1
Drumstick			60%	10%	30%				15%	38.0%	51%	19%	34%	15%	7.4
Wing			48%	7.0%	45%				10%	39.8%	49%	20%	30%	21%	6.6
BODY TISSUES															
Cattle															
Lean tissue										26.0%	78.1%	20.3%	17.7%	4.2%	5.2
Fatty tissue										76.0%	11.6%	8.8%	88.0%	0.4%	26.2
Bone tissue										69.0%	30.4%		26.1%	43.5%	
Non-carcass parts										45.0%	35.0%		55.0%	10.0%	
Sheep															
Lean tissue										26.0%	78.1%	20.3%	17.7%	4.2%	5.2
Fatty tissue										76.0%	11.6%	8.8%	88.0%	0.4%	26.2
Bone tissue										69.0%	30.4%		26.1%	43.5%	
Non-carcass parts										54.0%	38.0%		54.0%	8.0%	
Wool										98%	93%		6.0%	1.0%	
Pigs															
Lean tissue										28.5%	75.0%	21.4%	20.0%	5.0%	5.7
Fatty tissue										78.9%	8.6%	6.8%	90.5%	0.9%	27.6
Bone tissue										70.0%	30.4%		26.1%	43.5%	
Skin tissue										25.0%	77.5%		20.0%	2.5%	
Other non-carcass										45.0%	57.5%		40.0%	2.5%	
Chickens															
Lean tissue										26.0%	80.0%	20.8%	18.0%	2.0%	5.3
Fatty tissue										80.0%	8.0%	6.4%	90.0%	2.0%	27.7
Bone tissue										48.5%	42.0%		22.0%	36.0%	
Non-carcass parts										30.0%	73.0%		22.0%	5.0%	

[1] Based on (AHDB, 2020a, 2020b, 2020c; Atti and Hamouda, 2004; De Lange et al., 2003; Edman et al., 2023; Everts and Dekker, 1995; Gephart et al., 2021; Hussein et al., 2020; Johansen et al., 2022; Kyriazakis and Whittemore, 2006; Massuquetto et al., 2019; Ovi et al., 2021; Sen et al., 2004; Strid et al., 2014; Whittemore and Yang, 1989; Wirsenius, 2000)

[2] Based on (Aletor et al., 2000; Głowacz-Różyńska et al., 2016; Kiyanzad, 2005; Mahgoub et al., 2000; Mavromichalis et al., 2000; Nordgarden et al., 2002; Tacon and Metian, 2013; Villaverde et al., 2005; Wirsenius, 2000)

Table 29 Composition and energy value of products and co-products from processing of livestock and fish. Composition as % of dry matter unless otherwise stated. Energy numbers in MJ/kg dry matter unless otherwise stated. For sources, see table footnotes.

Item	DM (% of fresh)	Total protein	Edible protein (% fresh)	Total lipid	Carbo-hydrate	Dietary fiber	Ash	GE-HHV	Human ME (MJ/kg fresh)	Rumi-nant DE	Pig DE	Chicken ME
Cattle whole milk and dairy products[1]												
Whole milk (ECM composition)	12.6%	26.2%	3.4%	31.7%	38.1%		4.0%	25.3	2.9			
Milk/yogurt	10.9%	30.8%	3.4%	25.8%	39.0%		4.5%	24.2	2.3			
Cheese	61.3%	45.7%	28.0%	45.7%	2.6%		6.0%	29.2	15.4			
Butter	82%	0.7%	0.6%	97.1%	0.5%		1.7%	38.4	29.8			
Cream	48.1%	6.9%	3.4%	83.2%	8.8%		1.0%	35.9	16.1			
Skim-milk powder	95%	41%	36%	1.2%	52%		5.9%	19.2	15.4			
Whole-milk powder	95%	28%	25%	33.4%	35%		4.0%	25.8	21.9			
Sheep/goat whole milk and dairy products[2]												
Whole milk	15.6%	31.6%	4.9%	33.5%	34.9%		5.6%	25.8	3.5			
Milk/yogurt	15.6%	31.6%	4.9%	33.5%	34.9%		5.6%	25.8	3.5			
Cheese	47.0%	38.3%	18.0%	51.1%	4.3%		6.4%	29.9	12.3			
Egg[1]												
Whole hen egg	39.2%	33.3%	10.9%	26.3%	1.1%		38.8%	18.5	5.1			
Yolk & white (88% of fresh weight)	23.7%	52.3%	12.4%	41.5%	1.7%		3.6%	29.1	5.8			
Shell (12% of fresh weight)	100%						100%					
Meat (average for different retail-weight cuts, see Table 20)[3]												
Beef from suckler cattle herd (0% bone)	32.4%	58.1%	18.8%	38.9%			3.1%	29.0	7.9			
Lamb (7,1% bone)	38.3%	47.5%	18.2%	44.6%			7.8%	28.8	8.7			
Pork (7,0% bone)	38.1%	51.1%	19.5%	40.1%			8.8%	27.8	8.2			
Chicken (18% bone)	34.6%	56.3%	19.5%	33.3%			10.4%	26.4	6.3			
Fish fillets, shell-free seafood[4]												
Captured												
Freshwater fish	30.9%	77.1%	23.8%	18.0%			4.9%	25.3	6.1			
Pelagic fish	41.3%	68.8%	28.4%	27.6%			3.6%	27.1	9.0			
Demersal fish	34.3%	70.0%	24.0%	25.7%			4.4%	26.6	7.3			
Crustaceans	21.9%	88.6%	19.4%	4.6%			6.8%	22.7	3.7			
Farmed												
Carp	24.8%	72.6%	18.0%	22.6%			4.8%	26.0	5.1			
Tilapia	23.2%	86.2%	20.0%	8.6%			5.2%	23.7	4.1			
Other freshwater fish	21.7%	73.7%	16.0%	20.7%			5.5%	25.6	4.4			
Salmon	35.5%	56.9%	20.2%	39.7%			3.4%	29.0	8.7			
Other non-freshwater fish	27.2%	73.5%	20.0%	22.1%			4.4%	26.0	5.6			

Item	DM (% of fresh)	Total protein	Edible protein (% fresh)	Total lipid	Carbo-hydrate	Dietary fiber	Ash	GE-HHV	Human ME (MJ/ kg fresh)	Rumi-nant DE	Pig DE	Chicken ME
Crustaceans	20.7%	87.9%	18.2%	4.8%			7.2%	22.6	3.5			
Dairy by-products[5]												
Cattle whey (dried)	90%	10%		1.0%	80%		9.0%	16.8		15.1	14.9	8.9
Cattle buttermilk	12.1%	38%		8.3%	51%		3.1%	21.1	2.2			
Sheep whey (dried)	90%	10%		1.0%	80%		9.0%	16.8		15.1	14.9	8.9
Slaughter by-products[6]												
Offal for human consumption	33%	53%	17%	26%			21.0%	23	6.1			
Fat for human consumption	100%	0%	0%	100%		39.3	0%	39	37.0			
Rendered fat	100%	0%		100%		39.3	0%	39				
Meat and bone meal	94%	60%		9.6%			31%	18		13.4	11.6	11.5
Blood meal	92%	84%		1.7%			14.3%	20				
Fish and shrimp meal[5]												
Captured												
Freshwater fish	94.0%	82.7%		2.8%			14.4%	20.6		19.0	17.5	15.0
Pelagic fish	94.0%	81.5%		4.9%			13.6%	21.2		19.0	17.5	15.0
Demersal fish	94.0%	82.7%		2.8%			14.4%	20.6		19.0	17.5	15.0
Crustaceans	94.0%	65.0%		5.5%			29.5%	17.5		14.0	13.0	11.0
Reduction fish	94.0%	87.8%		3.5%			8.8%	22.1		19.0	17.5	15.0
Farmed												
Carp	94.0%	82.8%		2.7%			14.5%	20.6		18.5	17.0	14.5
Tilapia	94.0%	83.0%		2.6%			14.4%	20.6		18.5	17.0	14.5
Other freshwater	94.0%	82.9%		2.6%			14.5%	20.6		18.5	17.0	14.5
Salmon	94.0%	74.9%		10.1%			15.0%	21.7		18.5	17.0	14.5
Other non-freshw.	94.0%	82.4%		3.6%			14.0%	20.9		18.5	17.0	14.5
Crustaceans	94.0%	65.0%		5.5%			29.5%	17.5		14.0	13.0	11.0
Fish Oil												
Captured	100%	0%		100%			0%	39.3				
Farmed	100%	0%		100%			0%	39.3				

[1] Based on (Public Health England, 2021; U.S Department of Agriculture, n.d.)
[2] Whole milk composition based on (Balthazar et al., 2017); other on (Public Health England, 2021; U.S Department of Agriculture, n.d.)
[3] Calculated from data in Table 28
[4] Based on (Tacon and Metian, 2013)
[5] Based on (INRA, n.d.; National Academies of Sciences, 2021, 2016; Sauvant, 2004; Wirsenius, 2000)
[6] Offal composition based on (Public Health England, 2021; U.S Department of Agriculture, n.d.); other based on (INRA, n.d.; National Academies of Sciences, 2021, 2016; Sauvant, 2004; Wirsenius, 2000)

Table 30 Composition and energy value of materials and energy products and related by-products. Composition as % of dry matter unless otherwise stated. Energy numbers in MJ/kg dry matter unless otherwise stated. For sources, see table footnotes.

Item	DM (% of fresh)	Density (kg/ liter)	Protein	Lipid	Alcohol	Total C	GE-HHV	GE-LHV	Ruminant DE	Pig DE	Chicken ME
Cotton products and by-products[1]											
Cotton lint	90%		1.4%	0.7%			17.5				
Cottonseed	91%		22.5%	20.0%			22.5		13.8	13.5	8.5
Cotton oil	100%		0.0%	100%			39.3				
Cotton meal	89%		44.4%	3.6%			19.8		14.3	14.0	10.6
Biomass-based fuels and by-products[2]											
Biodiesel (HVO)	100%	0.78					46.7	43.6			
Bioethanol	100%	0.79			100%		29.8	26.8			
Wheat distillers' grains	10.0%		38.0%	7.2%			20.8		16.1	12.5	7.7
Maize distillers' grains	10.0%		29.0%	4.5%			19.7		16.1	12.5	7.7
Fossil-based fuels[3]											
Gas		0.0008				72%	52.6	47.4			
Oil		0.90				84%	46.0	42.0			
Diesel		0.84				86%	45.6	42.6			
Kerosene		0.80				85%	45.8	42.6			
Gasoline		0.75				85%	46.7	43.7			

[1] Based on (INRA, n.d.; National Academies of Sciences, 2021, 2016; Sauvant, 2004; Wirsenius, 2000)
[2] Based on (INRA, n.d.; National Academies of Sciences, 2021, 2016; Prussi et al., 2020; Sauvant, 2004; Wirsenius, 2000)
[3] Based on (Prussi et al., 2020)

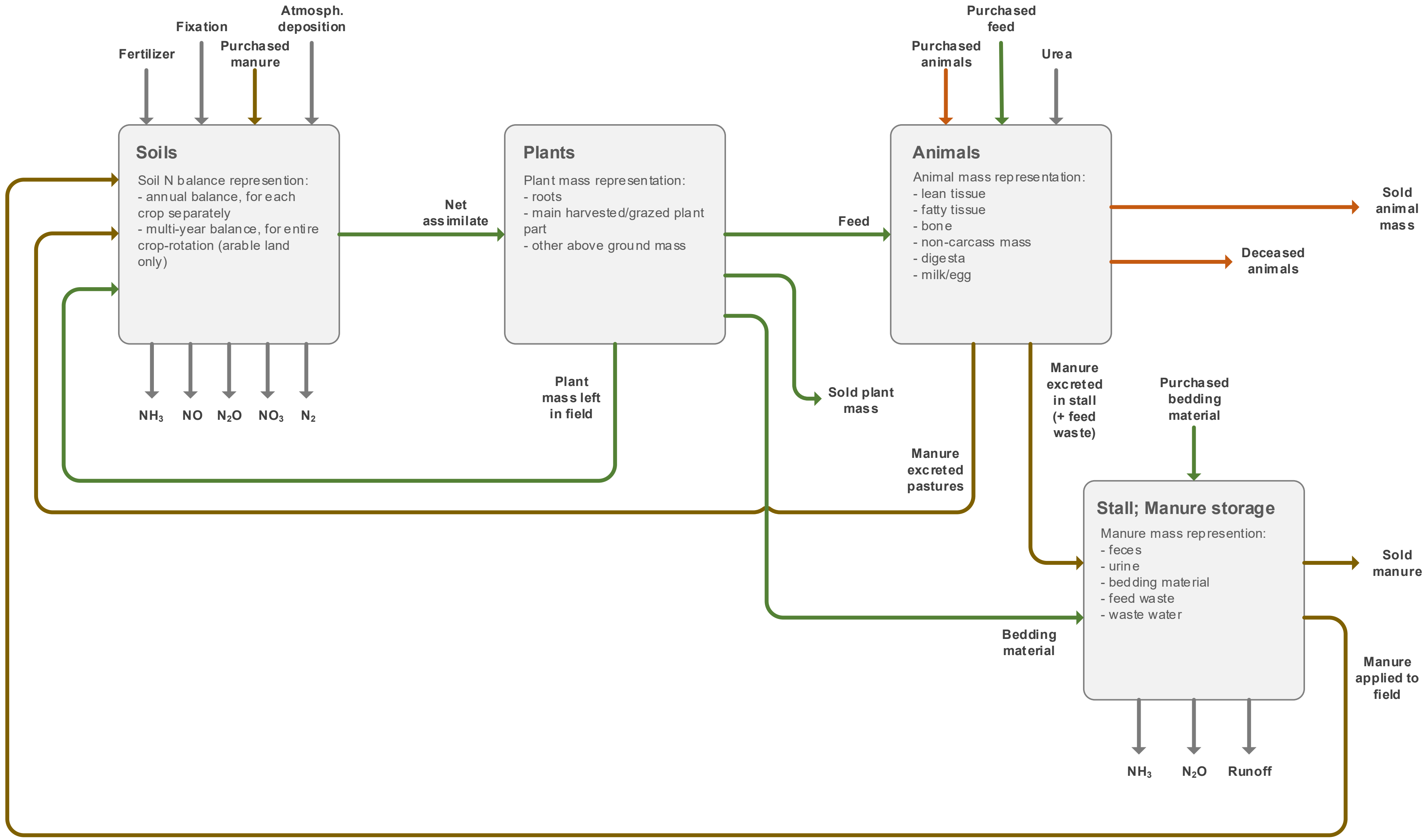

Figure 3 Schematic of the representation of nitrogen flows in crop and livestock modules in the ClimAg model