# Equations used in the analysis

Nitrogen (N) flows and emissions modelling along livestock supply chains is based on material flows analysis and mass balance principle at each process or stage of the supply chains. Thus, total N inputs are equals to total N outputs (products, losses and stock change).

N input = N products + N losses + N stock

In this assessment, the system boundary is from “cradle to the primary processing of animal products”. It includes three interconnected stages: feed production, animal production and processing of animal products. It also considers the loops (recycles of crop residues in the soils) and recycles (e.g. manure application to cropland or grassland).

This document summarises the detailed methodology and algorithms used for N module of the Global Livestock Environmental Assessment Model (GLEAM). For more details on GLEAM, see GLEAM documentation1.

## Animal Module

The calculation of the emissions of NH3, N2O, NOx and N2 is based on European Environmental Agency guidelines38. The emissions are calculated based on the fraction of the total ammoniacal nitrogen (TAN) using the framework developed by Vonk et al39. Specifically, NH3 emissions are estimated from manure management at two levels: NH3 from N deposited in house or yard (the latter referring to confinement area in the USA), and emissions of N compounds (NH3, N2O, NOx, N2) during manure storage and treatment.

### Manure management systems

MMSs during the storage and treatment phase can be considered as solid or liquid manure. A special case is constituted by category “Daily Spread”, which can be liquid or solid depending on the species. The table below shows how to classify this category for each species considered in GLEAM.

**Table 1. Classification of daily spread category of MMS**

|  |  |  |
| --- | --- | --- |
|  | **Liquid** | **Solid** |
| Daily spread | Dairy cattle (mixed), pig | Other cattle (beef), buffalo, small ruminant, poultry |

*Note: When the manure is collected from the house to storage, a part of it is directly spread on agricultural land (cropland or grassland), without any further storage. Thus, NH3 emissions of daily spread are only considered “in house” and during the spreading are allocated to animal production.*

### Emission factors

**Table 2. NH3-N emissions factors from manure management systems, the proportion of TAN based on EEA guidelines**38

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Livestock | Manure type | EFyard | EFhouse | EFstorage | EFspreading | EFgrazing |
| Dairy cattle | Slurry | 0.30 | 0.20 | 0.20 | 0.55 | 0.10 |
| Solid | 0.30 | 0.19 | 0.27 | 0.79 | 0.10 |
| Non-dairy cattle (young cattle, beef, suckling cows) | Slurry | 0.53 | 0.20 | 0.20 | 0.55 | 0.06 |
| Solid | 0.53 | 0.19 | 0.27 | 0.79 | 0.06 |
| Sheep | solid | 0.75 | 0.22 | 0.28 | 0.90 | 0.09 |
| Buffalo | Slurry | NA | 0.20 | 0.17 | 0.55 | 0.13 |
| Solid | 0.75 | 0.22 | 0.28 | 0.90 | 0.09 |
| Goats | Slurry | NA | 0.20 | 0.17 | 0.55 | 0.13 |
| Solid | 0.75 | 0.22 | 0.28 | 0.90 | 0.09 |
| Pigs (fattening) | Slurry | 0.28 | 0.28 | 0.14 | 0.40 |  |
| Solid | 0.28 | 0.27 | 0.45 | 0.81 |  |
| Pigs (sows and piglets) | Slurry | NA | 0.22 | 0.14 | 0.29 |  |
| Solid | NA | 0.25 | 0.45 | 0.81 |  |
| Pasture(outdor) | NA |  |  |  | 0.25 |
| Laying hens | slurry | NA | 0.41 | 0.14 | 0.69 |  |
| Solid | NA | 0.41 | 0.14 | 0.69 |  |
| Broilers | solid | NA | 0.28 | 0.17 | 0.66 |  |

For a country (e.g. USA) with an MMS category of *confinement area*, in house NH3 emissions for MMSconfinment are calculated using emissions factors from the yard.

**Table 3. Emission factors for direct N2O emissions for animal species**

|  |  |  |
| --- | --- | --- |
| Manure type | Species | EF N-N2O |
| Liquid manure without natural crust & Lagoon | Cattle/Buffalo/Pig | 0 |
| Liquid manure with natural crust | Cattle/Buffalo | 0.01 |
| Pig | 0.01 (pit1/pit2/liquid crust) |
| Solid manure | Cattle/goats/sheep/Buffalo | 0.02 |
| Broilers/Layers | 0.002 |
| Pig | 0.01 |

**Table 4. Emission factors for N2O for animal species**

|  |  |  |
| --- | --- | --- |
|  | EF N-N2 | EF N-NOx |
| Liquid manure (slurry) | 0.003 | 0.0001 |
| Solid manure | 0.30 | 0.01 |

* 1. ***Calculation of total ammoniacal nitrogen (TAN)***

The sum of the amount of ammonia (NH3) and ammonium (NH4+) is called total ammoniacal N (TAN). Gaseous N emissions are calculated based on TAN. The excretion of TAN is calculated as the sum of excretion of urine N and net mineralized organically bound N in faeces. The net mineralized organically bound N is used since TAN can also be immobilized and become organic N39.

### N excretion (see GLEAM)

Nexcretion,c = 365 \* (Nintake,c - Nretention,c)

Repeat for all animal cohorts *c*

Unit: kg N animal-1 year-1

### Total Ammoniacal Nitrogen (TAN)

1. *N in the dung (solid)*

Ndung,c = Nintake,c \* (1- Feeddigestibility,c)

Where Feeddigestibility,c = average feed ration digestibility for each cohort *c*

Repeat for all animal cohorts *c*

Unit: kg N animal-1 year-1

1. *N in the dung mineralized*

Ndung\_liquid,c = Ndung,c \* Shareliquid\_manure

Ndung\_solid,c = Ndung,c \* Sharesolid\_manure

Ndung\_mobilized (organic),c = (Ndung\_liquid,c \* Nmineralization-liquid) + (Ndung\_solid,c \* Nmineralization-solid)

Where *Nmineralization* refers to the proportion of mineralization of organically bound N in manure stored in the animal house (liquid or solid)

|  |  |  |  |
| --- | --- | --- | --- |
|  | Liquid | Solid | References |
| Nmineralization | 0.10 | 0.25 | Vonk et al., 2016 |

*Note: The proportions of liquid and solid are calculated based on the classification of the MMSs. The category of manure deposited on pasture (MMSpasture) is excluded in the calculation of TAN in the house as well as for the calculation of emissions in the house and storage, therefore the EF is 0.*

Repeat for all animal cohorts *c*

Unit: kg N animal-1 year-1

1. *N in the urine*

Nurine,c = Nexcretion,c – Ndung,c

Repeat for all animal cohorts *c*

Unit: kg N animal-1 year-1

1. *TAN*

NTAN,c = Nurine,c + Ndung\_mobilized (organic),c

Repeat for all animal cohorts *c*

Unit: kg N animal-1 year-1

### NH3 emissions from manure management systems (First step)

NNH3,c = NNH3\_house,c + NNH3\_ms,c

Repeat for all animal cohorts *c*

Unit: kg N-NH3 animal-1 year-1

### NH3 emissions from animal house

NNH3\_house,c**=** NNH3\_house (liquid),c + NNH3\_ house (solid),c

*For Feedlots production systems*

NNH3\_house (liquid),c =NTAN,c \* ((Share­liquid\_manure - MMSconfinement) \* EF\_NH3\_house (liquid),c + MMSconfinement \* EF\_NH3\_yard)

NNH3\_house (solid) ),c =NTAN,c \* (Share­solid\_manure – MMSpasture)\* EF\_NH3\_house (solid)

*For other production systems*

NNH3\_house (liquid),c =NTAN,c \* Share­liquid\_manure \* EF\_NH3\_house (liquid),c

NNH3\_house (solid) ),c =NTAN,c \* ((Share­solid\_manure – MMSpasture - MMSconfinement)\* EF\_NH3\_house (solid) + MMSconfinement \* EF\_NH3\_yard)

Where:

MMSpasture is the proportion of manure deposited on pasture

MMSconfinement is the proportion of manure deposited in confinement areas

Repeat for all animal cohorts *c*

Unit: kg N-NH3 animal-1 year-1

### NH3 emissions from manure storage

NNH3\_ms,c  = **Ʃj** ((NTAN,c - NNH3\_house,c) \* MMSj \* EF\_NH3\_storage,j)

For each manure management system category *j*, except for MMSdaily, MMSpasture and MMSburned.

Note: for MMSconfinement, the manure is solid (with the only exception of feedlot where is liquid). Therefore, NH3 emissions are estimated for this category using EFstorage for solid manure.

Repeat for all animal cohorts *c*

Unit: kg N-NH3 animal-1 year-1

### NH3 emissions from the daily spread

NNH3\_daily\_spread,c  = **(**NTAN,c - NNH3\_house,c) \* MMSdaily \* EF\_NH3\_spreading

Note: These emissions will be allocated to animal products even if they occur during the application to the land.

Repeat for all animal cohorts *c*

Unit: kg N-NH3 animal-1 year-1

### N2O emissions from manure management systems

NN2O,c**=** Ndirect\_ N2O,c + N­indirect\_N2O,c

Repeat for all animal cohorts *c*

Unit: kg N-N2O animal-1 year-1

#### Direct N2O emissions

Ndirect\_N2O,c = NTAN,c \* Ʃj (MMSj[[1]](#footnote-1) \* EF\_N2Odirect)

For each manure management system category *j*

Repeat for all animal cohorts *c*

Unit: kg N-N2O animal-1 year-1

#### Indirect N2O emissions

Nindirect\_N2O,c = NNH3,c \* EF\_N2Oindirect

EF\_N2Oindirect : Nitrous oxide emission factor for indirect emission following atmospheric deposition of NH3 and NOx, 0.01 kg N-N2O/kg N

Repeat for all animal cohorts *c*

Unit: kg N-N2O animal-1 year-1

### NH3 emissions from manure management systems (Second step)

NNH3\_final,c  = NNH3,c - Nindirect\_N2O,c

Repeat for all animal cohorts *c*

Unit: kg N- NH3 animal-1 year-1

### NOx emissions from manure management

NNOx,c = NTAN,c \* Ʃj (MMSj[[2]](#footnote-2) \* EF\_NOx,c)

Repeat for all animal cohorts *c*

Unit: kg N- NOx animal-1 year-1

#### NOx emissions from manure burned as fuel

NNOx\_burned,c = Nexcretion,c \* MMSburned - NTAN,c \*MMSburned \* EF\_NH3\_house (solid)

Repeat for all animal cohorts *c*

Unit: kg N- NOx animal-1 year-1

### N2 emissions from manure management

NN2,c = NTAN,c \* Ʃj (MMSj2 \* EF\_N2)

For each manure management system category *j*

Repeat for all animal cohorts *c*

Unit: kg N- N2 animal-1 year-1

### N loss from leaching

Nleach,c = Nexcretion,c \* CFleachmanure

CFleachmanure = Ʃ (MMSj2 \* Leachi)

*i* – LEACHliquid or LEACHsolid

*j* – Manure management system category

Repeat for all animal cohorts *c*

Unit: kg N-NO3.animal-1 year-1

### Total N losses from MMS per animal

Nemissions\_tot,c = NN2O,c + NNH3\_final,c  + NNOx,c + NN2,c + Nleach,c + NNH3\_daily\_spread,c

Repeat for all animal cohorts *c*

Unit: kg N.animal-1 year-1

### Organic N losses - discharge per animal

Ndischarge,c = (Nexcretion,c –Nemissions\_tot,c) \* (1 - MMSpasture – MMSconfined – MMSdaily - MMSburned) \* Discharge\_fraction

Repeat for all animal cohorts *c*

Unit: kg N-NO3.animal-1 year-1

### NOx loss from incineration

NNOx\_incineration,c = (Nexcretion,c –Nemissions\_tot,c) \* (1 - MMSpasture – MMSconfined – MMSdaily - MMSburned) \* Incineration\_fraction

Repeat for all animal cohorts *c*

Unit: kg N-NOx.animal-1 year-1

### Manure N disposed of in public sewage

Npubbsewage,c = (Nexcretion,c –Nemissions\_tot,c) \* (1 - MMSpasture – MMSconfined – MMSdaily - MMSburned) \* Pubbsewage\_fraction

Repeat for all animal cohorts *c*

Unit: kg N.animal-1 year-1

### Manure N disposed of in dumping

Ndumping,c = (Nexcretion,c –Nemissions\_tot,c) \* (1 - MMSpasture – MMSconfined – MMSdaily - MMSburned) \* Dumping\_fraction

Repeat for all animal cohorts *c*

Unit: kg N.animal-1 year-1

### NOx loss from energy

NNOx\_energy,c = NNOx\_burned,c + NNOx\_incineration,c

Repeat for all animal cohorts *c*

Unit: kg N-NOx.animal-1 year-1

### Indirect Emissions N2O

Reference: *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*

### N2O emissions from N leaching

NN2O\_leaching,c = Nleach,c \* EF\_N2O\_rivers

Where: EF\_N2O\_rivers =0.0075 kg N2O-N/kg N input

### N2O emissions from discharged manure

NN2O\_discharge,c = Ndischarge,c \* EF\_N2O\_discharge

Where: EF\_N2O\_ discharge = 0.01 kg N2O-N/kg N input

Note EF\_N2O\_discharge is equal to the sum of EFrivers (0.0075) and EFestuaries (0.0025).

### N2O emissions from public sewage

NN2O\_PublicSewage,c = Npubbsewage,c \* EF\_N2O\_sewage

Where: EF\_N2O\_ sewage = 0.01 kg

Repeat for all animal cohorts *c*

Unit: kg N-N2O.animal-1 year-1

### N2O emissions from dumping

NN2O\_Dumping,c = Ndumping,c \* EF\_N2O\_dumping

Where: EF\_N2O\_ dumping = 0.2 kg

Repeat for all animal cohorts *c*

Unit: kg N-N2O.animal-1 year-1

### Manure N losses

Nlosses,c = Nemissions\_tot,c + Ndischarge,c + NNOx\_energy,c + Npubbsewage,c + Ndumping,c

Repeat for all animal cohorts *c*

Unit: kg N.animal-1 year-1

### Manure N not collected

Nnot-collected,c = Nexcretion,c \* MMSconfinement – NTAN,c \* MMSconfinement \* (EFNH3yard + EFNH3solid + EFN2O + EFNOx + EFN2 + EFleachN)

These are N losses from confinement for different N compounds

Repeat for all animal cohorts *c*

Unit: kg N.animal-1 year-1

### Manure N for recycling

Nrecycled,c = Nexcretion,c –Nlosses,c –Nnot-collected,c

Repeat for all animal cohorts *c*

Unit: kg N.animal-1 year-1

### Manure N for recycling in agriculture

Nrecycled\_agr,c = Nrecycled,c –Nrecycled,c \* fishpond\_fraction

Repeat for all animal cohorts *c*

Unit: kg N.animal-1 year-1

### Manure N compounds

N-N20,c = NN2O,c + NN2O\_leaching,c + NN2O\_Discharge,c + NN2O\_PublicSewage,c + NN2O\_Dumping,c

N-NH3,c =NNH3\_final,c

N-NOx,c =NNOx,c + NNOx\_energy,c

N-NO3­,c = Nleach,c + Ndischarge,c - NN2O\_Discharge,c - NN2O\_leaching,c

N-N2,c = NN2,c

Repeat for all animal cohorts *c*

Unit: kg N.animal-1 year-1

### Total outputs – all animals

Nintake = Ʃc(365 \* headsc \* Nintake,c)

Nexcretion = Ʃc(headsc \* Nexcretion,c)

Losses:

* N-N20 = Ʃc(headsc \* N-N20,c)
* N- NH3= Ʃc(headsc \* N- NH3,c)
* N- NOx = Ʃc(headsc \* N- NOx,c)
* N- NO3­= Ʃc(headsc \* N- NO3­,c)
* N-N2= Ʃc(headsc \* N- N2,c)

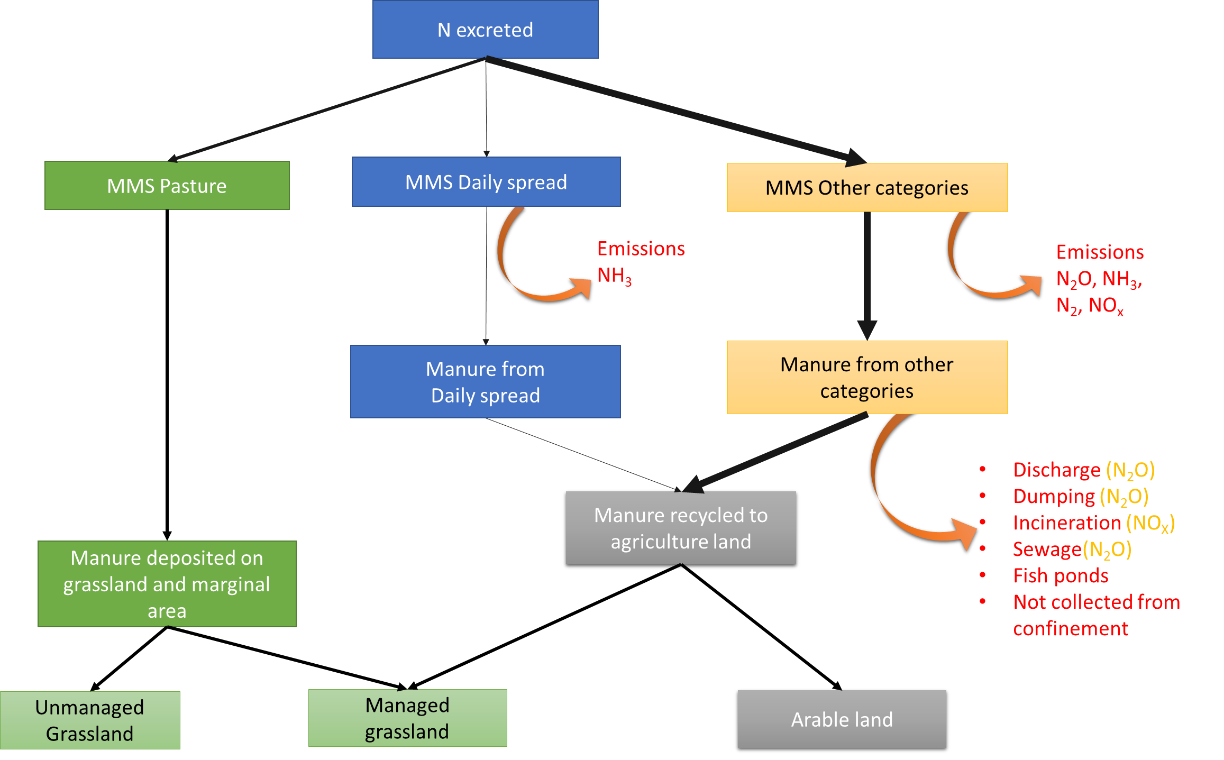
N Outputs:

Nretention = Ʃc(365 \* headsc \* Nretention,c)

Nrecycled = Ʃc(headsc \* Nrecycled,c)

Nrecycled\_agr = Ʃc(headsc \* Nrecycled\_agr,c)

## Manure Module



**Figure S12. Diagram of manure storage and application to land**

### Input data

Cropland\_ha = hectares of croplands, calculated from GLC70 share layers

Grassland\_ha = hectares of grassland, calculated from GLC share layers

Herbaceous\_ha = hectares of herbaceous vegetation, calculated from GLC share layers

Shrubland\_ha = hectares of shrublands, calculated from GLC share layers

Sparse\_ha = hectares of sparse vegetation, calculated from GLC share layers

Bare\_ha = hectares of bare soils, calculated from GLC share layers

HerdNrecycled\_agr,h = total N available for recycle in agriculture for each pig herd *h,* unit: kg N

HerdNrecycled,h = total N available for recycle for each herd *h,* unit: kg N

MMSpastur,hr  = proportion of manure deposited on pasture for each ruminant herd *hr*

Threshold = maximum amount of N that can be deposited or applied per hectare = 700 kg N/ha17.

### Surfaces

Three main surfaces need to be defined for manure application or deposition: 1) cropland, used for the N available for application from ruminants and monogastrics; 2) grassland, used for the application of the surplus manure not applied on cropland from ruminants and monogastrics and for part of the deposited manure from ruminants; 3) other natural areas (herbaceous, shrubland, sparse vegetation and bare areas), used for part of the deposited manure from ruminants.

Cropland\_ha = from GLC share

Grassland\_ha = from GLC share

OtherNatural\_ha = Herbaceous\_ha + Shrubland\_ha + Sparse\_ha + Bare\_ha

Unit: ha

### Totalization of the N available

#### N available by the herd

1. *Pigs*

HerdNavailableh = HerdNrecycled\_agr,h

1. *Other species*

HerdNavailableh = HerdNrecycled,h

For each herd *h*

­Unit : kg N

#### N available for deposition by ruminant herd

HerdNavailabledep\_hr = HerdNexcretion\_hr \* MMSpasture\_hr

For each ruminants herd *hr*

­Unit : kg N

#### N available for application by herd

1. *Monogastrics*

HerdNavailableappl,h = HerdNavailableh

1. *Ruminants*

HerdNavailableappl,h = HerdNavailableh - HerdNavailabledep,h

For each herd *h*

­Unit : kg N

#### Total N available for application or deposition

Navailableappl = **Ʃ** h (HerdNavailappl,h)

For each herd *h*

Navailabledep = **Ʃ** hr (HerdNavaildep,hr)

For each ruminant herd *hr*

Navailabledep\_grass =Navailabledep \* (Grassland\_ha / (Grassland\_ha + OtherNatural\_ha))

Navailabledep\_othnat =Navailabledep \* (OthNat \_ha / (Grassland\_ha + OtherNatural\_ha))

*Note: N available for deposition from ruminants needs to be allocated to grassland and other natural areas, according to the proportion of available hectares from the two categories. This allocation excludes the N available for deposition in areas where there is no cover of neither grassland nor the other natural areas considered (mostly woodlands) and that, therefore, remains unassigned and allocated to the “Surplus manure-N from deposition”.*

Unit : kg N

### Shares of N available from each herd

Shareappl,h = HerdNavailableappl,h / Navailableappl

For each herd *h*

Sharedep,hr = HerdNavailabledep,hr / Navailabledep

For each ruminants herd *hr*

Note: These shares will be necessary to allocate N inputs from manure to different herd and production systems when calculating the indicators.

### Manure-N deposited on other natural areas from ruminants

Nmax\_othnat = OthNat\_ha \* Threshold

IF:

Navailabledep\_othnat ≤ Nmax\_othnat

THEN:

Ndepositedothnat = Navailabledep\_othnat

ELSE:

Ndepositedothnat = Nmax\_othnat

Unit: kg N

### Manure-N applied on croplands

Nmax\_cropland = Croplands\_ha \* Threshold

IF:

Navailableappl ≤ Nmax\_cropland

THEN:

Nappliedcropland = Navailableappl

ELSE:

Nappliedcropland = Nmax\_cropland

1. *Note: at first, all N available for application from ruminants and monogastrics is used for croplands.*

Unit: kg N

### Manure-N applied or deposited on grasslands

Nmax\_grass = Grassland\_ha \* Threshold

Navailalbeappl\_grass = Navailableappl  - Nappliedcropland

Note: N in excess from the application to croplands is available for application on grasslands

Nmax\_grass\_dep = Nmax\_grass \* (Navailabledep\_grass / (Navailabledep\_grass + Navailableappl\_grass))

Nmax\_grass\_appl = Nmax\_grass \* (Navailableappl\_grass / (Navailabledep\_grass + Navailableappl\_grass))

*Note: in order to keep track of the amount of N applied or deposited, the maximum amount of N allowed on grasslands must be allocated to N applied or deposited, according to the proportion of N available from the two sources for grasslands.*

**N deposited on grassland**

IF:

Navailabledep\_grass ≤ Nmax\_grass\_dep

THEN:

Ndepositedgrass = Navailabledep\_grass

ELSE:

Ndepositedgrass = Nmax\_grass\_dep

**N applied on grassland**

IF:

Navailableappl\_grass ≤ Nmax\_grass\_appl

THEN:

Nappliedgrass = Navailableappl\_grass

ELSE:

Nappliedgrass = Nmax\_grass\_appl

Unit: kg N

### Manure-N application or deposition rates and surplus manure

#### Total Manure-N deposited or applied

Ndeposited = Ndepositedgrass + Ndepositedothnat

Napplied = Nappliedgrass + Nappliedcropland

Unit: kg N

#### Surplus Manure-N from deposition or application

Nsurplusdep = Navailabledep - Ndeposited

Nsurplusappl = Navailableappl - Napplied

Nnotassigndep = Navailabledep – (Navailabledep\_grass + Navailabledep\_othnat)

*Note: this is the amount of N available for deposition in areas where there is no cover of neither grassland nor the other natural areas considered and that, therefore, remains unassigned. These areas should be mostly woodlands. This N is already included in Nsurplusdep. Here it’s calculated separately, to keep track of its magnitude.*

Unit: kg N

### Surfaces

The agricultural area is aggregated for the calculation of deposition and application rates.

Grassland\_hadep = Grassland\_ha \* (Ndepositedgrass / (Ndepositedgrass + Nappliedgrass))

Grassland\_haappl = Grassland\_ha \* (Nappliedgrass / (Ndepositedgrass + Nappliedgrass))

*Note: hectares of grassland need to be allocated between N deposited and N applied, since they are receiveing both the fluxes of N.*

HAdep = Grassland\_hadep +OthNat\_ha

HAappl = Grassland\_haappl + Cropland\_ha

Unit: ha

### Rates

Ndepha = Ndeposited / HAdep

Napplha = Napplied / HAappl

Unit: kg N.ha-1

## Feed Module

### Input data

* Crop residue (GLEAM) – *kg N/ha*
* BNF (Biological N fixation)4–6– *kg N/ha*
* Ndfa (fraction of plant N delivers from N2 fixation) – a *fraction*
* Synthetic fertilizer – *kg N/ha*
* Manure (GLEAM raster for local feeds, adjusted by FAO trade matrix for non-locals)– *kg N/ha*
* Gross yield (DMYGcrop), Yield of crop residues (DMYGcr) (see GAEZ; dry matter yield of the main crop or crop residues, respectively) – *kg N/ha*
* Atmospheric N deposition12 – *kg N/ha*
* Mineralization factor (Miner\_f) = 0.1 for grass , 0.3 for crop  *– fraction*
* N content of the main crop (Ncrop), N content crop residues (Ncr), N content below-ground biomass Nbg (derived from GLEAM) – k*g N/kg DM*
* Rbg-bio (fraction of below-ground residues to above-ground biomass by feed component) - *fraction*40
* Nyield-w (N yield of the whole plant; this is calculated following the IPCC guidelines40) – k*g N/ha*
* FUE (GLEAM) *– a fraction*
* MFA (GLEAM) *– a fraction*
* Feed fraction (Feed\_frac, GLEAM; share of each component in the ration) *– a fraction*
* Total feed intake per herd (Herd\_DM\_intake, DM) – *kg DM/year*
* Manure unregulated disposed of (Manure\_discharge, share of manure that is discharged) – a *fraction*

### Total N output [kg N/ha]

Nyield-wi = (DMYGcrop,i \* Ncrop,i + DMYGcr,i \* Ncr,i) + (Rbg-bio,i \* (DMYGcrop,i + DMYGcr,i) \* Nbg,i)

total\_output\_hai = Nyield-wi

Repeat for all feed items *i*

### Total N input [kg N/ha]

total\_input\_hai = ferti + crop\_residi + manurei + at\_depi + BNFi

BNFi = Nyield-wi \* Ndfai

Note: the equation above is used only for soy products, pulses, legumes and rapeseed. Other feed items use default BNF values.

Repeat for all feed items *i*

### N loss surface soil [kg N/ha]

#### Direct N loss N2O

1. *Grass*

dir\_N2O\_lossi = (Nfertillizeri + Ncrop\_residuesi) \* 0.01 + Nmanurei \* 0.02

1. *Other Crops*

dir\_N2O\_lossi = (Nfertillizeri + Ncrop\_residuesi + Nmanurei) \* 0.01 *(0.003 for rice)*

Repeat for all feed items *i*

#### Indirect N loss NH3

ind\_NH3\_lossi = (Nfertillizeri + Ncrop\_residuesi) \* 0.1 + Nmanurei \* 0.2

Repeat for all feed items *i*

#### Direct Runoff Organic N and NO3

*Calculation of runoff fraction*

The surface runoff fractions are expressed in percentage of the N applied as synthetic fertilizer and manure71. The following factors are included in estimate:

* The slope
* Precipitation
* Land cover

The surface runoff is calculated as follows:

runoff= **LF** surface runoff, max \* **f**lu \* **f**p / 100

Where:

**runoff** = Runoff fraction of the N applied via fertilizer and manure (including grazing)

**LF** surface runoff, max = the maximum runoff fraction for different slope classes, based on Reuter et al 72

|  |  |
| --- | --- |
| **Slope** | **LF surface runoff, max** |
| Level (dominant slope ranging from 0 to 8%) | 10% |
| Sloping (dominant slope ranging from 8 to 15%) | 20% |
| Moderately steep (dominant slope ranging from 15 to 25%) | 35% |
| Steep (dominant slope over 25%) | 50% |

**f**lu – reduction factor for land cover (**f**lu cropland = 1, **f**lu grassland = 0.25) obtained from FAO70

**f**p – reduction factor for precipitation based on Harris et al73

|  |  |
| --- | --- |
| **Precipitation surplus, mm** | **fp** |
| >300 | 1 |
| 100-300 | 0.75 |
| 50-100 | 0.50 |
| <50 | 0.25 |

*Calculation of runoff N losses*

N\_runoffi = (Nfertilizeri + Nmanurei) \* runoff

Repeat for all feed items *i*

#### Total N loss surface soil

1. *Grass*

Surface\_loss\_crop\_hai = dir\_N2O\_loss\_grassi + ind\_NH3\_lossi + n\_runoffi

1. *Other Crops*

surface\_loss\_crop\_hai = dir\_ N2O\_loss\_cropi + ind\_NH3\_lossi + n\_runoffi

Repeat for all feed items *i*

#### Organic N stock [kg N/ha]66,74

miner\_f\_grass = 0.1

miner\_f\_crop = 0.3

#### N stock in manure

1. *Grass*

stock\_manurei = (Nmanurei - (Nmanurei \* runoff + Nmanurei \*(0.02 + 0.2)))\*miner\_f\_grass

1. *Rice*

stock\_manurei = (Nmanurei - (Nmanurei \* runoff + Nmanurei \*(0.003 + 0.2)))\*miner\_f\_crop

1. *Other crops*

stock\_manurei = (Nmanurei - (Nmanurei \* runoff + Nmanurei \*(0.003 + 0.2)))\*miner\_f\_crop

Repeat for all feed items *i*

#### N stock in residues

1. *Grass*

stock\_residuesi = (crop\_residuesi - crop\_residuesi \* (0.01 + 0.1)) \* miner\_f\_grass

1. *Rice*

stock\_residuesi = (crop\_residuesi - crop\_residuesi \* (0.003 + 0.1)) \* miner\_f\_crop

1. *Other crops*

stock\_residuesi = (crop\_residuesi - crop\_residuesi \* (0.01 + 0.1)) \* miner\_f\_crop

Repeat for all feed items *i*

#### Total organic N stock

organic\_stocki = stock\_manurei + stock\_residi

Repeat for all feed items *i*

#### N surplus [kg N/ha]

surplusi = total\_input\_hai – surface\_loss\_crop\_hai - organic\_stocki - total\_output\_hai

Repeat for all feed items *i*

#### Leaching in soil ant total N losses [kg N/ha]

leaching = 0.1

If surplusi > 0

Soil\_leachingi = surplusi \* leaching + (surplusi \* (1 – leaching)) \* 0.7

Note: 70% of surplus will be lost via leaching

If surplusi ≤ 0

Soil\_leachingi = 0

Repeat for all feed items *i*

#### Final calculation of N2O emissions [kg N/ha]

Indirect\_N20\_leachingi = (soil\_leachingi + n\_runoffi) \* 0.0075

Total\_N2O\_emissionsi = dir\_N2O\_lossi + Indirect\_N20\_leachingi

Repeat for all feed items *i*

#### Total N losses [kg N/ha]

Total\_loss\_crop\_hai = surface\_loss\_crop\_hai + soil\_leachingi

Repeat for all feed items *i*

#### Total N stock [kg N/ha]

IF surplusi > 0

Extra\_stocki = (surplusi \* (1 – leaching )) \* 0.3

IF surplusi ≤ 0

Extra\_stocki = surplusi

Total\_stock\_changei = Extra\_stocki + organic\_stocki

Repeat for all feed items *i*

#### N Feed intake by feed component (kg N)

Total\_N\_intakei = herd\_DM\_intake \* feed\_fraci \* N\_contenti[[3]](#footnote-3) / 1000

Repeat for all feed items *i*

#### N allocation fractions

1. *For grass*

FracNgrass = Ngrass \* DMYGgrass / output\_hagrass

Note: for GRASS feed items, FUE is not considered in order to account for the grazing of different species on the same pastures, avoiding over estimation of the required area in later calculations.

1. *For crops*

FracNi = Ncrop,i \* DMYGcrop,i \* FUEi / output\_ha,i

1. *For crop residues*

FracNi = Ncr,i \* DMYGcr,i \* FUEi / output\_hai

1. *For by-products*

FracNi = Nby-prod,i \* DMYGcrop,i \* MFAi \* FUEi / output\_hai

Repeat for all feed items *i*

#### Area requirement (ha)

areai = Total\_N\_intakei / (output\_hai \* FracNi)

Repeat for all feed items *i*

### Total N flows (kg N)

#### Crop total N input

crop\_total\_input = Ʃi (total\_input\_hai \* areai)

#### Crop total N output

crop\_total\_output = Ʃi (total\_output\_hai \* areai)

#### Crop total N soil stock changes

crop\_total\_stock\_change = Ʃi (stock\_change\_hai \* areai)

#### Crop total N losses

crop\_total\_loss = Ʃi (total\_loss\_crop\_hai \* areai)

### Nitrogen compounds (kg N)

#### Total NH3 emissions

crop\_total\_ammonia = Ʃi (ind\_NH3\_lossi \* areai)

#### Total N2O emissions

crop\_total\_nitrous\_oxide = Ʃi (Total\_N2O\_emissionsi \* areai)

#### Total N leaching and runoff (NO3-, organic N compound)

crop\_total\_runoff\_leaching = Ʃi (((n\_runoffi + soil\_leachingi) - Indirect\_N20\_leachingi) \* area)

### Allocation of feed module outputs for livestock aggregation

#### Allocation factors by feed component

ALLOCi = Total\_N\_intakei / (crop\_total\_outputi - crop\_total\_residuesi)

Repeat for all feed items *i*

#### Total flows and compounds allocation

Total\_area\_a = Ʃi (areai \* ALLOCi)

crop\_total\_input\_a = Ʃi (total\_input\_hai \* areai \* ALLOCi)

crop\_total\_output\_a = Ʃi (total\_output\_hai \* areai \* ALLOCi)

crop\_total\_stock\_change\_a = Ʃi (stock\_change\_hai \* areai \* ALLOCi)

crop\_total\_loss\_a = Ʃi (total\_loss\_crop\_hai \* areai \* ALLOCi)

crop\_total\_ammonia\_a = Ʃi (ammonia\_hai \* areai \* ALLOCi)

crop\_total\_nitrous\_oxide\_a = Ʃi (nitrous\_oxide\_hai \* areai \* ALLOCi)

crop\_total\_runoff\_leaching\_a = Ʃi (N\_runoff\_leaching\_hai \* areai \* ALLOCi)

## PROCESSING MODULE

### Pigs (meat)

#### Processing inputs

*Slaughter animals*

Np\_inputc = (Slaughter\_weightc ^0.75) \* 0.025 \* exit\_numberc

Repeat for all animal cohorts *c*

*Dead animals*

xNp\_inputc = (Average\_live\_weightc ^0.75) \* 0.025 \* x\_numberc

Repeat for all animal cohorts *c*

*Total N inputs*

HerdNp\_input = Ʃc (Np\_inputc + xNp\_inputc)

Unit: kg N.year-1

#### Processing outputs

Np\_outputc = Np\_inputc \* (dress\_Carcass + share\_edible\_inedible)

Where:

* share\_edible\_inedible: Industrial = 0.16, Intermediate=0.16, backyard=0.24

Source: See FAO report <http://www.fao.org/wairdocs/lead/x6114e/x6114e04.htm>

* Share inedible refers to the inedible products used in different industries (e.g. fats, blood, etc)
* Edible refers to offals that are edible

HerdNp\_output = Ʃc (Np\_outputc)

Repeat for all animal cohorts *c*

Unit: kg N.year-1

#### Processing losses (wastewater)

HerdNp\_loss = HerdNp\_input – HerdNp\_output

Unit: kg N.year-1

### Chicken (meat and eggs)

#### Processing inputs

*Slaughter animals*

Np\_inputc = (Slaughter\_weightc ^0.75) \* 0.028 \* exit\_numberc

Repeat for all animal cohorts *c*, excluding MF1, MF2 and MF3 for industrial Layers

*Dead animals*

xNp\_inputc = (Average\_live\_weightc ^0.75) \* 0.028 \* x\_numberc

Repeat for all animal cohorts *c*, excluding MF1, MF2 and MF3 for industrial Layers

*Eggs*

EGGSp\_input = EGGtotkg \* 0.0185

*Total N inputs*

HerdNp\_input = Ʃc (Np\_inputc + xNp\_inputc) + EGGSp\_input

For all animal cohorts *c*, excluding MF1, MF2 and MF3 for industrial Layers

Unit: kg N.year-1

#### Processing outputs

*Meat*

Np\_outputc = Np\_inputc \* (dress\_Carcass + share\_edible\_inedible)

share\_edible\_inedible = 0.158 (default value)

Source: See FAO report <http://www.fao.org/wairdocs/lead/x6114e/x6114e04.htm>

* Share inedible refers to the inedible products used in different industries (e.g. fats, blood, etc)
* Edible refers to offals that are edible

Repeat for all animal cohorts *c*, excluding MF1, MF2 and MF3 for industrial Layers

*Eggs*

EGGSp\_output = EGGSp\_input

*Total N outputs*

HerdNp\_output = Ʃc (Np\_outputc) + EGGSp\_output

For all animal cohorts *c*, excluding MF1, MF2 and MF3 for industrial Layers

Unit: kg N.year-1

#### Processing losses (waste water)

HerdNp\_loss = HerdNp\_input – HerdNp\_output

Unit: kg N.year-1

### Ruminants (meat)

#### Processing inputs

*Slaughter animals*

Np\_inputAF = Slaughter\_weightAF^0.75 \* ((268 – (7.03 \* Negro,RF / GrowF)) / 1000 / 6.25) \* exit\_numberAF

Np\_inputAM = Slaughter\_weightAM^0.75 \* ((268 – (7.03 \* Negro,RM / GrowM)) / 1000 / 6.25) \* exit\_numberAM

Np\_inputRF = Slaughter\_weightRF^0.75 \* ((268 – (7.03 \* NEgro,RF / GrowF)) / 1000 / 6.25) \* exit\_numberRF

Np\_inputRM = Slaughter\_weightRM^0.75 \* ((268 – (7.03 \* NEgro,RM / GrowM)) / 1000 / 6.25) \* exit\_numberRM

Np\_inputMF = Slaughter\_weightMF^0.75 \* ((268 – (7.03 \* NEgro,MF / GrowF)) / 1000 / 6.25) \* exit\_numberMF

Np\_inputMM = Slaughter\_weightMM^0.75 \* ((268 – (7.03 \* NEgro,MM / GrowM)) / 1000 / 6.25) \* exit\_numberMM

*Dead animals*

xNp\_inputAF = Average\_live\_weightAF^0.75 \* ((268 – (7.03 \* NEgro,RF / GrowF)) / 1000 / 6.25) \* x\_numberAF

xNp\_inputAM = Average\_live\_weightAM ^0.75 \* ((268 – (7.03 \* NEgro,RM / GrowM)) / 1000 / 6.25) \* x\_numberAM

xNp\_inputRF = Average\_live\_weightRF ^0.75 \* ((268 – (7.03 \* NEgro,RF / GrowF)) / 1000 / 6.25) \* x\_numberRF

xNp\_inputRM = Average\_live\_weightRM ^0.75 \* ((268 – (7.03 \* NEgro,RM / GrowM)) / 1000 / 6.25) \* x\_numberRM

xNp\_inputMF = Average\_live\_weightMF ^0.75 \* ((268 – (7.03 \* NEgro,MF / GrowF)) / 1000 / 6.25) \* x\_numberMF

xNp\_inputMM = Average\_live\_weightMM ^0.75 \* ((268 – (7.03 \* NEgro,MM / GrowM)) / 1000 / 6.25) \* x\_numberMM

*Total N inputs*

HerdNp\_input = Ʃc (Np\_inputc + xNp\_inputc)

For all animal cohorts *c*

Unit: kg N.year-1

#### Processing outputs

Np\_outputc = Np\_inputc \* (dress\_Carcass + share\_edible\_inedible)

Where:

* share\_edible\_inedible: edible = 0.1; inedible 0.116; tot = 0.216
* Share inedible refers to the inedible products used in different industries (e.g. fats, blood, etc)
* Edible refers to offals that are edible

HerdNp\_output = Ʃc (Np\_outputc)

For all animal cohorts *c*

Unit: kg N.year-1

#### Processing losses (wastewater)

HerdNp\_loss = HerdNp\_input – HerdNp\_output

Unit: kg N.year-1

### Ruminants (milk)

#### Processing inputs

Milk\_Np\_input = Milkproteinkg / 6.38

Unit: kg N.year-1

#### Processing losses (waste water)

Milk\_Np\_loss = Milk\_Np\_input \* Milk\_loss

Where: Milk\_loss = 0.0015 in developed countries, 0.03 in developing countries.

#### Processing outputs

Milk\_N\_output = Milk\_Np\_input – Milk\_Np\_loss

## NITROGEN USE INDICATORS CALCULATIONS

### Construction of the matrices for the calculation of the life cycle nutrient use efficiency

The calculation of life-cycle nitrogen use efficiency (Life-cycle-NUEN) and life-cycle net nitrogen balance (Life-cycle-NNBN) is given in Uwizeye et al.2

## EMBEDDED NITROGEN IN TRADED FEED

To calculate the virtual N and embedded N associated with the international trade, we first calculate the N loss intensity (NLI) of each traded feed item in exporting countries. To this purpose, calculations are based only on the following feed items from monogastrics: 5 (on-farm cassava), 6 (on-farm wheat grain), 8 (on-farm maize grain), 10 (on-farm barley grain), 14 (on-farm soybeans), 43 (palm kernel cake); results from the listed items will be valid also for ruminants. NLI of each feed item in each exporting country is obtained as follows:

NLIi,k = Total\_loss\_crop\_hai,k \* ALLOCi,k / DMYNi,k

Where: NLI is the N loss intensity of the traded feed item *k* in the country i; Total\_loss\_crop\_ha is the total loss of N per ha of crop; DMYN is the net yield of the feed item in kg DM; and ALLOC is the allocation factor to the main co-product traded. DMYN and ALLOC are calculated as follows:

For k = Barley, Cassava, Maize, Soybean, Wheat

DMYNi,k = DMYGi,k \* FUEk

For k = Palm

DMYNi,k = DMYGi,k \* FUEk \* MFAk

For k = Barley, Cassava, Maize, Soybean, Wheat

ALLOCi,k = Ncontentk \* DMYNi,k / (total\_output\_hak - crop\_residk)

For k = Palm

ALLOCi,k = Ncontentk \* DMYNi,k / (total\_output\_hak)

Then, we estimate the amount of feed intake imported by the consuming countries based on the total intake of traded feed item by country, production system and species and the traded matrix obtained from FAOSTAT. For each country *i*, the feed intake is disaggregated using the share of the traded feed item consumed by origins (exporters).

Feed imported from country i = Feed intake in consuming countries x proportion of feed imported from country i

Then, the virtual N is calculated as follows:

Embedded N in exporting countries = NLIi,k x Feed imported from country i

The embedded N is calculated as follows:

Feed N imported from country i = N intake in consuming countries x proportion of feed imported from country i

*The output is a matrix table with exporting countries in rows and importing countries in column. Each data point represent the N losses left in exporting countries.*

1. MMSburned excluded [↑](#footnote-ref-1)
2. MMSburned excluded [↑](#footnote-ref-2)
3. This is the N content of the actual feed component [↑](#footnote-ref-3)