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## Document describing the incorporation into the model complex of the facility

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# ANIMALCHANGE

## SEVENTH FRAMEWORK PROGRAMME

### THEME 2: FOOD, AGRICULTURE AND FISHERIES, AND BIOTECHNOLOGIES



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#### DELIVERABLE 9.3

**Deliverable title:** Document describing the incorporation into the model complex of the facility

**Abstract:** This document describes how the ability to simulate mitigation and adaptation measures was included in the modelling complex. The strategic decision to focus on the simple farm modelling means that this document focuses on the FarmAC model.

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## Introduction

This document describes how the ability to simulate mitigation and adaptation measures was included in the modelling complex. The strategic decision to focus on the simple farm modelling means that this document focuses on the FarmAC model.

A list of the mitigation and adaptation measures is shown in the table below.

<b>Component</b>	<b>Measure</b>	<b>Target emission</b>
<i>Mitigation</i>		
Cattle	Nitrate in feed ration	Methane
	Supplementary fat	Methane
Housing	Low emission flooring	Ammonia
	Acidification	Ammonia and methane
Manure storage	Covering	Ammonia
	Acidification	Ammonia and methane
	Anaerobic digestion	Ammonia, methane, nitrous oxide
Field	Reduced fertiliser or manure	Nitrous oxide, nitrate leaching
	Cover cropping	Nitrate leaching
	Low emission fertiliser or manure application	Ammonia
	Field acidification	Ammonia
	Suspension of residue burning	Ammonia, nitrous oxide, black carbon, carbon monoxide
<i>Adaptation</i>		
		<b>Target effect</b>
Cattle	Increased supplementary feeding	Buffer variations in locally-produced feed
Field	Irrigation	Drought
	Multi-species cropping	Production robustness
	N fixing crops	Production robustness

The work was developed during a series of workshops.

The work is reported here in the form of a revised description of the FarmAC model. The revisions relative to Deliverable 9.2 are as follows:

- A revised modelling of cattle production.
- The addition of the effect of nitrate feeding on enteric methane emission.
- The introduction of acidification in animal housing, manure storage and during field application.
- The introduction of anaerobic digestion.
- A revised method of simulating crop dry matter production.
- A revised method of simulating nitrate leaching.
- The introduction of crop residue burning.

## FarmAC - model definition

### 1 Overview

The objective of the model is to simulate greenhouse gas emissions and nitrogen (N) losses from farming systems. To do this, the model simulates C and N inputs, transformations, outputs and losses from livestock, animal housing and manure storage, and fields. The model results are expressed as annual fluxes but for the crop/soil system, a simple dynamic model is used to simulate flows over a number of years and the results averaged. This approach enables the model to simulate changes in the amount of C and N stored in the soil. The crop/soil system is defined in terms of a number of crop sequences, where a crop sequence can represent a single field or a whole crop rotation. Livestock are represented as livestock categories. A livestock category can appear more than once on the farm e.g. to describe the grazing animals during the growing season and housed animals for the remainder of the year. This allows differences in diet to be reflected in the production and excretion. On farms where livestock are housed for part or all of the year, the flows of C and N through the animal housing and manure storage is simulated, in addition to the deposition of excreta during grazing.

The flows of carbon simulated are as follows:

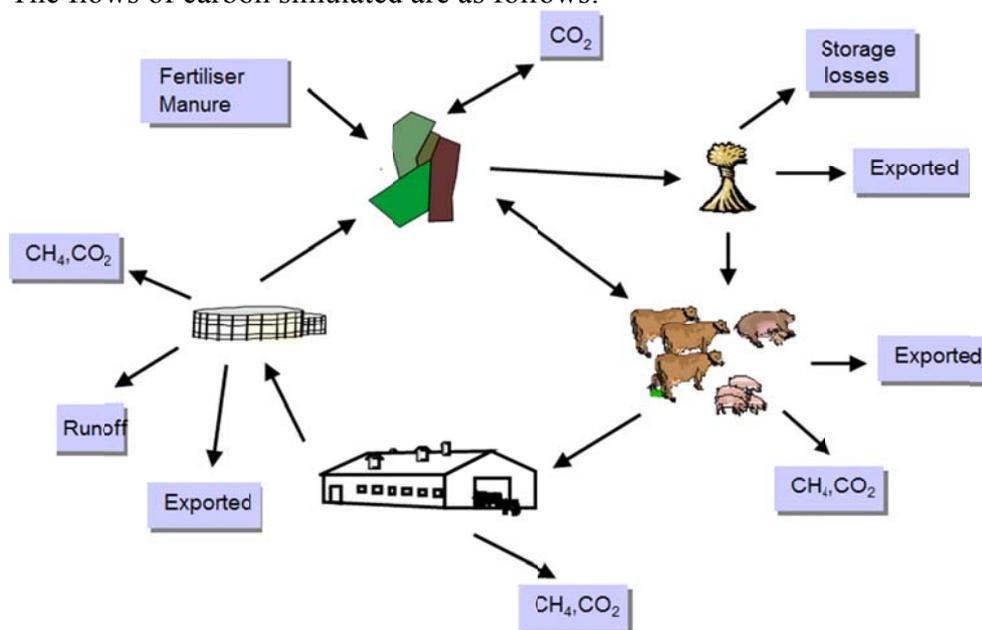


Figure 1 Flows of carbon on the farm

The flows of nitrogen simulated are as follows:

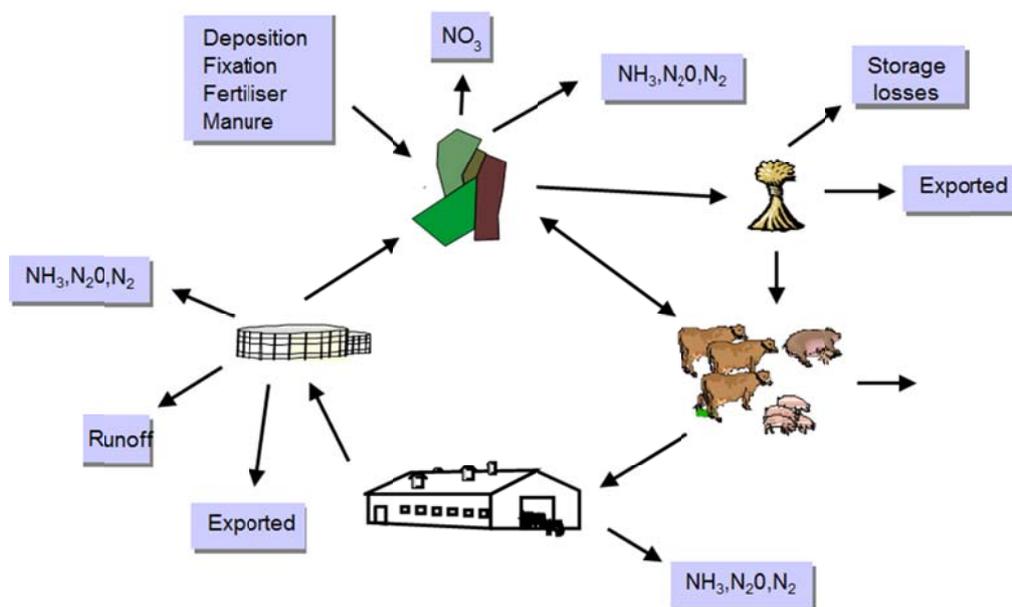


Figure 2 Flows of nitrogen on the farm

The model uses a mixture of Tier 2 (emission factor) and Tier 3 methodologies, and relies on inputs that should be available to educated, competent farmers. The model can be used to investigate a range of management options designed to compensate for negative effects of climate change or take advantage of positive effects.

FarmAC is a hybrid static/dynamic model; the simulation of C and N processes in the field is dynamic whereas the simulation of the corresponding processes in livestock, livestock housing and manure storage is static. Dynamic modelling in the field is necessary in order to estimate changes in the C and N stored in the soil. The model is suitable for investigating C and N flows averaged over the medium term (10 to 20 years).

The model takes as inputs:

#### Fields/crop sequences

- the sequence of crops within a variable number of fields or sequences.
- the production of each crop product in each crop sequence.
- whether any secondary crop product (e.g. straw) is harvested, incorporated into the soil or burned.
- the amount, type and timing of fertiliser N applied to each crop in each crop sequence and whether it is incorporated into the soil.
- the amount, type and timing of each animal manure applied to each crop in each crop sequence, the application technique and whether it is incorporated into the soil.

#### Livestock

- the number of each livestock category on the farm.
- the feed ration for each livestock category.

#### Manure management

- the housing type or types used for each livestock category.
- the manure storage used for each livestock category.

The model produces as outputs:

Fields

- the input of N via fertiliser, manure, fixation and atmospheric deposition for each crop in each crop sequence.
- the loss of N as NH<sub>3</sub>, N<sub>2</sub>O, N<sub>2</sub> and NO<sub>3</sub> for each crop in each crop sequence.
- the change in C and N sequestered in the soil for each crop sequence.

Livestock

- the export of N in milk and meat for each livestock category on the farm.
- the enteric CH<sub>4</sub> emission for each livestock category on the farm.

Manure management

- the NH<sub>3</sub> emission from each housing type used by each livestock category.
- the emission of CH<sub>4</sub>, CO<sub>2</sub>, N<sub>2</sub>O, NH<sub>3</sub> and N<sub>2</sub> from each manure storage used for each livestock category.
- the loss of N by runoff/leaching from each manure storage used for each livestock category.

## 2 Agroecological zones

Many of the factors controlling farm-scale C and N flows are closely related to the local climate, crop types and soil types. As a consequence, most of the parameters within this model can be expected to be location-specific. The model therefore recognises a number of agroecological zones. The basic agroecological zones used in the model and for which default parameters are provided are shown in Table 1. However, users can choose to use region-specific or farm-specific agroecological zones, should they have location-specific data available. All parameters except universal constants (e.g. the universal gas constant) can be separately defined for each agroecological zone.

Table 1 Agroecological zones

Zone Identifier	Zone Name	Zone Description
1	EUMaritimeZone	Maritime (European land-based)
2	EUContinentalZone	Continental (European land-based)
3	EUMountainZone	Mountain (European land-based)
4	EUMediterraneanZone	Mediterranean (European land-based)
5	EUBorealZone	Boreal (European land-based)
6	NonEU_Arid	Arid (non-European land-based)
7	NonEU_SemiArid	Semi-arid (non-European land-based)
8	NonEU_SubHumid	Sub-humid (non-European land-based)
9	NonEU_Humid	Humid (non-European land-based)
10	NonEU_Tropical	Tropical highland (non-European land-based)

The main climatic variables used in the model are the air temperature and the drought index. These are defined with monthly resolution. For air temperature, if monthly values are not available, approximate values can be calculated from the mean annual air temperature and the amplitude of the annual variation (see Appendix I).

### 3 Crop production

Provided the farm has cropped land (including pasture but excluding non-agricultural land), the farmland is considered to consist of one or more crop sequences. The number of potential crops  $C$  is a model parameter. A single crop produces  $P_c$  products, where  $P_c \geq 1$ . The products are defined in terms of their type and characteristics e.g. high-protein grain, low-quality straw, medium quality silage.

A submodel is used to simulate the change in C and N sequestered in the soil (see below). Since the soil submodel must simulate a number of years cropping in order to calculate the change in sequestering, the modelling of crop production must do likewise. Where more than one field/crop sequence produces the same product (e.g. spring barley grain), the production from all crop sequences/fields is pooled and averaged over the duration of the sequence in order to calculate the average annual DM production of product  $p$  from crop  $c$  ( $D_{\text{crop},c,p}$ ; kg yr<sup>-1</sup>) (see Equation (0.19)).

#### 3.1 Energy

The energy in crop production is commonly expressed in two forms. The first is the gross energy concentration of the crop product. This is the energy released if a crop product is oxidised by combustion and is mainly applied to secondary products that are utilised in this manner (e.g. straw). The second form is the concentration of energy in the crop product that is available for utilisation by livestock. There is a range of energy systems used in connection with livestock production in Europe. In principle, all energy systems designed to assess the energy in crop products that is available to livestock take the following into account:

- The digestible energy of the feed. The difference between gross and digestible energy represents the loss of energy in faeces.
- The metabolisable energy of the feed. This is the amount of energy available in the nutrients absorbed from the digestive system by the livestock, when the latter is working at maximum efficiency. The difference between gross and digestible energy represents the loss of energy in urine and gaseous emissions from the digestive system (principally methane). The loss of energy in urine is equivalent to about 4% of gross energy (IPCC 2006, chapter 10.3, p 10.42).
- The net energy of the feed. The difference between the metabolisable and net energy represents the inefficiency with which the metabolisable energy is used for life processes (e.g. maintenance, growth). Some systems use a single efficiency factor for all life processes whereas others differentiate between the different processes.

The energy system used here is based on metabolisable energy (ME; MJ).

For each crop product, the energy available in product  $p$  of crop  $c$  ( $E_{c,p}$ ; MJ yr<sup>-1</sup>, ME) is:

$$E_{c,p} = D_{\text{crop},c,p} e_{c,p} \quad (0.1)$$

Where  $e_{c,p}$  is the concentration of available energy in product  $p$  of crop  $c$  (MJ (kg DM)<sup>-1</sup>, ME).  $e_{c,p}$  is a parameter.

Note: for most grain and processed crop products, the metabolisable energy concentration will be known. For roughage crop products (e.g. grass, hay, straw), the metabolisable energy concentration ( $ME_{\text{conc},c,p}$ ; MJ (kg DM)<sup>-1</sup>, ME) can be calculated from organic matter digestibility using the relationship given on p 8 of (CSIRO, 2007):

$$ME_{\text{conc},c,p} = 16.9 \zeta_{\text{OM},c,p} - 1.986 \quad (0.2)$$

where  $\zeta_{OM,c,p}$  is the organic matter digestibility (kg (kg organic matter)<sup>-1</sup>). The latter is given by:

$$\zeta_{OM,c,p} = \frac{\zeta_{DM,c,p} + 0.47ash_{c,p}}{(1 - ash_{c,p})} \quad (0.2)$$

where  $ash_{c,p}$  is the ash content of the crop product  $p$  from crop  $c$  (kg (kg DM)<sup>-1</sup>), the factor 0.47 is the proportion of the ash that is digestible (value from Rednex project) and  $\zeta_{DM,c,p}$  is the corresponding apparent DM digestibility (kg (kg DM)<sup>-1</sup>). Both  $ash_{c,p}$  and  $\zeta_{DM,c,p}$  are parameters.

### 3.2 Carbon

The annual production of carbon in crop product  $p$  of crop  $c$  ( $C_{crop,c,p}$ ; kg yr<sup>-1</sup>) is:

$$C_{crop,c,p} = D_{crop,c,p} (1 - ash_{c,p}) \alpha \quad (0.3)$$

where  $\alpha$  is the C content of organic matter (kg (DM kg)<sup>-1</sup>; normally 0.46).

### 3.3 Nitrogen/Protein

The annual production of nitrogen (N) in each crop product  $N_{yield,c,p}$  (kg yr<sup>-1</sup>) is:

$$N_{yield,c,p} = D_{c,p} n_{c,p} \quad (0.4)$$

where  $n_{c,p}$  is the N content of product  $p$  of crop  $c$  (kg (DM kg)<sup>-1</sup>).  $n_{c,p}$  is a parameter.

### 3.4 Dry matter lost during processing and storage

Dry matter may be lost during the processing of crop products (e.g. silage making) or due to deterioration in storage. The effect of this is simulated here as follows:

$$X_{pro,c,p} = \phi_{c,p} X_{c,p}$$

Where  $X_{c,p}$  represents the C or N harvested in product  $p$  of crop  $c$  ( $C_{crop,c,p}$  or  $N_{c,p}$  kg),  $\phi_{c,p}$  is the proportion of the harvested material lost and  $X_{pro,c,p}$  is the mass lost (kg).

## 4 Ruminants (cattle and sheep)

Livestock are described in terms of categories of animals with specific characteristics e.g. dairy cows, heifers, bull calves. All livestock numbers are expressed as the annual average number present, not the number produced. The annual average number present is input by the user. Note that if data are only available for a number produced, this number must be multiplied by the production period expressed in years in order to obtain the average number present. For example, if the data that are available describe the number of animals produced within a category called 'Calves, birth to 6 months old', the average number of animals present will be one half of the number of animals produced.

Ruminant diets are defined in terms of feed items. A feed item can be a crop product (home-grown or imported) or it can be an imported feed or feed additive. The types of feed items in the diet and their amount are model inputs. The potential number of feed items is  $F$ , which is a model parameter. Since all crop products are assumed to be potential feed items,  $F$  has a minimum value equating to the number of crop products produced on the farm.

The livestock diets are inputs to the model. It is assumed that the livestock are capable of consuming the diet fed; the model has no mechanism for constraining feed intake according to feed quality. The animal liveweight changes and milk production (if relevant) are simulated by modelling energy and protein partitioning, using a factorial approach. Energy and protein available from the diet are thus partitioned first to maintenance, then to liveweight gain and finally, if relevant, to milk production.

#### 4.1 Intake

The annual DM intake of ruminant category  $g$  ( $I_g$ ; kg yr<sup>-1</sup>) is:

$$I_g = dZ_g \sum_{f=1}^F I_{g,f} \quad (0.5)$$

where  $d$  is the average number of days in a year (365.25),  $Z_g$  is the average number of animals in category  $g$  and  $I_{g,f}$  is average daily DM intake of feed item  $f$  (kg) by animals in category  $g$ .  $Z_g$  and  $I_{g,f}$  are model inputs.

The total amount of available energy available to livestock from a particular category depends partly on the composition of the diet (in particular the amount of fibre) and partly on the time during which degradation by microorganisms can occur i.e. the residence time of the feed in the rumen. The methods used to assess the energy availability in feed items normally return a value appropriate for a long residence time. For livestock with a high intake rate relative to their body size e.g. high-yielding dairy cattle, the availability of the energy in the diet will be lower than that indicated by the standard measurement methods. The variable  $\mu_g$  is introduced here to account for this effect, where  $\mu_g \leq 1$ .

The annual consumption of potentially-available energy by category  $g$  ( $E_{pot,g}$ ; MJ yr<sup>-1</sup>, ME) is:

$$E_{pot,g} = dZ_g \sum_{f=1}^F (I_{g,f} e_f) \quad (0.5)$$

where  $e_f$  is the available energy content of feed item  $f$  (MJ (kg DM)<sup>-1</sup>, ME) and a parameter. The annual consumption of available energy by category  $g$  ( $E_{int,g}$ ; MJ yr<sup>-1</sup>, ME) is:

$$E_{int,g} = \mu_g E_{pot,g} \quad (0.5)$$

Where  $\mu_g$  is a variable that reduces the availability of energy at high intake rate. The value of  $\mu_g$  is dependent on the energy intake relative to the maintenance requirement ( $E_{Db,g}$ ; MJ yr<sup>-1</sup>, ME) (see Equation(0.7) ):

If  $E_{int,g} \leq E_{Db,g}$ ,  $\mu_g=1$ , otherwise

$$\mu_g = 1 - \mu_b (E_{Dp,g} - E_{Db,g}) \quad (0.6)$$

where  $E_{Db,g}$  is the energy intake above which energy availability is reduced (MJ yr<sup>-1</sup>) and  $\mu_b$  is a parameter.

The annual intake of N by category  $g$  ( $N_{int,g}$ ; kg yr<sup>-1</sup>) is:

$$N_{int,g} = dZ_g \sum_{f=0}^F (I_{g,f} n_f) \quad (0.6)$$

where  $n_f$  is the N content of feed item  $f$  (kg (kg DM)<sup>-1</sup>).  $n_f$  is a parameter with a value 6.25.

## 4.2 Maintenance

### 4.2.1 Energy

The maintenance energy demand of livestock category  $g$  ( $E_{m,g}$ ; MJ yr<sup>-1</sup>) is here simulated by a reduced form of the relationship used in (CSIRO, 2007):

$$E_{m,g} = \frac{dZ_g (0.28L_g^{0.75}) e^{-0.03age_g}}{0.02 \frac{E_{int,g}}{D_{int,g}} + 0.5} \quad (0.7)$$

where  $L_g$  is the liveweight of the animal,  $age_g$  is the age of the animal (years) daily maintenance energy demand. If there is insufficient energy to satisfy the maintenance demand, energy is taken from body reserves (see below).

### 4.2.2 Protein

Protein is equated to N \* 6.25. The intake of protein can therefore be defined in Equation (0.6). Part of the protein consumed is partitioned to faecal N, using the relationship provided by INRA, where faecal N ( $N_{faeces,g}$ ; kg yr<sup>-1</sup>) is calculated as follows:

$$N_{faeces,g} = dZ_g (6.3I_g + 0.17N_{int,g} - 31.0) \quad (0.8)$$

The remaining N ( $N_{met,g}$ ; kg yr<sup>-1</sup>) is available for maintenance or production:

$$N_{met,g} = N_{int,g} - N_{faeces,g} \quad (0.9)$$

If  $N_{met,g}$  is less than zero, protein is taken from body reserves (see below).

### 4.2.3 Remobilisation

If there is insufficient energy in the diet to support maintenance, energy is remobilised from body reserves. In this situation, an amount of energy ( $E_{remob,g}$ ; MJ yr<sup>-1</sup>, ME) is recovered with 80% efficiency and a weight loss ( $L_{wl,g}$ ; kg yr<sup>-1</sup>) is recorded:

$$L_{wl,g} = \frac{E_{remob,g}}{0.8e_{Dpgrowth,g}} \quad (0.10)$$

Where  $e_{Dpgrowth,g}$  is the concentration of energy in liveweight (MJ kg<sup>-1</sup>, ME). An associated amount of N is remobilised ( $N_{remob,g}$ ; kg yr<sup>-1</sup>), the amount being defined as:

$$N_{remob,g} = L_{wl,g} n_{growth,g} \quad (0.11)$$

Where  $n_{growth,g}$  is the concentration of N in liveweight (kg kg<sup>-1</sup>).  $N_{remob,g}$  is added to  $N_{met,g}$ .

If there is insufficient protein for maintenance ( $N_{met,g} < 0$ ), N is remobilised from body reserves. The associated loss of liveweight and the energy remobilisation are calculated using equations (0.10) and (0.11), replacing energy with the appropriate nitrogenous equivalents.

### 4.3 Growth and milk production

Some or all of the energy and protein remaining after satisfying the maintenance requirements is potentially available for production. The energy available for production ( $E_{\text{potprod},g}$ ; MJ yr<sup>-1</sup>) is:

$$E_{\text{potprod},g} = E_{\text{int},g} - E_{\text{m},g}$$

While the protein available is  $N_{\text{met}}$ .

#### 4.3.1 Meat-producing animals

For meat-producing animals, all the energy and protein remaining after satisfying the maintenance requirements is potentially available for growth. The growth rate is determined by whichever of the two nutrients is most limiting. The energy-limited growth rate ( $J_{\text{Egrowth},g}$ ; kg day<sup>-1</sup>) is:

$$J_{\text{Egrowth},g} = \frac{k_{\text{growth},g} E_{\text{potprod},g}}{dZ_g e_{\text{growth},g}}$$

Where  $e_{\text{growth},g}$  is the energy concentration in weight gain (MJ (kg produced)<sup>-1</sup>) and  $k_{\text{growth},g}$  is the efficiency of use of energy for weight gain. The value of  $k_{\text{growth},g}$  is calculated using the relationship taken from (CSIRO, 2007):

$$k_{\text{growth},g} = \frac{0.042 E_{\text{int},g}}{I_g} + 0.006$$

The protein-limited growth rate ( $J_{\text{Pgrowth},g}$ ; kg day<sup>-1</sup>) is:

$$J_{\text{Pgrowth},g} = \frac{0.7 N_{\text{met},g}}{dZ_g n_{\text{growth},g}}$$

Where  $n_{\text{growth},g}$  is the nitrogen concentration in weight gain (kgN (kg produced)<sup>-1</sup>) and 0.70 is the efficiency of use of energy for weight gain.

The actual growth ( $J_{\text{growth},g}$ ; kg day<sup>-1</sup>) is then  $\min(J_{\text{Pgrowth},g}, J_{\text{Egrowth},g})$ . Any excess energy is assumed to be lost as heat whereas any excess  $N_{\text{met}}$  is lost as urine N.

#### 4.3.2 Dairy animals

For dairy animals, energy and protein may be used for both growth and milk production. Furthermore, some lactating livestock may support a higher milk production and can be supported from current intake, by remobilizing body tissue. These effects are simulated in the model by introducing an obligatory growth rate ( $J_{\text{oblig},g}$ ; kg day<sup>-1</sup>) which can be either positive or negative.

If  $J_{oblig,g} < 0$ :

$$E_{potprod,g} = E_{int,g} - (E_{m,g} + 0.8dZ_g J_{oblig,g} e_{growth,g})$$

$$N_{met,g} = N_{int,g} - (N_{faeces,g} + 0.7dZ_g J_{oblig,g} n_{growth,g})$$

else

$$E_{potprod,g} = E_{int,g} - \left( E_{m,g} + \frac{dZ_g J_{oblig,g} e_{growth,g}}{k_{growth,g}} \right)$$

$$N_{met,g} = N_{int,g} - \left( N_{faeces,g} + \frac{dZ_g J_{oblig,g} n_{growth,g}}{0.7} \right)$$

As for growth, the milk production is determined by whether energy or protein is most limiting. The energy-limited milk production rate ( $J_{Emilk,g}$ ; kg day<sup>-1</sup>) is:

$$J_{Emilk,g} = \frac{k_{milk,g} E_{potprod,g}}{dZ_g e_{milk,g}}$$

Where  $e_{milk,g}$  is the energy concentration in milk (MJ (kg produced)<sup>-1</sup>) and  $k_{milk,g}$  is the efficiency of use of energy for weight gain. The value of  $e_{milk,g}$  (MJ kg<sup>-1</sup>) is calculated by multiplying a unit mass of Energy-Corrected Milk (ECM) with an energy density of 3.054 MJ (kg ECM)<sup>-1</sup>; (CSIRO, 2007). The value of  $k_{milk,g}$  is calculated using the relationship taken from (CSIRO, 2007):

$$k_{milk,g} = \frac{0.02E_{int,g}}{I_g} + 0.4$$

The protein-limited milk production rate ( $J_{Pmilk,g}$ ; kg day<sup>-1</sup>) is:

$$J_{Pmilk,g} = \frac{0.7N_{met,g}}{dZ_g n_{milk,g}}$$

The actual milk production rate ( $J_{milk,g}$ ; kg day<sup>-1</sup>) is then  $\min(J_{Pmilk,g}, J_{Emilk,g})$ . Any excess energy is assumed to be lost as heat whereas any excess  $N_{met}$  is lost as urine N.

#### 4.4 Carbon

The annual intake of C by category  $g$  ( $C_{int,g}$ ; kg yr<sup>-1</sup>) is:

$$C_{int,g} = dZ_g \sum_{f=0}^F I_{g,f} c_f \quad (0.11)$$

where  $c_f$  is the concentration of C in feed item  $f$  (kg (kg DM)<sup>-1</sup>)  $c_f$  is a parameter.

Carbon leaves the animal in the form of animal products (principally milk and meat), in excreta and as CO<sub>2</sub> and CH<sub>4</sub>.

The annual exports of C in milk and meat by category  $g$  ( $C_{\text{milk},g}$  and  $C_{\text{meat},g}$ ;  $\text{kg yr}^{-1}$ ) are calculated as follows:

$$C_{X,g} = dZ_g J_g c_{X,g} \quad (0.11)$$

where  $X$  is either milk or meat and  $c_{X,g}$  is the concentration of C in  $X$  ( $\text{kg kg}^{-1}$ ).  $c_{\text{milk},g}$  and  $c_{\text{meat},g}$  are parameters.

A proportion of the C is lost in the form of  $\text{CH}_4$ . The calculation of the annual C lost ( $C_{\text{LiveCH}_4,g}$ ;  $\text{kg}$ ) depends upon the emission inventory system chosen:

If a Tier 2 approach is chosen, the IPCC (2006) methodology is used (Intergovernmental Panel on Climate, 2006):

$$C_{\text{LiveCH}_4,g} = \left(\frac{12}{16}\right) D_{\text{int},g} \frac{GE_g 0.365 Y_{m,g}}{55.65} \quad (0.11)$$

where  $GE_g$  is the gross energy intake of category  $g$  and  $Y_{m,g}$  is the methane conversion factor for livestock category  $g$ .

Otherwise:

$C_{\text{LiveCH}_4,g}$  is calculated using the relationship from (Kirchgessner et al., 1995):

$$C_{\text{LiveCH}_4,g} = \left(\frac{12}{16}\right) (\phi_g + D_{\text{int},g} (79CF_g + 10NFE_g - 212Fat_g) + 162.5N_g) \quad (0.11)$$

where  $\phi_g$  is a constant,  $N_g$  is the annual intake of N (see below) and  $CF_g$ ,  $NFE_g$  and  $Fat_g$  are respectively the proportions of crude fibre, nitrogen-free extract and raw lipid in the diet ( $\text{kg (kg DM)}^{-1}$ ). The proportions of crude fibre, nitrogen-free extract and raw lipid in the diet are calculated as a weighted average of the constituents of the diet:

$$X_g = \frac{\sum_{f=0}^F (I_{g,f} X_f)}{D_{\text{int},g}} \quad (0.12)$$

where  $X$  is the proportion of crude fibre, nitrogen-free extract or raw lipid in the feed item  $f$  ( $\text{kg (kg DM)}^{-1}$ ). The proportions of crude fibre, nitrogen-free extract or raw lipid in each feed item are parameters.

The C in excreta is contained in both faeces and urine. The C excreted annually in faeces of category  $g$  ( $C_{\text{faeces},g}$ ;  $\text{kg}$ ) is calculated as follows:

$$C_{\text{faeces},g} = C_{\text{int},g} (1 - \mu_g \zeta_{OM,g}) \quad (0.13)$$

where  $\zeta_g$  and  $ash_g$  are respectively the apparent DM digestibility and the ash content of the diet of category  $g$  ( $\text{kg (kg DM)}^{-1}$ ).  $\zeta_{OM,g}$  and  $ash_g$  are calculated as weighted averages of the feed items in the diet, as in Equation (0.12).

The C excreted annually in urine ( $C_{\text{urine},g}$ ;  $\text{kg yr}^{-1}$ ) is calculated as:

$$C_{\text{urine},g} = 0.04 C_{\text{int},g} \quad (0.13)$$

where use of the constant 0.04 assumes that the proportion of C consumed that is excreted as urine is the same as the proportion of gross energy excreted as urine (IPCC 2006).

The C lost from the animals as CO<sub>2</sub> ( $C_{LiveCO_2,g}$ ; kg) is then calculated by difference:

$$C_{LiveCO_2,g} = C_{int,g} - (C_{milk,g} + C_{meat,g} + C_{CH_4,g} + C_{faeces,g} + C_{urine,g}) \quad (0.13)$$

#### 4.4.1 Mitigation and adaptation measures

Nitrate in the diet. If nitrate is present in the feed ration (either as nitrate deliberately added to reduce methane emission or as nitrate naturally occurring in a feed item), a fraction ( $nrf_g$ ) of the methane will be abated:

$$nrf_g = \frac{Y[NO_3]}{[C_{LiveCH_4,g}]} \quad (0.13)$$

where  $[NO_3]$  is the molar concentration of nitrate in the diet,  $[C_{LiveCH_4,g}]$  is the molar concentration of methane in the absence of nitrate and  $Y$  is an efficiency parameter.

Fat in the diet. If using a Tier 2 approach, the effect of fat in the diet must be introduced through the value of  $Y_m$ . If using a Tier 3 approach, the effect will be taken into account automatically.

Supplementary feeding. If local sources of feed are not available, supplementary (imported) feed can be used.

### 4.5 Nitrogen

The annual export of N in milk and meat ( $N_{milk,g}$  and  $N_{meat,g}$ ; kg yr<sup>-1</sup>) are calculated as follows:

$$N_{X,g} = dZ_g J_g n_{X,g} \quad (0.14)$$

where  $X$  is either milk or meat and  $n_{X,g}$  is the concentration of N in  $X$  (kg kg<sup>-1</sup>). Values of  $n_{X,g}$  are parameters.

The N excreted annually in urine ( $N_{urine,g}$ ; kg yr<sup>-1</sup>) is calculated by difference:

$$N_{urine,g} = N_{int,g} - (N_{milk,g} + N_{meat,g} + N_{faeces,g}) \quad (0.14)$$

where N in faeces ( $N_{faeces,g}$ ) is calculated in Equation (0.8).

## 5 Animal housing and manure storage

The housing type is denoted by the subscript  $h$ . A given livestock category can be housed in zero, one or two housing types; zero means that the livestock are at pasture all year round while occasions where a livestock category uses two housing types are associated with specific functions (e.g. dairy cattle will usually spend some time in a milking parlour) or pregnancy (e.g. different housing types will often be used for lactating and non-lactating sows). A range of housing types will normally be available for a given category of livestock;

the user chooses the housing type. The housing type then determines the type of manure produced. Often, a housing type will only produce one type of manure (e.g. slurry, farmyard manure). However, in some types of animal housing there is a partial separation of the excreta into liquid and solid fractions. This means that up to two types of manure store may be associated with a single housing type. A range of manure storage types will normally be available for a given manure type; the user chooses the relevant manure storage type.

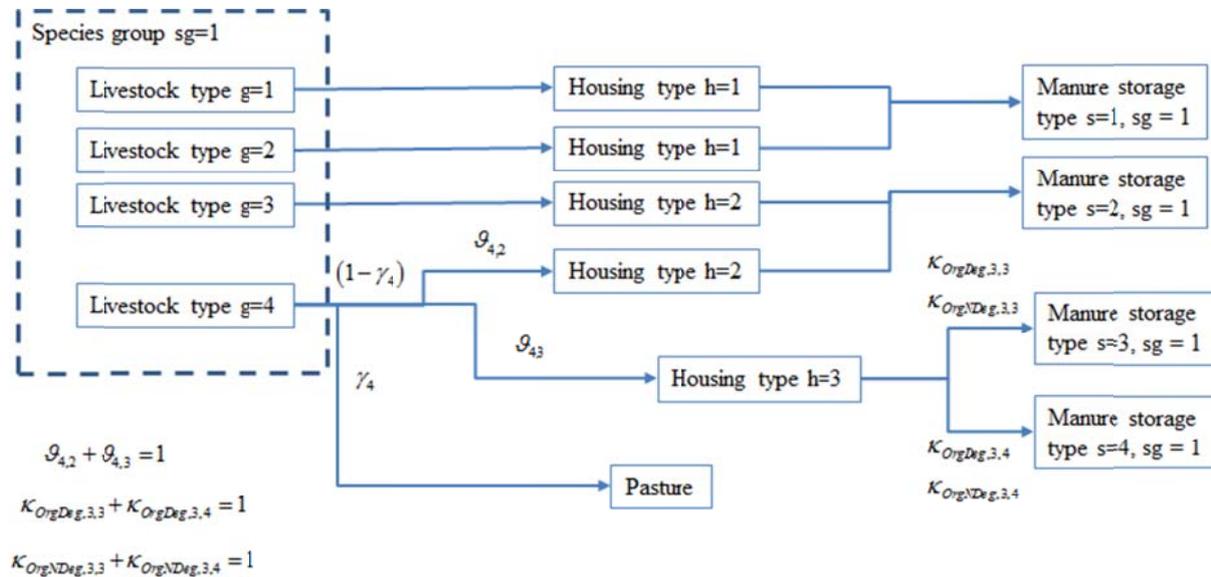


Figure 3 Schematic of the organisation of livestock, housing and manure storage.

The modelling of animal housing and manure storage currently only considers N and C. In animal housing, the only fluxes simulated are the addition of C and N in bedding, the loss of N via  $\text{NH}_3$  emission and the loss of urine C as  $\text{CO}_2$ . Conceptually, animal housing and manure storage are considered as separate sources of gaseous emission, even though in some instances, the manure is stored within the animal housing.

In storage, organic N and ammonium N are considered separately for both the Tier 2 and 3 approaches. In contrast, the Tier 2 approach considers total C whereas in the Tier 3 approach, C is partitioned into two fractions. Sommers et al (2009) partitioned manure organic matter between two fractions, one is assumed to be slowly degradable in manure storage and the other easily degradable. However, the degradation rate of the slowly degradable organic matter was very low and contributed little to the nutrient dynamics. For simplicity, here we partition the organic matter into degradable and non-degradable fractions.

The flows of C and N are followed separately for each animal category.

### 5.1 Animal housing

Conceptually, the livestock are not considered part of the animal housing, even though they are within that housing for all or part of the year. The feed consumed by livestock whilst it is in animal housing is considered to enter the livestock and not the housing. However, the livestock feed that is spilt or spoilt in the housing is considered as an input to the housing.

The other inputs to the animal housing are from the livestock (urine and faeces) and in the form of bedding.

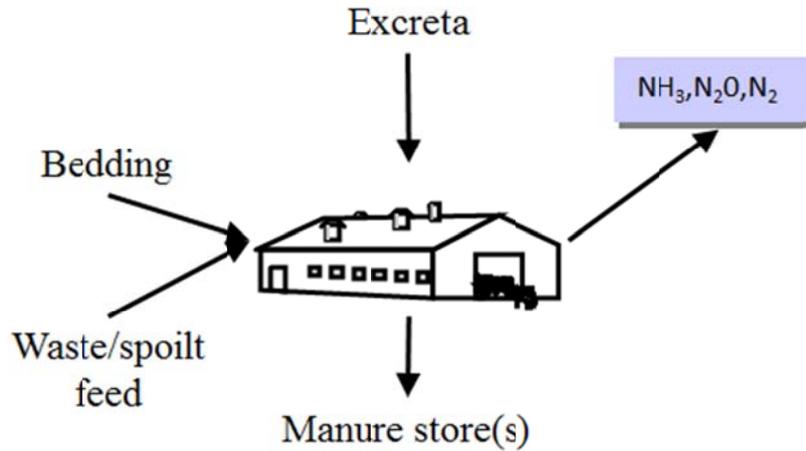


Figure 4 Inputs, outputs and gaseous emissions from animal housing

#### 5.1.1 Bedding and feed waste

The amount of bedding used in animal housing depends on the amount of bedding added per animal per day, the number of animals using the housing and the duration of the period the housing is in use. The rate of use of bedding depends on the type of housing and the type of animals housed. Here, the rate of use of bedding ( $b_{g,h}$ ; kg DM d<sup>-1</sup>) is:

$$b_{g,h} = \rho_h L_g \quad (0.14)$$

where  $\rho_h$  is the bedding factor (kg DM (kg animal liveweight)<sup>-1</sup> d<sup>-1</sup>) for housing type  $h$  and  $L_G$  is the average liveweight of the livestock category  $g$  (kg). Both  $\rho_h$  and  $L_G$  are parameters. The annual amount of bedding DM used for animal category  $g$  in housing  $h$  ( $D_{\text{bedding},g,h}$ ; kg DM yr<sup>-1</sup>) is:

$$D_{\text{bedding},g,h} = \vartheta_{g,h} (1 - \gamma_g) Z_g 365 b_{g,h} \quad (0.14)$$

where  $\vartheta_{g,h}$  is the proportion of the housing time that livestock category  $g$  spends in housing type  $h$ ,  $\gamma_g$  is the proportion of the year that the animal category  $g$  is at pasture.  $\gamma_g$  is assumed to equate to the proportion of the DM intake of category  $g$  that is obtained from feed items consumed at pasture:

$$\gamma_g = \frac{\sum_{f=1}^F \chi_{\text{pas},g,f} I_{g,f}}{D_{\text{int},g}} \quad (0.14)$$

where  $\chi_{\text{pas},g,f}$  is 1 if feed item  $f$  is consumed at pasture by livestock type  $g$  and zero otherwise.  $\chi_{\text{pas},g,f}$  is a model input.

A proportion of the feed provided to livestock is wasted by spillage or spoilage. The annual amount of dry matter in this waste ( $D_{\text{waste},g,h}$ ; kg yr<sup>-1</sup>) for livestock category  $g$  and housing type  $h$  is:

$$D_{\text{waste},g,h} = \frac{\omega_{\text{waste},g,h} \vartheta_{g,h} Z_g \sum_{f=1}^F (1 - \chi_{\text{pas},g,f}) I_f}{(1 - \omega_{\text{waste},g,h})} \quad (0.14)$$

where  $\omega_{\text{waste},g,h}$  is proportion of the feed provided to livestock category  $g$  that is wasted by spillage in housing type  $h$ . The wasted dry matter is assumed to be added to the manure produced.

### 5.1.2 Carbon

The C entering annually the animal housing  $h$  from category  $g$  ( $C_{\text{inhouse},g,h}$ ;  $\text{kg yr}^{-1}$ ) is:

$$C_{\text{inhouse},g,h} = \vartheta_{g,h} (1 - \gamma_g) (C_{\text{faeces},g} + C_{\text{urine},g}) + C_{\text{bedding},g,h} + C_{\text{waste},g,h} \quad (0.14)$$

where  $C_{\text{bedding},g,h}$  and  $C_{\text{waste},g,h}$  are the C added annually in bedding and wasted/spoilt feed for animal category  $g$  in housing type  $h$ .  $C_{\text{bedding},g,h}$  and  $C_{\text{waste},g,h}$  are calculated as:

$$C_{X,g,h} = D_{X,g,h} c_X \quad (0.14)$$

where  $X$  represents either *bedding* or *waste*.  $c_X$  is the concentration of C ( $\text{kg (kg DM)}^{-1}$ ). For bedding, this is calculated as:

$$C_{\text{bedding}} = \frac{\sum_{c=1}^C \sum_{p=1}^{P_c} \chi_{\text{bedding},c,p} D_{c,p} (1 - a_{c,p}) \alpha}{\sum_{c=1}^C \sum_{p=1}^{P_c} \chi_{\text{bedding},c,p} D_{c,p}} \quad (0.14)$$

where  $\chi_{\text{bedding},c,p}$  is 1 if product  $p$  from crop  $c$  is suitable for use as bedding and zero otherwise. If no crop products suitable for use as bedding are produced on the farm,  $C_{\text{bedding}}$  is assigned the value for a default bedding. The crop product assigned to be the default bedding is a parameter.

The C content of feed that is wasted or spoilt ( $c_{\text{waste},g}$ ;  $\text{kg (DM kg)}^{-1}$ ) is:

$$c_{\text{waste},g} = \frac{\sum_{f=1}^F ((1 - \chi_{\text{pas},g,f}) I_f (1 - a_f) \alpha)}{\sum_{f=1}^F (1 - \chi_{\text{pas},g,f}) I_f} \quad (0.14)$$

The urine C is assumed to be as urea or low-molecular weight compounds that are very rapidly decomposed to  $\text{CO}_2$ , which is then assumed to be lost to the environment. This loss of C is thus ( $C_{\text{CO}_2\text{house},g,h}$ ;  $\text{kg yr}^{-1}$ ) is:

$$C_{\text{CO}_2\text{house},g,h} = \vartheta_{g,h} (1 - \gamma_g) C_{\text{urine},g} \quad (0.14)$$

The C from livestock category  $g$  in housing type  $h$  annually entering manure storage ( $C_{\text{instore},g,h}$ ;  $\text{kg yr}^{-1}$ )

$$C_{\text{instore},g,h} = C_{\text{inhouse},g,h} - C_{\text{CO}_2,g,h} \quad (0.14)$$

## 5.2 Nitrogen

The N excreted must be partitioned between ammoniacal N and organic N; gaseous emissions only occur from the ammoniacal N. The N in urine is present in the form of urea and other low molecular weight N-containing compounds. These are assumed to decompose rapidly and results in the formation of  $\text{NH}_4\text{-N}$  (TAN). The annual formation of TAN from livestock excreta is equated to the urine N ( $N_{\text{urine},g}$ ). The N entering animal house  $h$  from livestock category  $g$  ( $N_{\text{TANinhouse},g,h}$ ;  $\text{kg yr}^{-1}$ ) is therefore:

$$N_{TANinhouse,g,h} = \vartheta_{g,h} (1 - \gamma_g) N_{urine,g,h} \quad (0.14)$$

The organic N inputs to animal housing are from livestock faeces, bedding and spilt/spoilt feed. The annual input of organic N into the animal house  $h$  from livestock category  $g$  ( $N_{Orginhouse,g,h}$ ; kg yr<sup>-1</sup>) is:

$$N_{Orginhouse,g,h} = \vartheta_{g,h} (1 - \gamma_g) N_{faeces,g,h} + D_{bedding,g,h} n_{bedding} + D_{waste,g,h} n_{waste,g,h} \quad (0.14)$$

where  $n_{bedding}$  (kg (kg DM)<sup>-1</sup>) is the N content of the bedding and  $n_{waste,g,h}$  (kg (kg DM)<sup>-1</sup>) is the N content of the wasted/spoilt feed.  $n_{bedding}$  and  $n_{waste,g,h}$  are calculated in the same way as the relevant C contents (see Equations (0.14) and (0.14)).

TAN is lost from the animal housing via NH<sub>3</sub> volatilisation. The annual NH<sub>3</sub> volatilisation from animal house  $h$  that is attributable to livestock category  $g$  ( $N_{NH3house,g,h}$ ; kg yr<sup>-1</sup>) is:

$$N_{NH3house,g,h} = \vartheta_{g,h} (1 - \gamma_g) EF_{NH3,h,\theta} N_{TANin,g,h} \quad (0.14)$$

where  $EF_{NH3house,h,\theta}$  is the annual emission factor for NH<sub>3</sub> for animal housing type  $h$  (kg (kg TAN)<sup>-1</sup>).

When using a Tier 2 approach, is a parameter constant. If using a Tier 3 approach,  $EF_{NH3house,h,\theta}$  is the annual emission factor if livestock were housed all year round. The emission of NH<sub>3</sub> from a given type of livestock in a given type of animal housing will vary with ambient temperature, due to its direct effect on the concentration of NH<sub>3</sub> in air, relative to the concentration in the manure on ventilation rates and on the indirect effect on ventilation rate. For simplicity, only the direct effect is considered here. Using Henry's Law, the NH<sub>3</sub> emission factor at a given mean temperature ( $\theta$ ; K) is expressed as a function of a reference emission factor at the mean temperature of 293K ( $EF_{NH3house,h,ref}$ ; kg (kg TAN)<sup>-1</sup>):

$$EF_{NH3house,h,\theta} = \frac{K_{H,ref}}{K_{H,\theta}} EF_{NH3house,h,ref} \quad (0.14)$$

Where  $K_{H,\theta}$  can be given (from Equation 27 in Hales and Drewes, 1979) as:

$$\log_{10} K_{H,\theta} = -1.69 + \frac{1447.7}{\theta} \quad (0.14)$$

$K_{H,ref}$  is evaluated using Equation (0.14) at the reference temperature.

$EF_{NH3house,h,ref}$  is a parameter.

For animal housing that is used year-round for part or all of the day,  $\theta$  is evaluated as the mean annual air temperature. The assumption here is that there will be an emitting surface present at all times. Where the housing is empty for part of the year, it is assumed that the housing will be cleaned when the livestock are removed. In this case,  $\theta$  is evaluated as the mean of the period during which the housing is occupied. The proportion of the year when the housing is occupied is  $1 - \gamma_g$ . Here we assume that this is a single period, centred on a particular month of the year for each livestock category ( $m_{housing,g}$ ; month). The method used to evaluate  $\theta$  is given in Appendix I.

For both the Tier 2 and 3 approaches, the TAN entering manure storage from livestock category  $g$  and housing type  $h$  ( $N_{TANinstore,g,h}$ ;  $\text{kg yr}^{-1}$ ) is:

$$N_{TANinstore,g,h} = N_{TANinhouse,g,h} - N_{NH3house,g,h} \quad (0.15)$$

### 5.2.1 Mitigation measure – low-emission housing, acidification

Mitigation measures for both low-emission housing and acidification of slurry in housing are simulated by modifying the emission factor ( $EF_{NH3house,h,\theta}$ ).

## 5.3 Manure storage

The manure from a single animal house can be stored in either one or two types of manure store. The store or stores can either be within the animal house or external to it. The storage type or types  $s$  are linked to the housing type in the database and are input by the  $LE$ . The manure storage is defined in terms of the livestock species producing the manure, the type of manure stored and the type of storage. For example, dairy cattle slurry, no crust and dairy cattle slurry, with crust would be separate types of storage whereas farmyard manure from cattle would be considered one type of manure storage, even if the manure came from dairy cows, heifers and beef calves. A grouping of livestock categories within a species (a species grouping) is indicated here using the subscript  $sg$ .

Wishing to avoid the complexity necessary to describe the consequences of variations in the rate of input and rate of removal of manure to and from manure storage, the transformations of C and N are treated as if manure storage were a batch operation.

The model does not consider flows of ash or water. For later use in the field, the annual production of manure from species group  $sg$  and store type  $s$  ( $V_{sg,s}$ ;  $\text{m}^3 \text{yr}^{-1}$ ) is a parameter.

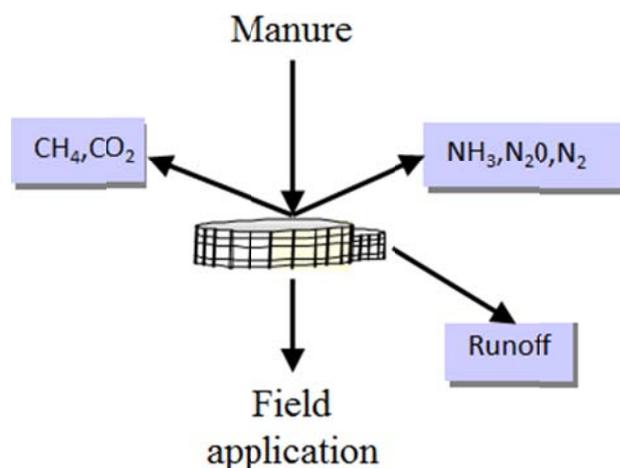


Figure 5 Inputs, outputs and losses from manure storage

### 5.3.1 Carbon

The non-degradable C content of faeces is assumed to equate to the crude fibre content of the diet, which is calculated in Equation (0.12). Likewise, the non-degradable C content of bedding or wasted or spoilt feed is equated to its crude fibre content ( $CF_{\text{bedding}}$  and  $CF_{\text{waste},g}$ ; kg (kg DM)<sup>-1</sup>).  $CF_{\text{bedding}}$  is calculated as a weighted average of the crop products used as bedding (i.e. in a similar way as for the diet).  $CF_{\text{waste},g}$  is calculated as a weighted average of the feed items fed off pasture i.e.:

$$CF_{\text{waste},g} = \frac{\sum_{f=1}^F \left( (1 - \chi_{\text{pas},g,f}) I_f CF_f \right)}{\sum_{f=1}^F (1 - \chi_{\text{pas},g,f}) I_f} \quad (0.15)$$

The manure may be sent to more than one type of manure store, in which case, the C must be partitioned.

The total non-degradable C from livestock category  $g$  in housing type  $h$  entering storage annually ( $C_{\text{OrgNDeg},g,h}$ ; kg yr<sup>-1</sup>) is:

$$C_{\text{OrgNDeg},g,h} = \vartheta_{g,h} \left( (1 - \gamma_g) D_{\text{int},g} CF_{\text{int},g} c_g + CF_{\text{bedding}} C_{\text{bedding},g,h} + CF_{\text{waste},g} C_{\text{waste},g,h} \right) \quad (0.15)$$

where  $CF_{\text{int},g}$  is the crude fibre content of the diet (kg (kg DM)<sup>-1</sup>) and is calculated as in Equation (0.12).

The total non-degradable C from species grouping  $sg$  entering storage type  $s$  annually ( $C_{\text{OrgNDegInstore},sg,s}$ ; kg yr<sup>-1</sup>) is therefore:

$$C_{\text{OrgNDegInstore},sg,s} = \sum_{h=1}^H \kappa_{\text{OrgNDeg},h,s} \sum_{g=1}^{G_{sg}} C_{\text{OrgNDeg},g,h} \quad (0.15)$$

where  $H$  is the number of animal housing types,  $G_{sg}$  is the total number of livestock categories in the species group  $sg$  and  $\kappa_{\text{OrgNDeg},h,s}$  is the proportion of the non-degradable C partitioned to manure storage  $s$  from house  $h$ .

The C input as degradable C into the same manure storage ( $C_{\text{OrgDegInstore},sg,s}$ ; kg yr<sup>-1</sup>) constitutes the remainder of the faecal, bedding and spilt/spoilt feed C:

$$C_{\text{OrgDegInstore},sg,s} = \sum_{h=1}^H \left( \kappa_{\text{OrgDeg},h,s} \sum_{g=1}^{G_{sg}} (C_{\text{instore},g,h} - C_{\text{OrgNDeg},g,h}) \right) \quad (0.15)$$

where  $\kappa_{\text{OrgDeg},h,s}$  is the proportion of the degradable C from housing type  $h$  that is partitioned to manure storage  $s$ , The sum of the values of  $\kappa_{\text{OrgDeg},h,s}$  for all the  $H$  housing types must be unity.

C is lost from storage by the emission of CO<sub>2</sub> and CH<sub>4</sub>, represented here by  $C_{\text{CO2St}}$  and  $C_{\text{CH4St}}$  (kg yr<sup>-1</sup>). The values of  $C_{\text{CO2St},sg,s}$  and  $C_{\text{CH4St},sg,s}$  used here depend upon the emission inventory system that is chosen:

#### For Tier 2

The emission of methane C ( $C_{\text{CH4St},sg,s}$ ) is calculated using the IPCC methodology (Intergovernmental Panel on Climate, 2006):

$$C_{CH4St,sg,s} = \frac{d}{\alpha} \left( \sum_{g=1}^{G_{sg}} \kappa_{OrgNDeg,h,s} C_{faeces,g,h} + \kappa_{OrgDeg,h,s} C_{urine,g,h} \right) \left[ B_{o,sg,s} 0.67 MCF_{sg,s} \right] \quad (0.15)$$

where  $B_{o,sg,s}$  and  $MCF_{sg,s}$  are respectively the maximum  $CH_4$  producing capacity and the methane conversion factor for manure produced by livestock species group  $sg$  and manure storage  $s$ .

$C_{CO2St,sg,s}$  is then calculated as:

$$C_{CO2St,sg,s} = \frac{C_{CH4St,sg,s} (1 - \tau)}{\tau} \quad (0.15)$$

where  $\tau$  is the proportion of the decomposed C that is emitted as  $CH_4$ .  $\tau$  is a parameter.

The total degradation of the C in organic matter  $C_{degSt,sg,s}$  (kg) is then the sum of  $C_{CO2St,sg,s}$  and  $C_{CH4St,sg,s}$ .

### For Tier 3

A relationship based on that used by (Sommer et al., 2009) is used to describe the rate of degradation of the degradable organic matter ( $c_{deg,s}$ ;  $d^{-1}$ ):

$$c_{deg,s} = b_{1,s} e^{\left( \ln Arr - E_{app} \left( \frac{1}{R_{gas} \theta_s} \right) \right)} \quad (0.15)$$

where  $b_{1,s}$  is a parameter,  $Arr$  is the Arrhenius parameter ( $d^{-1}$ ),  $E_{app}$  is the apparent activation energy ( $J mol^{-1}$ ),  $R_{gas}$  is the universal gas constant ( $J K^{-1} mol^{-1}$ ) and  $\theta_s$  is the mean temperature of the manure store during the period of storage (K).  $Arr$ ,  $E_{app}$  and  $R_{gas}$  are parameters. Note that  $c_{deg,s}$  is assumed to be a function of the storage type only.

The manure storage is considered here to be a batch operation with the duration of storage equal to the average length of time the manure from species group  $sg$  remains in manure storage  $s$  ( $t_{store,sg,s}$ ; d). The total decomposition of organic C over this period ( $C_{degSt,sg,s}$ ;  $kg yr^{-1}$ ) is then:

$$C_{degSt,sg,s} = C_{OrgDegInstore,sg,s} \left( 1 - e^{-c_{deg,s} t_{store,sg,s}} \right) \quad (0.15)$$

$t_{store,sg,s}$  is calculated as the average storage time for the manure from all livestock categories in the species group, weighted by the contribution of C:

$$t_{store,sg,s} = \frac{\sum_{h=1}^H \sum_{g=1}^{G_{sg}} \left( (1 - \gamma_g) \left( \kappa_{OrgDeg,h,s} C_{OrgDeg,g,h} + \kappa_{OrgNDeg,h,s} C_{OrgNDeg,g,h} \right) \right)}{2 \sum_{h=1}^H \sum_{g=1}^{G_{sg}} \left( \kappa_{OrgDeg,h,s} C_{OrgDeg,g,h} + \kappa_{OrgNDeg,h,s} C_{OrgNDeg,g,h} \right)} \quad (0.15)$$

The emission of  $CH_4$ -C is then:

$$C_{CH4St,sg,s} = \tau C_{deg,sg,s} \quad (0.15)$$

The remaining decomposed C is emitted as  $CO_2$ :

$$C_{CO2St,sg,s} = (1 - \tau) C_{deg,sg,s} \quad (0.15)$$

For both Tier 2 and 3 calculations, to comply with the requirements of the soil C model (see below), the C in manure removed from the storage for application to the soil or for export must be characterised as either fresh organic C ( $C_{manFOM,sg,s}$ ; kg) or humic C ( $C_{manHUM,sg,s}$ ; kg).  $C_{manHUM,sg,s}$  is calculated as:

$$C_{\text{manHUM},sg,s} = \varpi C_{\text{deg},sg,s} \quad (0.16)$$

where  $\varpi$  is a humification coefficient (dimensionless), describing the proportion of degraded C that is converted to humic C.  $\varpi$  is a parameter.

$C_{\text{manFOM},sg,s}$  is then:

$$C_{\text{manFOM},sg,s} = C_{\text{OrgDeg},sg,s} + C_{\text{OrgnDeg},sg,s} - C_{\text{deg},sg,s} (1 + \varpi) \quad (0.17)$$

The total C in the manure store ( $C_{\text{man},sg,s}$ ; kg yr<sup>-1</sup>) is then;

$$C_{\text{man},sg,s} = C_{\text{manHUM},sg,s} + C_{\text{manFOM},sg,s} \quad (0.17)$$

### 5.3.2 Nitrogen

The TAN entering manure storage  $s$  from species group  $sg$  ( $N_{\text{TANinstore},sg,s}$ ; kg yr<sup>-1</sup>) is:

$$N_{\text{TANinstore},sg,s} = \sum_{h=1}^H \kappa_{\text{TAN},h,s} \sum_{g=1}^{G_{sg}} (N_{\text{TANin},g,h} - N_{\text{NH3house},g,h}) \quad (0.17)$$

where  $\kappa_{\text{TAN},h,s}$  is a parameter describing the proportion of TAN from housing type  $h$  that is partitioned to manure storage  $s$ .

The N in organic matter is assumed to be associated with the degradable fraction, so the partitioning of organic N between manure storage types is assumed to be the same as for degradable organic matter.

The organic N entering the manure storage ( $N_{\text{Orginstore},sg,s}$ ; kg yr<sup>-1</sup>) is:

$$N_{\text{Orginstore},sg,s} = \sum_{h=1}^H \kappa_{\text{OrgDeg},h,s} \sum_{g=1}^{G_{sg}} N_{\text{Orginhouse},g,h} \quad (0.17)$$

Nitrogen is lost from manure storage in the gaseous form as NH<sub>3</sub>, N<sub>2</sub>O and N<sub>2</sub>, and as TAN and organic N in surface runoff or leaching.

### Organic N

#### For Tier 2

The mineralisation of organic N in manure is assumed to be 10%, which is the default value used in the EEA/EMEP Guidebook (European Environment, 2013).

#### For Tier 3

We assume here that the degradation of organic matter results in a proportion of the N being bound in stable humus-like organic compounds with a constant C:N ratio of  $cn_{\text{HUM}}$  (a parameter). The degradable organic N from species group  $sg$  in manure storage  $s$  at the end of the storage period ( $N_{\text{DegOrgout},sg,s}$ ; kg yr<sup>-1</sup>) is:

$$N_{\text{DegOrgout},sg,s} = N_{\text{Orginstore},sg,s} e^{-(\Omega_{\text{org},s} + c_{\text{deg},s}) t_{\text{store},sg,s}} \quad (0.17)$$

where  $\Omega_{\text{org},s}$  is the proportion of organic N lost in surface run-off or leaching from manure storage type  $s$ .

The cumulative organic N in runoff/leaching in degradable organic matter for species group  $sg$  and manure storage type  $s$  ( $N_{\text{runoff},sg,s}$ ;  $\text{kg yr}^{-1}$ ) is:

$$N_{\text{RunoffOrg},sg,s} = \left( \frac{\Omega_{org,s}}{\Omega_{org,s} + c_{deg,s}} \right) N_{\text{Orginstore},sg,s} \left( 1 - e^{-(\Omega_{org,s} + c_{deg,s})t_{store,sg,s}} \right) \quad (0.17)$$

The amount of humic N present at the end of the storage period for species group  $sg$  and manure storage type  $s$  ( $N_{\text{HUM},sg,s}$ ;  $\text{kg yr}^{-1}$ ) is as follows:

$$N_{\text{HUM},sg,s} = \left( \frac{\varpi}{cn_{\text{HUM}}} \right) C_{\text{OrgDeg},sg,s} \left( e^{-(\Omega_{org,s} + c_{deg})t_{store,sg,s}} - e^{-\Omega_{org,s}t_{store,sg,s}} \right) \quad (0.17)$$

This formulation assumes that there is no humic N in the fresh animal excreta.

The runoff of humic N ( $N_{\text{runoffHUM},sg,s}$ ;  $\text{kg yr}^{-1}$ ) is:

$$N_{\text{runoffHUM},sg,s} = \frac{c_{deg}}{\Omega_{org,s} + c_{deg}} \left( \frac{\varpi}{cn_{\text{HUM}}} \right) C_{\text{DegOrg},sg,s} \left( 1 - e^{-(\Omega_{org,s} + c_{deg})t} \right) - N_{\text{HUM},sg,s} \quad (0.17)$$

The organic N ex store for species group  $sg$  and manure storage type  $s$  ( $N_{\text{Orgoutstore},sg,s}$ ;  $\text{kg yr}^{-1}$ ) is as follows:

$$N_{\text{Orgoutstore},sg,s} = N_{\text{DegOrgout},sg,s} + N_{\text{HUM},sg,s} \quad (0.17)$$

### TAN

The TAN in manure storage is supplemented by additions from the animal housing and through the mineralisation of organic N and is depleted by the emission of  $\text{NH}_3$ ,  $\text{N}_2\text{O}$  and  $\text{N}_2$ .

### For Tier 2

$\text{N}_2\text{O}$  emissions are calculated as:

$$N_{\text{storeN}_2\text{O},sg,s} = EF_{\text{storeN}_2\text{O},s} \left( N_{\text{TANinstore},sg,s} + N_{\text{Orginstore},sg,s} \right) \quad (0.17)$$

where  $N_{\text{storeN}_2\text{O},sg,s}$  is the annual emission of  $\text{N}_2\text{O}$ -N ( $\text{kg yr}^{-1}$ , N) for species group  $sg$  and storage type  $s$  and  $EF_{\text{storeN}_2\text{O},s}$  is the emission factor ( $\text{kg kg}^{-1}$ ) for manure storage type  $s$ .  $EF_{\text{storeN}_2\text{O},sg,s}$  is a parameter and the value is taken from Table 10.21 of (Intergovernmental Panel on Climate, 2006). This formula is close but not identical to that of the IPCC; the only difference is that here, the contribution of added bedding and waste feed is included.

Annual  $\text{NH}_3$ -N emissions ( $N_{\text{storeNH}_3,sg,s}$ ;  $\text{kg yr}^{-1}$ ) are calculated as:

$$N_{\text{storeNH}_3,sg,s} = EF_{\text{storeNH}_3,sg,s} \left( N_{\text{TANinstore},sg,s} + 0.1N_{\text{Orginstore},sg,s} \right) \quad (0.17)$$

where  $EF_{\text{storeNH}_3,sg,s}$  is an emission factor that varies with species group  $sg$  and manure storage type  $s$ . The value of  $EF_{\text{storeNH}_3,sg,s}$  is taken from Table 3.7 of (European Environment, 2013).

The annual emission of  $\text{N}_2$  from manure storage  $s$  ( $N_{\text{storeN}_2,sg,s}$ ;  $\text{kg yr}^{-1}$ ) is:

$$N_{\text{storeN}_2,sg,s} = \lambda_m N_{\text{storeN}_2\text{O},sg,s} \quad (0.17)$$

where  $\lambda_m$  is a constant (and a parameter).

The runoff/leaching of TAN ( $N_{\text{runoffTAN},sg,g}$ ;  $\text{kg yr}^{-1}$ ) is calculated as:

$$N_{\text{runoffTAN},sg,g} = \Omega_{\text{TAN},s} \left( N_{\text{TANinstore},sg,s} + 0.1N_{\text{Orginstore},sg,s} \right) \quad (0.17)$$

The TAN ex storage ( $N_{\text{TANOutstore},g,s}$ ;  $\text{kg yr}^{-1}$ ) is:

$$N_{\text{TANOutstore},sg,g} = N_{\text{TANinstore},sg,s} + 0.1N_{\text{Orginstore},sg,s} - \left( N_{\text{storeN}_2\text{O},sg,s} + N_{\text{storeN}_2,sg,s} + N_{\text{storeNH}_3,sg,s} + N_{\text{runoffTAN},sg,g} \right)$$

### For Tier 3

The derivation of the relationships describing the Tier 3 dynamics of organic N and TAN in manure storage are shown in Appendix II.

The TAN ex storage ( $N_{\text{TANOutstore},g,s}$ ;  $\text{kg yr}^{-1}$ ) is:

$$N_{\text{TANOutstore},sg,s} = \frac{c_{\text{deg},s} \left( \frac{1}{cn_{sg,s}} - \frac{\varpi}{cn_{HUM}} \right) C_{\text{OrgDeg},sg,s}}{\left( EF_{\text{sum},s} + \Omega_{\text{TAN},s} \right) - \left( \Omega_{\text{org},s} + \frac{c_{\text{deg},s}}{cn_{sg,s}} \right)} e^{-\left( \Omega_{\text{org},s} + \frac{c_{\text{deg},s}}{cn_{sg,s}} \right) t_{\text{store},sg,s}} + \left( N_{\text{TANinstore},sg,s} - \frac{c_{\text{deg},s} \left( \frac{1}{cn_{sg,s}} - \frac{\varpi}{cn_{HUM}} \right) C_{\text{OrgDeg},sg,s}}{\left( EF_{\text{sum},s} + \Omega_{\text{TAN},s} \right) - \left( \Omega_{\text{org},s} + \frac{c_{\text{deg},s}}{cn_{sg,s}} \right)} \right) e^{-\left( EF_{\text{sum},s} + \Omega_{\text{TAN},s} \right) t_{\text{store},sg,s}} \quad (0.17)$$

where  $cn_{sg,s}$  is the C:N ratio of the degradable organic matter for species group  $sg$  and manure storage type  $s$  and  $EF_{\text{sum}}$  ( $\text{d}^{-1}$ ) is the sum of emission factors for  $\text{NH}_3$ ,  $\text{N}_2\text{O}$  and  $\text{N}_2$  respectively ( $EF_{\text{storeNH}_3,sg,s}$ ,  $EF_{\text{storeN}_2\text{O},s}$  and  $EF_{\text{storeN}_2,s}$ ;  $\text{d}^{-1}$ ).

$cn_{sg,s}$  is defined by:

$$cn_{sg,s} = \frac{C_{\text{OrgDeg},sg,s}}{N_{\text{Orginstore},sg,s}}$$

If liquid manure is stored, the value of  $EF_{\text{NH}_3,g,s}$  is calculated using Equation (0.14), replacing  $EF_{\text{NH}_3\text{house},h,\text{ref}}$  with  $EF_{\text{storeNH}_3,sg,s,\text{ref}}$  ( $\text{d}^{-1}$ ; a parameter). If solid manure is stored, the temperature of the storage may depend on the ambient temperature or, if self-heating occurs, may be determined by the storage type itself. For solid storage,  $EF_{\text{storeNH}_3,sg,s}$  is also calculated using Equation (0.14), with the exception of storage in which self-heating is considered to be dominant, where  $EF_{\text{storeNH}_3,sg,s}$  is equated to  $EF_{\text{storeNH}_3,sg,s,\text{ref}}$ . The value of  $EF_{\text{storeN}_2\text{O},sg,s}$  is a parameter.

$EF_{\text{storeN}_2,s}$  is calculated as for the Tier 2 method:

$$EF_{\text{storeN}_2,g,s} = \lambda_m EF_{\text{storeN}_2\text{O},sg,s} \quad (0.17)$$

The TAN lost via runoff/leaching or gaseous emissions ( $N_{\text{TANlost},sg,g}$ ;  $\text{kg yr}^{-1}$ ) is:

$$N_{\text{TANlost},sg,s} = N_{\text{Orginstore},sg,s} + N_{\text{TANinstore},g,s} - \left( N_{\text{DegOrgout},sg,s} + N_{\text{runoffOrg},sg,s} + N_{\text{TANoutstore},g,s} \right) \quad (0.17)$$

The runoff/leaching of TAN ( $N_{\text{runoffTAN},sg,g}$ ;  $\text{kg yr}^{-1}$ ) is then:

$$N_{\text{runoffTAN,sg,g}} = \frac{\Omega_{\text{TAN,s}}}{\Omega_{\text{TAN,s}} + EF_{\text{NH}_3,s} + EF_{\text{N}_2\text{O},s} + EF_{\text{N}_2,s}} N_{\text{TANlost,sg,s}} \quad (0.17)$$

The gaseous emissions of N ( $N_{\text{storeX,sg,s}}$ ; kg yr<sup>-1</sup>) are;

$$N_{\text{storeX,sg,s}} = \frac{EF_{X,s}}{\Omega_{\text{TAN,s}} + EF_{\text{NH}_3,s} + EF_{\text{N}_2\text{O},s} + EF_{\text{N}_2,s}} N_{\text{TANlost,sg,s}} \quad (0.18)$$

Where  $X$  is NH<sub>3</sub>, N<sub>2</sub> or N<sub>2</sub>O.

### 5.3.3 Mitigation measures

The mitigation measures available for manure storage are as follows:

- covering storage to reduce NH<sub>3</sub> emission.
- acidification of slurry to reduce NH<sub>3</sub> and GHG emissions.
- anaerobic digestion of slurry to reduce NH<sub>3</sub> and GHG emissions.

The effect of the covering of storage on NH<sub>3</sub> emission is simulated via the emission factor,  $EF_{\text{storeNH}_3,\text{sg,s}}$ . The effect of the acidification of slurry (either slurry acidified in animal housing or tank acidification) on NH<sub>3</sub> emission is also simulated via  $EF_{\text{storeNH}_3,\text{sg,s}}$ , whereas the way the effect on GHG emissions is simulated depends on the approach used. For the Tier 2 approach, the manure conversion factor ( $Y_m$ ) is modified. For the Tier 3 approach, the degradation rate parameter ( $b_{1,s}$ ) is modified.

The simulation of anaerobic digestion of slurry is here limited to monosubstrate digestion (i.e. without the use of any supplementary substrate). The capture of CH<sub>4</sub> is simulated using a gas capture efficiency factor ( $gcap_s$ ), such that equation (0.15) is modified as follows:

$$C_{\text{CH}_4\text{St,sg,s}} = gcap_s \tau C_{\text{deg,sg,s}}$$

## 6 Crop and soil

The agricultural area on the farm is divided into one to many fields, each of which has a sequence of crops. Each field occupies a given area ( $A_{\text{seq}}$ ; ha) and is a model input. In a given crop sequence  $r$ , the period number in the crop sequence ( $q$ ), the crop identifier ( $c$ ), starting date ( $t_{\text{start},q,r}$ ; yr) and end date ( $t_{\text{end},q,r}$ ; yr) for each period in the crop sequence are all model inputs. The length of the  $r$ th crop sequence ( $t_{\text{seq},r}$ ; yr) is:

$$t_{\text{seq},r} = t_{\text{end},Q,r} - t_{\text{start},1,r} \quad (0.18)$$

There can be no gaps in the sequence of crops; bare soil is here considered to be a crop. It is mandatory that  $t_{\text{seq},r}$  is an integer i.e. the last cropping period ends a whole number of years after the start of the first cropping period. This allows the crop sequence to be repeated a number of times, if necessary. Figure 6 shows an example of a cropping sequence.

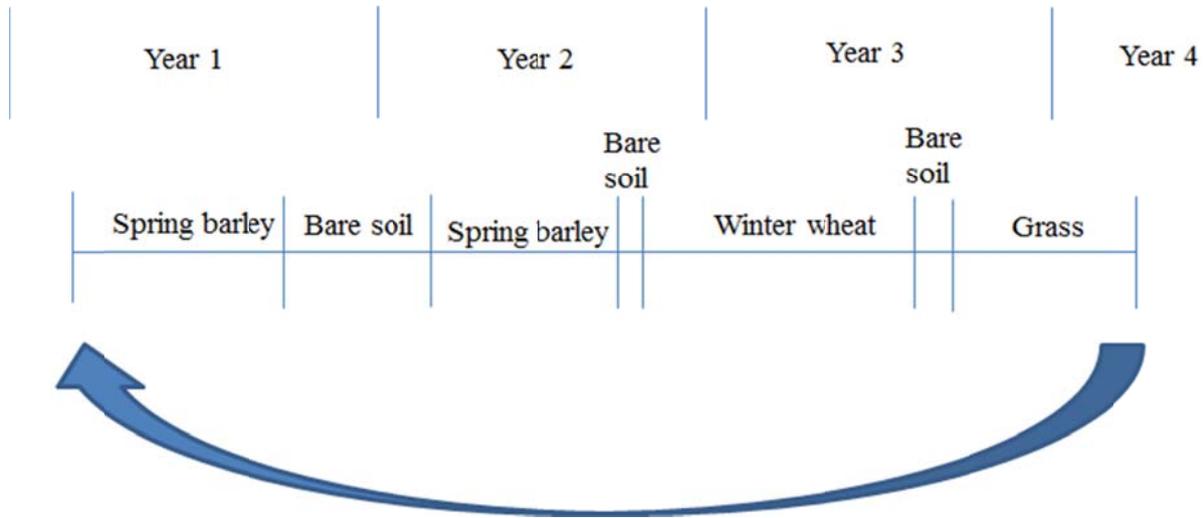


Figure 6 Example crop sequence

### 6.1 Crop production

The DM production of a given crop in a given period of a particular crop sequence depends on a range of factors. Some factors are not controllable by the farmer (e.g. temperature, rainfall) whereas others can be controlled or mediated to a greater or lesser extent (e.g. irrigation, supply of nutrients). The approach used here is to focus on those factors that the farmer can influence and to oblige the user to quantify the effect of other factors. In practice, this means that for each period in which a crop is grown, the user must quantify the potential DM yield i.e. the DM yield achievable in the absence of water or N stress. Where crop can produce two crop products (e.g. grain and straw), the user must quantify the potential yield for both. The model then adjusts this value (if necessary) to allow for the effect of water and N stress.

The potential harvestable DM production of each crop product in each cropping period of each crop sequence ( $y_{pot,c,p,r,q}$ ; kg DM ha<sup>-1</sup>) is an input to the model.

Not all the crop above-ground DM production of a crop can be harvested. There are several reasons for this; the DM may have senesce prior to harvesting and fall to the soil surface as litter, be stubble that is below the cutting height of the harvester or be DM that escapes the device used to collect the harvested material. The DM production of product  $p$  from crop  $c$  in crop sequence  $r$  during period  $q$  that is available for use on the farm ( $Y_{c,p,r}$ ; kg DM) is calculated as:

$$Y_{c,p,r} = (1 - \omega_{store,c,p}) \sum_{q=1}^{Q_r} A_r (1 - \Psi_{AG,c,hv}) y_{prod,c,p,r,q} \quad (0.19)$$

where  $\Psi_{AG,c,hv}$  is the proportion of above-ground DM production of crop  $c$  that cannot be harvested and  $y_{prod,q,c,r}$  is the DM production of product  $p$  of crop  $c$  during period  $q$  in crop sequence  $r$  (kg ha<sup>-1</sup>).  $\Psi_{AG,c,hv}$  is additionally made specific to the harvesting method,  $hv$ . This is primarily to permit the simulation of the residues remaining from crops that can be harvested either by cutting or grazing, since the efficiency of the latter can vary considerably.  $\xi_{c,p}$  is a model parameter.  $\omega_{store,c,p}$  is the proportion of DM that is lost during the processing of

the crop product  $p$  from crop  $c$  e.g. during silage- or haymaking, or as the result of product deterioration in storage.

The modelled rate of harvestable DM production of each crop product in each cropping period of each crop sequence ( $y_{\text{modelled},c,r,q}$ ; kg DM ha<sup>-1</sup>) is calculated as follows. The model does not contain a water submodel. Instead, for a given soil type in a given agro-climatic zone and during a given cropping period, a drought index is defined ( $\eta$ ). This drought index represents the drought-induced reduction in the production of a typical cereal crop, relative to the production in an unstressed situation. For example, a drought that reduces the cereal production by 20% would mean that  $\eta = 0.2$ . The value of  $\eta$  is calculated as the weighted average of soil type and agro-climatic specific monthly values, for each cropping period. Furthermore, a drought sensitivity factor is assigned to permanent and annual crops ( $\eta_{\text{perm}}$  and  $\eta_{\text{ann}}$ ) that varies from 0 (no effect of any drought) to 1 (full effect of any drought). The potential harvestable yield of an annual crop product when N is unlimited ( $y_{N\text{max},c,p,r,q}$ ; kg DM ha<sup>-1</sup>) is:

$$y_{N\text{max},c,p,r,q} = \eta_{\text{ann}} \eta y_{\text{max},c,p,r,q} \quad (0.20)$$

For a permanent crop,  $\eta_{\text{ann}}$  is replaced by  $\eta_{\text{perm}}$ .

The N stress is calculated by comparing the crop N uptake when DM production at its potential value ( $N_{\text{max\_uptake},c,r,q}$ ; kg ha<sup>-1</sup>) with the mineral N available in the soil ( $N_{\text{min},c,r,q}$ ; kg ha<sup>-1</sup>) see equation (0.34)). When calculating  $N_{\text{max\_uptake},c,r,q}$  it is necessary to account for both above and below ground DM production:

$$N_{\text{max\_uptake},c,r,q} = \sum_{p=0}^{P_r} y_{N\text{max},c,p,r,q} \left( n_{c,p} \left( 1 + \Psi_{AG,c} + \beta_{c,p,r,q} \right) + \frac{c_{BG} \Psi_{BG,c}}{cn_{BG,c}} \right) \quad (0.21)$$

If  $N_{\text{max\_uptake},c,r,q}$  exceeds  $N_{\text{min},c,r,q}$  then crop production will be limited by the availability of mineral N. The value of  $y_{\text{modelled},c,p,r,q}$  is then:

$$y_{\text{modelled},c,p,r,q} = \frac{N_{\text{min},c,r,q} y_{N\text{max},c,p,r,q}}{N_{\text{max\_uptake},c,r,q}} \quad (0.22)$$

Otherwise,  $y_{\text{modelled},c,p,r,q} = y_{N\text{max},c,p,r,q}$ .

### 6.1 Soil C and N dynamics

The simple dynamic C-Tool model is used to assess the C sequestration in the soil (Petersen et al., 2002). This model considers three C pools; fresh, humic and resilient. C is input primarily into the fresh pool, although some C from manure may be input into the humic pool, if the manure has undergone decomposition in storage. The C flows from the fresh to humic to resilient pools with associated temperature-dependent rate constants and emissions of CO<sub>2</sub>. The inputs to this model are thus the fresh and humic C, and the air temperature. Since the model is dynamic, the C sequestered in the soil may change with time. This change will be particularly great if the management imposed differs markedly from that which has hitherto been the case, as a new equilibrium between C inputs, storage and losses is established. It is therefore necessary to initialise the C-Tool model to account for the previous land use. This procedure is described in Appendix III.

It is assumed here that the medium to long-term storage of organic matter in the soil is determined by the dynamics of C and that the C:N ratios of the stable and resistant organic

matter in the soil are constants. Consequently, changes in the N storage in the soil are driven by the C dynamics.

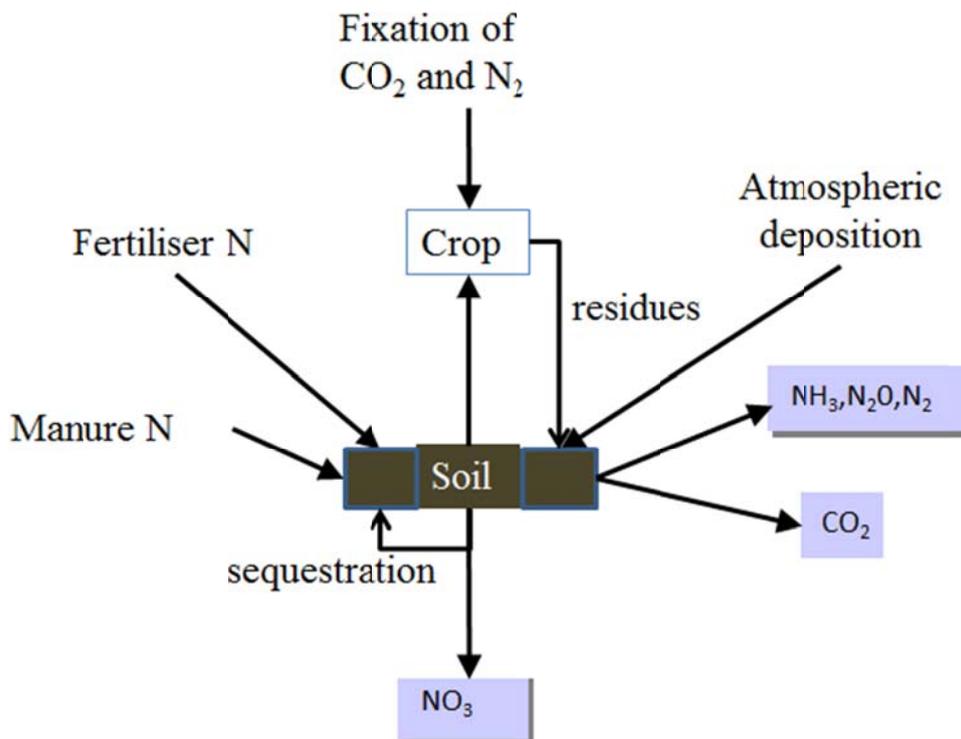


Figure 7 Inputs, outputs and losses from crops and soil

The modelling of the C and N in the soil is complicated by two factors. Firstly, most processes are simulated using static modelling (e.g. simple proportions or emission factors) whereas changes in C and N storage in the soil are simulated using dynamic modelling. Secondly, the system contains feedbacks e.g. a proportion of the mineral N available for crop uptake has its origins in plant residues input to the soil from the crop itself, yet the amount of those residues depends itself on the crop growth. This means it is necessary to iterate within the crop and soil models.

The iteration system used to estimate crop DM production is shown in Fig 8 below. The initial estimate of DM production is equated to the water-limited production ( $y_{pot}$ ). Based on this estimate, the crop residues input to the soil are calculated. The soil C and N model is then run for the duration of the crop, yielding an estimate of the mineralisation of soil N. The fixed N inputs are then calculated (i.e. fertiliser, manure, atmospheric N deposition etc). The losses of N from the soil are then calculated (i.e. ammonia volatilisation, nitrate leaching etc), allowing the calculation of crop-available N. The N-limited DM production ( $y_{modelled}$ ) is then calculated using Equation (0.22) and compared with the original estimate. If the two equate to one another (within a small error margin), the iteration is complete. Otherwise, a new estimate of DM production is calculated and the iterations continue.

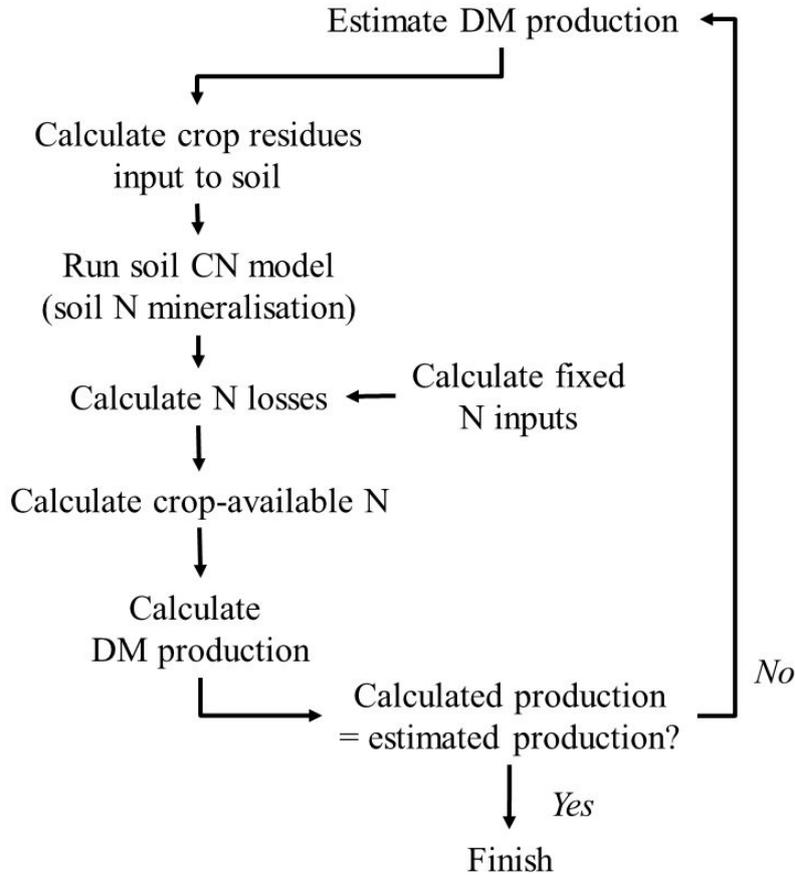


Figure 8 Iteration to find crop dry matter production

### 6.1.1 Carbon

Carbon is added to the field in crop residues (senescent or stubble stem and leaf material, senescent roots and root exudates) and in animal manure (including excreta) and mineral N fertiliser containing urea.

Some of the above-ground DM production is not harvested (see above) and apart from harvested storage organs, none of the below-ground DM production from roots, senescent roots and root exudates is harvested. The C added to the soil in residues from crop  $c$  in the  $r$ th crop sequence ( $C_{\text{residue},c,r}$ ;  $\text{kg yr}^{-1}$ ) is simulated as follows:

$$C_{\text{residue},q,c,r} = \sum_{p=1}^{P_c} \left( A_r y_{q,c,p,r} \left( c_{c,p} \left( \Psi_{AG,c,hv} + \beta_{c,p,r} \right) + c_{BG} \Psi_{BG,c} \right) \right) \quad (0.22)$$

where  $\psi_{BG,c}$  is the below-ground residue DM relative to DM yield ( $\text{kg (kg DM)}^{-1}$ ),  $c_{BG}$  is the concentration of C in below-ground DM production ( $\text{kg (kg DM)}^{-1}$ ) and  $\beta_{c,p,r}$  is 1 if the product remains on the field and zero otherwise.  $\psi_{BG,c}$  is a crop-specific parameter and  $\beta_{c,p,r}$  is an input. If some or all the crop residues are burnt,  $\psi_{BG,c}$  is assumed to be zero and  $\beta_{c,p,r}$  is evaluated as before. All the C from crop residues is added to the FOM pool in C-Tool.

The amount of C added in livestock excreta during grazing of crop  $c$  in the  $r$ th crop sequence is ( $C_{\text{excreta},q,c,r}$ ;  $\text{kg yr}^{-1}$ ):

$$C_{\text{excreta},q,c,r} = \sum_{c=1}^C \sum_{g=0}^G \left( \gamma_{g,q,c,r} (C_{\text{urine},g} + C_{\text{faeces},g}) \right) \quad (0.22)$$

where  $\gamma_{g,q,c,r}$  is the proportion of the year that livestock group  $g$  spends grazing crop  $c$  in period  $q$  in crop sequence  $r$ .  $\gamma_{g,c,r}$  is obtained as follows:

$$\gamma_{g,c,r} = \frac{\sum_{q=1}^{Q_r} \Phi_{q,c,r} \sum_{p=1}^{P_c} A_r y_{q,c,p,r} \sum_{f=1}^F \chi_{\text{pas},f} I_{g,f} \sum_{p=1}^{P_c} \Gamma_{c,p,f}}{\sum_{r=1}^R \sum_{q=1}^{Q_r} \Phi_{q,c,r} \sum_{p=1}^{P_c} A_r y_{q,c,p,r}} D_{\text{int},g} \quad (0.22)$$

where  $\Phi_{q,c,r}$  is the proportion of DM from crop  $c$  in period  $q$  in crop sequence  $r$  that is consumed in the field. The first quotient describes the proportion of DM from crop  $c$  in crop sequence  $r$  that is consumed at pasture whilst the second term describes the proportion of that DM that is consumed by livestock category  $g$ .

The C in excreta added to the FOM pool in C-Tool.

The FOM C added to the  $q$ th crop of the  $r$ th crop sequence in manure ( $C_{\text{manFOM},q,r}$ ;  $\text{kg yr}^{-1}$ ) is:

$$C_{\text{manFOM},q,r} = m_{\text{sg},s,q} A_r \frac{C_{\text{manFOM},sg,s}}{V_{\text{sg},s}} \quad (0.23)$$

where  $m_{\text{sg},s,q}$  is the volume of manure from species group  $sg$  in manure store type  $s$  that is applied in period  $q$  ( $\text{m}^3 \text{ha}^{-1}$ ) and is a model input. C in excreta added to the HUM pool in C-Tool ( $C_{\text{HUM},r}$ ;  $\text{kg yr}^{-1}$ ) is calculated as in Equation (0.23), replacing FOM with HUM. The additions of fresh and humic C in manure removed from manure storage ( $C_{\text{manFOM},g,h,s}$  and  $C_{\text{manHUM},g,h,s}$  respectively) are calculated in Equations (0.16) and (0.17). Some or all of the manure of a particular type may be imported. The C composition of imported manure is a model input and if manure of the same type is produced on the farm, the C composition is a volume-weighted average of the two sources.

Note that for all the manure storage the following must be true:

$$\sum_{r=1}^R \sum_{q=1}^{Q_r} (C_{\text{manFOM},q,r} + C_{\text{manHUM},q,r}) = \sum_{sg=1}^{SG} \sum_{s=1}^S C_{\text{man},sg,s} \left( 1 + \frac{m_{\text{imp},sg,s} - m_{\text{exp},sg,s}}{V_{\text{sg},s}} \right) \quad (0.24)$$

where  $SG$  and  $S$  are respectively the total number of species groups and manure storage types present on the farm and  $m_{\text{imp},sg,s}$  and  $m_{\text{exp},sg,s}$  are the masses of manure from species group  $sg$  imported or exported from manure store  $s$  ( $\text{m}^3 \text{yr}^{-1}$ ). This formulation assumes that the concentration of C in manure imported is the same as that which is produced on the farm.

The C added in urea fertiliser to the  $q$ th crop of crop sequence  $r$  ( $C_{\text{fert},q,r}$ ;  $\text{kg yr}^{-1}$ ) is:

$$C_{\text{fert},q,r} = \frac{12}{28} A_r n_{z=\text{urea},q,r} \quad (0.24)$$

where  $n_{z=\text{urea},q,r}$  is the mass of urea N applied in period  $q$  of crop sequence  $r$  ( $\text{kg ha}^{-1}$ , N). This C is assumed to be lost immediately.

The outputs of the C-Tool model are the changes in the amount of C in the fresh organic matter, humic and resilient pools for each crop sequence ( $\Delta C_{\text{FOM},q,r}$ ,  $\Delta C_{\text{humic},q,r}$  and  $\Delta C_{\text{resil},q,r}$ ; kg).

The change in soil C in period  $q$  of the  $r$ th crop sequence ( $C_{\Delta\text{soil},r}$ ; kg) is then:

$$C_{\Delta\text{soil},q,r} = C_{\Delta\text{FOM},q,r} + C_{\Delta\text{humic},q,r} + C_{\Delta\text{resil},q,r} \quad (0.25)$$

### 6.1.2 Nitrogen

The sources of N input to soil are N fixation, atmospheric N deposition, manure N and fertiliser N. Changes in the amount of N stored in organic matter in the soil can either be a source or sink of N. Losses occur via the emission of  $\text{NH}_3$  from N applied in fertilisers and manure,  $\text{N}_2$  and  $\text{N}_2\text{O}$  emissions from the soil and the leaching of  $\text{NO}_3$ . The model distinguishes between mineral and organic N, with crop uptake and losses to the environment only occurring from the mineral N pool.

The C-Tool model only considers C. For this model, the C:N ratios of the humic and resistant pools are considered to be constant. For the fresh organic matter pool, the N is made a variable ( $N_{\text{FOM},r}$ ; kg).

The change in soil N storage for  $q$ th crop in the  $r$ th crop sequence ( $\Delta N_{\text{soil},q,r}$ ; kg) is:

$$\Delta N_{\text{soil},q,r} = \Delta N_{\text{FOM},q,r} + \frac{\Delta C_{\text{humic},q,r}}{cn_{\text{humic}}} + \frac{\Delta C_{\text{resil},q,r}}{cn_{\text{resil}}} \quad (0.26)$$

where  $\Delta C_{\text{humic},q,r}$  and  $\Delta C_{\text{resil},q,r}$  are the changes in the humic and resistant soil C pools during the period of crop  $q$  in crop sequence  $r$ .  $cn_{\text{humic}}$  and  $cn_{\text{resil}}$  are the C:N ratios of the humic and resistant pools respectively (model parameters). The change in  $\Delta N_{\text{FOM}}$  (kg) is calculated as:

$$\Delta N_{\text{FOM},q,r} = \frac{\Delta C_{\text{FOM},q,r} N_{\text{FOM},q,r}}{C_{\text{FOM},q-1,r}} \quad (0.27)$$

The TAN added in period  $q$  of the  $r$ th crop sequence in manure from species group  $sg$  and storage  $s$  ( $N_{\text{TANapp},sg,s,q,r}$ ;  $\text{kg yr}^{-1}$ ) is:

$$N_{\text{TANapp},sg,s,q,r} = m_{sg,s,q,r} A_r \frac{N_{\text{TANOutstore},sg,s}}{V_{sg,s}} \quad (0.28)$$

If some or all of the manure of a particular type is imported, the TAN composition of imported manure is a model input and if manure of the same type is produced on the farm, the TAN composition is a volume-weighted average of the two sources.

The masses of degradable and humic organic N applied to the same crop ( $N_{\text{degOrgapp},sg,s,q,r}$  and  $N_{\text{humOrgapp},sg,s,q,r}$ ;  $\text{kg yr}^{-1}$ ) are calculated as in Equation (0.28), replacing  $N_{\text{TANoutstore}}$  with  $N_{\text{Orgoutstore}}$ .

The addition of N in animal excreta ( $N_{\text{excreta},q,r}$ ; kg) is:

$$N_{\text{excreta},q,r} = \sum_{c=1}^C \sum_{g=0}^G \left( \gamma_{g,q,c,r} (N_{\text{urine},g} + N_{\text{faeces},g}) \right) \quad (0.29)$$

The input of N in fertiliser type  $z$  to crop  $c$  in period  $q$  in crop sequence  $r$  ( $N_{\text{fert},z,q,r}$ ;  $\text{kg yr}^{-1}$ ) is:

$$N_{\text{fert},z,q,r} = n_{z,q} A_r \quad (0.30)$$

where  $n_{z,q,r}$  is the rate of application of fertiliser type  $z$  in period  $q$  in crop sequence  $r$  ( $\text{kg ha}^{-1}$ ).

The input of N via atmospheric deposition in period  $q$  in crop sequence  $r$  ( $N_{\text{atm},c,r}$ ;  $\text{kg yr}^{-1}$ ) is:

$$N_{\text{atm},q,r} = n_{\text{dep}} A_r (t_{\text{end},q,r} - t_{\text{start},q,r}) \quad (0.31)$$

where  $n_{\text{dep}}$  is the rate of atmospheric deposition ( $\text{kg ha}^{-1} \text{yr}^{-1}$ ), a parameter.

The NH<sub>3</sub> emission from fertilisers applied in period  $q$  of crop sequence  $r$  ( $N_{\text{NH}_3\text{fert},q,r}$ ; kg yr<sup>-1</sup>) is:

$$N_{\text{NH}_3\text{fert},q,r} = \varepsilon_{\text{fert},a} EF_{\text{NH}_3\text{fert},z} N_{\text{fert},z,q,r} \quad (0.32)$$

where  $\varepsilon_{\text{fert},a}$  is a reduction factor ( $\leq 1$ ) for application technique  $a$  and  $EF_{\text{NH}_3\text{fert},z}$  is an emission factor for fertiliser type  $z$ .  $EF_{\text{NH}_3\text{fert},z}$  is calculated using Equation (0.14), replacing  $EF_{\text{NH}_3\text{house},h,\text{ref}}$  with  $EF_{\text{NH}_3\text{fert},z,\text{ref}} \cdot EF_{\text{NH}_3\text{fert},z,\text{ref}}$  and  $\varepsilon_{\text{fert},a}$  are parameters.

The NH<sub>3</sub> emission from manure from species group  $sg$  and storage  $s$  applied in period  $q$  of crop sequence  $r$  ( $N_{\text{manNH}_3,sg,s,q,r}$ ; kg yr<sup>-1</sup>) is

$$N_{\text{manNH}_3,sg,s,q,r} = \varepsilon_{\text{man},a} EF_{\text{NH}_3\text{man},sg,s} N_{\text{TAN},sg,s,q,r} \quad (0.33)$$

where  $\varepsilon_{\text{man},a}$  is a reduction factor ( $\leq 1$ ) for application technique  $a$  and  $EF_{\text{soilNH}_3\text{man},sg,s}$  is an emission factor for manure type  $sg$  and storage type  $s$ .  $EF_{\text{NH}_3\text{man},sg,s}$  is calculated using Equation (0.14), replacing  $EF_{\text{NH}_3\text{house},h,\text{ref}}$  with  $EF_{\text{NH}_3\text{man},sg,s,\text{ref}} \cdot EF_{\text{NH}_3\text{man},sg,s,\text{ref}}$  and  $\varepsilon_{\text{man},a}$  are parameters. Equation (0.33) is additionally used to calculate the NH<sub>3</sub> emissions from excreta deposited during grazing.

The N added to the soil in crop residues in the  $q$ th period in the  $r$ th crop sequence ( $N_{\text{residue},q,r}$ ; kg yr<sup>-1</sup>) is simulated as follows:

$$N_{\text{residue},q,r} = \sum_{c=1}^C \sum_{p=0}^{P_c} A_r y_{q,c,p,r} \left( n_{c,p} (\Psi_{AG,c} + \beta_{q,p,r}) + \frac{c_{BG} \Psi_{BG,c}}{cn_{BG,c}} \right) \quad (0.33)$$

where  $cn_{BG,c}$  is the C:N ratio of below-ground organic matter inputs for crop  $c$  (a parameter).

The emission of N<sub>2</sub>O from the soils ( $N_{\text{soilN}_2\text{O},q,r}$ ; kg yr<sup>-1</sup>) are calculated as:

$$N_{\text{soilN}_2\text{O},q,r} = EF_{\text{N}_2\text{O},\text{fert}} N_{\text{fert},q,r} + EF_{\text{N}_2\text{O},\text{man}} (N_{\text{TAN},sg,s,q,r} + N_{\text{Org},sg,s,q,r}) + EF_{\text{N}_2\text{O},\text{resid}} N_{\text{resid},q,r} + EF_{\text{N}_2\text{O},\text{soil}} \Delta N_{\text{soil},r} \quad (0.34)$$

where  $EF_{\text{N}_2\text{O},\text{fert}}$ ,  $EF_{\text{N}_2\text{O},\text{man}}$ ,  $EF_{\text{N}_2\text{O},\text{resid}}$  and  $EF_{\text{N}_2\text{O},\text{soil}}$  are emission factors (kg kg<sup>-1</sup> yr<sup>-1</sup>) for fertiliser (including atmospheric deposition), manure (including excreta), crop residues and changes in soil N storage.

The emission of N<sub>2</sub> from soil ( $N_{\text{N}_2,q,r}$ ; kg yr<sup>-1</sup>) is calculated as:

$$N_{\text{soilN}_2,q,r} = \lambda_s N_{\text{soilN}_2\text{O},q,r} \quad (0.34)$$

where  $\lambda_s$  is a parameter.

The total of the losses of N from the soil in gaseous form ( $N_{\text{gas},q,r}$ ; kg) is:

$$N_{\text{gas},q,r} = N_{\text{soilN}_2\text{O},q,r} + N_{\text{soilN}_2,q,r} + \sum_{z=1}^Z N_{\text{NH}_3\text{fert},z,q,r} + \sum_{sg=1}^{SG} \sum_{s=1}^S N_{\text{manNH}_3,sg,s,q,r} \quad (0.34)$$

The mineral N in the soil, after gaseous emissions ( $N_{\text{min},q,r}$ ; kg) can now be calculated:

$$N_{\text{min},q,r} = \Delta N_{\text{soil},r} + \sum_{z=1}^Z N_{\text{fert},z,q,r} + \sum_{sg=1}^{SG} \sum_{s=1}^S N_{\text{TANapp},sg,s,q,r} + \sum_{c=1}^C \sum_{g=0}^G (\gamma_{g,q,c,r} N_{\text{urine},g}) + N_{\text{atm},q,r} - N_{\text{gas},q,r} \quad (0.34)$$

Note that  $\Delta N_{\text{soil},q,r}$  can be either positive or negative, depending on whether mineral N is created by the net mineralisation of soil N or is immobilised in soil organic matter.

The loss of N via the leaching of nitrate occurs when there is  $\text{NO}_3\text{-N}$  in the soil and there is drainage of soil water. Whilst in the absence of drainage, there will be no  $\text{NO}_3$  leaching during the period a given crop is growing, the crop may leave  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4^+\text{-N}$  that can be later be nitrified and manure or residues that can later be mineralised and then nitrified. These can all be considered to be the residual leaching potential for the crop. Wishing to avoid having to simulate the mineralisation of organic N, nitrification and the soil water balance, we here identify a nitrate leaching factor for each period (*NO3fact*), which is calculated as follows:

$$\text{NO3 fact} = \frac{\sum_{t=t_{\text{start},q,r}}^{t_{\text{end},q,r}} \eta_{t,q,r}^*}{t_{\text{end},q,r} - t_{\text{start},q,r}} \quad (0.35)$$

where  $\eta_{t,q,r}^*$  is 0 if  $\eta_{t,q,r} > 0$ , otherwise is 1.

The nitrate N leached ( $N_{\text{NO}_3,q,r}$ ;  $\text{kg yr}^{-1}$ ) is then:

$$N_{\text{NO}_3,q,r} = \text{NO3 fact} N_{\text{min},q,r} \quad (0.36)$$

The mineral N potentially available for uptake by the crop ( $N_{\text{avail},q,r}$ ; kg) is then calculated:

$$N_{\text{avail},q,r} = N_{\text{min},q,r} - (N_{\text{gas},q,r} + N_{\text{NO}_3,q,r}) \quad (0.37)$$

If  $N_{\text{avail},q,r}$  exceeds the maximum crop N uptake ( $N_{\text{max\_uptake},c,r,q}$ ), the excess mineral N is made available to the following crop.

### 6.1 Mitigation and adaptation measures

The mitigation and adaptation measures available in the field are:

- increasing (adaptation) or decreasing (mitigation) the amount of N fertiliser or manure,
- the introduction of N fixing crops to increase the N fixed from the atmosphere or of winter cover crops to reduce nitrate leaching,
- the use of irrigation,
- the use of low-emission fertiliser and manure application methods (e.g. rapid incorporation, injection),
- the field acidification of slurry,
- the use of multispecies cropping and
- the suspension of crop residue burning.

The changes to the amount of N fertiliser or manure, the use of irrigation and the introduction of N fixing and cover crops are implemented solely on the basis of changes made by the user to the model inputs. The effect of the use of low-emission application methods and the field acidification of slurry are achieved by modifying either of the emission factors  $N_{\text{NH}_3\text{man}}$  (for manure) or  $N_{\text{NH}_3\text{fer}}$  (for fertiliser).

To simulate the suspension of crop residue burning, it was first necessary to incorporate the facility to burn such residues. The burning of crop residues leads to the emission of black carbon (soot;  $C_{\text{burnBC}}$ ), carbon monoxide (CO;  $C_{\text{burnCO}}$ ), CO<sub>2</sub> ( $C_{\text{burnCO}_2}$ ), NH<sub>3</sub> ( $N_{\text{burnNH}_3}$ ), N<sub>2</sub>O ( $N_{\text{burnN}_2\text{O}}$ ), NO<sub>x</sub> ( $N_{\text{burnNO}_x}$ ) and N<sub>2</sub> ( $N_{\text{burnN}_2}$ ), all units are kg yr<sup>-1</sup>. The emissions are simulated using the emission factors for black carbon ( $EF_{\text{burnBC}}$ ), carbon monoxide ( $EF_{\text{burnCO}}$ ), NH<sub>3</sub> ( $EF_{\text{burnNH}_3}$ ), N<sub>2</sub>O ( $EF_{\text{burnN}_2\text{O}}$ ) and NO<sub>x</sub> ( $EF_{\text{burnNO}_x}$ ):

$$C_{\text{burnBC},q,c,r} = EF_{\text{burnBC}} \sum_{p=1}^{P_c} \left( A_r y_{q,c,p,r} \left( c_{c,p} \left( \Psi_{AG,c,hv} + \beta_{c,p,r} \right) \right) \right)$$

$$C_{\text{burnCO},q,c,r} = EF_{\text{burnCO}} \sum_{p=1}^{P_c} \left( A_r y_{q,c,p,r} \left( c_{c,p} \left( \Psi_{AG,c,hv} + \beta_{c,p,r} \right) \right) \right)$$

$$C_{\text{burnCO}_2,q,c,r} = \left( 1 - (EF_{\text{burnBC}} + EF_{\text{burnCO}}) \right) \sum_{p=1}^{P_c} \left( A_r y_{q,c,p,r} \left( c_{c,p} \left( \Psi_{AG,c,hv} + \beta_{c,p,r} \right) \right) \right)$$

$$N_{\text{burnNH}_3,q,r} = EF_{\text{burnNH}_3} \sum_{c=1}^C \sum_{p=0}^{P_r} A_r y_{q,c,p,r} \left( n_{c,p} \left( \Psi_{AG,c} + \beta_{q,p,r} \right) + \frac{c_{BG} \Psi_{BG,c}}{cn_{BG,c}} \right)$$

$$N_{\text{burnN}_2\text{O},q,r} = EF_{\text{burnN}_2\text{O}} \sum_{c=1}^C \sum_{p=0}^{P_r} A_r y_{q,c,p,r} \left( n_{c,p} \left( \Psi_{AG,c} + \beta_{q,p,r} \right) + \frac{c_{BG} \Psi_{BG,c}}{cn_{BG,c}} \right)$$

$$N_{\text{N}_2,q,r} = \left( 1 - (EF_{\text{burnNH}_3} + EF_{\text{burnN}_2\text{O}}) \right) \sum_{c=1}^C \sum_{p=0}^{P_r} A_r y_{q,c,p,r} \left( n_{c,p} \left( \Psi_{AG,c} + \beta_{q,p,r} \right) + \frac{c_{BG} \Psi_{BG,c}}{cn_{BG,c}} \right)$$

The values of all emission factors are available from (European Environment, 2013). Burning is assumed to be complete, with no above-ground residue C entering the soil.

## 7 Farm balances

### 7.1 C balance

The principle source of C input to the farm will normally be via crop C fixation from the atmosphere, with the import of C in animal feed as a secondary major source on intensive livestock farms. There may also be minor imports of C in urea, animal manure and lime (for soil amendment). C is exported from the farm in agricultural products. The soil may be a source or sink for C.

#### 7.1.1 C inputs

The input of C in crops ( $C_{\text{crop}}$ ; kg yr<sup>-1</sup>) is:

$$C_{\text{crop}} = \sum_{c=1}^C \sum_{p=1}^P C_{\text{crop},c,p} \quad (0.38)$$

The input of C in imported manure ( $C_{\text{man,imp}}$ ; kg yr<sup>-1</sup>) is:

$$C_{\text{man,imp}} = \sum_{sg=1}^{SG} \sum_{s=1}^S m_{\text{imp},sg,s} C_{\text{man},sg,s} \quad (0.38)$$

where  $c_{\text{man,sg,s}}$  is the concentration of C in imported manure from species group  $sg$  and storage type  $s$  ( $\text{kg m}^{-3}$ ).  $c_{\text{man,sg,s}}$  is a parameter.

The import of C in bedding is calculated by summing the demand for bedding from all livestock species groups ( $C_{\text{bedding,req}}$ ;  $\text{kg yr}^{-1}$ ) and subtracting the bedding available on the farm i.e. the production of bedding material minus any bedding sold ( $C_{\text{bedding,prod}}$ ;  $\text{kg yr}^{-1}$ ):

$$C_{\text{bedding,req}} = c_{\text{bedding}} \sum_{g=1}^G \sum_{h=1}^{H_g} D_{\text{bedding,g,h}} \quad (0.38)$$

$$C_{\text{bedding,prod}} = \sum_{c=1}^C \sum_{p=1}^P \chi_{\text{bedding,c,p}} \left( C_{\text{crop,c,p}} - (C_{\text{soldCrop,c,p}} + C_{\text{return,c,p}}) \right) \quad (0.38)$$

where  $C_{\text{return,c,p}}$  is the annual amount of C in product  $p$  of crop  $c$  that is chopped and returned to the soil ( $\text{kg yr}^{-1}$ ):

$$C_{\text{return,c,p}} = \sum_{r=1}^R A_{c,r} y_{c,p,r} c_{c,p} \beta_{c,p,r} \quad (0.38)$$

and  $C_{\text{soldCrop,c,p}}$  is the C in crop sold:

$$C_{\text{soldCrop,c,p}} = D_{\text{soldCrop,c,p}} c_{c,p} \quad (0.38)$$

where  $D_{\text{sold,c,p}}$  ( $\text{kg yr}^{-1}$ ) is an input.

The annual amount of product  $p$  of crop  $c$  that is sold ( $D_{\text{sold,c,p}}$ ;  $\text{kg DM yr}^{-1}$ ) is:

$$D_{\text{sold,c,p}} = D_{\text{crop,c,p}} \frac{\sigma_{c,p}}{100} \quad (0.39)$$

where  $\sigma_{c,p}$  is the proportion of product  $p$  from crop  $c$  that is sold. The value of  $\sigma_{c,p}$  is an input.

The C in imported bedding is then:

$$\begin{aligned} &\text{if } C_{\text{bedding,req}} > C_{\text{bedding,prod}} \\ C_{\text{bedding,imp}} &= C_{\text{bedding,req}} - C_{\text{bedding,prod}} \end{aligned} \quad (0.39)$$

The C imported in animal feed is calculated by first summing the C intake of each feed item by all livestock ( $C_{\text{feed,req}}$ ;  $\text{kg yr}^{-1}$ ):

$$C_{\text{feed,req}} = d \sum_{g=1}^G \left( Z_g \sum_{f=1}^F I_{g,f} c_f \right) \quad (0.39)$$

The C imported in feed ( $C_{\text{feed,imp}}$ ;  $\text{kg yr}^{-1}$ ) is then:

$$C_{\text{feed,imp}} = C_{\text{feed,req}} + C_{\text{sold}} + C_{\text{return}} + C_{\text{bedding}} - C_{\text{crop}} \quad (0.39)$$

where  $C_{\text{return}}$  is the annual amount of C in crop products chopped and returned to the soil ( $\text{kg yr}^{-1}$ ) is:

$$C_{\text{return}} = \sum_{c=1}^C \sum_{p=1}^P C_{\text{return,c,p}} \quad (0.39)$$

and  $C_{\text{soldCrop}}$  is the amount of C exported from the farm in crop products ( $\text{kg yr}^{-1}$ )

$$C_{\text{soldCrop}} = \sum_{c=1}^C \sum_{p=1}^P C_{\text{soldCrop,c,p}} \quad (0.39)$$

If  $C_{\text{feed,imp}} < 0$ ,  $C_{\text{feed,imp}} = 0$ .

The total input of C to the farm ( $C_{input}$ ;  $\text{kg yr}^{-1}$ ) is then:

$$C_{input} = C_{crop} + C_{bedding,imp} + C_{feed,imp} + C_{man,imp} \quad (0.39)$$

### 7.1.2 C outputs

C is exported from the farm in crop products ( $C_{soldCrop}$ ; see Equation (0.39)), milk ( $C_{milk}$ ;  $\text{kg yr}^{-1}$ ), the net liveweight gain of livestock ( $C_{meat}$ ;  $\text{kg yr}^{-1}$ ) and manure exported ( $C_{man,exp}$ ;  $\text{kg yr}^{-1}$ ):

$$C_{milk} = \sum_{g=1}^G C_{milk,g} \quad (0.39)$$

$$C_{meat} = \sum_{g=1}^G C_{meat,g} \quad (0.39)$$

$$C_{man,exp} = \sum_{sg=1}^{SG} \sum_{s=1}^S \frac{C_{man,sg,s} m_{exp,sg,s}}{V_{sg,s}} \quad (0.39)$$

The total export of C ( $C_{export}$ ;  $\text{kg yr}^{-1}$ ) is:

$$C_{export} = C_{soldCrop} + C_{milk} + C_{meat} + C_{man,exp} \quad (0.39)$$

The C balance of the farm ( $C_{bal}$ ;  $\text{kg yr}^{-1}$ ) is then:

$$C_{bal} = C_{import} - C_{export} + C_{\Delta soil} \quad (0.39)$$

where  $C_{\Delta soil}$  ( $\text{kg yr}^{-1}$ ) is the change in soil C storage:

$$C_{\Delta soil} = \sum_{r=1}^R (C_{\Delta soil,r}) \quad (0.39)$$

### 7.1.3 Other C flows

The C consumed in animal feed grown on the farm is ( $C_{feed,home}$ ;  $\text{kg yr}^{-1}$ ) is:

$$C_{feed,home} = C_{feed,req} - C_{feed,imp} \quad (0.39)$$

The total C lost as  $\text{CO}_2$  and  $\text{CH}_4$  from livestock ( $C_{LiveCO_2}$  and  $C_{LiveCH_4}$  respectively;  $\text{kg yr}^{-1}$ ) are:

$$C_{LiveCO_2} = \sum_{g=1}^G C_{LiveCO_2,g} \quad (0.39)$$

$$C_{LiveCH_4} = \sum_{g=1}^G C_{LiveCH_4,g} \quad (0.39)$$

The C entering animal housing as excreta, bedding and feed waste (respectively  $C_{inhouse,excreta}$ ,  $C_{inhouse,bedding}$  and  $C_{inhouse,waste}$ ;  $\text{kg yr}^{-1}$ ) are:

$$C_{inhouse,excreta} = \sum_{g=1}^G \sum_{h=1}^H \vartheta_{g,h} (1 - \gamma_g) (C_{faeces,g,h} + C_{urine,g,h}) \quad (0.39)$$

$$C_{inhouse,bedding} = \sum_{g=1}^G \sum_{h=1}^H C_{bedding,g,h} \quad (0.39)$$

$$C_{inhouse,waste} = \sum_{g=1}^G \sum_{h=1}^H C_{waste,g,h} \quad (0.39)$$

The C in manure ex storage ( $C_{man}$ ;  $\text{kg yr}^{-1}$ ) is:

$$C_{man} = \sum_{sg=1}^{SG} \sum_{s=1}^S C_{man,sg,s} \quad (0.39)$$

The C in  $\text{CO}_2$ ,  $\text{CH}_4$  and runoff from housing and manure storage ( $C_{MMSCO_2}$ ,  $C_{MMSCH_4}$  and  $C_{runoff}$ ;  $\text{kg yr}^{-1}$ ) are:

$$C_{MMSCO_2} = \sum_{g=1}^G \sum_{h=1}^H C_{CO_2house,g,h} + \sum_{sg=1}^{SG} \sum_{g=1}^G C_{CO_2St,sg,s} \quad (0.39)$$

$$C_{MMSCH_4} = \sum_{sg=1}^{SG} \sum_{g=1}^G C_{CH_4St,sg,s} \quad (0.39)$$

The C lost during the processing or spoilage of crop products is assume to occur as  $\text{CO}_2$  ( $C_{store}$ ;  $\text{kg yr}^{-1}$ )

$$C_{store} = \sum_{r=1}^R A_r \sum_{q=1}^{Q_r} \sum_{c=1}^C \left( \sum_{p=0}^{P_c} \omega_{store,c,p} C_{c,p} \mathcal{Y}_{q,c,p,r} \right) \quad (0.40)$$

The crop C entering the soil from roots ( $C_{BG}$ ;  $\text{kg yr}^{-1}$ ) is:

$$C_{BG} = \sum_{r=1}^R C_{residue,r} - C_{return} \quad (0.40)$$

C added to the soil in excreta from grazing animals ( $C_{excreta}$ ;  $\text{kg yr}^{-1}$ ) is:

$$C_{excreta} = \sum_{r=1}^R C_{excreta,r} \quad (0.40)$$

C added to the soil in urea fertiliser ( $C_{urea}$ ;  $\text{kg yr}^{-1}$ ) is:

$$C_{urea} = \sum_{r=1}^R C_{urea,r} \quad (0.40)$$

The C lost in  $\text{CO}_2$  from decomposition of organic matter in the soil is:

$$C_{CO_2soil} = \sum_{r=1}^R (C_{manFOM,r} + C_{manHUM,r} + C_{fert,r} + C_{excreta,r} + C_{residue,r}) - C_{\Delta soil} \quad (0.40)$$

## 7.2 N balance

### 7.2.1 N inputs

N is input to the farm via N fixation, deposition from the atmosphere, fertilisers, imported manure, animal feed and bedding.

The annual N fixation for the whole farm ( $N_{fix}$ ; kg yr<sup>-1</sup>) is calculated as:

$$N_{fix} = \sum_{r=1}^R A_r \sum_{q=1}^{Q_r} \sum_{c=1}^C \left( \sum_{p=0}^{P_c} y_{q,c,p,r} \left( n_{c,p} \left( \Psi_{AG,c} + 1 \right) + \frac{c_{BG} \Psi_{BG,c}}{cn_{BG,c}} \right) - v_c N_{min,r} \right) \quad (0.40)$$

where  $v_c$  is a crop-specific parameter with value  $\leq 1$  that allows for the uptake of non-fixed mineral N by the crop to increase with increasing mineral N availability. If Equation (0.40) would return a negative value,  $N_{fix} = 0$ .

The annual N deposition ( $N_{atm}$ ; kg) is calculated as:

$$N_{atm} = \sum_{r=1}^R \sum_{q=1}^{Q_r} N_{atm,q,r} \quad (0.40)$$

The import of N in N fertiliser ( $N_{fert}$ ; kg yr<sup>-1</sup>) is:

$$N_{fert} = \sum_{r=1}^R \sum_{q=1}^{q_r} \sum_{z=1}^Z N_{fert,z,q,r} \quad (0.40)$$

The import of N in manure ( $N_{man,imp}$ ; kg yr<sup>-1</sup>) is:

$$N_{man,imp} = \sum_{sg=1}^{SG} \sum_{s=1}^S m_{imp,sg,s} n_{man,sg,s} \quad (0.40)$$

where  $n_{man,sg,s}$  is the concentration of N in imported manure from species group  $sg$  and storage type  $s$  (kg m<sup>-3</sup>).

The amount of N imported in bedding ( $N_{bedding,imp}$ ; kg yr<sup>-1</sup>) is calculated using Equations (0.38) to (0.39), replacing the concentration of C with the concentration of N where appropriate.

Likewise, the amount of N imported animal feed ( $N_{feed,imp}$ ; kg yr<sup>-1</sup>) are calculated using Equations (0.39) to (0.39), replacing C with N where appropriate. Note that the calculation of the N yield of crops ( $N_{yield}$ ; kg yr<sup>-1</sup>) is:

$$N_{yield} = \sum_{r=1}^R \sum_{q=1}^{Q_r} \sum_{c=1}^C N_{crop,q,c,r} \quad (0.40)$$

### 7.2.2 N export

N is exported in crop products ( $N_{soldCrop}$ ), milk ( $N_{milk}$ ; kg yr<sup>-1</sup>), the net liveweight gain of livestock ( $N_{meat}$ ; kg yr<sup>-1</sup>) and exported manure ( $N_{man,exp}$ ; kg yr<sup>-1</sup>). These values are calculated as in Equations (0.39), (0.39), (0.39) and (0.39) respectively, replacing C by N where appropriate.

### 7.2.3 N balance

The farm N balance ( $N_{bal}$ ; kg yr<sup>-1</sup>) is:

$$N_{bal} = N_{fix} + N_{atm} + N_{fert} + N_{man,imp} + N_{bedding} + N_{feed,imp} - (N_{soldCrop} + N_{milk} + N_{meat} + N_{man,exp}) \quad (0.41)$$

Where the farm owns or manages cropland, it is common to calculate a N surplus ( $N_{surp}$ ; kg ha<sup>-1</sup> yr<sup>-1</sup>).

$$N_{surp} = \frac{N_{bal}}{\sum_{r=1}^R A_{rot,r}} \quad (0.42)$$

#### 7.2.4 Other N flows

The N consumed in animal feed grown on the farm is ( $N_{feed,home}$ ; kg yr<sup>-1</sup>) is calculated using Equation (0.39), replacing C by N.

The N entering animal housing as excreta bedding and feed waste (respectively  $N_{inhouse,excreta}$ ,  $N_{inhouse,bedding}$  and  $N_{inhouse,waste}$ ; kg yr<sup>-1</sup>) are calculated using Equations (0.39) to (0.39), replacing C by N.

The N in manure ex storage ( $N_{man}$ ; kg yr<sup>-1</sup>) is:

$$N_{man} = \sum_{sg=1}^{SG} \sum_{s=1}^S (N_{TANOutstore,g,s} + N_{Orgoutstore,sg,s}) \quad (0.42)$$

The N in NH<sub>3</sub> from housing ( $N_{NH3housing}$ ; kg yr<sup>-1</sup>) is:

$$N_{NH3house} = \sum_{g=1}^G \sum_{h=1}^H N_{NH3house,g,h}$$

The N in NH<sub>3</sub>, N<sub>2</sub>O and N<sub>2</sub> emitted from manure storage ( $N_{storeNH3}$ ,  $N_{storeN2O}$  and  $N_{storeN2}$ ; kg yr<sup>-1</sup>) are:

$$N_{storeX} = \sum_{sg=1}^{SG} \sum_{g=1}^G N_{storeX,sg,s} \quad (0.42)$$

where X is NH<sub>3</sub>, N<sub>2</sub>O or N<sub>2</sub> as appropriate.

The N input to fields ( $N_{field}$ ; kg yr<sup>-1</sup>) is:

$$N_{field} = N_{atm} + N_{fix} + N_{manapp} + N_{excreta} + N_{fert} + N_{residues} \quad (0.42)$$

where  $N_{manapp}$  (kg yr<sup>-1</sup>) is the N added in manure:

$$N_{manapp} = \sum_{r=1}^R \sum_{c=1}^{C_r} (N_{TANapp,r,c} + N_{orgapp,r,c}) \quad (0.42)$$

N added to the soil in excreta from grazing animals ( $N_{excreta}$ ; kg yr<sup>-1</sup>) is:

$$N_{excreta} = \sum_{r=1}^R N_{excreta,r} \quad (0.42)$$

N added to the soil in crop residues ( $N_{residue}$ ; kg yr<sup>-1</sup>) is:

$$N_{residue} = \sum_{r=1}^R N_{residue,r} \quad (0.42)$$

### **7.3 Greenhouse gas budget**

The elements of the greenhouse gas budget are as follows. The direct emissions are of CH<sub>4</sub> from enteric fermentation and manure storage, N<sub>2</sub>O emissions from manure storage and soils and the change in C sequestered in soil. The indirect emissions are the N<sub>2</sub>O emission from NO<sub>3</sub> leaching from the farm and the NO<sub>3</sub> leaching resulting from the deposition of NH<sub>3</sub> emitted from animal housing, manure storage and field-applied fertiliser and manure.

## 8 Appendix I Calculation of air temperature

The air temperature during a particular month  $m$  is estimated using a sinusoidal function, based on the mean annual air temperature ( $\theta_{mean}$ ; K), an amplitude of deviation from the mean ( $\theta_a$ ; K), an offset parameter that determines the timing of the maximum deviation from the mean ( $m_{offset}$ ; month) and a parameter  $\rho$ , where  $\rho = 2\pi/12$ :

$$\theta_m = \theta_{mean} + \theta_a \sin(\rho(m + m_{offset})) \quad \text{II1}$$

The midpoint of the grazing season is defined as  $m_{graze}$  (month) and is an input. The proportion of the year during which the animals graze has previously been defined ( $\gamma_g$ ). The start and end of the grazing period ( $m_{start}$  and  $m_{end}$ ; month) are then:

$$m_{start} = m_{graze} - 6\gamma_g \quad \text{II2}$$

$$m_{end} = m_{graze} + 6\gamma_g \quad \text{II3}$$

The mean temperature during the grazing period is obtained by first integrating equation III1:

$$\int \theta_{mean} + \theta_a \sin(\rho(m + m_{offset})) dm = \theta_{mean} m + \frac{\theta_a}{\rho} (\sin(m_{offset}\rho)\sin(m\rho) - \cos(m_{offset}\rho)\cos(m\rho))$$

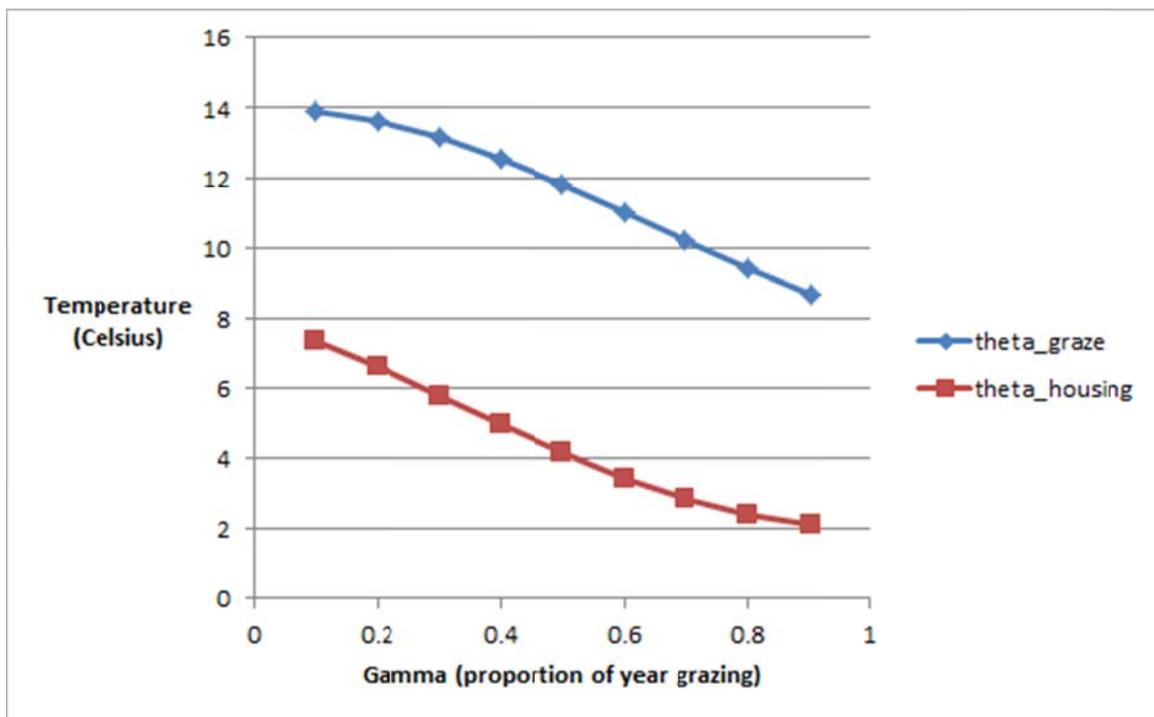
Expressing the right hand side of the above equation as being a function of  $m$  ( $F(m)$ ), the mean temperature during the grazing period ( $\theta_{graze}$ ; K) is:

$$\theta_{graze} = \frac{F(m_{end}) - F(m_{start})}{m_{end} - m_{start}}$$

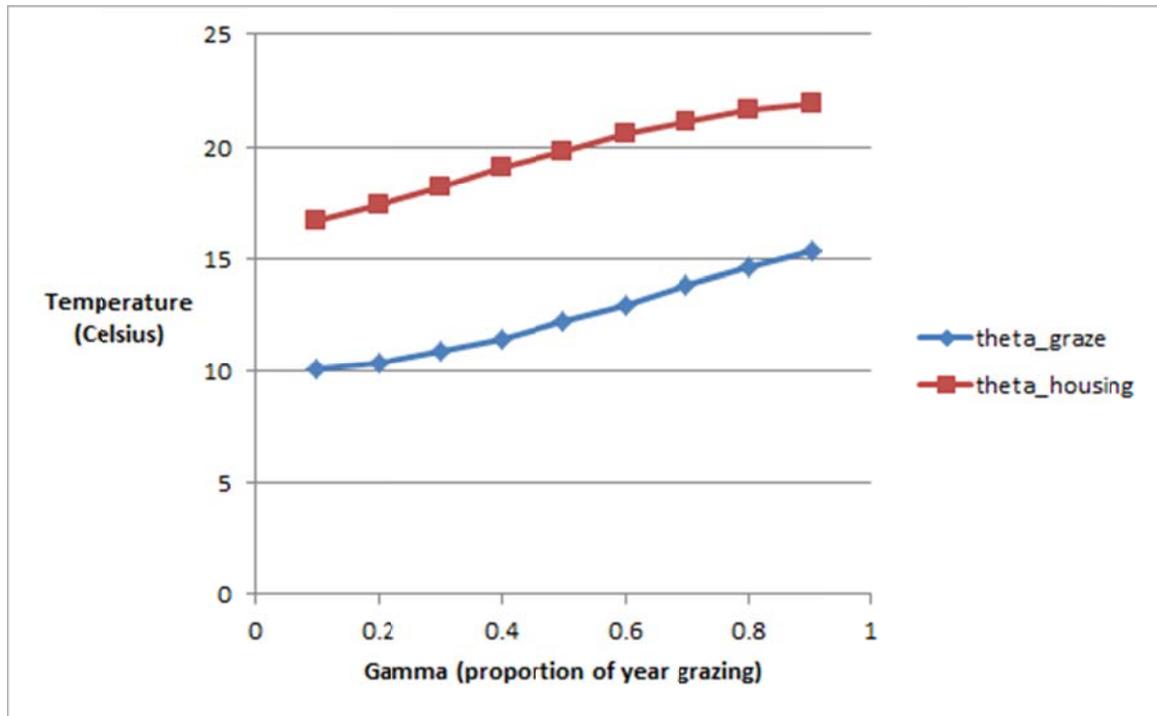
And the mean temperature during the housing period ( $\theta_{housing}$ ; K) is:

$$\theta_{housing} = \frac{F(12) - (F(m_{end}) - F(m_{start}))}{12 - (m_{end} - m_{start})}$$

Example 1 - N Europe, grazing centred in the summer (month 6), mean temperature 8C, amplitude 6C, offset 9 months:



Example 2 - S Europe, grazing centred in the winter (month 12) ), mean temperature 16C, amplitude 6C, offset 9 months:



## 9 Appendix II Derivation of the Tier 3 development of N in manure storage

### Organic N

The rate of change of degradable organic N ( $N_{DegOrg}$ ; kg) is:

$$\frac{dN_{DegOrg}}{dt} = -(\Omega_s + c_{deg})N_{DegOrg} \quad (0.42)$$

where  $\Omega_{org,s}$  is the rate of loss of organic N in storage as surface runoff ( $d^{-1}$ ),  $c_{deg}$  is the rate of decomposition of easily-degraded organic matter in storage ( $d^{-1}$ ).

$$\frac{dN_{DegOrg}}{dt} = -(\Omega_{org,s} + c_{deg})N_{DegOrg} \quad (0.42)$$

$$\frac{1}{N_{DegOrg}} dN_{DegOrg} = -(\Omega_{org,s} + c_{deg}) dt \quad (0.42)$$

Integrating Equation (0.42) gives:

$$\ln(N_{DegOrg}) = -(\Omega_{org,s} + c_{deg})t \quad (0.42)$$

Or

$$N_{DegOrg,t} = N_{DegOrg,t=0} e^{-(\Omega_{org,s} + c_{deg})t} \quad (0.42)$$

The cumulative degradable organic N in runoff is:

$$N_{RunoffOrg,t} = \left( \frac{\Omega_{org,s}}{\Omega_{org,s} + c_{deg}} \right) N_{DegOrg,t=0} \left( 1 - e^{-(\Omega_{org,s} + c_{deg})t} \right)$$

A proportion of the degraded organic N is assumed to be partitioned to humic N. The amount of total organic N present at any time is the sum of the remaining degradable N and the humic N.

### Humic N

Rate of change of humic N ( $N_{HUM}$ ; kg):

$$\frac{dN_{HUM}}{dt} = -\Omega_{org,s} N_{HUM} + c_{deg} \left( \frac{\varpi}{cn_{HUM}} \right) C_{DegOrg,t} \quad (0.42)$$

$$\frac{dN_{HUM}}{dt} = -\Omega_{org,s} N_{HUM} + c_{deg} \left( \frac{\varpi}{cn_{HUM}} \right) C_{DegOrg,t=0} e^{-(\Omega_{org,s} + c_{deg})t} \quad (0.42)$$

The general form:

$$\frac{dy}{dx} = -ky + qe^{ax} \quad (0.42)$$

On integration has the solution:

$$y(x) = \frac{qe^{ax}}{a+k} + \left( y_0 - \frac{q}{a+k} \right) e^{-kx} \quad (0.42)$$

In this case,  $y=N_{HUM}$ ,  $y_0=N_{HUM,t=0}$ ,  $x=t$ ,

$$a = -(\Omega_{org,s} + c_{deg})$$

$$q = c_{\text{deg}} \left( \frac{\varpi}{cn_{\text{HUM}}} \right) C_{\text{DegOrg},t=0}$$

$$k = \Omega_{\text{org},s}$$

So

$$N_{\text{HUM},t} = \left( \frac{\varpi}{cn_{\text{HUM}}} \right) C_{\text{DegOrg},t=0} e^{-(\Omega_{\text{org},s} + c_{\text{deg}})t} + N_{\text{HUM},t=0} e^{-\Omega_{\text{org},s}t} - \left( \left( \frac{\varpi}{cn_{\text{HUM}}} \right) C_{\text{DegOrg},t=0} \right) e^{-\Omega_{\text{org},s}t}$$

$$N_{\text{HUM},t} = \left( \frac{\varpi}{cn_{\text{HUM}}} \right) C_{\text{DegOrg},t=0} \left( e^{-(\Omega_{\text{org},s} + c_{\text{deg}})t} - e^{-\Omega_{\text{org},s}t} \right) + N_{\text{HUM},t=0} e^{-\Omega_{\text{org},s}t}$$

### Runoff of humic N

The formation of humic N ( $N_{\text{humicForm},t}$ ; kg) is:

$$\frac{dN_{\text{humicForm}}}{dt} = c_{\text{deg}} \left( \frac{\varpi}{cn_{\text{HUM}}} \right) C_{\text{DegOrg},t}$$

$$\frac{dN_{\text{humicForm}}}{dt} = c_{\text{deg}} \left( \frac{\varpi}{cn_{\text{HUM}}} \right) C_{\text{DegOrg},t=0} e^{-(\Omega_{\text{org},s} + c_{\text{deg}})t}$$

$$N_{\text{humicForm},t} = \frac{c_{\text{deg}}}{\Omega_{\text{org},s} + c_{\text{deg}}} \left( \frac{\varpi}{cn_{\text{HUM}}} \right) C_{\text{DegOrg},t=0} \left( 1 - e^{-(\Omega_{\text{org},s} + c_{\text{deg}})t} \right)$$

So the runoff of humic N ( $N_{\text{runoffHumic},t}$ ; kg) is:

$$N_{\text{runoffHumic},t} = N_{\text{runoffForm},t} - N_{\text{HUM},t}$$

### TAN

TAN is created by the mineralisation of organic N and is lost by gaseous emissions and runoff.

$$\frac{dTAN}{dt} = -(EF_{\text{sum}} + \Omega_{\text{TAN},s})TAN + \frac{dN_{\text{min}}}{dt} \quad (0.42)$$

where  $TAN_t$  is the TAN at time  $t$ ,  $EF_{\text{sum}}$  is the sum of EFs for  $\text{NH}_3$ ,  $\text{N}_2\text{O}$  and  $\text{N}_2$ ,  $\Omega_{\text{TAN},s}$  is the rate of loss of TAN in storage as surface runoff ( $\text{d}^{-1}$ ) and  $N_{\text{DegOrg},t}$  is the amount of organic N at time  $t$ .

The mineralised N ( $N_{\text{min}}$ ; kg) created via the degradation

$$\frac{dN_{\text{min}}}{dt} = \left( c_{\text{deg}} \left( \frac{1}{cn} - \frac{\varpi}{cn_{\text{HUM}}} \right) \right) C_{\text{DegOrg},t} \quad (0.42)$$

Substitute Equation (0.42) for  $\frac{dN_{\text{min}}}{dt}$  in Equation (0.42):

$$\frac{dTAN}{dt} = -(EF_{\text{sum}} + \Omega_{\text{TAN},s})TAN + \left( c_{\text{deg}} \left( \frac{1}{cn} - \frac{\varpi}{cn_{\text{HUM}}} \right) \right) C_{\text{DegOrg},t} \quad (0.42)$$

Substitute Equation (0.42) for  $N_{DegOrg,t}$  in Equation (0.42):

$$\frac{dTAN}{dt} = -(EF_{sum} + \Omega_{TAN,s})TAN + \left( c_{deg} \left( \frac{1}{cn} - \frac{\varpi}{cn_{HUM}} \right) \right) C_{DegOrg,t=0} e^{-(\Omega_{org,s} + c_{deg})t} \quad (0.42)$$

Noting that the general form:

$$\frac{dy}{dx} = -ky + qe^{ax} \quad (0.42)$$

has the solution:

$$y = \frac{qe^{ax}}{a+k} + ce^{-kx} \quad (0.42)$$

When  $x=0$ :

$$y_0 = \frac{q}{a+k} + c \quad (0.42)$$

so

$$c = y_0 - \frac{q}{a+k} \quad (0.42)$$

$$y = \frac{qe^{ax}}{a+k} + \left( y_0 - \frac{q}{a+k} \right) e^{-kx} \quad (0.42)$$

In this case,  $y=TAN_t$ ,  $y_0=TAN_0$ ,  $x=t$  and:

$$a = -(\Omega_{org,s} + c_{deg})$$

$$q = \left( c_{deg} \left( \frac{1}{cn} - \frac{\varpi}{cn_{HUM}} \right) \right) C_{DegOrg,t=0}$$

$$k = (EF_{sum} + \Omega_{TAN,s})$$

Expanding Equation (0.42):

$$TAN_t = \frac{c_{deg} \left( \frac{1}{cn} - \frac{\varpi}{cn_{HUM}} \right) C_{org,t=0}}{(EF_{sum} + \Omega_{TAN,s}) - (\Omega_{org,s} + c_{deg})} e^{-(\Omega_{org,s} + c_{deg})t} + \left( TAN_{t=0} - \frac{c_{deg} \left( \frac{1}{cn} - \frac{\varpi}{cn_{HUM}} \right) C_{org,t=0}}{(EF_{sum} + \Omega_{TAN,s}) - (\Omega_{org,s} + c_{deg})} \right) e^{-(EF_{sum} + \Omega_{org,s})t} \quad (0.42)$$

Partitioning losses of TAN

$$N_{min,t} = N_{DegOrg,t=0} - (N_{DegOrg,t} + N_{runofOrgf,t})$$

$$N_{TANlost,t} = N_{min,t} + TAN_{t=0} - TAN_t$$

$$N_{runoffTAN,t} = \frac{\Omega_{TAN}}{\Omega_{TAN} + EF_{sum}} N_{TANlost,t}$$

$$N_{NH3,t} = \frac{EF_{NH3}}{\Omega_{TAN} + EF_{sum}} N_{TANlost,t}$$

## 10 Appendix III Adaptation and initialisation of C-Tool

### 10.1 Adaptation

The original C- Tool model only considers C. To account for N, the following assumptions were made:

The C:N ratio of the HUM and ROM is assumed to be 10.

The N in the FOM material is known.

The degradation rate of N in FOM is identical to the degradation rate of the C.

The degradation of FOM leads to the mineralisation of organic N. A proportion of this N becomes immobilised in new HUM material. Normally, more N is mineralised through the degradation of FOM than is immobilised in new HUM material, and the excess contributes to the mineral N available for crop growth. However, if large quantities of FOM with a high C:N ratio are added (e.g. cereal straw), it is possible for the N immobilised in new HUM material to exceed the amount mineralised from the FOM. In this instance, mineral N will be removed from the soil. If the supply of mineral N from other sources (e.g. fertiliser, manure) is insufficient to satisfy this demand, the model reports an error.

### 10.2 Initialisation

The model is initialised by starting the simulation 50 years before the period of interest. This is to allow the state of the soil C and N pools to adapt to the prior land use. The historic farm type (arable, pig, grassland) is an input to the model. Based on the historic farm type, the following parameters are defined:

- The total initial C content of the soil (kg ha<sup>-1</sup>).
- The proportions of the total initial C present as humus (HUM) and resistant organic matter (ROM).
- The initial C:N ratio in the soil.
- The annual input of fresh organic matter (FOM) to the soil (kg C ha<sup>-1</sup> yr<sup>-1</sup>).
- The C:N of this FOM.
- The soil depth (m).
- The thermal diffusivity of the soil (m<sup>2</sup> s<sup>-1</sup>).

During the initialisation, the model uses the zone-specific climate data. The annual FOM and FOM N is input to the soil evenly over the year.

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