The FARM-N farm-scale model of losses of nitrogen

This document contains a description of the FARM-N farm-scale model of the losses of nitrogen (N) to the atmospheric and aquatic environments. The model uses the N-flow approach, which tracks the flow of N into, within and out of the farm.

The document also contains a list of abbreviations and a key to symbols.

1. Modelling the N surplus on arable farms

On arable farms, the inputs that must be quantified are the N imported in fertiliser, manure and seed, the input of N via wet and dry deposition from the atmosphere and the N fixed in N-fixing crops (Fig 1). The outputs that must be quantified are the N exported in crop products (e.g. grain and straw).

Figure 1 N inputs, outputs and losses to the environment from arable farms

The N imported in seed (N_{seed}; kg N yr^{-1}) is calculated as:

$$N_{seed} = \sum_{j=1}^{J}\sum_{s=1}^{S} A_{j,s} n_{seed,j} \qquad (1.1)$$

Where $A_{j,s}$ (ha) is the area of crop j on soil type s, $n_{seed,j}$ is the amount of seed N sown for the jth crop (kg ha^{-1}), J is the number of crops grown and S is the number of soil types present. The area of each crop on each soil type is an input to the model and fallow is here considered to be a crop with no yield.

The input of N via wet and dry deposition from the atmosphere (N_{atm}; kg N yr^{-1}) is:

$$N_{atm} = \sum_{j=1}^{J}\sum_{s=1}^{S} A_{j,s} n_{atm} \qquad (1.2)$$

where n_{atm} is the rate of deposition of atmospheric N (kg N ha^{-1} yr^{-1}). Note that atmospheric deposition to areas of the farm not cultivated (including roadways, buildings etc) are ignored here.

The input of N via the fixation of N_2 by bacteria living in symbiosis with N-fixing crops (N_{fix}; kg N yr^{-1}) is based on Høgh-Jensen et al (2003) and is calculated by a crop-specific N fixation rate per unit area of crop:

$$N_{fix} = \sum_{j=1}^{J}\sum_{s=1}^{S} A_{j,s} n_{fix,j} \qquad (1.3)$$

where $n_{fix,j}$ is the fixation rate of the jth crop (kg N ha^{-1} yr^{-1}).

The farm can import either mineral fertiliser, animal manure or both to satisfy the crop fertiliser requirements. The model requires as input the annual amount of mineral and manure N applied to each crop and soil type. The application of N in manure of the *m*th manure type to the *j*th crop on the *s*th soil type ($N_{\mathrm{mapp,m,j,s}}$; kg N yr^{-1}) is:

$$N_{mapp,m,j,s} = A_{j,s} n_{mapp,m,j,s} \tag{1.4}$$

Where $n_{\mathrm{mapp,m,j,s}}$ (kg N ha^{-1} yr^{-1}) is the application rate of the *m*th manure type to the *j*th crop on the *s*th soil type. Likewise for the application of N in the *r*th fertiliser type to the *j*th crop on the *s*th soil type ($N_{\mathrm{fapp,m,j,s}}$; kg N ha^{-1} yr^{-1}):

$$N_{fapp,r,j,s} = A_{j,s} n_{fapp,r,j,s} \tag{1.5}$$

Where $n_{\mathrm{fapp,r,j,s}}$ (kg N ha^{-1} yr^{-1}) is the application rate of N in the *r*th fertiliser type to the *j*th crop on the *s*th soil type.

The import of N to the farm in manure (N_{mimp}; kg N yr^{-1}) and fertiliser (N_{fimp}; kg N yr^{-1}) is:

$$N_{mimp} = \sum_{m=1}^{M} \sum_{j=1}^{J} \sum_{s=1}^{S} A_{j,s} n_{mapp,m,j,s} \tag{1.6}$$

$$N_{fimp} = \sum_{r=1}^{R} \sum_{j=1}^{J} \sum_{s=1}^{S} A_{j,s} n_{fapp,r,j,s} \tag{1.7}$$

N is exported from the farm in crop products. A single crop can produce more than one product (e.g. grain and straw). The N exported in crop products (N_{cexp}; kg N yr^{-1}) equates to the N harvested:

$$N_{cexp} = \sum_{c=1}^{C_j} \sum_{j=1}^{J} \sum_{s=1}^{S} \varepsilon_{c,j} A_{j,s} y_{c,j,s} \alpha p_{c,j} \tag{1.8}$$

where $\varepsilon_{\mathrm{c,j}}$ is unity if the product is harvested and zero if not (e.g. if straw is shred and returned to the soil), $y_{\mathrm{c,j,s}}$ is the dry matter (DM) yield of the *c*th product of the *j*th crop on the *s*th soil type (kg DM ha^{-1} yr^{-1}), $p_{\mathrm{c,j}}$ is the concentration of CP in the *c*th product of the *j*th crop (kg CP (DM kg)$^{-1}$), α (kg N (kg CP)$^{-1}$) is the concentration of N in CP (usually estimated to be 0.16) and C_{j} is the total number of crop products for the *j*th crop.

The farm N surplus (N_{surp}; kg N yr^{-1}) is then calculated as:

$$N_{surp} = N_{fix} + N_{mimp} + N_{fimp} + N_{seed} + N_{atm} - N_{cexp} \tag{1.9}$$

2. Partitioning the N surplus on arable farms

The arable farm N surplus can be partitioned to a number of recipients (Fig 1);

$$N_{surp} = N_{fvol} + N_{mvol} + N_{N2soil} + N_{N2Osoil} + N_{NO3} + N_{\Delta soil} \tag{2.1}$$

where N_{fvol} is the ammonia volatilisation from field-applied mineral fertiliser, N_{mvol} is the ammonia volatilisation from animal manure, N_{N2soil} and $N_{N2Osoil}$ are, respectively, the emission of dinitrogen and nitrous oxide following nitrification or denitrification in the soil, $N_{NO3soil}$ is nitrate leaching from the soil and $N_{\Delta soil}$ is the change in the storage of N in the soil (which could be positive or negative). These losses/changes are in units of kg N yr^{-1}.

The volatilisation of ammonia from field-applied mineral fertiliser (N_{fvol}) is calculated using an emission factor approach, by summing the separate emissions from the R fertiliser types present:

$$N_{fvol} = \sum_{r=1}^{R} \delta_{fert,r} \sum_{j=1}^{J} \sum_{s=1}^{S} A_{j,s} n_{fapp,r,j,s} \quad (2.2)$$

Where $\delta_{fert,r}$ is the emission factors specific for the rth fertiliser type and $N_{fapp,r}$ is the amount of the rth fertiliser type applied (kg N (kg N applied)$^{-1}$). A similar approach is used to calculate the volatilisation of ammonia from animal manure (N_{mvol}):

$$N_{mvol} = \sum_{m=1}^{M} \delta_{man,m} \sum_{j=1}^{J} \sum_{s=1}^{S} A_{j,s} n_{mapp,m,j,s} \quad (2.3)$$

Where $\delta_{man,m}$ is the emission factor specific for the mth manure type.

The emission of dinitrogen (N_2) and nitrous oxide (N_2O) due to denitrification is modelled using the empirical denitrification model SIMDEN (Vinther and Hansen, 2004). The denitrification is calculated as (N_2O emission) x (N_2/N_2O ratio). The N_2O emission is derived from the input of N in mineral fertiliser and animal manure and emission factors recommended by the IPCC methodology. Tabulated values of the N_2/N_2O ratios are based on literature values, which were found to be related to hydraulic properties of the soil and the clay content. The inputs to this model are therefore the amount of N added in inorganic fertiliser or manure (applied N minus the ammonia emission), the N fixed in N-fixing crops, soil fertility level (low, medium, high) and the clay content of the soil.

The loss of N via the leaching of nitrate is modelled using the N-LES model (Simmelsgaard and Djurhuus, 1998 - updated by Kristensen et al. (2003)- which takes as input the soil type, cropping plan, the addition of N in fertiliser and manure (applied N minus the ammonia emission), N removed in crop yield and the annual drainage. To approximate current Danish practice, all manure is assumed to be applied in the spring.

The change in N stored in the soil is modelled using the simple dynamic soil C model C-TOOL (Petersen et al, 2002), with an assumption of constant C:N ratios for the different carbon pools and a simplification of the parameterisation in Gyldenkærne et al. (2007). The changes in soil organic N are calculated as net mineralisation (gross mineralisation minus immobilisation). The gross mineralisation is proportional to the content of soil organic matter (SOM), but corrected for the C:N ratio as described in Thomsen et al. (2008). For the pools with a turnover ratio < 1000 years, a C/N ratio of 10 is assumed. The input from root deposition and crop residues is calculated from allometric functions, as described in Gyldenkærne et al. (2007). The model is unsuitable for organic soils (>10% organic matter).

The use of a dynamic model creates two problems. The first is how to initialise the model to account for the history of field management. The initialisation of the model is achieved by requiring the input of the existing farm type, according to the following categories; cattle farm, pig farm, arable farm. The initial content of SOM is based then on a nationwide soil sampling (Heidmann et al., 2001), in which a significantly higher amount of SOM was found on dairy farms, relative to pig and arable farms. The second problem is that soil processes take many years to fully respond to a change in field management. Given that the FARM-N model is intended to describe the average, annual N flows, the question arises over what future time period the change should be calculated. It is assumed here that the intention is not to model short-term trends, so a time period of 10 years was chosen for calculations with C-TOOL. Consequently, the N input is multiplied by the "humification coefficient", the fraction which is assumed to enter the humus pools with a halving time of decades. The humification coefficient is calculated from the clay content, according to Petersen et al. (2005).

In the situations such as here, where a number of independent models are used to estimate different N losses, the sum of the modelled losses and the changes in soil N ('cumulative partitioning') will usually differ from the calculated N surplus. This difference is commonly referred to as 'unaccounted N'. Since here it is assumed that the N surplus is determined with greater accuracy than the individual losses and change in soil N, there is a need for an algorithm to reconcile these estimates with the N surplus. Here, regardless of whether it is positive or negative, the residual N is allocated according to Table 1, so that the mass conservation of N is respected. This fairly crude partitioning algorithm is based on expert judgement, according to Petersen et al. (2006, table 7).

Table 1 Algorithm for partitioning 'unaccounted N' (N surplus – [sum of N losses + change in soil organic N]).

Destination	**Fraction**
Harvest	0.45
Soil organic N changes	0.10
Denitrification	0.10
Nitrogen leaching	0.35

3. Modelling the N surplus on livestock farms

The calculations for farms with livestock differ from those for arable farms because additional inputs, outputs and emissions must be taken into account. On pig farms, these include the import of N in animal feed and bedding and the export of N in livestock sold or manure. Cattle farms have the same inputs and only one possible additional export of N from the farm, in milk sold (Fig 2). In addition, some crop products will usually be used to provide cattle feed (grazed grass or conserved forage for winter feed) or bedding for animals, so the import of feed and export of crop products must be adjusted accordingly.

3.1 Crop products

To allow for some or all the crop products to be used in the livestock husbandry, all crop products are classified according to their use. Four product uses are defined (Table 2).

Table 2 Potential crop product use

Crop product use	Product use indicator (u)
Must be sold	1
Bedding (e.g. straw)	2
Non-grazed, non-straw roughage (e.g. silage)	3
Grazed roughage (e.g. grass)	4

Each crop produces one or more of these crop products; for example, a wheat crop could produce grain (u=1) and straw (u=2), whereas a roughage crop could be grazed (u=4) or harvested for silage (u=3). The total harvested dry matter yield of the uth product of the jth crop ($Y_{u,j}$; kg DM yr^{-1}) is:

$$Y_{u,j} = \sum_{s=1}^{S} \varepsilon_{c,j} A_{j,s} y_{c,j,s} \tag{3.1}$$

The cumulative yield of the uth crop product (Y_u; kg DM yr^{-1}) is:

$$Y_u = \sum_{j=1}^{J} Y_{u,j} \tag{3.2}$$

The protein concentration in the uth crop product (p_u; kg (kg DM)$^{-1}$) is:

$$p_c = \frac{\sum_{j=1}^{J} p_{c,j} Y_{c,j}}{Y_c} \tag{3.3}$$

The concentration of energy in the uth crop product (e_u; MJ (kg DM)$^{-1}$) is:

$$e_u = \frac{\sum_{j=1}^{J} e_{u,j} Y_{u,j}}{Y_u} \tag{3.4}$$

Where $e_{u,j}$ is the concentration of energy in the uth product of the jth crop (MJ (kg DM)$^{-1}$).

3.2 Livestock feed

Each livestock species within the FARM-N model consists of one or more livestock categories. If there are I livestock species present on the farm, where the ith species consists of K_i categories, then the number of animals in each category ($L_{i,k}$) is an input to the model. There are currently two livestock species represented in the model; pigs, i = 1 and cattle, i = 2.

The livestock feeding is based on the concept of demands for energy and protein. The demands for energy and protein are those that are necessary to support maintenance and a given level of production. Note that these do not relate to the minimum or recommended supply but the normal feeding associated with a given level of production. It will therefore often include an element of oversupply that results from farmers including a safety margin in their feed rationing.

If the energy demand of the kth category of the ith livestock species is $e_{\mathrm{dem,i,k}}$ (MJ animal^{-1} yr^{-1}), then the total annual demand for energy for the kth cattle category of the ith livestock species ($E_{\mathrm{dem,i,k}}$; MJ yr^{-1}) can be calculated:

$$E_{dem,i,k} = e_{dem,i,k} L_{i,k} \tag{3.5}$$

Likewise, if the CP demand of the kth category of the ith livestock species is $p_{\mathrm{dem,i,k}}$ (kg CP animal^{-1} yr^{-1}), then the total annual demand for CP for the kth category of the ith livestock species ($P_{\mathrm{dem,i,k}}$; kg CP yr^{-1}) can be calculated:

$$P_{dem,i,k} = p_{dem,i,k} L_{i,k} \tag{3.6}$$

$e_{\mathrm{dem,i,k}}$ and $p_{\mathrm{dem,i,k}}$ are model inputs.

3.2.1 Pig feeding

All intensive pig rearing is assumed to occur in animal housing, with all pig feed classed as concentrate. For simplicity, it is assumed that all pig feed is imported.

The N in the feed of the kth pig category ($N_{\mathrm{feed,1,k}}$; kg N yr^{-1}) is:

$$N_{feed,1,k} = \alpha P_{dem,1,k} \tag{3.7}$$

The N in the concentrate feed for pigs ($N_{\mathrm{feed,1}}$; kg N yr^{-1}) is therefore:

$$N_{feed,1} = \sum_{k=1}^{K_1} N_{feed,1,k} \tag{3.8}$$

3.2.2 Cattle feeding

Unlike pigs, cattle can be fed a number of different feed types; non-grazable roughage, grazable roughage and concentrate. It is assumed that because roughage feed is generally cheaper than concentrate feed, the feed ration will maximise the amount of roughage, while satisfying the cattle's demand for energy. However, the maximum DM intake of a cattle category ($D_{\mathrm{max,k}}$; kg DM yr^{-1}) is limited by the concentration of indigestible fibre in the diet. A variety of methods are used in Europe to calculate $D_{\mathrm{max,k}}$ as a function of the concentration of indigestible fibre in the diet. To overcome this problem, we define a generalised variable f to represent the concentration of indigestible fibre in feed. Furthermore, to make the calculation tractable, we consider only two feeds; a roughage feed which has a concentration of energy (e_{rough}; MJ (kg DM)$^{-1}$) and indigestible fibre (f_{rough}) equal to the weighted average of roughage on the farm (grazable and non-grazable) and a concentrate feed with a concentration of energy and indigestible fibre (e_{conc}; MJ (kg DM)$^{-1}$) and (f_{conc}) typical of grain-based concentrates. The amount of concentrate DM in the diet ($D_{\mathrm{conc,k}}$; kg DM yr^{-1}) can then be obtained by solving the following two simultaneous equations:

$$D_{conc,k} = \max\left(\frac{E_{dem,k} - D_{rough,k}e_{rough}}{e_{conc}}, 0\right) \quad (3.9)$$

where $D_{\mathrm{rough,k}}$ (kg DM yr^{-1}) is the DM intake of roughage of the *k*th cattle category.

$$D_{conc,k} = D_{\max,k} - \max\left(\frac{D_{rough,k}f_{rough}}{f_{conc}}, 0\right) \quad (3.10)$$

To satisfy the demand for protein, a minimum amount of protein must be supplied ($P_{\mathrm{dem,k}}$; kg CP yr^{-1}). If the cattle are mainly fed on roughage feed, the demand for protein is almost inevitably satisfied from this source; the model cannot currently describe situations where this is not the case. If a concentrate feed is required, then as previously for energy and fibre, the concentration of CP in the average roughage feed is calculated (p_{rough}; kg CP (kg DM)$^{-1}$). The concentration of CP in the concentrate that is necessary to satisfy the demand of the *k*th cattle category for CP ($p_{\mathrm{conc,k}}$; kg CP (kg DM)$^{-1}$) is then:

$$p_{conc,k} = \max\left(p_{conc,\min}, \frac{P_{dem,k} - D_{rough,k}p_{rough}}{D_{conc,k} + D_{rough,k}}\right) \quad (3.11)$$

Where $p_{\mathrm{conc,min}}$ (kg CP (kg DM)$^{-1}$) is the CP content of the concentrate feed available that has the lowest CP concentration. It is assumed that a concentrate feed with a sufficiently high CP concentration is always available.

The N in the feed of the *k*th cattle category ($N_{\mathrm{feed,2,k}}$; kg N yr^{-1}) is:

$$N_{feed,2,k} = \alpha\left(D_{rough,k}p_{rough} + D_{conc,k}p_{conc,k}\right) \quad (3.12)$$

The N in the cattle feed ($N_{\mathrm{feed,2}}$; kg N yr^{-1}) is therefore:

$$N_{feed,2} = \sum_{k=1}^{K_2} N_{feed,2,k} \quad (3.13)$$

3.3 *Bedding*

The use of straw for bedding is dependent on the animal housing present. If the requirement for bedding in animal housing type *h* is b_{h} (kg DM animal^{-1} yr^{-1}) then the total demand for bedding (D_2; kg DM yr^{-1}) is:

$$D_2 = \sum_{i=1}^{2}\sum_{k=1}^{K_i}\sum_{h=1}^{H} L_{i,k}\eta_{i,k,h}b_h \quad (3.14)$$

where $\eta_{\mathrm{i,k,h}}$ is the proportion of the *i*th livestock species of category *k* that are housed in animal housing type *h* and *H* is the total number of housing categories.

3.4 *Import and export of N in crop products*

N can be imported in the form of concentrates for livestock, or to cover a deficiency in bedding material or roughage feed. N can be exported in the form of cash products, surplus bedding or surplus roughage. Since the production and demand for the different types of crop products varies, each type of crop product (as defined in Table 2) is treated separately, so that $N_{cimp,u}$ and $N_{cexp,u}$ is the N imported and exported of the *u*th crop product category respectively. Both are in units of kg DM yr^{-1}.

3.4.1. Cash crops

The export of cash crop products is:

$$N_{c\exp,1} = \alpha p_1 Y_1 \tag{3.15}$$

3.4.2 Bedding

If the production of bedding is insufficient ($Y_2<D_2$), supplementary bedding must be imported to the farm. Here, bedding with a protein concentration the same as that of the home-produced bedding is assumed to be imported. If no crop products that are potential bedding are produced on the farm, bedding with a standard composition is bought. The N imported with the bedding ($N_{cimp,2}$; kg N yr^{-1}) is then:

$$N_{cimp,2} = \alpha p_2 \left(D_2 - Y_2\right) \tag{3.16}$$

All the potential bedding will be used on the farm and the export of N from the farm in potential bedding ($N_{cexp,2}$; kg N yr^{-1}) is zero. Alternatively, if sufficient bedding is produced on the farm ($Y_2>D_2$), $N_{imp,2}$ will then be zero and any surplus production is sold. $N_{cexp,2}$ is given by:

$$N_{cexp,2} = \alpha p_2 \left(Y_2 - D_2\right) \tag{3.17}$$

3.4.3 Non-grazed roughage crop products

To calculate the import or export of non-grazed roughage crop products ($N_{cimp,3}$), the demand of the cattle is compared to the farm production. If there is an excess in the supply of these products ($Y_3>D_3$) then $N_{cimp,3}$ is zero and the surplus is exported:

$$N_{cexp,3} = \alpha p_3 \left(Y_3 - D_3\right) \tag{3.18}$$

If there is a deficit in the supply of non-grazed roughage then $N_{cexp,3}$ is zero and the imported N is:

$$N_{cimp,3} = \alpha p_3 \left(D_3 - Y_3\right) \tag{3.19}$$

Note that it is assumed here that the imported and home-grown roughage have the same protein concentration.

3.4.4 Import of concentrate feed

Since all pig feed is imported as concentrate, the N in this feed is equated to the N in pig feed ($N_{feed,1}$). The N imported in concentrate feed (N_{conc}; kg N yr^{-1}) is:

$$N_{conc} = N_{feed,1} + \alpha \sum_{k=1}^{K_2} P_{conc,k} \qquad (3.20)$$

Where the second term is the N imported in concentrate feed for cattle.

3.5 Export of animal products

The N in the growth of the *k*th livestock category of the *i*th livestock species ($N_{growth,i,k}$; kg N yr^{-1}) is calculated from :

$$N_{growth,i,k} = L_k g_{i,k} n_{growth,i,k} \qquad (3.21)$$

Where $g_{i,k}$ is the live weight (LW) growth of the *k*th livestock category of the *i*th livestock species (kg LW yr^{-1}) of the *i*th livestock species and $n_{growth,i,k}$ is the concentration of N in that growth (kg N (kg LW)$^{-1}$). $g_{i,k}$ is a model input and $n_{growth,i,k}$ is a model parameter. Note that $g_{i,k}$ includes the growth of livestock that die prematurely; it is assumed that these animals are disposed of off-farm. The total N in animal growth (N_{growth}; kg N yr^{-1}) is:

$$N_{growth} = \sum_{i=1}^{2} \sum_{k=1}^{K_i} N_{growth,i,k} \qquad (3.22)$$

The N in milk production (N_{milk}; kg N yr^{-1}) is calculated as:

$$N_{milk} = \sum_{k=1}^{K_2} Q_k n_{milk,k} \qquad (3.23)$$

Where Q_k is the milk yield of the *k*th cattle category (kg ECM animal^{-1} yr^{-1}) (ECM = energy-corrected milk) and $n_{milk,k}$ is the concentration of N in milk of the *k*th cattle category (kg N (kg ECM)$^{-1}$). Q_k is a model input and $n_{milk,k}$ a parameter.

The export of N in animal products (N_{aexp}; kg N yr^{-1}) is then:

$$N_{aexp} = N_{growth} + N_{milk} \qquad (3.24)$$

3.6 Import and export of manure

Manure can be both imported to and exported from livestock farms. The demand for N in the manure from the *i*th livestock category and *m*th manure type (e.g. slurry) ($N_{mapp,m,i}$; kg N yr^{-1}) is determined as for arable farms. The on-farm production of the same manure type ($N_{exstore,m,i}$; kg N yr^{-1}) is determined below (see Equation (4.18)). The manure N imported (N_{mimp}) and manure N exported (N_{mexp}; kg N yr^{-1}) is then:

If $N_{mapp,m,i} > N_{exstore,m,i}$:

$$N_{mimp,m,i} = N_{mapp,m,i} - N_{exstore,m,i} \tag{3.25}$$
$$N_{mexp,m,i} = 0 \tag{3.26}$$

Else

$$N_{mexp,m,i} = N_{exstore,m,i} - N_{mapp,m,i} \tag{3.27}$$
$$N_{mimp,m,i} = 0 \tag{3.28}$$

And

$$N_{mimp} = \sum_{m=1}^{M}\sum_{i=1}^{I} N_{mimp,m,i} \tag{3.29}$$
$$N_{mexp} = \sum_{m=1}^{M}\sum_{i=1}^{I} N_{mapp,m,i} \tag{3.30}$$

Where M is the number of manure types produced or used on the farm.

3.7 The N surplus on livestock farms

The N surplus for the farm is then:

$$N_{surp} = N_{fix} + N_{fimp} + N_{mimp} + N_{seed} + N_{atm} + N_{cimp} - N_{cexp} - N_{aexp} - N_{mexp} \tag{3.31}$$

For details of N_{seed}, N_{atm}, N_{fix} and N_{fimp}, see the arable farm section.

4. **Partitioning the N surplus on livestock farms**

In comparison with arable farms, there are the additional losses from livestock farms in the form of ammonia, dinitrogen and nitrous oxide from animal housing (N_{NH3house}, N_{N2house} and N_{N2Ohouse}), manure storage (N_{NH3store}, N_{N2store} and N_{N2Ostore}) and ammonia emission from urine deposited during grazing (N_{NH3graz}). All losses are in units of kg N yr^{-1} and all are model inputs.

The generalised balance equation for all farm types is then:

$$0 = N_{surplus} - \begin{pmatrix} N_{NH3house} + N_{N2house} + N_{N2Ohouse} + \\ N_{NH3store} + N_{N2store} + N_{N2Ostore} + \\ N_{fvol} + N_{mvol} + N_{N2soil} + N_{N2Osoil} + N_{NO3soil} \\ N_{NH3graz} + N_{\Delta soil} \end{pmatrix} \tag{4.1}$$

where N_{fvol} is the ammonia volatilisation from field-applied mineral fertiliser, N_{mvol} is the ammonia volatilisation from animal manure, N_{N2soil} and N_{N2Osoil} are, respectively, the emission of dinitrogen and nitrous oxide following nitrification or denitrification in the soil, N_{NO3soil} is nitrate leaching from the soil and $N_{\Delta\mathrm{soil}}$ is the change in the storage of N in the soil. For details of N_{fvol}, N_{mvol}, N_{N2soil}, N_{N2Osoil}, N_{NO3soil} and $N_{\Delta\mathrm{soil}}$ see the arable farm section.

In the case of excreta deposited in animal housing, the manure management chain contains a series of NH_3, N_2O and N_2 emission sources (animal house – manure storage – field-applied manure). An N flow approach is used here, to enable the consequent interactions between the emission sources to be described. The model is based on the methods used in the development of the Danish fertiliser and manure regulations (Anon., 2006) and means that for these losses, and for the calculation of the N in manure ex storage, the fate of the N excreted by each livestock category is followed separately as it passes through the animal housing and manure storage.

2.8.1 Gaseous emissions from livestock housing and grazing livestock

The gaseous emissions are estimated using a livestock N balance and emission factor approach. Details of the methods and parameterisation are described in detail in Poulsen et al (2001) and Hutchings et al. (2001), so are only briefly described here.

The N excretion of the *k*th livestock category of the *i*th livestock species ($N_{excr,i,k}$; kg N yr^{-1}) is based on a N balance for the animals:

$$N_{excr,i,k} = N_{feed,i,k} - \left(N_{growth,i,k} + N_{milk,i,k}\right) \quad (4.2)$$

The excretal N deposited by the *k*th livestock category in the *h*th animal housing category ($N_{excr,i,k,h}$; kg N yr^{-1}) is:

$$N_{excr,i,k,h} = \left(1 - \tau g_{i,k}\right)\kappa_{i,k,h} N_{excr,i,k} \quad (4.3)$$

Where $\tau g_{i,k}$ is the proportion of the year that the *k*th livestock category of the *i*th livestock species spend grazing and $\kappa_{i,k,h}$ is the proportion of the *k*th livestock category of the *i*th livestock species in the *h*th animal housing. The N deposited by the *k*th livestock category of the *i*th livestock species during grazing ($N_{graz,i,k}$; kg N yr^{-1}) is then:

$$N_{graz,i,k} = \tau g_{i,k} N_{excr,i,k} \quad (4.4)$$

The volatilisation of ammonia from excreta deposited by grazing cattle ($N_{NH3graz}$) is calculated using an emission factor approach:

$$N_{NH3graz} = \delta_{graz} \sum_{k=1}^{K_2} N_{graz,2,k} \quad (4.5)$$

where δ_{graz} is an ammonia emission factor (kg NH_3-N (N kg)$^{-1}$).

The gaseous emissions of N from excreta deposited by the *k*th livestock category of the *i*th livestock species in the *h*th animal housing ($N_{house,i,k,h}$; kg N yr^{-1}) are:

$$N_{house,i,k,h} = N_{NH3house,i,k,h} + N_{N2house,i,k,h} + N_{N2Ohouse,i,k,h} \quad (4.6)$$

Where $N_{NH3housing,i,k,h}$, $N_{N2housing,i,k,h}$ and $N_{N2Ohousing,i,k,h}$ (kg N yr^{-1}) are the emissions of NH_3, N_2 and N_2O from the *k*th livestock category of the *i*th livestock species in the *h*th animal housing category:

$$N_{NH3house,i,k,h} = \delta_{NH3house,h} N_{excr,i,k,h} \quad (4.7)$$

$$N_{N2house,i,k,h} = \delta_{N2house,h} N_{excr,i,k,h} \tag{4.8}$$

$$N_{N2Ohouse,i,k,h} = \delta_{N2Ohouse,h} N_{excr,i,k,h} \tag{4.9}$$

where $\delta_{NH3house,h}$, $\delta_{N2house,h}$ and $\delta_{N2Ohouse,h}$ are emission factors for ammonia, dinitrogen and nitrous oxide for the *h*th housing type (kg N (kg N)$^{-1}$).

The emissions from all animal housing are:

$$N_{NH3house} = \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{h=1}^{H} N_{NH3house,i,k,h} \tag{4.10}$$

$$N_{N2house} = \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{h=1}^{H} N_{N2house,i,k,h} \tag{4.11}$$

$$N_{N2Ohouse} = \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{h=1}^{H} N_{N2Ohouse,i,k,h} \tag{4.12}$$

An animal house can produce manure of more than one type. Although manure of the same type (e.g. slurry) might be stored in one store and thereby mixed between livestock species and categories, it is convenient to assume here that a given manure type is mixed between livestock categories but not species. The N in *m*th manure ex housing from the *i*th animal species ($N_{exhouse,m,i}$; kg N yr^{-1}) is therefore:

$$N_{exhouse,m,i} = \sum_{k=1}^{K} \sum_{h=1}^{H} \varpi_{m,h} \left(N_{excr,i,k,h} - N_{house,i,k,h} \right) \tag{4.13}$$

Where $\omega_{m,h}$ is the proportion of the manure from the *h*th housing type that is partitioned to the *m*th manure type.

2.8.2 Gaseous emissions from manure storage

The total gaseous emission of N from the storage of the *m*th manure from the *i*th species ($N_{store,m,i}$; kg N yr^{-1}) is:

$$N_{store,m,i} = N_{NH3store,m,i} + N_{N2store,m,i} + N_{N2Ostore,m,i} \tag{4.14}$$

Where $N_{NH3store,m,i}$, $N_{N2store,m,i}$ and $N_{N2Ostore,m,i}$ (kg N yr^{-1}) are the emissions of NH_3, N_2 and N_2O respectively from storage of the *m*th manure type from the *i*th livestock category. An emission factor approach is used to calculate the gaseous emissions:

$$N_{NH3store,m,i} = \delta_{NH3store,m,i} N_{exhouse,m,i} \tag{4.15}$$

$$N_{N2store,m,i} = \delta_{N2store,m,i} N_{exhouse,m,i} \tag{4.16}$$

$$N_{N2Ostore,m,i} = \delta_{N2Ostore,m,i} N_{exhouse,m,i} \tag{4.17}$$

where $\delta_{NH3store,m.i}$, $\delta_{N2store,m,i}$ and $\delta_{N2Ostore,m,i}$ are the relevant emission factors for manure storage for the *m*th manure type and *i*th animal species. In practice, the emissions of N_2 and N_2O from animal housing are ignored, unless the manure remains in the animal house for long periods.

The N in *m*th manure ex storage from the *i*th animal species ($N_{exstore,m,i}$; kg N yr^{-1})

$$N_{exstore,m,i} = N_{exhouse,m,i} - N_{store,m,i} \quad (4.18)$$

The total gaseous emissions from all manure storage on the farm are then:

$$N_{NH3store} = \sum_{i=1}^{I}\sum_{m=1}^{M} N_{NH3store,m,i} \quad (4.19)$$

$$N_{N2store} = \sum_{i=1}^{I}\sum_{m=1}^{M} N_{N2store,m,i} \quad (4.20)$$

$$N_{N2Ostore} = \sum_{i=1}^{I}\sum_{m=1}^{M} N_{N2Ostore,m,i} \quad (4.21)$$

As for arable farms, the separate models of emission and changes in soil N will normally yield results that sum to a value that is either greater than or less than the farm N surplus, so that the N not accounted for must be partitioned. It is assumed here that all NH_3 emission estimates are correct; the algorithm described in the companion paper is then used here. However, whereas on pig and arable farms, a correction to the N in crop yield translates into a correction in the N exported in crops sold, on cattle farms it is translated into a correction of the N consumed by the cattle. This in turn leads to a corresponding correction in the amount of N imported in animal feed.

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Key to symbols

Symbol	*Description*	*Units*	*First used in equation*
$A_{j,s}$	Area of crop j on soil type s	ha	1.1
b_h	Requirement for bedding in animal housing type *h*	kg DM animal^{-1} yr^{-1}	3.14
C_j	Total number of crop products for the *j*th crop		1.8
$D_{conc,k}$	DM intake of concentrate of the *k*th cattle category	kg DM yr^{-1}	3.9
$D_{max,k}$	Maximum DM intake of the *k*th cattle category	kg DM yr^{-1}	3.10
$D_{rough,k}$	DM intake of roughage of the *k*th cattle category	kg DM yr^{-1}	3.9
D_u	Total demand for the *u*th crop product	kg DM yr^{-1}	3.14
$E_{dem,i,k}$	Total annual demand for energy for the *k*th cattle category of the *i*th livestock species	MJ yr^{-1}	3.5
$e_{dem,i,k}$	Energy demand of the *k*th category of the *i*th livestock species	MJ animal^{-1} yr^{-1}	3.5
e_{rough}	Concentration of energy in the average roughage feed	MJ (kg DM)$^{-1}$	3.9
e_u	Concentration of energy in the *u*th crop product	MJ (kg DM)$^{-1}$	3.4
f_{conc}	Concentration of fibre in the average concentrate feed		3.10
f_{rough}	Concentration of fibre in the average roughage feed		3.10
$g_{i,k}$	Live weight growth of the *k*th livestock category of the *i*th livestock species	kg LW yr^{-1}	3.21
H	Total number of housing categories		3.14

I	Number of livestock on the farm		
J	Number of crops sown		1.1
K_i	Number of categories in the ith livestock species		3.13
K_i	Number of categories of the *i*th livestock species		
$L_{i,k}$	Number of animals in the *k*th category of the *i*th livestock species		3.5
M	Number of manure types produced or used on the farm		
N_{aexp}	Export of N in animal products	kg N yr^{-1}	3.24
N_{atm}	N input in wet and dry deposition from atmosphere	kg N yr^{-1}	1.2
n_{atm}	Rate of deposition of atmospheric N	kg N ha^{-1} yr^{-1}	1.2
N_{cexp}	N exported in crop products	kg N yr^{-1}	1.8
$N_{cexp,u}$	Exported of the *u*th crop product category	kg DM yr^{-1}	3.17
$N_{cimp,u}$	Import of the *u*th crop product category	kg DM yr^{-1}	3.16
N_{conc}	N imported in concentrate feed	kg N yr^{-1}	3.20
$N_{excr,i,k}$	N excretion of the *k*th livestock category of the *i*th livestock species	kg N yr^{-1}	4.2
$N_{excr,i,k,h}$	The excretal N deposited by the *k*th livestock category in the *h*th animal housing category	kg N yr^{-1}	4.3
$N_{exhouse,m,i}$	N in *m*th manure ex housing from the *i*th animal species	kg N yr^{-1}	4.13
$N_{exstore,m,i}$	N in *m*th manure ex storage from the *i*th animal species	kg N yr^{-1}	4.18
$N_{exstore,m,i}$	On-farm production of the manure from the *i*th livestock category and *m*th manure type	kg N yr^{-1}	3.25
$N_{fapp,m,j,s}$	Application of N in the *r*th fertiliser type to the *j*th crop on the *s*th soil type	kg N ha^{-1} yr^{-1}	1.5

$n_{fapp,r,j,s}$	Application rate of N in the *r*th fertiliser type to the *j*th crop on the *s*th soil type	kg N ha^{-1} yr^{-1}	1.5
$N_{feed,1,k}$	N in the feed of the *k*th pig category	kg N yr^{-1}	3.7
$N_{feed,2}$	N in the cattle feed	kg N yr^{-1}	3.13
$N_{feed,2,k}$	N in the feed of the *k*th cattle category	kg N yr^{-1}	3.12
$N_{feed,i}$	N in the feed of the *i*th livestock species	kg N yr^{-1}	3.8
N_{fimp}	Import of N to the farm in fertilizer	kg N yr^{-1}	1.7
N_{fix}	N input via fixation from the atmosphere	kg N yr^{-1}	1.3
$n_{fix,j}$	N fixation rate of the *j*th crop	kg N ha^{-1} yr^{-1}	1.3
N_{fvol}	Ammonia volatilisation from field-applied mineral fertiliser	kg N yr^{-1}	1.10
$N_{graz,i,k}$	N deposited by the *k*th livestock category of the *i*th livestock species during grazing	kg N yr^{-1}	4.4
N_{growth}	Total N in animal growth	kg N yr^{-1}	3.22
$n_{growth,i,k}$	Concentration of N in growth of the *k*th livestock category of the *i*th livestock species	kg N (kg LW)$^{-1}$	3.21
$\mathrm{N}_{growth,i,k}$	N in the growth of the *k*th livestock category of the *i*th livestock species	kg N yr^{-1}	3.21
$N_{house,i,k,h}$	Gaseous emissions of N from excreta deposited by the *k*th livestock category of the *i*th livestock species in the *h*th animal housing	kg N yr^{-1}	4.6
$N_{mapp,m,j,s}$	Application of N in manure of the *m*th manure type to the *j*th crop on the *s*th soil type	kg N yr^{-1}	1.4
$n_{mapp,m,j,s}$	Application rate of the *m*th manure type to the *j*th crop on the *s*th soil type	kg N ha^{-1} yr^{-1}	1.4
N_{mexp}	Manure N exported	kg N yr^{-1}	3.30
N_{milk}	N in milk production	kg N yr^{-1}	3.23

$n_{\mathrm{milk,k}}$	Concentration of N in milk of the *k*th cattle category	kg N (kg ECM)$^{-1}$	3.23
N_{mimp}	Import of N to the farm in manure	kg N yr^{-1}	1.6
N_{mvol}	Ammonia volatilisation from animal manure	kg N yr^{-1}	1.10
N_{N2house}	Emission of dinitrogen from animal housing	kg N yr^{-1}	4.1
$N_{\mathrm{N2housing,i,k,h}}$	Emissions of N_2 from the *k*th livestock category of the *i*th livestock species in the *h*th animal housing category	kg N yr^{-1}	4.6
N_{N2Ohouse}	Emission of nitrous oxide from animal housing	kg N yr^{-1}	4.1
$N_{\mathrm{N2Ohousing,i,k,h}}$	Emissions of N_2O from the *k*th livestock category of the *i*th livestock species in the *h*th animal housing category	kg N yr^{-1}	4.6
N_{N2Osoil}	Emission of nitrous oxide following nitrification or denitrification in the soil	kg N yr^{-1}	1.10
N_{N2Ostore}	Emission of ammonia, dinitrogen and nitrous oxide from manure storage	kg N yr^{-1}	4.1
$N_{\mathrm{N2Ostore,m,i}}$	Emissions of ammonia from from storage of the *m*th manure type from the *i*th livestock category	kg N yr^{-1}	4.14
N_{N2soil}	Emission of dinitrogen following nitrification or denitrification in the soil	kg N yr^{-1}	1.10
N_{N2store}	Emission of ammonia, dinitrogen and nitrous oxide from manure storage	kg N yr^{-1}	4.1
$N_{\mathrm{N2store,m,ii}}$	Emissions of ammonia from from storage of the *m*th manure type from the *i*th livestock category	kg N yr^{-1}	4.14
N_{NH3graz}	Ammonia emission from urine deposited during grazing	kg N yr^{-1}	4.1
N_{NH3house}	Emission of ammonia from animal housing	kg N yr^{-1}	4.1
$N_{\mathrm{NH3housing,i,k,h}}$	Emissions of NH_3 from the *k*th livestock category of the *i*th livestock	kg N yr^{-1}	4.6

	species in the *h*th animal housing category		
$N_{NH3store}$	Emission of ammonia, dinitrogen and nitrous oxide from manure storage	kg N yr^{-1}	4.1
$N_{NH3store,m,i}$	Emissions of ammonia from from storage of the *m*th manure type from the *i*th livestock category	kg N yr^{-1}	4.14
$N_{NO3soil}$	Nitrate leaching from the soil	kg N yr^{-1}	1.10
N_{seed}	N imported in seed	kg N yr^{-1}	1.1
$n_{seed,j}$	Amount of seed N sown for the *j*th crop	kg ha^{-1}	1.1
$N_{store,m,i}$	Total gaseous emission of N from the storage of the *m*th manure from the *i*th species	kg N yr^{-1}	4.14
N_{surp}	Farm N surplus	kg N yr^{-1}	1.9
$N_{\Delta soil}$	Change in the storage of N in the soil	kg N yr^{-1}	1.10
$p_{c,j}$	Concentration of crude protein in the *c*th product of the *j*th crop	kg $(kg)^{-1}$, DM	1.8
$P_{conc,k}$	CP content of the concentrate feed that is necessary to satisfy the CP demand of the *k*th cattle category	kg CP $(kg\ DM)^{-1}$	3.11
$P_{dem,i,k}$	Total annual demand for crude protein for the *k*th category of the *i*th livestock species	kg CP yr^{-1}	3.6
$p_{dem,i,k}$	Crude protein demand of the *k*th category of the *i*th livestock species	kg CP $animal^{-1}$ yr^{-1}	3.6
$P_{dem,k}$	Minimum protein supply in diet	kg CP yr^{-1}	3.11
p_{rough}	CP content in the average roughage feed	kg CP $(kg\ DM)^{-1}$	3.11
p_u	Protein concentration in the *u*th crop product	kg $(kg\ DM)^{-1}$	3.3
Q_k	Milk yield of the *k*th cattle category	kg ECM $animal^{-1}$ yr^{-1}	3.23
S	Number of soil types present		1.1

u	Crop product identifier; see Table 2		3.1
$y_{c,j,s}$	Dry matter (DM) yield of the *c*th product of the *j*th crop on the *s*th soil type	kg DM ha^{-1} yr^{-1}	1.8
Y_u	Cumulative yield of the *u*th crop product		3.2
$Y_{u,j}$	Total harvested dry matter yield of the *u*th product of the *j*th crop	kg DM yr^{-1}	3.1
α	Concentration of N in crude protein	kg kg^{-1}	1.8
$\delta_{fert,r}$	Ammonia emission factor for the *r*th fertiliser type	kg N (kg N applied)$^{-1}$	2.1
δ_{graz}	Ammonia emission factor for grazing	kg NH_3-N (N kg)$^{-1}$	4.5
$\delta_{man,m}$	Ammonia emission factor for the *m*th manure type	kg N (kg N applied)$^{-1}$	2.2
$\delta_{N2house,h}$	Emission factor for dinitrogen for the *h*th housing type	kg N (kg N)$^{-1}$	4.8
$\delta_{N2Ohouse,h}$	Emission factor for nitrous oxide for the *h*th housing type	kg N (kg N)$^{-1}$	4.9
$\delta_{N2Ostore,m,i}$	Emission factors nitrous oxide for manure storage for the *m*th manure type and *i*th animal species	kg N (kg N)$^{-1}$	4.17
$\delta_{N2store,m,i}$	Emission factors dinitrogen for manure storage for the *m*th manure type and *i*th animal species	kg N (kg N)$^{-1}$	4.16
$\delta_{NH3house,h}$	Emission factor for ammonia for the *h*th housing type	kg N (kg N)$^{-1}$	4.7
$\delta_{NH3store,m.i}$	Emission factors ammonia for manure storage for the *m*th manure type and *i*th animal species	kg N (kg N)$^{-1}$	4.15
$\varepsilon_{c,j}$	Harvest indicator (unity if the product is harvested and zero if not)		1.8
$\eta_{i,k,h}$	Proportion of the *i*th livestock species of category *k* that are housed in animal housing type *h*		3.14
$\kappa_{i,k,h}$	Proportion of the *k*th livestock category		4.3

	of the *i*th livestock species in the *h*th animal housing		
$\tau g_{i,k}$	Proportion of the year that the *k*th livestock category of the *i*th livestock species spend grazing		4.3
$\omega_{m,h}$	Proportion of the manure from the *h*th housing type that is partitioned to the *m*th manure type		4.13

Abbreviations

Abbreviation	*Description*
CP	Crude protein
DM	Dry matter
ECM	Energy-corrected milk
LW	Live weight

Filnavn:	FARM-N_scientific_description
Bibliotek:	C:\Margit\personlig
Skabelon:	C:\Programmer\AUDesign\Word\Skabeloner\Normal.dot
Titel:	FARM-N scientific documentation
Emne:	
Forfatter:	NJH
Nøgleord:	
Kommentarer:	
Oprettelsesdato:	29/07/2010 10:13
Versionsnummer:	7
Senest gemt:	29/07/2010 10:32
Senest gemt af:	NJH
Redigeringstid:	12 minutter
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Sider:	22
Ord:	8,191 (ca.)
Tegn:	39,318 (ca.)