# **Supplementary S2. GHG emission calculation**

Culled cows and calves

Milk

Meat from calves

and culled cows

‘Avoided burden’ GHG emissions from meat replacement

GHG emissions from heifer rearing

**Upstream**

* Transport
* Cultivation
* Feed mill
* Processing
* Land use change
* Other inputs

Animal production

Manure in stable and pasture

**Dairy farm**

Replacement

heifer

GHG emissions from feed production

GHG emissions from enteric fermentation

GHG emissions from manure management

**Figure S2.1** A flowchart of dairy production system from cradle to farm gate and associated greenhouse gas emissions

## **GHG emissions from feed production**

* 1. **Daily energy requirement**
* Daily energy requirement are estimated in VEM (Dutch feed energy system). Total VEM is the sum of which energy from maintenance, milk production, pregnant, growth, and grazing activities

kg\_FPCM = (0.337 + 0.116 × %F + 0.06 × %P) × MY

Milk yield from cows was corrected at 4.0 percent fat and 3.3 percent protein (Opio et al., 2013) P.106. Where kg\_FPCM is fat-and-protein-corrected milk (kg). %F is percentage of fat in milk. %P is percentage of protein in milk. MY is the daily milk yield (kg).

VEM maintenance = (42.4 x body weight^0.75 x (1 + (kg\_FPCM - 15) x 0.00165)) (Rijksdienst voor Ondernemend Nederland (RVO), 2023) (P.11)

VEM for milk production = (442 x kg\_FPCM x (1 + (kg\_FPCM -15) x 0.00165)) (Rijksdienst voor Ondernemend Nederland (RVO), 2023) (P.11)

VEMgrazing = 419 (Rijksdienst voor Ondernemend Nederland (RVO), 2023) (Table2)

VEM.growth = 625, 325, 125 ,125 for parity 1, 2, 3, 4, (CVB, 2022) (Table 1.1)

VEMpregnant = 250, 400, 650, 1100, 1700, 2750 for gestation month of 4, 5, 6, 7, 8, 9 (CVB, 2022) (Table 1.3)

VEM total = VEMmaintenance & milk yield + VEMgrazing + VEMgrowth + VEMpregnant

**1.2 Feed composition**

* The feed composition is calculated in an Excel file using data from FeedPrint (Wageningen Livestock Research and Blonk Milieu Advies, 2022) and CVB table (CVB, 2022) and CBS data (Centraal Bureau voor de Statistiek (CBS), 2022, 2019). Check excel file feed.composition.xlsx
* Silage ration = maise silage : grass silage = 50 : 50
* Concentrate ration for stable cow = concentrate: high protein concentrate : wet concentrate = 0.5 : 0.35 : 0.15
* Concentrate ration for grazing cow = concentrate: high protein concentrate: wet concentrate = 0.85 : 0 : 0.15 (Centraal Bureau voor de Statistiek (CBS), 2019) (Table B5.2)

**Table S2.2** Energy, nitrogen content, and greenhouse gas emissions from feed production, enteric fermentation for each feeds

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Input variables** | **Roughagea** | **Fresh grass** | **Concentrate** | **High protein concentrate** |
| Energy (VEMb/ kg DM) | 917.7 | 1006.3 | 1087.4 | 1089.3 |
| Nitrogen content (g/ kg DM) | 19.4 | 37 | 28.8 | 32 |
| GHG emissions from feed production (kg CO2e/ kg DM)c | 0.40 | 0.58 | 0.92 | 1.14 |
| GHG emission from enteric fermentation (kg CO2e/ kg DM)c | 0.018 | 0.02 | 0.019 | 0.032 |

* a mixture of 50:50 of grass silage and maize silage   
  b VEM is feed unit milk in Dutch feed energy system. 1 VEM = 6.9 kJ Net Energy for lactation (CVB, 2018)  
  c GHG emissions from feed production and enteric fermentation was calculated from FeedPrint NL program (Vellinga et al., 2013).

**1.3 Feed intake**

* If a cow is dry or milk yield ≤ 20 kg, it is fed from only roughage.
* If a cow produces milk yield 21 – 40 kg, the roughage is fed for VEM maintenance & 20 kg milk yield & pregnant & growth & grazing. The rest of VEM is from concentrate feed.
* If a cow produces milk yield > 40 kg, the roughage is fed for VEM maintenance & 20 kg milk yield & pregnant & growth & grazing. The concentrate is fed for VEM for producing the rest of milk yield up to 40 kg.
* The ration is depended on cow status (lactating or dry), milk yield (≤ 20 kg, 21-40 kg or > 40 kg) and grazing period.
* Grazing period from 1st April – 30th September, 8 hours per day. Only lactating cow graze
* The cow graze for 8 hours = 6.5 kg DM of fresh grass (Rijksdienst voor Ondernemend Nederland (RVO), 2023) (Table 2).
* From these assumptions and energy content in feed from table S2.2. Feed intake for per cow per day was estimated.
  1. **GHG from feed production**
* GHG from feed production includes feed production (fertiliser & energy), land use and feedmill (Vellinga et al., 2013). The data are provided from FeedPrint program.

GHG from feed production = Dry matter intake × emission from feed production (kg CO2e/ kg DM)

## **GHG emissions from enteric fermentation**

* From VEM and feed composition, we can calculated feed intake of each cows per day, and consequently calculated the GHG emission from enteric fermentation.
* GHG from enteric fermentation provided from FeedPrint program, which is calculated from rumen simulation model (Bannink et al., 2010, 2008).
* Enteric fermentation emits CH4 which can be converted to CO2 equivalent by multiplying 27 (Intergovernmental Panel On Climate Change (IPCC), 2023) (Table 7.15)

GHG from enteric fermentation = DMI × emission from enteric fermentation (kg CH4/ kg DM)) × 27

## **GHG from manure management**

Manure

Pasture (solid)

Stable (slurry)

Direct N2O-N

CH4

NH3-N

NOx-N and NO3-N leaching

Indirect N2O-N

N2O

- If a cow grazed for 8 hours, 1/3 of manure was produced in pasture (solid form), and 2/3 was produced in stable (slurry from) during grazing period of the year. Outside grazing period, all manure was produced in stable.

**3.1 N in manure**

* Nitrogen in manure is the amount of nitrogen in manure (including urine and feces). It can be calculated from N in feed deducted by N retention in cow.

N manure = N intake - N retention in milk - N retention for growth - N retention for pregnant

N intake = DMI × %Crude protein × 6.25 (Intergovernmental Panel On Climate Change (IPCC), 2019) (P. 58)

N retention in milk = milk yield × (%protein/100) /6.38 (Intergovernmental Panel On Climate Change (IPCC), 2019) (equation 10.33)

N retention for growth = 0.00196 kg N/ day (Rijksdienst voor Ondernemend Nederland (RVO), 2023) (Table 6)

N retention for pregnant = 0.0045 kg N/ day (Rijksdienst voor Ondernemend Nederland (RVO), 2023) (Table 6)

* 1. **TAN in manure**
* Total ammoniacal nitrogen (TAN) is the nitrogen that excrete in urine. It can be calculated from the amount of nitrogen that can absorbed from feed deducted by nitrogen retention in cow.

N TAN = N absorbable - N retention in milk, growth and pregnant

N absorbable = Dry matter intake × %CP × digestibility/ 6.25 (Velthof et al., 2009)

* 1. **Direct N2O**
* Convert N2O-N to N2O by multiplying 44/28 (Intergovernmental Panel On Climate Change (IPCC), 2019) (equation 10.25)
* N2O is converted to CO2 equivalent by multiplying 273 (Intergovernmental Panel On Climate Change (IPCC), 2023) (Table 7.15)

Table1. Emission factor for direct N2O emissions, NO3-N leaching and NH3-N + NOX-N volatizing of manure in stable and pasture.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Stable |  |  | |  | | |  |  |
| N2O-N direct | kg/kg TAN | | | 0.0015 | | | (De Vries et al., 2011)Table 3.2 | |
| NH3-N | kg/kg TAN | | | 0.1000 | | | (De Vries et al., 2011) Table 3.2 | |
| NOx-N | kg/kg TAN | | | 0.0015 | | | (De Vries et al., 2011) Table 3.2 | |
| Pasture |  |  | |  | | |  |  |
| N2O-N direct | kg/kg N | | | 0.033 | | | (Vonk et al., 2018) P.70 | |
| NOx-N | kg/kg N | | | 0.012 | | | (Vonk et al., 2018) P.65 | |
| NH3-N | kg/kg TAN | |  | 0.053 | | | (Vonk et al., 2018) P.62 | |
| NO3-N leach | kg/kg N | |  | 0.12 | | | (Velthof and Mosquera Losada, 2011) P.10 | |
| All |  | |  | |  | |  |  |
| N2O-N indirect | kg/kg NH3-N + NOX-N | | 0.01 | | |  | (Intergovernmental Panel On Climate Change (IPCC), 2019) eq 10.27 | |
|  | kg/kg NO3-N | | 0.0075 | | |  | (Intergovernmental Panel On Climate Change (IPCC), 2019) eq.10.29 | |

Direct N2O from stable = N TAN × 0.0015 × (44/28) × 273

Direct N2O from pasture = N manure × 0.033 × (44/28) × 273

* 1. **Indirect N2O**
* Indirect N2O emits from volatilisation of N in forms of NH3-N, NOx-N and NO3-N leach.

Indirect N2O from stable = (( N TAN × 0.1 × 0.01) + ( N TAN × 0.0015 × 0.01)) × 44/28 × 273

Indirect N2O from pasture = (( N TAN × 0.053 ×0.01) + ( N manure × 0.012 ×0.01) + (N manure × 0.12 × 0.0075)) × (44/28) ×273

* 1. **CH4**

CH4 = manure amount (in tonne) × organic matter (OM) × potential methane production (B0) × methane conversion factor (MCF) × 0.67 × 27 (Vellinga, 2013) P.62

Manure amount = ((DMI × 2.63) + 9.4) (only including urine and feces) (Nennich et al., 2005)

For stable: OM = 64 kg per 1000 kg manure, B0 = 0.25,MCF = 0.17

For pasture: OM = 64 per 1000 kg manure, B0 = 0.25, MCF = 0.01 (van der Maas et al., 2011) (Table A8.4, A8.6)

Multiplying 0.67 to convert m3 to kg CH4 (Intergovernmental Panel On Climate Change (IPCC), 2019) (eq. 10.23)

Multiplying 27 to convert kg CH4 to kg CO2e (Intergovernmental Panel On Climate Change (IPCC), 2023) (Table 7.15)

## **4. GHG emissions from meat replacement**

* System expansion was applied to included co-product of meat by avoided burden method (Thomassen et al., 2008).
* We assumed that meat from calves and cows replaces meat from chicken, pork and beef in the market (Mostert et al., 2018).
* GHG emissions related to the production of chicken, pork and beef were 3.75, 4.06 and 23.1 kg CO2e per kg edible product, respectively (De Vries and De Boer, 2010; Mogensen et al., 2015). Average meat consumption for chicken, pork and beef were 32.9, 22.8 and 14.4 kg per year, respectively (OECD, 2023).
* Weighting emissions with average meat consumption resulted in GHG emissions from replaced meat of 10.4 kg CO2e per kg edible product.
* We assume live weight of calves is 44 kg, and 1 kg of animal live weight consisted of 0.406 kg edible product (Van Middelaar et al., 2014).

GHG meat replacement from calves = 44× 0.406 × 10.4

GHG meat replacement from culled cows = Body weight × 0.406 × 10.4

## **5. GHG emissions from heifer rearing**

* Emission for heifers rearing = 5626 kg CO2eq (540 kg BW) from our own calculation (Check R code for heifer calculation for more detail).
* Additional GHG emissions associated with heifer rearing was added for each replacement of culled cows.

**Total GHG emissions = GHG feed production + GHG enteric fermentation + GHG manure - GHG emissions from meat replacement from calves - GHG emissions from meat replacement from culled cows + GHG emissions from heifer rearing**

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