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Development of a new modelling framework to estimate the Carbon footprint from Basque dairy farms

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There is world-wide concern for the contribution of dairy farming to global warming. However, there is still a need to improve the quantification of the Carbon-footprint of dairy farming systems under different production systems and locations since most of the studies (e.g at farm-scale or using LCA) have been carried out using too simplistic and generalised approaches. A new modelling approach in order to estimate the C footprint from milk in the Basque Country has been developed. This working paper provides a description of the model and shows a case study for a set of dairy farms in the province of Bizkaia.

Keywords: farm-model, GHG, dairy, burden, C-footprint

JEL Classification: Q16, Q54

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1. Introduction

The contribution to the global anthropogenic greenhouse gas (GHG) emissions from milk production has been recently estimated at about 3% (FAO, 2010). There is however large uncertainties associated to these estimates due to over-simplification of methodologies and lack of site-specific farm activity data. So far, there have been studies that have estimated the GHG emissions from specific dairy systems using different approaches such as whole farm-modelling (e.g. Schils et al., 2007; del Prado *et al*., 2011), life cycle analysis (LCA) (De Vries and De Boer, 2010) or a combination of both (Rotz et al., 2010). Using LCA, there have been recent efforts to estimate the global warming potential of the production of milk in the Iberian Peninsula, such as in Galicia (Spain) (Hospido et al., 2003) and Portugal (Castanheira et al., 2010). However, the approaches used for these studies have simplified the effect of site conditions on the potential GHG emissions and have lacked of a systems approach basis.

The typical dairy farm system in the Basque Country, as a consequence of lack of available land, has the general strategy to confine the animals for most of the year and to feed animals both a total mixed ration and grass silage. In order to properly simulate the impact of these farms on GHG emissions the modelling approach must have a robust representation of the N and C cycling in the soil-plant-animal system at the housing, the grasslands and the off-farm stages.

This paper presents a new model for estimating GHG emissions from milk production using a cradle to the farm gate LCA. This new model is intended to follow a systems approach and to simulate the effect of local conditions (climate and soil) on N_2O, CO_2 and CH_4 emissions and on farm economics.

The objectives of this paper is to describe a new modelling approach capable of simulating C and N flows and GHG emissions (from the cradle to the farm gate) in typical dairy farms in the Basque Country (northern Spain). A test will be carried out to simulate the C and N flows and to estimate the GHG burden from 17 farms in Bizkaia.

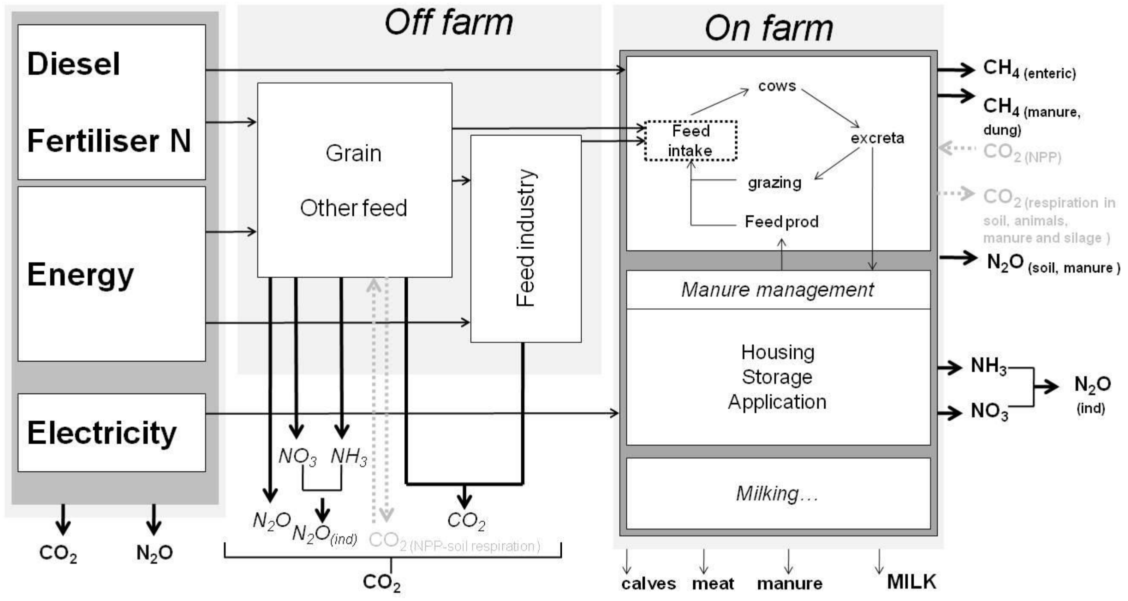
2. System boundaries of the study

The scope of the whole approach is the entire production process of raw milk, from the production of inputs to products leaving the farm gate. The main functional unit of this analysis is 1 kg of energy-corrected milk (ECM) and therefore GHG emissions were quantified as CO_2-eq per kg of ECM produced. Figure 1 shows the boundaries of the dairy system studied and the main forms and sources of GHG included in the assessment. We mainly differentiate between those emissions occurring at the farm level and those emissions occurring outside of the farm via management of purchased concentrates and forages and indirect energy use (synthesis and transportation of mineral fertilizers and concentrates).

At the housing stage we simulate the (i) CH_4 from animal enteric fermentation, manure storage and excreted C on the farm floor (ii) N_2O from manure storage and (iii) CO_2 from animal, manure storage and excreted C on the farm floor respiration and (iv) indirect N_2O emissions from NH_3 volatilized from excreta and manure handling and storage.

At the soil-stage we simulate the: (i) CH_4 from animal enteric fermentation during grazing and excreted C on the soil, (ii) N_2O from soil (fertilizer, excreta and manure-derived), (iii) emissions of CO_2 from soil and animal respiration and CO_2 sink from net primary production (NPP) and (iv) indirect N_2O emissions from NH_3 volatilized from manure application and urine during grazing and NO_3 leached.

Figure 1. System boundaries of the cradle-to-farm gate GHG assessment. Simulated N_2O, CH_4 and CO_2 values are in bold (off-farm GHG emissions are based on other studies). Carbon dioxide flows from the biogenic (short-time) C cycle (in grey) are simulated and included in the farm C balances but not in the GHG assessment. NPP: net primary production, N_2O (ind): indirect N_2O emissions from NO_3 leaching and NH_3 volatilization.



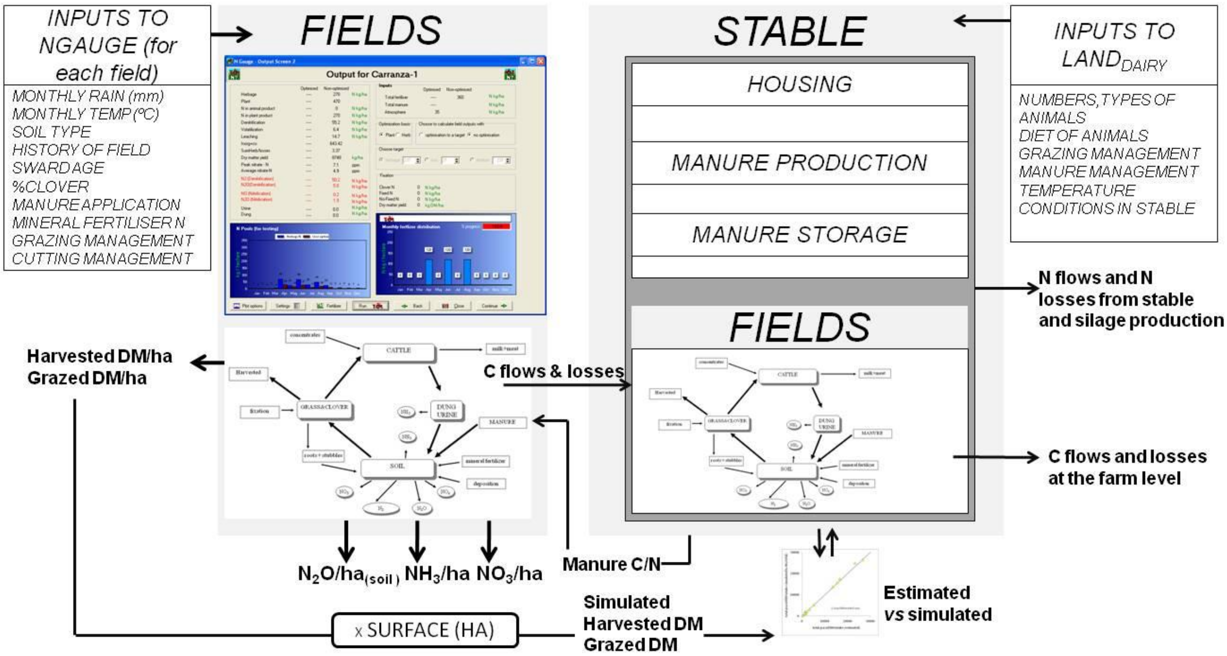
3. General modeling approach

Farm scale modelling was carried out using a combination of simulations from a modified version of the field-scale model for the soil-based stage (NGAUGE: Brown et al., 2005) and simulations from a new farm-scale submodel ($\mathrm{LAND}_{\mathrm{DAIRY}}$) for the rest of the on-farm stages and on-farm C cycle. Other calculations were carried out to estimate the off-farm associated emissions using the LCA software Simapro. Emissions from land use change are included in the off-farm estimated emissions.

The new farm-scale submodel is part of the landscape model LAND_GHG, which is currently under development under the project CGL2009-10176 from the Spanish National R+D+i Plan Programme and is partly based on existing modelling approaches ($\mathrm{SIMS}_{\mathrm{DAIRY}}$: del Prado et al., 2011 and DairyGHG: Rotz et al., 2010).

Figure 2 illustrates the overview of the modelling approach for the on-farm stages. The submodel $\mathrm{LAND}_{\mathrm{DAIRY}}$ simulates the effect of management on N and C flows for the non-fields stages of dairy farm production. This includes: housed animals, manure production and storage and silage making. $\mathrm{LAND}_{\mathrm{DAIRY}}$ also aggregates all on-farm calculations, including those resulting from NGAUGE, to produce farm-scaled simulated results. The submodel simulates some internal pools that are also estimated by the farmer. These internal outputs include a simulation of total volume of manure generated in the farm and an estimation of grazed or harvested plant required for direct animal grazing or for silage, respectively .

Figure 2. Modelling process for the on-farm stages.



4. The field-scale model: NGAUGE

A modified version of the NGAUGE model (Brown et al., 2005) was used to simulate N flows and losses in the fields of the farm. NGAUGE is a semi-empirically-based mass-balance model which simulates monthly N flows per hectare within and between the main components of grazed or cut grassland systems according to user inputs describing site conditions and farm management characteristics (e.g. monthly fertiliser and manure application). This version was largely implemented within the EU project GREENDAIRY, where several tests were carried out for specific fields of northern Spain.

The main inputs for the NGAUGE model are: monthly rainfall and average air temperature, soil type (texture and drainage class), history of the sward, sward age, sward composition (% clover), monthly management: manure application (manure type, m^3/ha, % DM, C/N ratio, %N and application method), mineral fertiliser N application (rate and timing), grazing (time of the year, intensity), cutting regimes (months for sward cutting, % cut). Some inputs were assumptions as no precise information was available (e.g. % clover: 10%, history of the sward: long term grass-clover). NGAUGE was calibrated to simulate similar yields (for harvests or grazing) to those estimated. Outputs included: DM yields, plant biomass and C and N flows and losses per hectare from the fields (e.g. Net fixed C, N fixation, N_2O, NH_3, NO_3, NO_x).

NGAUGE simulates total denitrification as a function of soil inorganic N, water-filled pore space (% WFPS) and temperature. Subsequently, N_2O is calculated from the N_2O:N_2 ratio, which is a function of WFPS, mineral N flux and mineralized N in the soil. Total N2O emission from nitrification is modelled as a function of the maximum potential rate of N2O emission from nitrification with modification factors based on nitrification rate and soil moisture. Nitrate leaching is predicted as a fraction of the total leachable N (from the balance between total N flows and plant N uptake, NH_3, denitrification and nitrification losses). This fraction is a function of the drainage volume and texture. Average and peak N concentrations are also predicted as a function of soil texture and N leaching. Ammonia emissions from urine, dung and manure application are a function of total ammonia nitrogen (N), %dry matter (manure), temperature and manure application method. For more details on simulation of N losses see Brown *et al.* (2005).

5. The new sub-model: $\text{LAND}_{\text{DAIRY}}$

$\text{LAND}_{\text{DAIRY}}$ has been developed to predict the N and C flows and losses at the farm scale following the principles of a mass-balance approach (as in SIMSDAIRY. Del Prado *et al.*, 2011) and using the field outputs simulated by NGAUGE as inputs.

Other inputs for the $\text{LAND}_{\text{DAIRY}}$ model include: (i) number and type of dairy cows (as defined by: total weight, average milk yield, milk protein % and butterfat milk %), (ii) number and type of followers (yearlings, calves and others), (iii) total DM intake in silage, fresh grass and concentrates and type of each feeds (crude protein: CP, acid detergent fibre: ADF, starch and total digestible nutrient: TDN) for each type of animal considered, (iv) grazing intensity and calving pattern, (v) manure and stable management: housing type, area covered by excreta, average temperature (ºC) in the stable, kg bedding and type, manure system type (slurry, FYM), manure storage type, average temperature (ºC) in the storage and storage removal rate (days).

The calculations can be summarised in different farm stages:

(1) Silage making: Using silage DM farmer estimates and information on analysis of different silage nutrient values. Silage making is assumed to be optimal and no significant CH_4 is formed in the process. The C (0.4 kg C/kg DM) lost to the air as CO_2 and NH_3 and NO_x losses are calculated to be proportional to the loss of DM (Schils *et al.* 2005).

(2) Animal intake and feed losses in the house: Total kg DM ingested for each animal type and periods are calculated from the input values and the grazed DM intake calculation. For the grazing period we assume that grazing animals ingested grazed grass and concentrates (proportionally to the grazing timing) and silage and concentrates while at the stable. A percentage of the DM offered in the stable is considered to remain on the floor of the stables and is simulated to be mixed with bedding material and animal excreta. Consequently, this mix is incorporated within the pool of manure collected in the house. Nitrogen and C flows for each of these pools are calculated using the input values of CP (for N) and the C contents of feed: 0.4 kg C/kg DM for forages and 0.4 or 0.45 C/kg DM for protein-poor and protein-rich concentrates, respectively (Rotz *et al.*, 2010).

(3) Partitioning of feed N consumed by the animals: Ingested N is assimilated in body-mass, secreted as milk or lost as urine and dung. Milk N is calculated from the total amount of milk and the protein content in the milk. The total N in liveweight gain (animal tissue growth) for each follower is calculated as a function of N intake (as in del Prado *et al.*, 2006). Excreted N is calculated by

subtracting N in milk and net body change from those N ingested by followers and lactating cows. To divide urine over dung losses the model uses the basis from Mills et al. (2008), whereby urine N is calculated as a function of N ingested and subsequently, faecal N (dung) is determined by subtracting urine N from that N in the total amount of excreta. Urine N is calculated for each type of animal as follows:

$$kg\ \mathrm{N\ urine/day} = 0.366 * (N\mathrm{intake}) + 14.52 \tag{1}$$

Where *Nintake* = daily N ingested.

(4) Partitioning of feed C consumed by the animals: ingested C is assimilated in body-mass, secreted as milk, respired (lost as CO_2), fermented in the rumen (and lost as CH_4) and excreted in dung and urine. Milk and meat C is calculated from the total milk N and meat production and the C content of milk (12 g C/g of milk N) and meat (0.23 g of C/g of animal mass) (Rotz et al., 2010). For the weight gain in cows the model N output was converted into product (meat) by following the equation 2.3 kg N=100 kg liveweight gain ha^{-1} (Cardenas et al., 2011). Excreted C is calculated from subtracting C in meat, milk, CH_4 and CO_2 lost from the total ingested C.

(5) Enteric CH_4: An empirical equation was incorporated within the model: Tier 2 methodology from IPCC (2006), whereby CH_4 is calculated as a function of gross energy intake:

$$kg\ CH4/day = \ (GE\ x\ Ym)/55.65 \tag{2}$$

Where *GE* = gross energy intake and *Ym*= methane conversion rate which is the fraction of gross energy in feed converted to methane (%).

(6) Animal respiration (CO_2): Animal respiration is predicted as a function of the DM intake and weight using a relationship developed by Kirchgessner et al. (1991) and used already in the DairyGHG model (Rotz et al., 2010):

$$kg\ CO2/day = \ -1.4 + 0.42\ DMi + 0.045\ \ [BW]\text{^}0.75 \tag{3}$$

Where *BW* = mass body weight and *DMi* = daily DM intake for each type of animal.

(7) General manure calculations: The model simulates the DM, N and C manure flows and losses along the different stages of manure management: production, storage and soil application. Losses from manure (DM, N and C) are simulated to occur at different levels: housing, storage and after application (simulated with NGAUGE). As mentioned before manure is formed in the stable by mixing excreta, feed losses and bedding material (generally straw). Whilst DM from bedding and feed lost to the stable floor is easily inferred, faecal and urine DM are simulated using equations from the DairyGHG model (Rotz and Chianese, 2009). The faecal DM is calculated by the total DM ingested by the animals multiplied by the fraction of indigestible nutrients of each feed (through standard values of total digestible nutrient concentration of the diet). Urine DM production is calculated as 5.7% of total urine mass. Urine mass production is predicted as a function of DM intake, CP intake, and milk production (Fox et al., 2004):

$$kg\ Urine\ DM/day = \left(3.55 + 0.16\ DMi + 6.73\left(\left(CPi - 0.35\ MILKA\right)\right)\left(\frac{BW}{454}\right)\right)0.057 \quad (4)$$

Where *DMi* is the daily DM intake, *CPi* is the crude protein intake and *BW* is mass body weight for each type of animal and *MILKA* is the milk production per dairy cow.

(8) Manure N losses in the stable: total initial ammonium N (TAN) in manure is calculated to be related to the urine, dung, bedding and feed loss in the manure. Ammonia, N_2O, NO_x and N_2 emissions are calculated from the pool of total ammoniacal nitrogen (TAN) in manure N according to different emission factors (EFs) for different manure management stages before application (housing and storage).

(9) Manure C losses in the stable: Carbon dioxide and CH_4 losses are calculated at housing and storage stages. Carbon dioxide emissions and CH4 emissions during the housing stage are calculated using equations from the DairyGHG model (Rotz and Chianese, 2009). Methane emissions from manure storage are simulated using Tier 2 methodology from IPCC (2006) as a function of manure volatile solids (VS) and mean air temperature:

$$kg\ CH4/day = \text{VSmanure}/day\ B0x0.67\ x\text{KMCF\_Factor} \tag{5}$$

Where *VSmanure* is the daily manure volatile solids, *B0* is the maximum CH_4 producing capacity (m^3/kg VS) for manure produced (0.24 m3/kg VS) and the *KMCF* is the CH_4 emission potential of manures.

The model simulates that the manure pit is emptied a number of times in a year (user input data) and that manure storage volume changes dynamically as it daily accumulates until emptied.

(10) Biogenic C flows at the grassland level: Carbon flows are estimated for each grassland field. Net C fixed by the plant is determined from the total NGAUGE simulated biomass (in DM) and considering that aboveground and belowground sward C content is 40%. Plant biomass can subsequently either be harvested (cut or grazed) or remain subject to incorporation into the soil or lost as CO_2 from soil respiration processes. For the animals, the same calculations as those mentioned for the farm stages were carried out to calculate C in milk, weight gain, excretion (urine + dung) and C losses from respiration (CO^2) and enteric CH4. Methane from dung and manure application is also estimated using Efs taken from $\text{SIMS}_{\text{DAIRY}}$ (del Prado *et al.*, 2011). Losses of Dissolved Organic C (DOC) were estimated at a rate of 0.10 t C ha^{-1} $year^{-1}$ (Byrne *et al.*, 2007).

(11) Farm C balance: Carbon emissions associated with on-farm energy consumption (such as electricity and diesel) as well as off-farm activities including N-fertiliser production, transport and application, and production, transport and processing of concentrate animal feed are not included in our C balances. Provided that no precise information has been gathered on management history of the fields we assumed no changes from year to year and therefore, a long-term C balance or a zero net soil C change. Since the biogenic farm C balance is determined by the difference between all fluxes of C into the farm and all C fluxes out of the farm, soil respiration was estimated from subtracting the C outputs without soil respiration (plant respiration, animals respiration, enteric fermentation, CO_2 and CH_4 losses by deposits of cattle dung and manure applied on the fields, on the barn floor, in the manure storage, in the silage making, losses of DOC, milk, meat and exported manure) from all C inputs (C uptake through photosynthesis, concentrates, bedding). Pre-farm emissions (CO_2-

equivalents) associated with purchased concentrates (and forage) and manufactured inorganic fertilizers. Emissions from direct energy use in the farm (electricity and diesel) were also calculated.

Data for inventory of crop cultivation stage of fodder ingredients were based on Nemecek (2007). Spanish electricity grid was modelled based on reports from Spanish Government (REE, 2010; Spanish Ministry of Industry, 2010) adapting Ecoinvent(R) electricity production mix. Additional secondary data for background systems such as fuel production, fertilisers and transportation were provided by the ecoinvent database (Frischknecht et al., 2007).

The NGAUGE model was calibrated to obtain a reasonable match between simulated and estimated (by the farmer) grass and clover harvest.

6. Case study: GHG from dairy farms in Bizkaia

Management and soil data from 17 commercial dairy farms was used to predict the GHG emissions from an average dairy farm in the Karrantza valley (Bizkaia, Spain). This area produces about 62 % of the total milk production in the province of Bizkaia. Data from a previous study (LORRA coop pers. commun) were used to define the type of soil in each farm. Soil textures were generally clay loam and loam. Mineral fertilizer N application was almost negligible and cow slurry was spread in most farms on their grassland fields. A small amount was exported. Weather data for 2010 was obtained from a nearby weather station (Cerroja).

Farm management was quite heterogeneous. For example, variables that may provide an indication of the intensity of the systems were very variable (e.g. milk output per cow ranged between 4000 to 11000 L milk cow-1; stocking rate: 1.3-3.7 LU ha-1 or milk output per hectare: 3000-26000L milk ha^{-1}).

Predicted mean ± SD total GHG emissions were 385 ± 175 t CO_2-eq yr-1. Greenhouse gas emissions ranged from 0.86 to 2.11 kg CO_2-eq/L milk ECM (mean ± SD=1.2 ± 0.3), 5.2 to 28.1 t CO_2-eq/ha (mean ± SD= 14.2 ± 6.3) and 3.9 to 12.1 t CO_2-eq/LU (mean ± SD= 6.6 ± 1.9).

Total GHG emissions were positively correlated with total purchased feed (R^2=0.95; P<0.00001), fat and protein corrected milk production (R^2=0.91; P<0.00001) and number of milking cows (R^2=0.81; P<0.0001).

Total GHG emissions per milk output was found to decrease in a linear fashion with increase in farm N use efficiency (P<0.05). Total GHG emissions per ha increased with increasing stocking rate (P<0.01), milk production per ha, cattle DM intake per ha and with farm N surplus.

A large proportion of total GHG emissions were associated to CH_4 output (29%-51%) and purchased feed (27-52%) (average values in Fig 3). Although total on-farm N_2O losses (direct N_2O and indirect emission from NH_3 and NO_3) represented the third source of GHG emissions (6-32%), a large proportion of GHG emissions from purchased feed were also due to N_2O emissions from off-farm soils. Nitrous oxide emissions showed the largest variability for both on-farm and off-farm emissions too. The large on-farm variability is reflecting different manure handling management (the largest N_2O emissions occurred at a farm where dung and urine were collected unmanaged in paddocks). Off-farm variability is influenced by differences mainly in the amount of purchased feed and not so much by differences in N_2O emissions per kg of purchased feed.

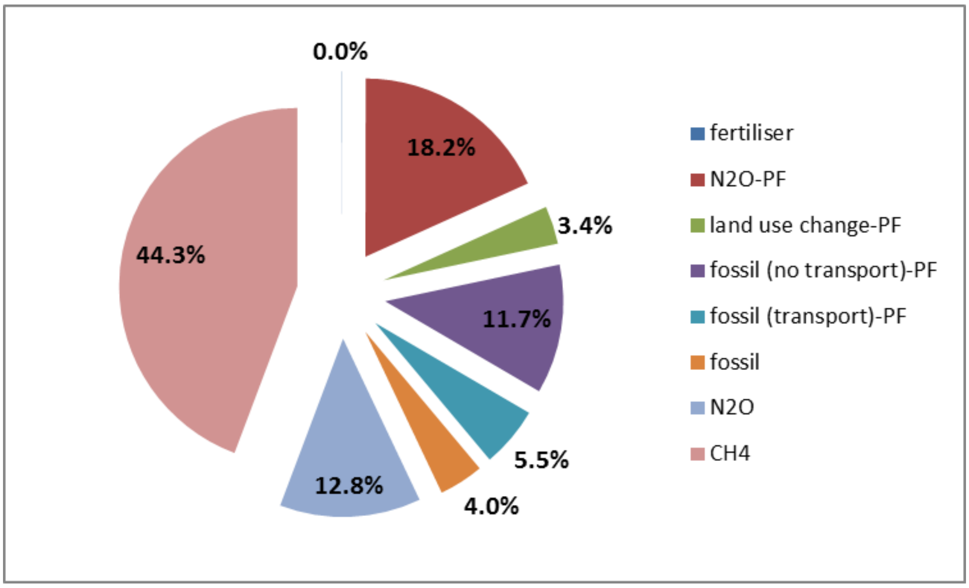


Fig 3. Contribution of different processes and different forms of GHG emissions to the total GHG emission at farm gate within the 17 farm studied. PF= pre-farm gate.

7. Some messages to take

This study showed that cow diet choice (source and origin) is an important management factor controlling GHG emissions per unit of product and may have a strong influence, sometimes positive, on competing human resources as food. Furthermore, the close relationship between GHG emissions and purchased feed indicates that purchased feed could be used as a proxy for estimating total GHG emissions from these farms.

Although the value of comparison among C-footprints resulting from studies analysing other systems and countries is very limited since methodologies and assumptions are often very different, the global warming potential resulting from the production of 1 kg of milk was within the range of existing studies.

The comparison with other modelling approaches has shown that the SIMS$_{\text{DAIRY}}$ modelling framework shares some of the strengths and limitations of other similar modelling approaches (generally, whole-farm system based ones).

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