Greenhouse gas emission intensities of grass silage based dairy and beef production: A systems analysis of Norwegian farms

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ABSTRACT

To increase food production while minimizing its influence on climate change, farming systems in future will need to reduce greenhouse gas (GHG) emissions per unit of product (i.e., GHG intensity). To assess the level and variation in GHG emissions intensity among Norwegian dairy farms, we conducted an analysis of 30 dairy farms to calculate farm scale emissions of GHGs, expressed as CO_2 equivalents (CO_2eq) per kg fat and protein corrected milk (FPCM), and CO_2eq per kg carcass weight (CW) sold. A model, HolosNor, was developed to estimate net GHG emissions, including soil C changes, from dairy farms. The model requires farm scale input data of soil physical characteristics, weather, and farm operations. Based on data from 2008 the estimated level of GHG intensity was 1.02 kg CO_2eq kg^{-1} FPCM, 21.67 kg CO_2eq kg^{-1} CW sold as culled cows and heifers, and 17.25 kg CO_2eq kg^{-1} CW sold as young bulls. On average, enteric CH_4 was the largest emission source both per unit FPCM and CW, accounting for 0.39 kg CO_2eq kg^{-1} FPCM, 8.34 kg CO_2eq kg^{-1} CW sold as culled cows and heifers, and 6.84 kg CO_2eq kg^{-1} CW sold as young bulls. Variation in the estimated soil N_2O emissions was the source that contributed the most to the total variation among the farms; the difference between the minimum and the maximum levels was estimated to be 0.30 kg kg CO_2eq kg^{-1} FPCM, and 6.43 and 6.49 kg CO_2eq kg^{-1} CW sold as culled cows/heifers and young bulls, respectively. Other GHG emission sources also varied considerably among the farms; similar to the N_2O emissions, higher emissions of enteric CH_4, indirect energy use due to manufacturing of farm inputs, and soil C change all contributed to the higher GHG intensity of some farms. Our study estimates large variation in GHG intensity among dairy farms in Norway and indicates a sensitivity of

the emissions to mitigation measures. Production of milk and beef is a complex biological system, thus mitigation options are likely to be most successful when applied in small steps. Thus, the most valuable contribution of the current work is the framework of an on-farm tool for assessing farm-specific mitigation options of Norwegian dairy and beef production.

1. Introduction

Livestock production has significant environmental impacts including greenhouse gas (GHG) emissions (Standford University, 2010). As assessed by IPCC accounting, animal agriculture is responsible for 8 – 10.8% of global GHG emissions and the emissions are closely related to ruminant numbers, particularly dairy and beef cattle numbers (O’Mara, 2011). There is a growing consensus that global GHG emissions, including those from dairy and beef cattle, will need to be substantially reduced to minimize the risk of unpleasant climate change (Godfray et al., 2011). As the global demand of beef and milk are expected to rise 72% and 82%, respectively, by 2050 compared with 2000 (FAO, 2006), GHG emission intensities (i.e., kg CO_2 equivalents [CO_2eq] per unit of food produced) have to be reduced considerably.

The Norwegian Parliament has set targets that will require a reduction in the nation’s GHG emissions of 15 to 17 Gg of CO_2eq by 2020; a 30% reduction from 1990. The agricultural sector is required to contribute 1.2 Gg of CO_2eq to this reduction, which is more than 20% of the sector’s current emission (Climate and Pollution Agency, 2010). A significant part of the agricultural contribution is to be achieved through reducing the

GHG emissions per unit of milk and beef (The Ministry of Agriculture and Food, 2009). As is the case globally, reduction in milk and beef production is not an option, as the population of Norway is expected to increase, albeit at a slower growth rate (20% increase by 2030; Statistics Norway, 2010) than the global average. Norwegian dairy farms are typically small-scale and combine milk production and bull-finishing. Thus, meat (beef) production is mainly a coproduct of the dairy industry, with culled dairy cows and young dairy bulls representing the major beef sources. More than 95% of the dairy cows are of the dual purpose Norwegian Red breed, a dairy breed in which beef production capacity accounts for about one-tenth of the combined selection index (Ødegard, 2000). The predominant feeds are timothy (*Phleum pratense*) and meadow fescue (*Festuca pratensis*) grass silages complemented by barley (*Hordeum vulgare*) based concentrates.

In general, dairy production is characterized by variation among farms and this variation implies variation in GHG emission intensities (Kristensen et al., 2011; Vellinga et al., 2011). The development and use of simulation models or simpler calculators for estimation of GHG emissions at the farm level has in many countries been useful in detecting tactical mitigation options (i.e., options within a production season that do not require a change of the whole farm strategy) (Shils et al., 2007; Beauchemin et al., 2010; Christie et al., 2011). Similar development and use of a whole farm model for estimating GHG emission intensities from Norwegian dairy and beef production would be helpful in identifying suitable GHG mitigation options. Thus, our objectives were to: (1) develop a whole farm model for estimating GHG emission intensities of milk and meat production that encompasses the farms' natural resource bases and management; (2) estimate the variation in GHG emission intensities of meat and milk production among Norwegian dairy farms; and (3) identify opportunities for mitigating GHG emission intensities of meat and milk production from Norwegian dairy farms to provide insights pertinent to agricultural policy makers in fulfilling the goals of emission reduction as specified by the Climate and Pollution Agency (2010).

2. Materials and methods

In the following section we first describe the model; thereafter, the farm specific operational and natural resource base data are described.

2.1. The whole-farm model

A farm scale model, the HolosNor model, was developed to estimate net GHG emissions from dairy production systems, including soil C changes, on the basis of robust, reliable, and easily available on-farm data. It is an empirical model based on the Holos model (Little et al., 2008) and the methodology of the Intergovernmental Panel on Climate Change (IPCC, 2006) with modifications that recognize the distinctness of Norwegian conditions. The following GHG sources are considered: enteric CH_4 and manure-derived CH_4 and N_2O; on-farm N_2O emissions from soils; off-farm N_2O emissions from N leaching, run-off and volatilization (indirect N_2O emissions); on-farm CO_2 emissions or carbon sequestration due to soil C changes; CO_2 emissions from energy used on-farm; and off-farm CO_2 and N_2O emissions from supply of inputs. All GHG emissions are expressed as CO_2eq to account for the global warming potential of the respective gases given a time horizon of 100 years: CH_4 kg × 25 + N_2O kg × 298 + CO_2 kg × 1 (IPCC, 2007). The GHG emission intensities are reported as kg CO_2eq kg^{-1} fat and protein corrected milk (FPCM) and kg CO_2eq kg^{-1} carcass weight (CW) sold.

Enteric CH_4 emissions are calculated for each class of cattle according to the IPCC (2006) Tier 2 methodology. Daily net energy requirements for cattle at each stage of production are estimated from energy expenditures for maintenance, activity, growth, pregnancy and lactation as appropriate. The gross energy intake required to meet requirements is then estimated taking into account the energy density of the diet and enteric CH_4 emissions are calculated from gross energy intake using the CH_4 conversion factor ($Ym = 0.065$; IPCC, 2006) divided by the energy content of CH_4 (55.64 MJ kg^{-1}) (Table 1). The Ym is adjusted to account for the digestibility of the dietary dry matter (DM) as suggested by Little et al. (2008) and Beauchemin et al. (2010) (Table 1).

Manure management CH_4 emissions estimates are based on volatile solids (VS) production, according to IPCC (2006), taking into account the gross energy intake of the animal and the digestibility of the diet. The VS production is multiplied by a maximum CH_4 producing capacity of the manure ($Bo = 0.24$ m^3 CH_4 kg^{-1} VS for cows and 0.18 m^3 CH_4 kg^{-1} VS for heifers and young bulls), a conversion factor from volume to mass (0.67 kg m^{-3}) and a CH_4 conversion factor specific to the manure management practice (Table 1).

Estimates of direct soil N_2O emissions are based upon the IPCC (2006) emission factor of 0.01 kg N_2O-N $kg^{-1}$of total N input, defined as the sum of N fertilizer applied, grass and crop residual N, and mineralized N (Table 1). The residue N is calculated as the sum of above ground and below ground residue N (Janzen et al., 2003). The mineralised N is derived from an N:C ratio of soil organic matter of 0.1 (Little et al., 2008). The N_2O

emission is strongly affected by soil moisture and temperature conditions (Watts and Hanks, 1978). Relative effects of % water filled pore space of top soil (WFPS) and of soil temperature at 30 cm depth (ts30 ºC) are derived from Sozanska et al. (2002) as described by Bonesmo et al. (2012) (Table 1). The seasonal variation in direct soil N_2O emissions is taken into account by dividing the year into four seasons, spring (April-May), summer (June-August), fall (September-November), and winter (December-March), with their respective values of total N input, WFPS, and ts30. This approach allows for a simple description of the seasonal interaction between the fertilization rate and the current soil moisture and temperature conditions.

Direct N_2O emissions from manure are calculated by multiplying the manure N content by an emission factor for the manure handling system (stored manure, liquid/ slurry with natural crust cover, or deposited on pasture) (Table 1). The manure N is estimated from DM intake (DMI), the crude protein (CP = 6.25 N) content of the diet, and N retention by the animals based on IPCC (2006) and NRC (2000). The DMI and CP where calculated for each animal category based on the feed characteristics and animal requirements.

The indirect soil N_2O emissions due to leaching and runoff are calculated according to IPCC (2006); the leaching fraction is set to 0.3, and the emission factor for leaching and runoff was set to 0.0075 kg N_2O-N kg^{-1} (Table 1). Emissions of N_2O due to volatilisation are calculated using the IPCC (2006) constants of 0.1 for the volatilisation fraction and 0.01 the emission factor (Table 1).

The estimates of soil C change are based upon the Introductory Carbon Balance Model (ICBM) of Andrén et al. (2004). The ICBM is a two-component model, comprising young (*Y*) and old (*O*) soil C, input of total C from crop residues and manure (i), two decay constants (k_1 and k_2; Table 1), a humification coefficient (*h*; Table 1), a farm specific index (re) accounting for the relative effects of soil moisture (r_w) and soil temperature (r_T), and finally a soil cultivation factor (r_c). For the individual farm, the r_w and r_T indices and their product ($r_w \times r_T = r_e$) are all estimated on a daily basis and averaged over the year (cf. section 2.2). The r_c is used to calculate the combined environmental and managerial effect, $r = r_e \times r_c$. The differential equations of Andrén and Kättrer (1997) describing the yearly C fluxes are:

$$\frac{dY}{dt} = i - k_1 rY$$

$$\frac{dY}{dt} = hk_1 rY - k_2 rO$$

As grasslands at the investigated farms had been maintained over several farming generations, the ICBM estimates of soil C change in the 100th year with continuous grass and arable cropping are used. Farm specific data for 2008 are used as inputs for the variables *i* and r_e of the ICBM throughout the 100-year period. A companion study for 2000-2009 confirmed climatic representativeness of the year 2008 (Skjelvåg et al., 2013). The normalised root mean square error, weighted by the number of dairy farms from each region in the present study, was less than five percentage units of the r_e index for 2008.

Direct emissions from diesel fuel and off-farm emissions of the manufacturing and production of farm inputs are estimated using appropriate emissions factor for Norway or Northern Europe (Bonesmo et al., 2012) (Table 1). Emissions related to purchased concentrates are estimated by first calculating the amount of energy and CP they supplied in order to estimate the amount of grain and soybean meal comprised by the concentrates. It is assumed that the grain replaced farm produced grain crops (barley and oats) and that the soybean meal was imported from South America. The emissions for purchased concentrates were then assessed as on-farm emissions from the individual farm's production of barley and oats (including soil N_2O, soil C change, and indirect and direct energy use), and off-farm emissions from the production and import soybean meal (Table 1). If grains are not grown on the farm, then an average emission for barley and oats grown in Norway is used (Bonesmo et al., 2012) (Table 1). Emissions of soil N_2O, soil C change, and indirect and direct energy from excess on-farm feed crop production are, similar to emissions from the farms' food crop production, not included in the total farm emissions related to milk and meat production.

INSERT TABLE 1 HERE

2.2. Farm operational and natural resource base data

The effects of variation in farm management practices on GHG emissions was explored by running the model with data from 30 Norwegian dairy farms for the year 2008. The data set was established by combining individual farm operational data from The Norwegian Farm Accountancy Survey (NILF, 2009) and the Norwegian dairy product cooperative (Tine, 2009) with farm level data for soil characteristics, provided by the Norwegian Forest and Landscape Institute, and farm level weather data for the year 2008 provided by the Norwegian Meteorological Institute. This combination resulted in a consistent farm data set of 30 dairy farms.

The animal related input data were obtained from the Norwegian Farm Accountancy Survey (NILF, 2009) and the Tine (2009) statistics (Table 2). The farms were all in stable production, and thus the yearly average farm specific characteristics and numbers of animals in each class were used as model inputs. Estimates of the time that the animals spent on pasture for each class of cattle were from NILF (2009). The areas (ha) and yields (kg ha^{-1}) of barley, oats, spring and winter wheat were specified in the Norwegian Farm Accountancy Survey (NILF, 2009) (Table 2). The areas and the farmers' estimates of grass silage yields were also available from the accountancy survey. For some farms, however, the farmers' estimated grass silage yields from leys were less than the animals' needs as calculated by our model because the leys also were grazed. In those cases, the individual farm's grass yield was assessed as the calculated animal needs. An additional 10% (DM basis) was added to all estimated grass yields to account for losses due to ensilaging (IGER DOW, 2012) (Table 2). Nine farms also had smaller areas of low productivity native pasture in addition to the grass leys. The DM yields of these pastures were calculated as the difference between total grass DM intake of animals and grass silage DM. The farm specific cost of mineral fertilizer was available from the accountancy survey. The on-farm use of mineral fertilizer was distributed among the crops based on the Norwegian recommendations for N application levels for the various crops; the relative rate of fertilizer application was: barley, 1.0; oats, 0.9; spring wheat, 1.2; winter wheat, 1.5; and grass production, 1.5. Based on these relative rates, the crop areas (ha) and the typical mineral fertilizer types and their prices, the farm specific levels of N, P, and K applied were estimated for the different field crops and the grassland. The farm specific cost of pesticides was available from NILF (2009). The distribution of the pesticide costs to the various crops was calculated using relative weighting factors: barley, 1.00; oats, 0.51; spring wheat, 1.05; winter wheat, 1.71; and grass production, 0.15. These weighting factors were derived from the typical types and mean application rates for each crop by pesticide category (glyphosates, other herbicides, insecticides, fungicides, and growth regulators for cereals) as determined according to a survey conducted in 2008 (Aarstad et al., 2009). From this information, the pesticide energy use (MJ ha^{-1}) was estimated according to Audsley et al. (2009). Farms that received regional payments for maintaining land under reduced tillage are specified in the accountancy survey (NILF, 2009), and from the payments received, the area with reduced tillage was estimated for each farm (Bonesmo et al., 2012). As no straw was sold from the farms (NILF, 2009), all straw was assumed to be left on the field. The farm expenditures for fuel and electricity (NILF, 2009) were distributed to the grassland and field crops according to their respective areas, and the energy use was calculated by dividing by the 2008 average consumer price of electricity (Statistics Norway, 2010) or the 2008 average on-farm price of fuel (BFJ, 2010) (Table 2).

INSERT TABLE 2 HERE

Soil survey records for the 30 farms, 59 to 71ºN, were provided by the Norwegian Forest and Landscape Institute for homogenous soil type mapping units down to 0.4 ha, each with specifications of top soil and subsoil layers. From these records soil moisture capacities were derived by pedotransfer functions of Riley (1996). The 2008 daily weather data from the network of the Norwegian Meteorological Institute were interpolated to each farm's geographical midpoint and altitude (Tveito et al., 2005). From these data, daily values and annual means of $r_w \times r_T$ of ICBM and seasonal values for WFPS and ts30 were calculated (Table 3). A detailed description of the processing of the farm's natural resource base data for field crops is given by Bonesmo et al. (2012). Additional steps for grasslands were: (1) the initial day of grass growth in spring was set to the first day after April 1st that the 7-d mean temperature exceeded 5.0°C; (2) from January 1st to the initial day of growth, leaf area index (LAI) was arbitrarily set to 0.1 and root depth to 10 cm; (3) after the initial day of growth, LAI was calculated from estimates of harvestable herbage DM yield according to the FORPRO model (Torssell and Kornher, 1983), adjusted for the gradual photoperiodic effect on growth cessation during autumn (Wu et al. 2004); (4) initial root depth was set to 10 cm after each harvest and increased linearly with LAI to maximum 70 cm at LAI = 7.0, except for the last harvest when current root depth was retained and increased according to LAI development until day of growth cessation; (5) the first harvest of the spring growth was taken at heading, estimated by the photothermal model of Bonesmo (1999), the second and the third harvests were taken when their estimated DM yields reached 70% of the DM yields of their preceding harvests, respectively.

Three farms in the mountainous areas of Southern Norway and one in Northern Norway had climatic conditions for two harvests only. All farms had estimates of small DM production from the last harvest to growth cessation in fall. Time of end cessation was set to the day when 7-d mean temperature was below 5°C. Thereafter LAI remained at about 0.8.

INSERT TABLE 3 HERE

2.3. *The GHG emissions intensities and sensitivity tests*

The GHG emission intensities were calculated for individual farms by relating the estimated total farm GHG emissions (CO_2eq) to the main products of milk (kg FPCM; Tyrell and Reid, 1965) and meat (kg CW) from culled cows and young bulls. The model estimated enteric CH_4, and manure CH_4 and N_2O for each category of animal: multiparous lactating cows, primiparous cows, non-lactating (dry) cows, heifers < 1 year, heifers > 1 year, finishing bulls < 1 year, finishing bulls > 1 year, and calves. The emissions for each individual class of animal were then assigned to two groups: (1) cows and replacement heifers (includes lactating and non-lactating primi- and multiparous cows and all heifers and calves up to 100 kg liveweight, LW), and (2) finishing bulls > 100 kg LW. The N_2O emissions from soil, CO_2 emissions or sequestration related to soil C change, the CO_2 emissions related to direct and indirect energy use, and the total CO_2eq for purchased feed were distributed to the two animal groups according to the proportions of feed resources consumed by each group. These proportions were calculated based on DMI and the proportions of forage and concentrate in the diet of the groups. The emissions from the calves within group 1 were split between the females and males, with the emissions for the male calves transferred to group 2, which comprised the finishing bulls.

Within group 1 the fraction allocated to milk (AR_{milk}) was determined based on the proportion of the herd's DMI required to supply the net energy required for FPCM production (F_L, kg DMI year^{-1}) relative to the total DMI required to the supply the energy for milk production plus the energy required for pregnancy and weight gain (F_G, kg DMI year^{-1}), similar to the basis for the empirical relationship of IDF (2010) according to Thoma et al. (2012):

$$AR_{milk} = \sum_{\substack{lactating\\herd}} F_L \Bigg/ \left(\sum_{\substack{lactating\\herd}} F_L + \sum_{\substack{beef\\culls}} F_G \right)$$

The calculated AR_{milk} were compared with the allocation ratios (AR) to milk determined by empirical relationships of IDF (2010), in which AR to milk were predicted from the beef milk ratio (BMR) as defined as kg beef (LW) sold per kg FPCM; $AR_{IDF} = 1 - 5.7714 \times BMR$.

To explore causes of variation in the estimated GHG emission intensities among farms, simple linear regressions were calculated between the estimated intensities and the largest sources of emission, selected model input data, and gross margin per kg milk sold (not corrected for fat and protein concentrations) and gross margin per kg CW sold. The gross margins specified for milk production and finishing of young bulls were obtained for the individual farms from Tine (2009). The gross margins were calculated separately for milk production and finishing of young bulls as the gross income minus production costs. The on-farm gross incomes used were exclusive of governmental payments.

A sensitivity analysis was performed to evaluate the impacts of possible errors and changes in selected emission factors perceived to be most important: CH_4 conversion factor (Ym), IPCC (2006) manure N_2O emission factor, IPCC (2006) N_2O emission factor, ICBM yearly rw × rT index for external influence on soil C change, the emission factor for fertiliser manufacturing (DNV, 2010), and the combined direct and indirect emission factor for fuel use. As a base-case for the sensitivity analysis, the farm with the emission intensity closest to the average GHG emission intensity was chosen. By varying one parameter at a time, the emission intensities were re-estimated and related to the base-case output. This approach enabled calculation of sensitivity elasticities expressed as the percentage change in the GHG emission intensities caused by a one percentage change in the selected key model parameters. The sensitivity of AR_{milk}, including its impact on the GHG emission intensities, to level of milk production was calculated for the base-case farm by varying milk production per cow without changing the feed conversion efficiencies for milk production and growth.

3. Results

The average GHG intensities for the 30 dairy farms were estimated as: 1.02 kg CO_2eq kg^{-1} FPCM, 21.67 kg CO_2eq kg^{-1} CW sold as culled cows and heifers, and 17.25 kg CO_2eq kg^{-1} CW sold as young bulls (Table 4). On average, enteric CH_4 contributed most to total GHG emissions; it was the largest source both for milk and meat production, accounting for 0.39 kg CO_2eq kg^{-1} FPCM, 8.34 kg CO_2eq kg^{-1} CW for culled cows and heifers, and 6.84 kg CO_2eq kg^{-1} CW for young bulls. The second largest source was soil N_2O, accounting for 0.21 kg CO_2eq kg^{-1} FPCM, 4.37 kg CO_2eq kg^{-1} CW sold as culled cows and heifers, and 3.08 kg CO_2eq kg^{-1} CW sold as finished young bulls. The total direct emissions from manure were similar in magnitude to soil N_2O emissions. The soil C balance was on average slightly positive (i.e., sequestration). The on-farm emission from fuel use was on average the smallest GHG emission source, accounting for 0.05 kg

CO_2eq kg^{-1} FPCM, 1.09 kg CO_2eq kg^{-1} CW sold as culled cows and heifers, and 0.75 kg CO_2eq kg^{-1} CW sold as finished young bulls. Of the total farm GHG emissions, the direct emissions from animals, including enteric CH_4 and manure CH_4 and N_2O, accounted for about 56% of the estimated emissions.

INSERT TABLE 4 HERE

The calculated AR were close to those estimated using the IDF (2010) equation; for 60% of the farms the deviations were equal to or less than 5% (Fig 1). Thus, the use of the IDF (2010) predicted AR would on average give an estimate of CO_2eq kg^{-1} FPCM close to our estimates using a DMI based calculated AR_{milk}.

INSERT FIG 1 HERE

There was large variation in estimated GHG emission intensities among farms (Table 4). The maximum GHG emission per kg FPCM was 1.7 times higher than the minimum, a difference of 0.56 kg CO_2eq kg^{-1} FPCM. For the GHG emissions per kg CW sold, the maximum levels were three and two times higher than the maximum levels for culled cows/heifers and young bulls, respectively, with differences of 25.5 and 11.2 kg CO_2eq kg^{-1} CW sold, respectively. The variation in the estimated soil N_2O emissions was the source that contributed most to the total variation in GHG emissions among the farms. The difference between the minimum and the maximum levels for soil N_2O emissions was 0.31 kg CO_2eq kg^{-1} FPCM, and 6.44 and 6.48 kg CO_2eq kg^{-1} CW sold as culled cows/ heifers and young bulls, respectively. Soil C change was the second largest cause of variation, with differences between the minimum and the maximum levels of 0.23 kg CO_2eq kg^{-1} FPCM, 6.87 kg CO_2eq kg^{-1} CW sold as culled cows and heifers, and 3.10 kg CO_2eq kg^{-1} CW sold as finished bulls.

In general, higher GHG emissions per kg FPCM could be explained by higher emissions from soil N_2O (regression slope 0.40, $r^2 = 0.55$), soil C loss (regression slope 0.32, $r^2 = 0.49$), and indirect energy use (regression slope 0.18, $r^2 = 0.51$) (Fig 2 A), whereas the variation in enteric CH_4 was not significantly correlated to the variation in total GHG emissions per kg FPCM (regression slope 0.04, $r^2 = 0.06$). The consequence of this is that the proportion of emissions caused by enteric CH_4 was lower at the farms with higher GHG emissions per kg FPCM. Despite the decline in the relative contribution of enteric CH_4 with increased GHG intensity of FPCM, enteric CH_4 emissions remained the highest among sources. Similar trends were estimated for the GHG emission per kg CW sold of finished young bulls (Fig 2 B). The relative increase in emissions from soil N_2O was the highest (regression slope 0.39, $r^2 = 0.54$), followed by indirect energy use (regression slope 0.16, $r^2 = 0.72$), and soil C loss (regression slope 0.14, $r^2 = 0.19$), whereas enteric CH_4 only increased slightly (regression slope 0.05, $r^2 = 0.01$) with increasing GHG emission per kg CW sold as young bulls.

INSERT FIG 2 HERE

Examination of the correlations between selected farm data and the estimated emission intensities per kg FPCM or per kg CW sold as young bulls revealed few strong relationships (Fig 3). There was an increase in GHG emission intensity per kg FPCM with increased use of N fertilizer per ha of grass forage production ($r^2 = 0.16$), but no significant relationship was observed between GHG emission intensity per kg FPCM and milk yield per cow or gross margin per litre of milk. Similar relationships were found for the estimated emission intensities per kg CW sold as young bulls (Fig 3). There was an increasing emission intensity with a higher rate of N fertilizer per ha in grass forage production ($r^2 = 0.28$), whereas no relationship was observed for daily LW gain or gross margin per kg CW sold as young bulls.

INSERT FIG 3 HERE

A farm that had GHG emission intensities close to the mean levels was chosen as a base-case for the sensitivity analysis. The emission intensities of that farm were 1.02 kg CO_2eq kg^{-1} FPCM, 18.65 kg CO_2eq kg^{-1} CW culled cows/heifers, and 20.84 kg CO_2eq kg^{-1} CW young bulls sold; the farm's AR_{milk} was 0.67.

INSERT TABLE 5 HERE

Among the sensitivity elasticities the highest one was in the CH_4 conversion factor (i.e., Ym) (Table 5). Reliable estimates of Ym for a given farm are thus very crucial for the assessment of the farm's GHG emission intensities. Moreover, diets and additives that reduce Ym are therefore effective measures to mitigate the whole farm GHG emission intensities; e.g., a measure that reduces the Ym by 20% reduces the GHG per kg FPCM by 7.4% and the GHG per kg CW young bulls sold by 7.8%. Estimated

GHG per kg FPCM was moderately sensitive to changes in the IPCC (2006) manure N_2O emission factor, IPCC (2006) soil N_2O emission factor, and the ICBM yearly $r_w \times r_T$ index of external influence on soil C change, ranging from 0.10 to 0.17% change in intensity per one percentage change in those parameters. Whereas the error in the $r_w \times r_T$ factor might not be larger than ± 5 %, the range of error of the IPCC (2006) soil N_2O factor is considered to be as large as ± 95%. As the effect of a change in the soil N_2O emission factor in our model is linear, the effect of a ± 95% error can be estimated to cause an error of ± 14.3% in the total GHG emission per kg FPCM. The sensitivity elasticities of the emissions factors related to fuel use and manufacturing were small. A 10% error in one of these factors (i.e., a combined emission factor for fuel of 3.3 instead of 3.0 kg CO_2 per litre or an emission factor for manufacturing of 4.4 instead of 4.0 kg CO_2 per kg N in fertiliser) would increase the GHG emission intensity by 0.4% and 0.5% for FPCM and kg CW of young bulls sold, respectively.

INSERT FIG 4 HERE

There was a non-linear response in the AR_{milk} for changes in the level of milk production (Fig. 4). A 10% increase in herd milk yield gave an increase in the AR_{milk} of 3% accompanied by a decrease in the GHG emissions intensities both for milk and beef by 5% as the emissions related to animal maintenance were distributed to a larger quantity of product.

4. Discussion

The foundation of the HolosNor model presented herein derives from approaches developed by the IPCC for estimating country specific GHG inventories. Further the holistic approach of livestock farms discussed by Janzen (2011) on the basis of the Canadian Holos model has provided inspiration and guidelines. The IPCC approach has been used by most whole farm GHG models of dairy and beef production systems (Crosson et al., 2011). Thus, our results can be compared with the range of estimates of GHG emissions per kg product as presented by Crosson et al. (2011), who summarized the findings of 35 whole farm modelling studies (from 31 published papers) of beef and dairy cattle production systems. However, it must be recognized that there are inevitable differences in quality of farm data, boundaries assumed, emission factors applied and co-production allocation approaches among the studies. The average GHG emission per kg milk reported by Crosson et al. (2011) was 1.02 and the median value was 1.00, which is similar to the average (1.02 kg CO_2eq kg^{-1} FPCM) and median (1.01 kg CO_2eq kg^{-1} FPCM) we report for the 30 Norwegian farms. Of the studies reported by Crosson et al. (2011), those by Cederberg and Stadig (2003) and Casey and Holden (2005) are the most relevant ones for comparison with our results as these studies represent grass-based dairy production systems of north-western Europe, Sweden and Ireland, respectively. Our average GHG is very similar to theirs; 1.05 and 1.08 kg CO_2eq kg^{-1} energy corrected milk [ECM; Tyrrell and Reid, 1965], respectively, for Swedish and Irish milk production. The main difference is that their estimates do not include soil C change. By excluding soil C change from our estimate the average GHG emission per kg FPCM would be 1.05 kg CO_2 eq. The recent study of Vellinga et al. (2011) of 24 grass-based Dutch dairy farms estimated an average of 1.08 kg CO_2eq kg^{-1} milk (not corrected to ECM or FPCM), not including soil C change and without allocation. Similarly, in a study of Danish dairy production the emission intensity of was 1.05 kg CO_2eq kg^{-1} ECM, with allocation to meat and milk (Kristensen et al., 2011). These two European studies were based on actual data from individual farms, similar to our study.

The range of the 35 estimates of emission intensity of milk production reported by Crosson et al. (2011) was from 0.46 to 1.57 kg CO_2eq kg^{-1} milk, a range that is much wider than that estimated for our 30 Norwegian farms (Table 4). However, it must be recognized that studies reported by Crosson et al. (2011) were based on slightly different methodologies than that used in our study and represented different farming systems world-wide, whereas our systems analysis represents grass-based dairy production in northern Europe. Thus, the range of our estimates 0.82 – 1.36 kg CO_2eq kg^{-1} FPCM reflects a considerable mitigation potential for Norwegian dairy farms. This variation in GHG emission intensity is similar to ranges reported by Casey and Holden (2005; 0.92 – 1.51 kg CO_2eq kg^{-1} ECM) for grass-based Irish dairy farms, Vellinga et al. (2011; 0.90 – 1.30 kg CO_2eq kg^{-1} milk) for grass-based Dutch dairy farms; and Kristensen et al. (2011; 0.83 – 1.22 kg CO_2eq kg^{-1} ECM) for grass-maize-based Danish dairy farms.

Few investigations of GHG emission per kg CW of finishing dairy bulls have been undertaken (Crosson et al., 2011); estimates range from 15.6 (Cederberg and Stadig, 2003) to 19.9 kg CO_2 eq kg^{-1} CW (Nguyen et al., 2010). Other estimates of kg CO_2eq per kg CW reported for the finishing of dairy bulls are 15.8 (Williams et al., 2006), and 16.0 and 17.9 (Nguyen et al., 2010). Casey and Holden (2006) estimated kg CO_2eq kg^{-1} LW of the finishing of dairy bulls to range from 7.2 to 11.3 which is similar to those of Nguyen et al. (2010) if scaled to the functional unit of kg CW. None of these estimates included soil C change. The average GHG emissions per kg CW estimated for our Norwegian farms of 17.8 kg CO_2eq kg^{-1} CW, excluding soil C change (Table 4), fits well into the range of those western European estimates. The average over the 31 modelling studies presented by Crosson et al. (2011) was 21.85 kg CO_2eq kg^{-1} CW and the median was 21.57 kg CO_2eq kg^{-1} CW, which is close to the average (21.67 kg CO_2eq kg^{-1} CW) and median (19.79 kg CO_2eq kg^{-1} CW) values for culled cows and heifers for the 30 Norwegian farms (Table 4). Similar to the observation for GHG emission intensities of FPCM, GHG emission intensity of CW is strongly affected by the AR_{milk}. Without any allocation to beef the average GHG emission intensity for FPCM would have been 1.45 kg CO_2eq kg^{-1} FPCM and the GHG emission intensity of CW sold of culled cows and heifers would have been zero, which would have been unreasonable. As the BMR for our farms were out of the range used to establish the empirical relationship used by IDF (2010) we calculated AR_{milk} based on a general method suggested by Thoma et al. (2012). When the empirical relationships of IDF (2010) were extrapolated to include the BMR observed for our farms, our calculated AR_{milk} values were close to that of IDF (2010). This suggests IDF (2010) to be appropriate for Norwegian farms, if such an empirical relationship should be used.

The IDF (2010) allocation approach was used in our study because it has been recommended by the global dairy industry; it was not our intent to develop a new approach. As the Norwegian red cattle is bred as a dual purpose breed (Sodeland et al., 2011), it was necessary to allocate emissions between meat and milk. The dual purpose of the Norwegian red cattle is of importance as meat from dairy herds (males, surplus heifers and culled dairy cows) constitutes as much as 75% of beef production in Norway

(Statistics Norway, 2010). However, it must be recognized that IDF (2010) biophysical approach implies a bias towards allocation of GHG emissions from milk production to beef production from culled cows and heifers. The calculation of AR attributes all the net energy required for pregnancy to beef (for calf development), yet parturition is a prerequisite for lactation. In theory, mitigation of GHG emission per kg milk and beef can be achieved by increasing productivity (i.e., milk yield per cow and year or increased CW per cow and year). For example, based on the responses in Fig. 4 an increase of milk yield by ten per cent would reduce the emission to 0.97 and 16.39 kg CO_2eq kg^{-1} product as FPCM and CW sold as culled cows, respectively. As the milk yield per cow and year is considerably lower in Norway than under similar production systems in Sweden and Finland and the finishing of young dairy bulls on Norwegian farms is far from optimal (Bonesmo and Randby, 2011) mitigation options for both in milk production and beef production from the dairy herds are feasible. However, in a country with milk quotas, as in Norway, an increase in milk yield would result in fewer dairy cows and less calves for beef production. If this loss in beef production were to be replaced by a suckler cow type beef production system, the net result may not actually lower total GHG emissions from Norwegian agriculture. As the variation among the farms was higher for the GHG per kg product for beef production than for milk production (Table 4), a large mitigation potential may be possible for meat production under this system.

Although theoretically, increasing animal productivity should reduce GHG emission per kg milk and beef, studies that use real farm data indicate that this is not always the case. Using farm data, Vellinga et al. (2011) found no reduction in GHG per kg milk when production exceeded 6500 kg milk per cow and year. Similarly, our study showed no significant relationship between milk yield and GHG emission intensity or between daily LW gain and GHG emission intensity (Fig. 3). Contradictory to what was observed at Norwegian crop farms (Bonesmo et al., 2012), no significant relationship between gross margin per unit of product and GHG emission was found for the 30 dairy farms. In crop production, the direct soil N_2O emission is the largest GHG and N fertilizer is the major input factor and cost. Dairy production is more complex and no single input is dominant for the net GHG emissions.

The range of enteric CH_4 emissions (0.36 - 0.45 CO_2eq kg^{-1} FPCM), were within the range of 0.35 – 0.58 CO_2eq kg^{-1} ECM reported for Irish dairy production (Casey and Holden, 2005). Our estimated Ym value for milking cows was on average 0.058 which was considerably higher than that of 0.054 found by Patel et al. (2011) for cows fed with 70% (DM basis) silage of timothy and meadow fescue and 30% barley based concentrate. For the 30 farms in our study, the average percentage of concentrate in the dietary DM was 35%, but the silage qualities used by these farms were lower than that used in the experiments of Patel et al. (2011). Bannink (2011) estimated enteric CH_4 from dairy cows fed grass and concentrate using a dynamic, mechanistic model of the fermentation process in the rumen and large intestine. Based on the result of Bannink (2011), a relationship between enteric CH_4 g per kg FPCM and kg fat corrected milk (FCM) can be derived: $24.12 - 0.386 \times kg^{-1}$ FCM cow^{-1} d^{-1}, $r^2 = 0.90$. Using this equation, our estimates would on average be 7% higher than those we reported using the IPCC (2006) methodology (as adapted by Little et al., 2008 and Beauchemin et al., 2010); average enteric CH_4 production for our farms was 15.61 g CH_4 kg^{-1} FPCM. Taking into account the uncertainty in DMI and the Ym value, and the difference in the approaches, a 7%

divergence is acceptable. The variation in CH_4 emissions among farms demonstrates potential for mitigation. However, as stated by Vellinga et al. (2011) the mitigation options in a complex biological production of milk and beef must be carefully evaluated. For example, using our estimated sensitivity elasticity for the change in Ym, a significant increase in the grass silage digestibility such that Ym reaches the level of those estimated for grass silage by Patel et al. (2011) would reduce the emissions by to 0.97 – 1.01 kg CO_2eq kg^{-1} FPCM and 16.44 – 17.02 kg CO_2eq kg^{-1} CW sold as young bulls depending on the proportion of concentrate fed.

Both the level of, and the variation in, the total N_2O emission among farms were higher in our study than in those reported by others; the ranges of 0.1 – 0.4 kg total N_2O emissions in CO_2eq per kg milk for Dutch farms (Vellinga et al., 2011) and of 0.2 – 0.4 kg total N_2O emissions in CO_2eq per kg ECM for Danish farms (Kristensen et al., 2011) were comparable with the range of the soil N_2O (not including N_2O from manure storage) per kg FPCM for our farms (Table 4). The N fertilizer use per area unit is higher in Norway than in most other European countries (Eurostat, 2011). Yet the high variation in direct N_2O emissions among farms, and also the significant relationship between N fertilizer application per ha and the GHG emission intensities (Fig. 4), suggests options for mitigation. However, the effect of a reduction in N fertilization rate is hard to predict as it depends on how close the farm is to optimum N use (Vellinga et al., 2011). Using our method for estimating farm specific soil N_2O emissions (Table 1), the estimates were 2% lower than using the IPCC emission factor of 0.01 kg N_2O kg^{-1} N supplied to soil. The soils were cold, lowering the N_2O emissions, and wet, increasing the N_2O emission, such that the multiplicative soil moisture and temperature index of the farms was on average 0.95, ranging from 0.78 in winter to 1.12 in summer, resulting in a 2% lower estimate compared with use of the IPCC emission factor because more N was supplied to the soil in summer than in winter. Although the average impact was small, the farm specific impact was significant; the farm specific index ranged from 0.73 to 1.14.

Emissions of CH_4 and N_2O from manure storage were together the third largest source (Table 4). Using our approach (Table 1), estimates of CH_4 emissions from manure storage were 4% higher than if estimated using the emission factor (average annual rate) of Sommer et al. (2004), and the estimates of manure N_2O emissions were 1% lower than had the emission factor of Hansen et al. (2006) been used. As the work of Sommer et al. (2004) and Hansen et al. (2006) are specific to manure management emissions including measurements and the development of detail models, it is reassuring that our estimates are close to those obtained by using the recommendations from their works. Further, the average (0.18 kg CO_2eq kg^{-1} FPCM) and range (0.13 - 0.23 kg CO_2eq kg^{-1} FPCM) of manure related emissions were comparable with those of Irish dairy production (Casey and Holden, 2005); average 0.22 and range 0.16 – 0.35 kg CO_2eq kg^{-1} ECM.

By integrating the ICBM model of Andrén et al. (2004) into our model, soil C change of the individual farms could be estimated (Table 4, Fig. 2). Use of the ICBM factors for ley was appropriate in our study because the ICMB factors refer to a classical Scandinavian grass-crop rotation of only a few years in length (usually 2 to 6 years with grass). In the current study, farms that had perennial grass production only had soil C gain accounting for -0.08 kg CO2 eq per kg FPCM, whereas for the farms that also grew crops (annual grain crops) had soil C loss accounting for 0.01 kg CO_2 eq per kg FPCM ($p < 0.01$). On average, soil C change for the farms in our study was close to zero, which corresponds to equilibrium, and was due to the assumption of continuous grass or crop-grass rotation for 100 years. Thus, the variation among farms was mostly caused by the weather conditions of the specific year. Based on similar assumptions, most other studies do not include soil C change (Crosson et al., 2011) although the steady-state concept for soil C for farms growing grass has been questioned (e.g., Soussana et al., 2007).

On-farm emissions due to use of fuel was the smallest source (Table 4). The estimated average of 0.05 and range of 0.01 - 0.14 kg CO_2 kg^{-1} FPCM was similar to that of Irish dairy production (Casey and Holden, 2005: average 0.1 and range 0.06 - 0.15 kg CO_2 kg^{-1} ECM). Although the lowest emission source, fuel use per kg FPCM is not unimportant as it is consumption of a non-renewable energy source.

5. Conclusion

The study estimated large variation in GHG emission intensity among dairy farms in Norway (0.82-1.36 kg CO_2eq kg^{-1} FPCM and kg 11.75-22.90 CO_2eq kg^{-1} CW young bulls), and further it indicated a sensitivity of the emissions to mitigation measures. Application of tactical mitigation options (i.e., options tailored to the strategy of a specific farm) to lower GHG emission intensity of meat and milk production assumes a significant variation within the production system. Thus, estimating this variation is considered more important than exact quantification of an average GHG emission intensity of dairy farming as such.

Production of milk and beef is a complex biological system, and mitigation measures invariably involve trade-offs at the farm level. These trade-offs may not be accounted for in single sensitivity analyses. Therefore, mitigation options are likely to be most successful when introduced gradually. Accordingly, we conclude that rather than focusing on single measures, a holistic system approach, based on the distinctness of each production system, is needed.

The HolosNor model takes into account the interactions between the farm's natural resource base and its management. Thus, the most valuable contribution of the current work is the framework of an on-farm tool for assessing farm-specific mitigation options of Norwegian dairy and beef production.

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Table 1.

Sources of GHG emissions, emission factors or equation used, and reference source.

Gas/source	Emission factor/ equation	Reference
Methane		
Enteric fermentation	(0.065/ 55.64) kg CH_4 (MJ gross energy intake)$^{-1}$	IPCC (2006)
Relative effect of digestiblity (DE %) of feed	1.769 - 0.01231 × DE	Little et al. (2008)[a], Beauchemin et al. (2010)[a]
Stored manure, liquid/ slurry with natural crust cover	(0.67 × 0.24 × 0.10) kg CH_4 (kg volatile solids)$^{-1}$	IPCC (2006)
Pasture manure	(0.67 × 0.24 × 0.01) kg CH_4 (kg volatile solids)$^{-1}$	IPCC (2006)
Direct nitrous oxide		
Soil N inputs (includes land applied manure, grass and crop residue, synthetic N fertilizer, mineralized N)	0.01 kg N_2O-N (kg N)$^{-1}$	IPCC (2006)
Relative effect of soil water filled pore space (WFPS mm)	0.4573 + 0.01102 × WFPS	Sozanska et al. (2002)[b], Bonesmo et al. (2012)[b]
Relative effect of soil temperature at 30 cm (ts30 ºC)	0.5862 + 0.03130 × ts30	Sozanska et al. (2002)[b], Bonesmo et al. (2012)[b]
Stored manure, liquid/ slurry with natural crust cover	0.005 kg N_2O-N (kg N)$^{-1}$	IPCC (2006)
Pasture manure	0.02 kg N_2O-N (kg N)$^{-1}$	IPCC (2006)
Indirect nitrous oxide		
Soil N inputs (includes land applied manure, grass and crop residue, synthetic N fertilizer, mineralized N)	Leaching: 0.0075 kg N_2O-N (kg N)$^{-1}$, $Frac_{leach}$ 0.3	IPCC (2006), Little et al. (2008)[c]
	Volatilization: 0.01 kg N_2O-N (kg N)$^{-1}$, $Frac_{volatilization}$ 0.1	IPCC (2006)
Stored manure, liquid/ slurry with natural crust cover	Leaching: 0.0075 kg N_2O-N (kg N)$^{-1}$, $Frac_{leach}$ 0	IPCC (2006)
	Volatilization: 0.01 kg N_2O-N (kg N)$^{-1}$, $Frac_{volatilization}$ 0.4	IPCC (2006)
Pasture manure	Leaching: 0.0075 kg N_2O-N (kg N)$^{-1}$, $Frac_{leach}$ 0.3	IPCC (2006), Little et al. (2008)[c]
	Volatilization: 0.01 kg N_2O-N (kg N)$^{-1}$, $Frac_{volatilization}$ 0.2	IPCC (2006)
Soil C change		
Young soil C decomposition rate	0.8 year^{-1}	Andrén et al. (2004)
Old soil C decomposition rate	0.007 year^{-1}	Andrén et al. (2004)
Humification coefficient of grass and crop residue	0.13	Kätterer et al. (2008)
Humification coefficient of cattle manure	0.31	Kätterer et al. (2008)
Direct energy		
Diesel fuel use	2.6 kg CO_2 litre^{-1}	Raux (2010)
Off-farm emissions		
Manufacturing N-based synthetic compound fertilizer	4 kg CO_2 eq (kg N)$^{-1}$	DNV (2010)
Manufacturing pesticides	0.069 kg CO_2 eq (MJ pesticide energy)$^{-1}$	Audsley et al. (2009)
Manufacturing silage additives	0.72 kg CO_2 eq (kg CH_2O_2)$^{-1}$	Flysjö et al. (2008)
Production of diesel fuel	0.4 kg CO_2 eq litre^{-1}	Ökoinst (2010)
Production of electricity	0.11 kg CO_2 eq kWh^{-1}	Berglund et al. (2009)
Purchased soya meal	0.93 kg CO_2 eq (kg DM)$^{-1}$	Dalgaard et al. (2008)
Purchased barley grain	0.62 kg CO_2 eq (kg DM)$^{-1}$	Bonesmo et al. (2012)

[a] Equation based on Little et al. (2008) and Beauchemin et al. (2010)

[b] Equation derived by Bonesmo et al. (2012) using data from Sozanska et al. (2002)

[c] Value simplified from equation given by Little et al. (2008)

Table 2.

Animal, crop and fuel usage data for the 30 Norwegian dairy farms used to estimate GHG emissions intensities.

Farm characteristics, units	n	Mean	Range [min, max]	Source of farm specific data
Dairy, beef [a]				
Milk, yield, kg raw milk year^{-1}	30	150517	[39636, 24393]	NILF (2009), Tine (2009)
Milk, fat content, %	30	4,11	[3.75, 4.38]	Tine (2009)
Milk, protein content, %	30	3,40	[3.28, 3.58]	Tine (2009)
Cows heifers, CW culled incl. sold live animals, kg year^{-1}	30	3398	[815, 5860]	NILF (2009), Tine (2009)
Cows heifers, number culled incl. sold loss -bought, year^{-1}	30	11	[0, 25]	NILF (2009), Tine (2009)
Cows, average number, year^{-1}	30	25	[9, 38]	NILF (2009), Tine (2009)
Cows, average final LW, kg	30	539	[435, 619]	NILF (2009), Tine (2009)
Cows, concentrate total, kg DM year^{-1}	30	44280	[16130, 89955]	Tine (2009)
Cows, time on pasture, %	30	30	[13, 44]	NILF (2009)
Heifers, average number, year^{-1}	30	25	[5, 44]	NILF (2009), Tine (2009)
Heifers, concentrate total, kg DM year^{-1}	30	6575	[1125, 17745]	Tine (2009)
Heifers, time on pasture, %	30	17	[0, 53]	NILF (2009)
Young bulls, number slaughtered, year^{-1}	18	19	[8, 56]	NILF (2009), Tine (2009)
Young bulls, average final LW, kg	18	586	[248, 674]	NILF (2009), Tine (2009)
Young bulls, averag slaughter age, months	18	18	[6.5, 22.5]	NILF (2009), Tine (2009)
Young bulls, concentrate total, kg DM year^{-1}	18	23895	[7000, 55735]	Tine (2009)
Energy, direct usage				
Fuel, litre year^{-1}	30	5495	[1685, 12980]	NILF (2009)
Electricity, kWh year^{-1}	30	42990	[14675, 107410]	NILF (2009)
Grass silage				
Silage yield, kg DM year^{-1}	30	164245	[37586, 386174]	NILF(2009)
Silage nutritve value, MJ NE$_L$ kg^{-1} DM	30	5,87	[5.59, 6.00]	Tine (2009)
Silage additive, kg CH_2O_2 year^{-1}	30	770	[0, 2450]	NILF (2009)
Ley area, ha	30	30	[10, 57]	NILF (2009)
Ley synthetic fertilzer, kg N ha^{-1}	30	100	[0, 215]	NILF (2009)
Ley pesticide, MJ ha^{-1}	30	40	[0, 290]	NILF (2009)
Crops [b]				
Barley area, ha	15	12	[2, 60]	NILF (2009)
Barley yield, kg DM ha^{-1}	15	3330	[1390, 5730]	NILF (2009)
Barley synthetic fertilizer, kg N ha^{-1}	15	60	[0, 120]	NILF (2009)
Barley reduced tilllage, ratio	15	0,7	[0, 1]	NILF (2009)
Barley pesticide, MJ ha^{-1}	15	144	[0, 356]	NILF (2009)
Oats area, ha	4	5	[2, 12]	NILF (2009)
Oats yield, kg DM ha^{-1}	4	3670	[2550, 4330]	NILF (2009)
Oats synthetic fertilizer, kg N ha^{-1}	4	57	[0, 80]	NILF (2009)
Oats reduced tillage, ratio	4	0,8	[0.6, 1.0]	NILF (2009)
Oats pesticide, MJ ha^{-1}	4	144	[0, 268]	NILF (2009)
Spring wheat area, ha	8	10	[3, 25]	NILF (2009)
Spring wheat yield, kg DM ha^{-1}	8	3760	[2460, 5620]	NILF (2009)
Spring wehat synthetic fertilizer, kg N ha^{-1}	8	100	[20, 140]	NILF (2009)
Spring wheat reduced tillage, ratio	8	0,8	[0.4, 1.0]	NILF (2009)
Spring wheat pesticide, MJ ha^{-1}	8	180	[0, 280]	NILF (2009)
Winter wheat area, ha	2	7	[6, 8]	NILF (2009)
Winter wheat yield, kg DM ha^{-1}	2	5040	[3970, 6130]	NILF (2009)
Winter wheat synthetic fertilzer, kg N ha^{-1}	2	125	[125, 125]	NILF (2009)
Winter wheat pesticide, MJ ha^{-1}	2	427	[374, 481]	NILF (2009)
[a] 18 of the 30 farms finished bulls				
[b] 17 of the 30 farms grew field crops				

Table 3.

Natural resource data for the 30 Norwegian dairy farms used to estimate GHG emissions intensities.

Farm characteristics, units	Grassland			Field crops		
	n	Mean	Range [min, max]		Mean	Range [min, max]
Soil temperature at 30 cm depth[a], winter, °C	30	0.7	[-0.9, 3.4]	17	0.7	[-0.3, 2.0]
Soil temperature at 30 cm depth, spring, °C	30	6.3	[2.7, 8.8]	17	7.3	[5.8, 9.4]
Soil temperature at 30 cm depth, summer, °C	30	14.3	[10.0, 16.6]	17	15.1	[13.6, 16.7]
Soil temperature at 30 cm depth, fall, °C	30	6.2	[3.7, 9.0]	17	6.3	[5.0, 8.3]
Water filled pore space[b], winter, %	30	74	[59, 86]	17	76	[65, 86]
Water filled pore space, spring, %	30	61	[45, 75]	17	65	[56, 78]
Water filled pore space, summer, %	30	55	[33, 70]	17	61	[53, 72]
Water filled pore space, fall, %	30	72	[47, 84]	17	76	[62, 85]
$r_w \times r_T$ yearly[c], dimensionless	30	1.41	[0.80, 1.90]	17	1.60	[1.34, 2.03]
Soil organic C, Mg ha^{-1}	30	71.3	[40.3, 99.5]	17	71.9	[55.8, 97.6]

[a] Estimated according to Kätterer and Andrén (2009)

[b] Estimated according to Bonesmo et al. (2012)

[c] Estimated according to Andrén et al. (2004)

Table 4.

Mean, minimum, and maximum values of GHG emission intensities, expressed as kg CO_2eq kg^{-1} fat and protein corrected milk (FPCM) and kg CO_2eq kg^{-1} carcass weight (CW), for culled cows/heifers and for young bulls based on data from 30 Norwegian dairy farms in 2008. Values less than 0 indicate removal from the atmosphere (i.e., soil C gain).

	GHG emissions, kg CO_2 eq kg^{-1} FPCM		GHG emissions, kg CO_2 eq kg^{-1} CW culled cows and heifers		GHG emissions, kg CO_2 eq kg^{-1} CW finished young bulls	
	Mean	Range [min, max]	Mean	Range [min, max]	Mean	Range [min, max]
Total GHGs	1.02	[0.82, 1.36]	21.67	[12, 37.46]	17.25	[11,75, 22.90]
Enteric CH_4	0.39	[0.36, 0.45]	8.34	[5.05, 15.44]	6.84	[4.12, 8.06]
Manure CH_4 N_2O	0.18	[0.13, 0.23]	3.89	[2.62, 7.48]	2.98	[2.21, 3.59]
Soil N_2O	0.21	[0.11,0.41]	4.37	[1.84, 8.27]	3.08	[0.29, 6.78]
Soil C change	-0.03	[-0.14, 0.10]	-0.82	[-4.79, 2.08]	-0.51	[-1.64, 1.45]
Off-farm barley, CO_2 eq	0.06	[0.00, 0.13]	1.33	[0.00, 3.93]	1.26	[0.00, 4.11]
Off-farm soya, CO_2 eq	0.09	[0.00, 0.17]	2.08	[0.00, 5.00]	1.88	[0.00, 5.22]
Indirect energy, CO_2 eq	0.07	[0.00, 0.14]	1.39	[0.10, 3.01]	0.97	[0.09, 1.99]
Direct energy, CO_2	0.05	[0.01, 0.11]	1.09	[0.33, 3.42]	0.75	[0.19, 1.45]

Table 5.

Sensitivity elasticities (%) for the effect of one percentage change in selected emission factors on the GHG emission intensities, kg CO_2eq kg^{-1} FPCM and kg CO_2eq kg^{-1} CW sold, young bulls.

Emission factor (EF)	Response	% change in kg CO_2eq kg^{-1} FPCM by 1% change in EF	% change in CO_2eq kg^{-1} CW sold, young bulls by 1 % change in EF
Enteric CH_4 conversion factor, Ym	Linear	0.37	0.39
Manure N_2O EF	Linear	0.10	0.04
IPCC soil N_2O EF	Linear	0.15	0.17
Soil C change external factor, $r_w \times r_T$	Non-linear[a]	0.17	0.19
Manufacturing fertilizer EF	Linear	0.04	0.05
Fuel combined EF	Linear	0.04	0.05

[a] Mean sensitivity elasticity (%) for the change +/- 10% of $r_w \times r_T$

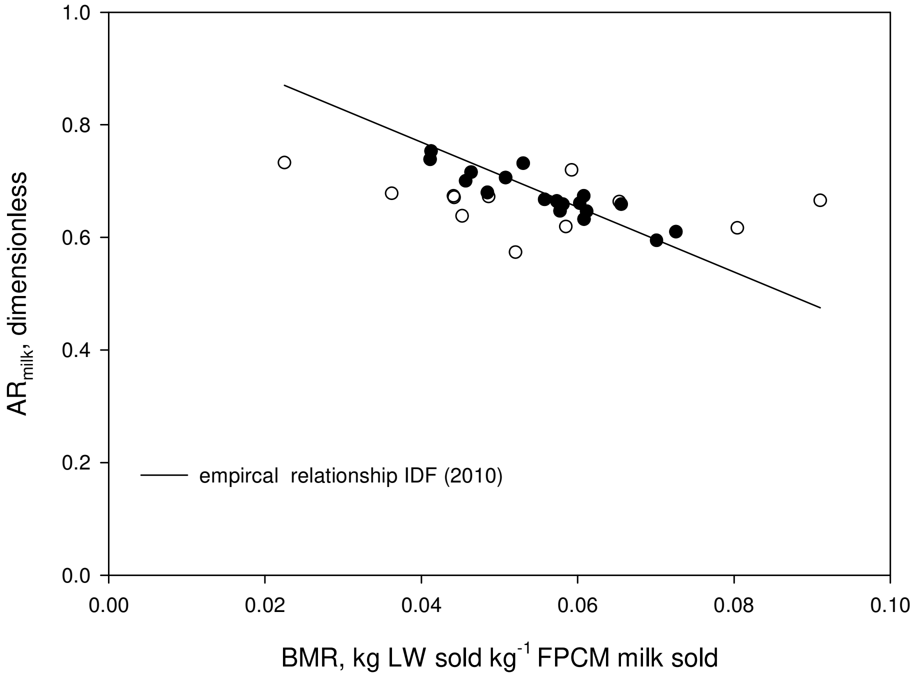

Fig 1. Calculated feed based ratios for allocation (AR_{milk}) of GHG emissions to milk (closed and open symbols) compared with empirical beef milk ratio (BMR) estimated AR for 30 Norwegian dairy farms. Closed symbols represent AR_{milk} less or equal to 5% deviation from the IDF (2010) equation.

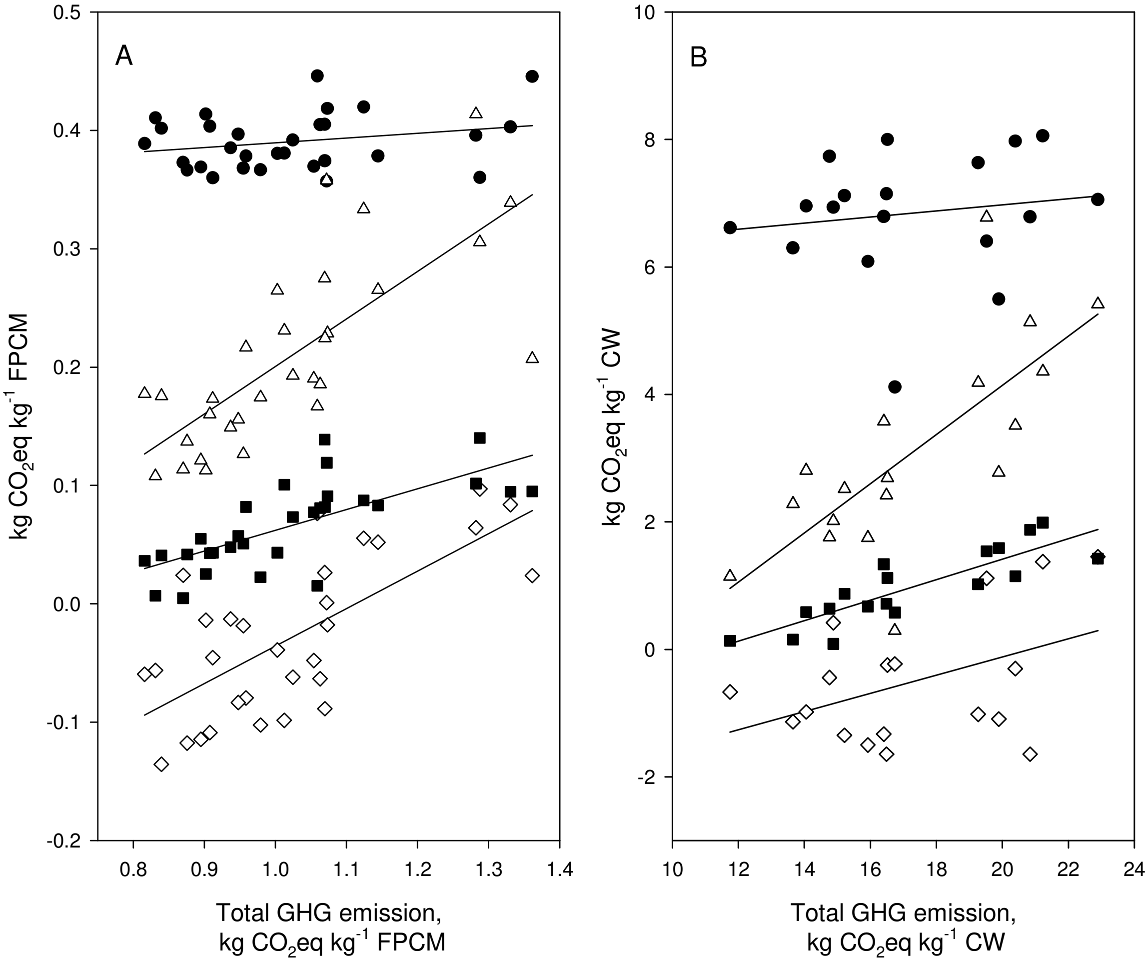

Fig 2. Relationships between estimated sources of GHG emission and total GHG emission as kg CO_2eq kg^{-1} FPCM (A) and kg CO_2eq kg^{-1} CW sold as young bulls (B) based on a data set for 30 dairy farms; closed circles enteric CH_4, open triangles soil N_2O, closed squares indirect energy, open diamonds soil C change, solid lines indicate trends. Values less than 0 indicate removal from atmosphere (i.e., soil C sequestration).

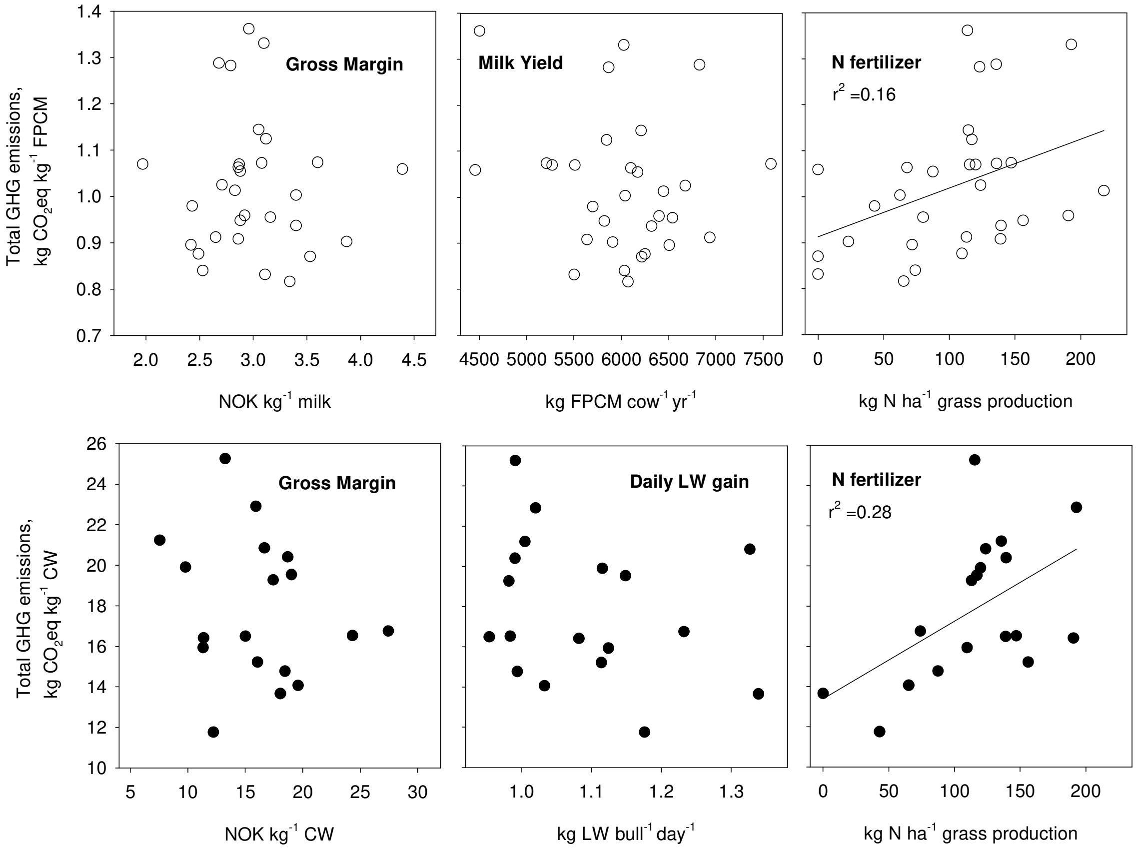

Fig 3. Relationships between estimated GHG emission intensities as kg CO$_2$eq kg^{-1} FPCM (open circles) and kg CO$_2$eq kg^{-1} CW sold as young bulls (closed circles) in data from 30 dairy farms: economic efficiency as the gross margin (NOK kg^{-1} FPCM and NOK kg^{-1} CW), production intensity (kg milk yield cow^{-1}, daily LW gain bull^{-1} d^{-1}); and grassland N fertilization rate (kg N ha^{-1}). Solid lines indicate trends.

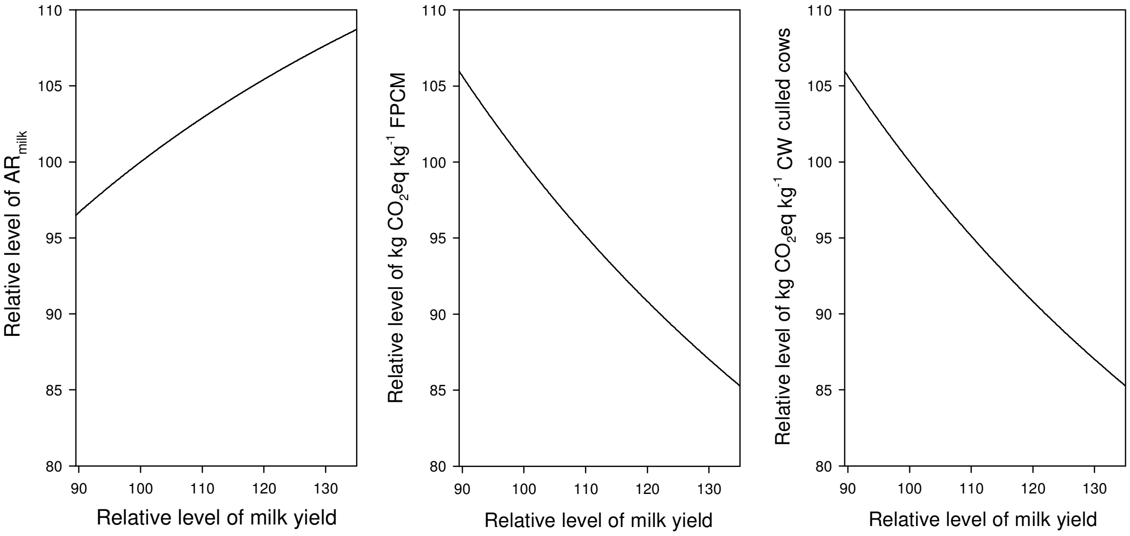

Fig 4. The sensitivity of AR$_{\text{milk}}$, including its impact on the GHG emission intensities, to level of milk production calculated by varying milk production per cow without changing the efficiencies for milk production and growth.