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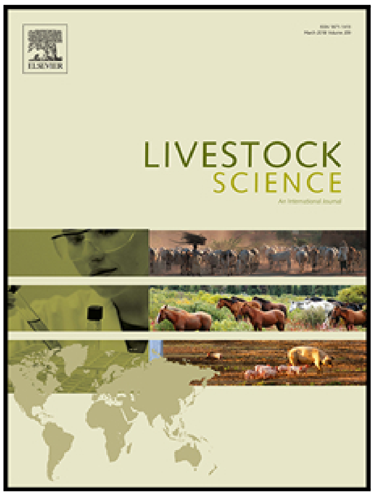

Variability in greenhouse gas emission intensity of semi-intensive suckler cow beef production systems

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Research highlights

- The whole-farm GHG model HolosNorBeef was used to estimate the variability of GHG emission intensity of Norwegian suckler cow beef production
- Enteric CH_4 was the largest source of total GHG emissions
- Soil C was the largest source of variation between individual farms
- When excluding soil C, the farms within region East and North re-ranked in terms of GHG emission intensity

Variability in greenhouse gas emission intensity of semi-intensive suckler cow beef production systems

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Abstract

Emission intensities from beef production vary both among production systems (countries) and farms within a country depending upon use of natural resources and management practices. A whole-farm model developed for Norwegian suckler cow herds, HolosNorBeef, was used to estimate GHG emissions from 27 commercial beef farms in Norway with Angus, Hereford, and Charolais cattle. HolosNorBeef considers direct emissions of methane (CH_4), nitrous oxide

(N_2O) and carbon dioxide (CO_2) from on-farm livestock production and indirect N_2O and CO_2 emissions associated with inputs used on the farm. The corresponding soil carbon (C) emissions are estimated using the Introductory Carbon Balance Model (ICBM). The farms were distributed across Norway with varying climate and natural resource bases. The estimated emission intensities ranged from 22.5 to 45.2 kg CO_2 equivalents (eq) (kg carcass)$^{-1}$. Enteric CH_4 was the largest source, accounting for 44% of the total GHG emissions on average, dependent on dry matter intake (DMI). Soil C was the largest source of variation between individual farms and accounted for 6% of the emissions on average. Variation in GHG intensity among farms was reduced and farms within region East, Mid and North re-ranked in terms of emission intensities when soil C was excluded. Ignoring soil C, estimated emission intensities ranged from 21.5 to 34.1 kg CO_2 eq (kg carcass)$^{-1}$. High C loss from farms with high initial soil organic carbon (SOC) content warrants further examination of the C balance of permanent grasslands as a potential mitigation option for beef production systems.

Keywords

Beef cattle; greenhouse gas emissions; farm scale model; regional differences; soil carbon; suckler cow production

1. Introduction

Globally, the agricultural sector accounts for 10-12% of greenhouse gas (GHG) emissions (Tubiello et al., 2014) with livestock production contributing a significant portion. It is estimated that food production will need to increase by 50% compared with 2012 levels to feed the global population in 2050 (FAO, 2017). As a consequence, beef consumption is expected to increase in both developed and developing countries (OECD/FAO, 2018) and, thus greenhouse gas (GHG) emissions from beef production are also likely to increase.

Beef products have been shown to have a relatively high GHG emission per kg food (Mogensen et al., 2012). However, there is substantial variation in emission intensities among countries (Gerber et al., 2013), and among farms within a country (Bonesmo et al., 2013). This variation in GHG intensity is partly due to methodological differences among studies, but fundamental differences in natural resource availability and farm management practices also contribute significantly (Alemu et al., 2017a; White et al., 2010). Exploring differences between farm systems in GHG intensity may help identify beef production systems and practices that are more efficient, which could lead to the development of mitigation options at farm level. Hristov et al., (2013) reviewed different management practices such as diet formulation, feed supplements, manure management, improved reproductive performance, and enhanced animal productivity to reduce GHG emissions from ruminant production and showed potential long term mitigating effects.

Globally, approximately 44% of livestock GHG emissions are in the form of CH_4 (Gerber et al., 2013). In Norway, enteric CH_4 accounts for 44-48% of total farm emissions from beef cattle production systems (Samsonstuen et al., 2019). The diet influences CH_4 emissions through the digestibility and fibre content of the feed. A high proportion of fiber in the diet yields a higher acetic:propionic acid ratio in rumen fluid, which leads to higher CH_4 emissions (Sveinbjörnsson, 2006). Enteric CH_4 emissions can be lowered through improved feed quality, use of inhibitors and by breeding animals for lower emissions (Difford et al., 2018).

Legesse et al. (2011) investigated the effect of management strategies for summer and winter feeding and found a 3 to 5% difference in CH_4 emissions across production systems. Concentrate-based beef production systems show lower GHG intensity compared with roughage based systems (de Vries et al., 2015). However, to ensure future food supply, grasslands less suitable for crop production might be preferred over highly productive cropland for production of feed for beef cattle. Beef production in Norway relies on use of pasture and forages because the total land in Norway is 90% “outfields” (i.e. rough grazing in forest, mountain and coast areas), with half the outfield area suitable as pastures or for forage production (Rekdal, 2014). According to Norwegian laws and regulations, all cattle must be kept on pasture for at least 8 weeks during the summer (Landbruks- og Matdepartementet., 2004). Grasslands have a large potential of storing C in plant biomass and soil organic matter through C sequestration (Wang et al., 2014). Grazing management influences the GHG emission intensity from beef production through diet quality (McCaughey et al., 2010), animal performance (Thornton and Herrero, 2010), nitrogen (N) fertilizer use (Merino et al., 2011), and soil C change (Alemu et al., 2017b). The effect of grazing management and stocking rate on C balance have been investigated by a number of studies (Reeder and Schuman, 2002; Soussana et al., 2007; Wang et al., 2014). Reeder and Schuman (2002) found significantly greater soil C content with light to moderate stocking rates compared with no grazing due to a more diverse plant community with fibrous rooting systems. Soussana et al. (2007) reported that managed grasslands in Europe are likely to act like atmospheric C sinks. However, when the study included C exports through grazing and harvesting and related emissions of CH_4 and N_2O, total GHG emissions from grazed European grasslands were not significantly different from zero. Alemu et al. (2017b) concluded that a whole-farm approach is important to evaluate the impacts of changes in farm management aimed at decreasing the environmental impact of beef production systems. Yet, soil C is not included in most whole-farm GHG studies (Crosson et al., 2011).

Samsonstuen et al. (2019) developed a whole farm model, HolosNorBeef, adapted to Norwegian conditions and estimated GHG emission intensities for average Norwegian beef cattle farms in two distinct geographical locations (low altitude flatlands suitable for grain production and high altitude mountains not suitable for grain production). The emission intensities in flatlands and mountains were 29.5 and 32.0 kg CO_2 eq kg^{-1} carcass for British breeds, and 27.5 and 29.6 CO_2 eq kg^{-1} for Continental breeds, respectively. However, the use of average farm scenarios did not account for variation in production systems, differences in resource base, breed differences, management practices, selection strategies, feed composition and feed quality that typically prevail among farms.

Thus, the aim of this study was to use the HolosNorBeef model to evaluate commercial herds of Aberdeen Angus, Hereford, and Charolais cattle in geographically different regions of Norway with different management practices, resources, and quality of feed available to establish the variability in emission intensities and corresponding soil carbon (C) balance from suckler cow beef production under Norwegian conditions.

2. Materials and methods

This analysis was based on a study of suckler cow efficiency and genotype × environment interactions. The project (Optibeef - Increased meat production from beef cattle herds) gathered comprehensive information from 2010 to 2014 on farm structure, herd management, animal production and economics for suckler cow herds with the breeds Aberdeen Angus (AA), Hereford (H) and Charolais (CH). To be included in the study the farms had to record a minimum of 60% of weaning weights (WW) and have a minimum of 10 purebred cows per herd. The requirements were met by 188 herds, and 27 farms (nine of each of the three breeds) were finally selected based on variety in geographical locations. The farms provided sufficient information to quantify whole-farm GHG emissions. Through market regulation and subsidies, farmers are encouraged to buy concentrates and sell grains produced on farm, rather than using it as feed in livestock production (LMD, 2018). Hence, other production enterprises on the farms not related to the cow-calf operation, such as production of natural resources, use of farm inputs (i.e. area, fertilizer, and pesticides) for grain production, ley area for horses, and finishing of calves not born on the farm, was excluded from the analysis.

The farms were distributed across Norway from Rogaland in the South to Troms in the North within climatic zones varying from 3 (good) to 8 (harsh) on the scale developed by the Norwegian Meterological Insitute and Det norske hageselskap (2006). The farms had a wide range of farm characteristics such as herd size, management practices, resource base and areas available for forage production. Thus, the farms were considered representatives of the broad spectrum of suckler cow farms in Norway.

2.1 Farm characteristics

The input data were farm specific production data, farm operational data and soil and weather data for the specific locations. The farm specific animal production data from the period 2010-2014 were obtained from the Norwegian Beef Cattle Recording System (Animalia, 2017; Table 1). Calving typically occurred in the period January-July, with an average calving date April 1st. However, three farms had a small proportion of the cows (0.18-0.41) calving during the autumn, with an average calving date October 1st.

The feeding of each group of cattle throughout the year including type and proportion of concentrates, forage type and quality and time spent on pasture, were available through interviews with the respective farmers. The nutritive values of all forages, concentrates, and pastures (Table 2) were estimated using laboratory analysis information for the specific municipalities (Eurofins, Moss, Norway), information from the two largest feed manufacturers in

Norway (Felleskjøpet SA, Oslo Norway; Norgesfor AS, Oslo Norway) and from the chemical composition of forage, grains and pasture (NMBU and Norwegian Food Safety Authority, 2008).

The manure was assumed to be deposited on pasture during the grazing period and during housing the manure handling system was deep bedding, solid storage or a combination set according to the management practices on the specific farm. All manure collected through the housing period was used for fertilizing ley areas. The areas (ha) and yields (kg ha^{-1}) of forage and use of fertilizers (kg N ha^{-1}; Table 3), were obtained through interviews with the farmers and the farm accounts. However, two farms had no grass silage production on the farm and buy grass silage from farms within the same area. Thus, the forage yield of the individual farms was assessed as the calculated forage requirement plus an additional 10% (DM basis) to account for losses due to ensilaging (DOW, 2012). The areas required for forage production on these specific farms were estimated based on yield statistics for the specific area (Statistics Norway, 2017) and the use of fertilizers was based on the Norwegian recommendations for N application levels for forage production (NIBIO, 2016).

The use of energy, fuel, and pesticides was calculated based on information from the respective farm accounts (Table 3). For each of the individual farms a cultivation factor ($r_w \times r_T$) was calculated based on annual mean indices of soil temperature (r_T) and soil moisture (r_w) according to Skjelvåg et al. (2012; Table 4). The cultivation factor was used together with initial soil C content in the Introductory Carbon Balance Model (ICBM; Andrén et al., 2004) to account for external effects such as soil moisture and temperature, and variation in resource base. Water filled pore space (WFPS) and soil temperature at 30 cm depth (ts30) for each individual farm were used for estimation of N_2O emissions. WFPS to saturation was calculated according to Skjelvåg et al. (2012) using detailed soil-type recordings available through NIBIO, whereas ts30 was calculated based on air temperature according to Kätterer and Andrén (2009). Due to expansion of the herd and/or sales of breeding stock, the herd size was not stable in most of the farms. Thus, carcass production assuming a constant herd size was calculated based on the corresponding replacement rate, farm specific slaughter weights, and dressing percentages from culled cows, surplus heifers and finishing bulls. Bulls not born on the farm were excluded as they were purchased and sold for breeding purposes, and did not contribute to carcass output.

2.2. Modelling GHG emissions

2.2.1 The HolosNorBeef model

The GHG emissions were estimated using HolosNorBeef developed by Samsonstuen et al. (2019). HolosNorBeef is an empirical model based on the HolosNor model (Bonesmo et al., 2013), BEEFGEM (Foley et al., 2011), HOLOS (Little et al., 2008), and the Tier 2 methodology of the Intergovernmental Panel on Climate Change (IPCC, 2006) modified for suckler beef production systems under Norwegian conditions. The model estimates the GHG emissions on an annual time step for the land use and management changes and on a monthly time step for animal production, accounting for differences in diet, housing, and climate. HolosNorBeef estimates the whole-farm GHG emissions by considering direct emissions of methane (CH_4) from enteric fermentation and manure, nitrous oxide (N_2O) and carbon dioxide (CO_2) from on-farm livestock production including soil carbon (C) changes, and indirect N_2O and CO_2 emissions associated with run-off, nitrate leaching, ammonia volatilization and from inputs used on the farm (Figure 1; adopted by Samsonstuen et al., 2019). All emissions are expressed as CO_2 eq to account for the global warming potential (GWP) of the respective gases for a time horizon of 100 years: CH_4 (kg) × 25 + N_2O × 298 + CO_2 (kg) (IPCC, 2007). Emission intensities from suckler cow beef production are related to the on farm beef production and expressed as kg CO_2 eq (kg beef carcass)$^{-1}$.

Methane emissions

Enteric CH_4 emissions are estimated for each age and sex class of cattle using an IPCC (2006) Tier 2 approach. Estimation of gross energy (GE) intake is based on energy requirements for maintenance, growth, pregnancy, and lactation according to Refsgaard Andersen (1990). The DM intake (DMI; Table 5) depends on both the energy requirements of the animal and the animals' intake capacity. The intake capacity is dependent on the fill value of the forage, as well as the substitution rate of the concentrates (Refsgaard Andersen, 1990). The GE intake to meet the energy requirements was estimated from the energy density of the diet (18.45 MJ kg^{-1} DMI; IPCC, 2006; Table 6). Enteric CH_4 was estimated from monthly GE intake using a diet specific CH_4 conversion factor for each cattle group (Ym = 0.065; IPCC, 2006; Table 6). The Ym factor is adjusted for the digestibility of the diet ($0.1058 - 0.006 \times DE$) as suggested by Beauchemin et al. (2010; Table 6).

Manure CH_4 emissions are estimated from the organic matter (volatile solid; VS) content of the manure. The VS production is calculated according to IPCC (2006), taking the GE content and digestibility of the diet into account. The VS are multiplied by a maximum CH_4 producing capacity of the manure (B_o=0.18 m^3 CH_4 kg^{-1}), a CH_4 conversion factor (MCF=0.01, 0.02, 0.17 kg CH_4 VS^{-1} for manure on pasture, solid storage manure and deep-bedding, respectively) and a conversion factor from volume to mass (0.67 kg m^{-3}; IPCC, 2006; Table 6).

Nitrous oxide emissions

Direct manure N_2O emissions are calculated based on the N content of manure and an emission factor for the manure handling system (0.01, 0.02, 0.05 kg N_2O-N (kg N)$^{-1}$ for deep-bedding, pasture manure, and solid storage, respectively; IPCC, 2006; Table 6). The N content of the manure is estimated according to IPCC (2006), based on the DMI, crude protein (CP; CP = 6.25 × N) content of the diet and N retention by the animals (Table 6).

Direct soil N_2O emissions are estimated by multiplying the total N inputs with an emission factor of 0.01 kg N_2O-N kg^{-1} N according to IPCC (2006). The total N inputs include above- and below ground crop residue N, using crop yields of Janzen et al. (2003), and mineralized N in addition to application of N fertilizer and manure. The derived C:N ratio of organic soil matter (0.1; Little et al., 2008) is used to calculate mineralization of N inputs (Table 6). The effect of location and seasonal variation was taken into account by including four seasons based on the local weather conditions and growing season; spring (April-May), summer (June-August), autumn (September-November) and winter (December-March), and the relative effects of percentage WFPS ($0.0473 + 0.01102 \times \mathrm{WFPS}$; Sozanska et al., 2002) of top soil and soil temperature at 30 cm depth (ts30; $0.5762 + 0.03130 \times \mathrm{ts30}$; Sozanska et al., 2002; Table 6).

Indirect N_2O emissions from soil are estimated from the assumed losses of N from manure, crop residues, and fertilizer according to IPCC (2006). The emissions from run-off, leaching and volatilization are estimated based on the fraction of the loss for the manure handling system adjusted using emission factors (0.0075 and 0.01 kg N_2O-N kg^{-1}) for leaching and volatilized ammonia-N, respectively (IPCC, 2006; Table 6). The emissions were based on the assumed fraction of N lost adjusted for emission factors for leaching (0.0, 0.0, 0.3, 0.3 kg N (kg N)$^{-1}$ for deep bedding, solid storage, pasture manure and soil N inputs including land applied manure, grass residue, synthetic N fertilizer and mineralized N, respectively; IPCC, 2006; Table 6). Emissions from volatilization were adjusted for the emission factors for volatilized ammonia-N (0.1, 0.2, 0.3, 0.45 kg N (kg N)$^{-1}$ for soil N inputs, pasture manure, deep bedding, and solid storage, respectively; IPCC, 2006; Table 6).

Soil C change

Soil C change is estimated based on the Introductory Carbon Balance Model (ICBM) by Andrén et al. (2004), which estimates the change in soil C from total C inputs (i) from grass residues and manure. The fraction of the young (Y) C pool entering the old (O) C pool is estimated based on a humification coefficient of grass residue (h= 0.13; Kätterer et al., 2008; Table 6) and a humification coefficient of cattle manure (h= 0.31; Kätterer et al., 2008; Table 6). The degradation of the pools is determined by the respective decomposition rates (k_y= 0.8 year^{-1} and k_o=0.007; Andrén et al., 2004; Table 6). The change in Y and O soil C stocks is estimated based on the humification rates and decomposition rates together with the relative effect of soil moisture and temperature $r_w \times r_T$ to account for regional differences due to soil type and climate.

The yearly fluxes of Y and O soil C are given by the differential equations of Andrén and Kätterer (1997):

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

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

Carbon dioxide emissions

Direct CO_2 emissions are estimated from on-farm use of diesel fuel using an emission factor (2.7 kg CO_2 eq L^{-1}; The Norwegian Environment Agency, 2017; Table 6). Off-farm emissions from production and manufacturing of farm inputs are estimated using emission factors for Norway or Northern-Europe; pesticides, 0.069 kg CO_2 eq (MJ pesticide energy)$^{-1}$ (Audsley et al., 2014); electricity, 0.11 kg CO_2 eq (kWh)$^{-1}$ (Berglund et al., 2009); diesel fuel, 0.3 kg CO_2 eq (L)$^{-1}$ (Öko-Instititut, 2010); silage additives, 0.72 kg CO_2 eq (kg CH_2O_2)$^{-1}$ (Flysjö et al., 2008); and N-based synthetic fertilizer, 4 kg CO_2 eq (kg N)$^{-1}$ (DNV, 2010; Table 6). Emissions related to the use of concentrates are estimated according to Bonesmo et al. (2013). The concentrates are assumed to be supplied by barley and oats grown in Norway (0.62 kg CO_2 eq kg DM^{-1}; Bonesmo et al., 2012; Table 6) and soybean meal imported from South Africa (0.93 kg CO_2 eq kg DM^{-1}; Dalgaard et al., 2008; Table 6). Emissions from on-farm production of field crops are not included in the total farm emissions as they are sold and not used as feed by the beef enterprise.

2.3 Sensitivity analysis and comparisons

A sensitivity analysis was performed to investigate the evaluate possible errors in the estimated soil C balance. The sensitivity of the yearly effect of temperature and soil moisture ($r_W \times r_T$) and initial soil organic carbon (SOC) was estimated by changing the factors 1% and recalculating the emission intensities.

Breeds and regions were compared through mean comparison of the estimated emission intensities (CO_2 eq (kg beef carcass)$^{-1}$) using the PROC GLM procedure of SAS® software, V9.4 (SAS Institute Inc., Cary, NC, 2017).

3. Results

The total farm GHG emission intensities showed no significant difference across breeds (Table 7). However, N_2O emissions from manure ($P \leq 0.01$) and emissions related to off-farm production of barley (P≤0.05) and soya (P≤0.01) differed across breeds. Angus showed most variation in total emission intensities. This variation decreased when soil C balance was ignored.

The farms showed wide variation in emission intensity (including soil C) with a mean estimate of 29.2 CO_2 eq (kg carcass)$^{-1}$ (median= 29.5, range 22.5 to 45.2; Table 7). Enteric CH_4 contributed most to the total GHG emissions, accounting for 44% of the total emissions. N_2O from soil and manure was the second largest source, accounting for 13% and 11%, respectively. Soil C balance accounted for 6% of the total emissions and had the largest variation across farms, ranging from -2.7 to 14.1 CO_2 eq (kg carcass)$^{-1}$ depending on location. On-farm emissions from burning of fossil fuels accounted for 9% and the indirect CO_2 emissions from manufacturing of farm inputs (i.e. N-fertilizers, fuels, electricity, pesticides) accounted for 8%.

Regions East and Mid had lowest mean emission intensities, whereas Southwest and North had greatest mean emission intensities (Table 8). Soil C differed across regions (P≤0.05) and was the largest source of variation, on average accounting for 0.1 to 1.4 CO_2 eq (kg carcass)$^{-1}$ of the total emissions in East and Mid, and 3.4 to 6.2 CO_2 eq (kg carcass)$^{-1}$ of the total emissions in Southwest and North. North had greater emissions from indirect and direct energy. By excluding the soil C balance, the variation between individual farms decreased and the emission intensity across all farms had a mean estimate of 27.5 CO_2 eq (kg carcass)$^{-1}$ (median= 26.9, range 21.5 to 34.1). Excluding soil C led to re-ranking of individual farms in terms of GHG emission intensity (Table 9).

The comparison of the least square mean (LSM) differences of emission intensities showed that the differences in manure N_2O emissions were significant both across breeds and regions (P≤0.01). Soil C differed across regions and direct energy differed across breeds (P≤0.05

and P≤0.05 respectively), while the difference between breeds and locations for other sources of emissions was not significant (Table 10).

Estimated GHG were moderately sensitive to changes in initial SOC and the yearly effect of soil temperature and soil moisture ($r_W \times r_T$). The sensitivity elasticity had a linear response ranging from 0.14 to 0.23 CO_2 eq (kg carcass)$^{-1}$ across region, caused by 1% change in initial SOC (Table 11). Changing the $r_W \times r_T$ 1%, caused a 0.12-0.19 CO_2 eq (kg carcass)$^{-1}$ across regions (Table 11).

4. Discussion

4.1 Animal production

Our study investigated the GHG emissions from commercial Norwegian farms from different geographical regions, compared with simulated farms used in other studies (e.g. Mogensen et al., 2015; White et al., 2010) with different management practices, cattle breeds, and natural resources. The farms investigated were distributed across the country and had a wide range of farm characteristics, representing the broad spectrum of suckler cow farms in Norway. Carcass weights used for estimating emission intensities from herds of Angus, Hereford, and Charolais were similar to carcass weights from intensive and extensive beef breed farming systems in Sweden and Denmark (Mogensen et al., 2015).

4.2 Greenhouse gas emissions

Under the current conditions for beef production in Norway, HolosNorBeef estimated mean emission intensities, including soil C, of 29.2 CO_2 eq (kg carcass)$^{-1}$ (median= 29.4, range 22.5 to 45.2) for 27 herds of Angus, Hereford, and Charolais. This range of emission intensities is similar to reports for other Nordic countries; Denmark 23.1 to 29.7 CO_2 eq (kg carcass)$^{-1}$ and

Sweden 25.4 CO_2 eq (kg carcass)$^{-1}$ (Mogensen et al., 2015). Emissions related to off-farm production of soya differed in terms of emission intensities across breeds. Observed feed intake and use of concentrates showed variation both across breeds and between farms within breed as a consequence of diet composition and feed requirements. In general, farms with lower quality forage fed a larger proportion concentrates to the replacement heifers. Bulls were on average fed 33% concentrates and were usually fed good quality silage. However, as increased production follows increased feed intake, the observed variability did not cause differences in total emission intensities across breeds.

4.2.1 Methane emissions

Enteric CH_4 contributed most to the total GHG emissions, accounting for 44% of the total emissions on average. HolosNorBeef estimated enteric CH_4 emissions based on the GE intake while adjusting the Ym for the digestibility of the diet (i.e. DE%). Hence, as shown by Samsonstuen et al. (2019), variation in Ym would cause a linear change in emission intensities. At equal GE intake, increased DE% would result in a linear decrease in Ym and a corresponding decrease in enteric CH_4 emissions. Within breed, Angus showed the largest variation in both % DE, DMI and enteric CH_4 emissions. Enteric CH_4 emissions are mainly related to variation in DMI (Herd et al., 2014) and feed quality (Ominski et al., 2011), with improved quality associated with lower emissions as the proportion of easily digested organic matter in the feed increases (Wims et al., 2010). Diets with more starch and less fiber produce less CH_4 per kg DM (Haque, 2018). In Sweden and Denmark, enteric CH_4 was reported as the largest source of emissions, accounting for 45.1-50.4% of total GHG emissions (Mogensen et al., 2015), depending on feeding intensity. In the present study, the DMI varied between and within farms dependent on the production and diet composition as the location of the farm dictated the available feed resources and use of pastures. Diet composition and forage quality changed throughout the year due to differences in animal requirements (e.g. for maintenance, growth, pregnancy, lactation) and availability of feed resources (e.g. pasture, silage, concentrates). For suckler cows, the variation in DMI within breed is mainly due to forage quality and use of concentrates, as the digestibility of the forage and proportion concentrates influences the forage intake capacity. Use of pasture also influenced the DMI as the cows were assumed to have a higher DMI from cultivated pastures than outfield pastures due to the availability of the feed. Feed requirements varied both between breeds and within breeds due to differences in weights at different ages. The variation in DMI from birth to slaughter is influenced by slaughter age and slaughter weight as it influences the feed required for growth. The DMI of heifers from birth to calving is influenced by the diet composition and requirements for growth. Surplus heifers were fed the same diet until they reached slaughter weight.

Manure CH_4 emissions varied from 2-8% of total emissions depending upon diet composition, housing conditions, and manure storage. HolosNorBeef calculated the manure CH_4 emissions on a monthly basis for each cattle class and determined the organic matter (i.e. VS) content of manure based on GE intake and the digestibility (i.e. DE%) of the diet. The DE% were variable, ranging from 59 to 71% among the farms leading to a large variation in manure CH_4 emissions between farms. This is similar to the range in DE% (49 to 81%) reported by Hanigan et al. (2013). Diet composition and DMI influence manure CH_4 emissions as increased organic matter (i.e., VS) content of manure increases the emissions from degradation (Monteny et al., 2001). Farms with low quality forage (e.g. straw or low quality silage) had lower manure CH_4 emissions as both the digestibility of the diet and the VS content of manure decreases. Crude protein (CP) and fiber content of the diet is significantly related to VS (Appuhamy et al., 2017), and Amon et al. (2007) showed that increased lignin and cellulose content in the manure reduces the CH_4 emissions as the digestibility decrease. However, manure management influence the manure CH_4 emissions as the CH_4 conversion is greater in deep bedding, compared with solid storage, due to anaerobic conditions. Thus, the greater CH_4 manure emissions were for farms using deep bedding during the housing period.

4.2.2 Regional variation

Soil C (discussed in section 4.2.3) differed across regions. By excluding the soil C balance, the variation between regions and individual farms decreased and the emission intensity across all farms had a mean estimate of 27.5 CO_2 eq (kg carcass)$^{-1}$ (median= 26.9, range 21.5 to 34.1). East and Mid had lowest mean emission intensities, whereas Southwest and North had greatest mean emission intensities. Direct comparisons across and within regions are challenging as not all breeds were represented in all regions. Unequal distribution of breeds might cause confounding of breed within region. As all breeds were represented in both East and North and two breeds were represented in the region Mid, the confounding of region with breed was of greatest concern in the region Southwest, which was confirmed by region*breed LSM solutions for all regions except Southwest. Two farms and only one breed within this region Southwest might suggest that this region should have been omitted and the two farms included in a "South Region". However, an increase in geographical area could have concealed differences across regions caused by differences in the resource base, such as initial SOC.

The use of input factors is to a large extent influenced by the resource base, as the use of e.g. pesticides, fertilizer, and diesel fuel is related to the areas available for forage production, as pastures, and the distance from the field to the farm. Nevertheless, the least square mean comparison reveals a significant difference in emission intensities between breeds from direct energy, suggesting that there are differences in use of diesel fuel between breeds, within regions. In general, the Southwest and North have smaller areas available, with a greater distance between farm and field and greater variation in climatic conditions. A large proportion of the farms were located in the East, which also had most variation within region. Differences in feed requirements between breeds increases the difference between individual farms within the region. The resource base in the East facilitates both good quality silage and the use of straw as forage due to grain production in the region, resulting in a great variety in diet composition and corresponding emissions between farms.

4.2.3 Soil C balance

The GHG contribution from soil C balance accounted for 6% of the total emission intensities on average and had the largest variation across farms, ranging from -2.73 to 14.11 CO_2 eq (kg carcass)$^{-1}$ depending on location. HolosNorBeef estimated the C balance between the soil and atmosphere using the two-compartment ICBM model (Andrén et al., 2004). The GHG contribution of soil C balance was influenced by the level of the initial SOC content, temperature and moisture in addition to forage production, application of manure, and N fertilizer. Inputs into ICBM are used to adapt the model to the local management and weather conditions (Bolinder et al., 2011). This model was previously calibrated to Norwegian conditions and used to estimate soil C change in the 100th year with continuous grass and arable cropping (Bonesmo et al., 2013; Skjelvåg et al., 2012). Skjelvåg et al. (2012) investigated the farm specific natural resource base in six municipalities in different parts of Norway and found a wide range in initial SOC content in top soil varying from 56.1 to 116.8 Mg ha^{-1}. The 30 Norwegian dairy farms investigated by Bonesmo et al. (2013) had an average initial SOC of 71.3 Mg ha^{-1}, ranging from 40.3 to 99.5 Mg ha^{-1}. In comparison, the current study had an average initial SOC of 75.7 Mg ha^{-1}, ranging from 44.8 to 168.4 Mg ha^{-1}.

On average, the C balance accounted for 0.1 to 1.4 CO_2 eq (kg carcass)$^{-1}$ of the total emissions in East and Mid, whereas in Southwest and North the average C balance accounted for 3.4 to 6.2 CO_2 eq (kg carcass)$^{-1}$ of the total emission. The resource base of the regions varies, whereas the East and Mid are regions with a climate suitable for grain production. The regions Southwest and North are less suitable for grain production, and the arable lands have been used for forage production or as pastures for decades, resulting in high initial SOC. The initial C in topsoil is crucial for estimating C balance as a high initial SOC content will lead to a decrease, and a low initial SOC will lead to an increase (Andrén et al., 2015). Hence, the estimated C loss from farms in Southwest and North is a result of high initial SOC. As the soil C content is difficult to measure, Andrén et al. (2015) suggested to modify the initial SOC if the changes between samplings are unrealistic. However, in the present study there is only a single estimate of the SOC content and modifying the initial SOC is not possible.

The ICBM model has been further developed into a multi-compartment model (ICBM/3) with several C pools to account for different decomposition rates of organic matter (Kätterer and Andrén, 2001). ICBM/3 divides the Y SOC pool into above ground residues, below ground residues and addition of manure and other organic matter. Multi-compartment models have pool-specific decomposition rates and humification factors, making the model more dynamic and adapted to various management practices. Future soil C balance estimations could possibly be improved by incorporating the newest version of ICBM/3 to HolosNorBeef, or by calibrating the existing ICBM model with multiple soil samples from areas with large initial SOC. However, the complexity of multi-compartment models (e.g. ICBM/3) increases the amount and detail level of the required input and decreases the transparency of the model. Such detailed input data for use in the multi-compartment model are not available at this point. According to Bolinder et al. (2011), single- and two-compartment models such as the ICBM model may replace more complex models in whole farm modelling and life cycle assessment (LCA) approaches as they are simple, transparent and can be programmed in a spreadsheet format. Kröbel et al., (2016) investigated the inclusion of both the two-compartment ICBM model and the multi-compartment Century model in the Canadian Holos model. The study indicated that the ICBM model allowed a more dynamic output of management and climate, increasing the flexibility and allowing more farm specific estimation compared with the more complex Century model (Kröbel et al., 2016). Hence, the two-compartment ICBM model may be sufficient for whole farm modelling of GHG emissions as it reflects the dynamics of the SOC stocks while taking the influence of crop yield, management, soil moisture and temperature into account.

Sensitivity elasticities showed an average change in emission intensities of 0.10 to 0.23 (SOC) and 0.12 to 0.19 CO_2 eq (kg carcass)$^{-1}$ ($r_W \times r_T$) across regions. However, there were no significant different response in sensitivity elasticities between regions, implying that the estimated difference in soil C balance occurs due to more than just variation in the initial SOC and $r_W \times r_T$.

Grazing influences plant production (Lee et al., 2010), plant diversity (Limb et al., 2018) and adds organic matter through manure (Baron et al., 2007). The influence of grazing management on C sequestration has been investigated in various studies (Pelletier et al., 2010; Reeder and Schuman, 2002; Soussana et al., 2007, 2010; Wang et al., 2015). The influence of grazing is complex, as the soil C dynamics are influenced by the animal, climate, soil, plant, management and their interactions (Bolinder et al., 2011; Schuman et al., 2002). HolosNorBeef does not include the effect of grazing management on C balance as the ICBM model does not account for the effect of grazing or stocking rate. Norwegian land contains approximately 60,000 (arable) to 100,000 kg C ha^{-1} (pastures; NIBIO, 2019) and the potential for mitigation by sequestering C in outfield pastures under Norwegian conditions has not been scientifically documented. Applying Norwegian conditions to US studies, the estimated potential for C sequestration is 1000 to 6000 kg CO_2 ha^{-1} year^{-1} (NIBIO, 2019). When considering pasture management strategies, the corresponding ecosystem services directly or indirectly influenced by pasture management should be taken into account.

5. Conclusions

A whole-farm approach that included changes in soil C estimated GHG emission intensities of 22.5 to 45.2 CO_2 eq (kg carcass)$^{-1}$ from representative suckler cow beef farms in Norway with Angus, Hereford, and Charolais cattle. The variation in DMI and diet composition between farms influenced both enteric and manure CH_4 emissions, and contributed to variation in emission intensities between individual farms. Including soil C balance in the emission intensity of beef production increased variability in GHG emissions among individual farms and caused a significant difference in estimated GHG intensities between regions. In addition to level of forage production, application of manure, and N fertilizer, the soil C balance was influenced by the level of the initial SOC content, temperature and moisture. Arable lands used for forage production or as pastures for decades result in high initial SOC in soils of some farms, which warrants further examination and additional measurement as the ICBM model is sensitive to high initial SOC and does not account for the effect of grazing or stocking rate.

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Tables

Table 1 Average animal numbers and performance for the 27 Norwegian beef cattle farms used to estimate GHG emission intensities (n=9 for each breed; Animalia, 2017).

	A.Angus			Hereford			Charolais		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Beef cows (year^{-1})	27	15	55	32	18	55	38	18	120
Calves born (year^{-1})	26	14	53	32	18	55	38	18	115
Replacement heifers (year^{-1})	9	4	17	9	4	87	10	4	28
Twinning frequency (%)	2.4	0.00	9.89	3.44	0.00	7.46	7.89	2.17	12.76
Still born (%)	1.96	0.00	7.59	3.19	1.90	6.32	2.05	0.51	7.22
Dead before 180 days (%)	1.86	0.00	4.82	0.57	0.00	1.51	1.47	0.00	4.24
Gender distribution (proportion heifers)	0.50	0.44	0.56	0.49	0.41	0.55	0.47	0.45	0.52
Heifers, birth weight (kg LW)	39	37	42	40	38	42	45	42	49
Heifers, weaning weight (kg LW)	242	214	265	247	211	283	286	263	329
Heifers, yearling weight (kg LW)	371	329	410	355	261	418	439	392	482
Heifers, carcass weight (kg)	226	193	278	196	130	244	248	186	273
Heifers, age at slaughter (month)	19.0	15.6	22.3	17.6	10.8	20.3	16.7	13.5	20.4
Heifers, age at first calving (month)	24.6	23.5	25.7	25.1	24.2	26.7	25.4	23.9	28.9
Young bulls, birth weight (kg LW)	41	38	44	42	40	44	48	44	53
Young bulls, weaning weight (kg LW)	266	226	291	281	213	321	321	285	384
Young bulls, yearling weight (kg LW)	371	329	410	461	379	537	549	510	600
Young bulls, carcass weight (kg)	290	231	350	291	265	323	356	320	402
Young bulls, age at slaughter (month)	16.3	15.4	17.3	16.5	13.3	18.9	16.3	14.7	18.4

LW= live weight

Table 2 Mean (M) and standard deviation (SD; in parenthesis) for nutritive values of forages, concentrates and pastures for the 27 Norwegian beef cattle farms used to estimate GHG emission intensities (n=9 for each breed).

	Angus				Hereford				Charolais			
	DM	FUm[ab]	CP	DE	DM	FUm	CP	DE	DM	FUm	CP	DE
Unit	%		g/kg DM	%	%		g/kg DM	%	%		g/kg DM	%
	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)
Concentrates[c]	0.88 (0.00)	1.07 (0.03)	163 (21)	77 (2)	0.88 (0.00)	1.05 (0.04)	165 (38)	76 (3)	0.88 (0.00)	1.08 (0.06)	157 (15)	78 (4)
Silage[c]	0.37 (0.15)	0.83 (0.08)	141 (4)	60 (5)	0.38 (0.12)	0.85 (0.03)	159 (11)	62 (2)	0.38 (0.10)	0.84 (0.04)	152 (16)	61 (3)
Straw, NH_3[d]	0.86	0.70	95	52	0.86	0.70	95	52	0.86	0.70	95	52
Straw, dry[d]					0.90	0.30	36	25				
Pasture[de]	0.20	0.95	196	68	0.20	0.95	196	68	0.20	0.95	196	68

DM= dry matter; FUm = feed units milk/kg DM; CP = crude protein; DE = digestible energy

[a]1FUm = 6.9 MJ net energy lactation

[b] Information from the farmer

[c] Forage analysis (Eurofins, 2015)

[d] NMBU and Norwegian Food Safety Authority (2008)

[e] Equal pasture quality on outfield pastures as cultivated pastures according to Rekdal (2014)

Table 3 Farm inputs and land use for the 27 Norwegian beef cattle farms used to estimate GHG emission intensities.

	East (n=16)			Southwest (n=2)			Mid (n=4)			North (n=5)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Input use												
Fuel (L $year^{-1}$)[a]	5681	34	15379	1709	804	2614	4364	1942	8780	4362	1392	6778
Electricity (kWh $year^{-1}$)[a]	47642	0	154303	6620	4670	8571	33860	19194	53665	20772	0	30961
Silage additive (kg CH_2O^2 $year^{-1}$)[a]	5062	0	37800	2250	0	4500	0	0	0	0	0	0
Ley synthetic fertilizer (kg N ha^{-1})[a]	9	0	18	15	8	22	5	0	11	12	4	18
Ley pesticide (MJ ha^{-1})[a]	10.4	0	25.3	2.8	2.5	3.1	0	0	0	0.5	0	2.6
Pasture synthetic fertilizer (kg N ha^{-1})[a]	7	0	25	0	0	0	4	0	16	3	0	10
Land use												
Ley area[*] (ha)	54.5	10.0	180.2	16.5	8.0	25.0	61.7	33.1	84.9	31.6	15.0	55.7
Silage yield (kg DM $year^{-1}$)[b]	241197	96688	1040000	36855	27810	45900	190266	119119	271250	131486	66000	280800
Cultivated pasture* (ha)	14.5	0	53.1	6.3	5.6	7.0	16.9	2.5	50.1	14.3	0	30.0

FUm= feed units milk

[*]outfield pasture areas are not included

[a] Farm accounts 2013/2014

[b] Information from the farmer

Table 4 Mean, minimum (Min) and maximum (Max) natural resource data for the grasslands of 27 Norwegian suckler cow farms used to estimate GHG emission intensities of beef production.

	East (n=16)	Southwest (n=2)	Mid (n=4)	North (n=5)

	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Soil temperature at 30 cm depth[a], winter (°C)	-0.3	-1.5	1.2	1.9	1.8	2.0	0.7	-0.5	1.6	0.8	-0.3	1.9
Soil temperature at 30 cm depth[a], spring (°C)	6.2	3.4	8.1	6.9	6.8	6.9	5.6	4.7	6.3	5.3	4.4	6.0
Soil temperature at 30 cm depth[a], summer (°C)	13.7	11.1	15.6	13.1	12.8	13.4	12.2	11.7	12.8	12.4	12.1	12.8
Soil temperature at 30 cm depth[a], autumn (°C)	5.5	2.8	8.4	8.1	8.0	8.1	6.0	4.6	7.4	6.1	4.5	7.4
Water filled pore space[b], winter (%)	71.2	51.5	85.5	65.9	64.5	67.4	51.2	43.4	56.7	66.4	44.6	92.6
Water filled pore space[b], spring (%)	56.7	41.7	68.4	55.0	53.9	56.1	41.4	35.3	46.5	59.6	35.3	90.2
Water filled pore space[b], summer (%)	47.0	31.1	62.5	50.9	49.1	52.7	35.7	29.2	40.6	45.2	21.7	56.7
Water filled pore space[b], autumn (%)	68.1	50.7	79.8	66.1	64.4	67.9	50.5	42.2	55.6	65.8	42.6	94.5
$r_w \times r_T$ yearly[c] (dimensionless)	1.0	0.6	1.4	1.4	1.4	1.4	1.0	0.8	1.2	1.1	0.7	1.4
SOC (Mg ha^{-1})	66.6	44.8	101.0	84.2	68.8	99.7	58.7	53.8	63.6	115.2	65.5	168.4

n= number of farms; SOC = soil organic carbon

[a] Estimated according to Katterer and Andren (2009).

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

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

Table 5 Mean and standard deviation (SD; in parenthesis) for feed intake (kg DM/animal/year), crude protein (% DM) and digestible energy (% DM) for the 27 Norwegian beef cattle farms used to estimate GHG emission intensities (n=9 for each breed).

	A.Angus			Hereford			Charolais		
	Cow	Heifer*	Bull**	Cow	Heifer*	Bull**	Cow	Heifer*	Bull**

	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Concentrates	12 (25)	477 (251)	680 (427)	13 (18)	520 (388)	845 (130)	185 (186)	896 (219)	1125 (214)
Grass silage	2150 (709)	1768 (419)	1605 (525)	1973 (571)	1278 (523)	1133 (320)	2325 (659)	1959 (460)	1565 (204)
Straw, NH_3	173 (518)	16 (48)	0 (0)	207 (337)	65 (114)	0 (0)	420 (543)	75 (174)	0 (0)
Straw, dry	0 (0)	0 (0)	0 (0)	21 (41)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Grazing, cultivated	764 (426)	446 (224)	306 (153)	856 (527)	756 (375)	435 (252)	863 (434)	713 (400)	163 (489)
Grazing, outfield***	258 (286)	103 (165)	53 (104)	396 (285)	197 (173)	173 (208)	87 (151)	66 (124)	371 (206)
Total DMI	3357 (285)	2810 (292)	2644 (811)	3466 (147)	2816 (387)	2586 (394)	3880 (161)	3709 (329)	3224 (226)
CP (% DM)	15.85 (1.10)	16.52 (0.66)	16.29 (0.97)	16.83 (0.75)	17.18 (0.64)	16.64 (0.73)	15.93 (1.45)	16.42 (1.20)	15.94 (1.08)
DE (% DM)	61.79 (1.99)	65.22 (2.50)	66.01 (3.35)	63.91 (1.29)	67.11 (2.02)	69.08 (1.93)	63.10 (1.79)	66.72 (2.09)	67.51 (1.67)

DM= dry matter; DMI = dry matter intake; CP = crude protein; DE = digestible energy

* Birth to calving, milk intake not included

** Birth to slaughter, milk intake not included

***Outfield includes permanent pastures, outfield areas with meadows, heath and marshlands

Table 6 Sources of GHG emissions, emission factors or equations used and reference source (Samsonstuen et al., 2019).

Gas/source	Emission factor/equation	Reference
Methane		
Enteric fermentation	(0.065/55.64) kg CH_4 (MJ GEI)$^{-1}$	(IPCC, 2006)
Relative effect of digestibility (DE%) of feed	0.1058-0.006 × DE	(Bonesmo et al., 2013)*
Max.CH_4 producing capacity of manure (B_o)	0.18 m^3 CH_4 kg^{-1}	(IPCC, 2006)
Deep bedding manure	0.17 kg CH_4 (VS)$^{-1}$	(IPCC, 2006)
Solid storage manure	0.02 kg CH_4 (VS)$^{-1}$	(IPCC, 2006)
Pasture manure	0.01 kg CH_4 (VS)$^{-1}$	(IPCC, 2006)
Direct nitrous oxide		
Soil N inputs**	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)***, (Bonesmo et al., 2012)***
Relative effect of soil temperature at 30cm (ts30°C)	0.5862+0.03130 × ts30	(Sozanska et al., 2002)***, (Bonesmo et al., 2012)***
Deep bedding manure	0.01 kg N_2O-N (kg N)$^{-1}$	(IPCC, 2006)
Solid storage manure	0.05 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**	Leaching:	
	EF= 0.0075 kg N_2O-N (kg N)$^{-1}$,	(IPCC, 2006), (Little et al., 2008)****
	$Frac_{leach}$=0.3 kg N (kg N)$^{-1}$	
	Volatilization:	
	EF= 0.01 kg N_2O-N (kg N)$^{-1}$,	(IPCC, 2006)
	$Frac_{volatilization}$=0.1 kg N (kg N)$^{-1}$	
Deep bedding manure	Leaching:	
	EF= 0.0075 kg N_2O-N (kg N)$^{-1}$,	(IPCC, 2006)
	$Frac_{leach}$=0 kg N (kg N)$^{-1}$	
	Volatilization:	
	EF= 0.01 kg N_2O-N (kg N)$^{-1}$,	(IPCC, 2006)
	$Frac_{volatilization}$=0.3 kg N (kg N)$^{-1}$	
Solid storage manure	Leaching:	
	EF= 0.0075 kg N_2O-N (kg N)$^{-1}$,	(IPCC, 2006)

	$Frac_{leach}$=0 kg N (kg N)$^{-1}$	
	Volatilization:	
	EF= 0.01 kg N_2O-N (kg N)$^{-1}$,	(IPCC, 2006)
	$Frac_{volatilization}$=0.45 kg N (kg N)$^{-1}$	
Pasture manure	Leaching:	
	EF= 0.0075 kg N_2O-N (kg N)$^{-1}$,	(IPCC, 2006), (Little et al.,
	$Frac_{leach}$ 0.3 kg N (kg N)$^{-1}$	2008)****
	Volatilization:	(IPCC, 2006)
	EF= 0.01 kg N_2O-N (kg N)$^{-1}$,	
	$Frac_{volatilization}$=0.2 kg N (kg N)$^{-1}$	
Soil carbon		
Young (ky) soil C decomposition rate	0.8 year^{-1}	(Andrén et al., 2004)
Old (ko) soil C decomposition rate	0.007 year^{-1}	(Andrén et al., 2004)
Humification coefficient (h) of grass and crop residue	0.13	(Katterer et al., 2008)
Humification coefficient (h) of cattle manure	0.31	(Katterer et al., 2008)
Direct carbon dioxide		
Diesel fuel use	2.7 kg CO_2 L^{1}	(The Norwegian Environment Agency, 2017)
Indirect carbon dioxide		
Manufacturing N-based synthetic compound fertilizer	4 kg CO_2eq (kg N)$^{-1}$	(DNV, 2010)
Manufacturing pesticides	0.069 kg CO_2eq (MJ pesticide energy)$^{-1}$	(Audsley et al., 2014)
Manufacturing silage additives	0.72 kg CO_2eq (kg CH_2O_2)$^{-1}$	(Flysjö et al., 2008)
Production of diesel fuel	0.3 kg CO_2eq L^{-1}	(Öko-Institut, 2010)
Production of electricity	0.11 kg CO_2eq kWh^{-1}	(Berglund et al., 2009)
Purchased soya meal	0.93 kg CO_2eq (kg DM)$^{-1}$	(Dalgaard et al., 2008)
Purchased barley grain	0.62 kg CO_2eq (kg DM)$^{-1}$	(Bonesmo et al., 2012)

GEI= Gross energy intake; VS = volatile solids; WFPS = water filled pore space; ts30 = soil temperature at 30cm; EF = emission factor; $Frac_{leach}$ = Leaching fraction; $Frac_{volatilization}$ = Volatilization fraction

*Equation derived by Bonesmo et al. (2013) based on IPCC (2006), Little et al. (2008) and Beauchemin et al. (2010).

**Includes land applied manure, grass and crop residue, synthetic N fertilizer, mineralized N

***Equation derived by Bonesmo et al. (2012) using data from Sozanska et al. (2002)

****Value simplified from equation given by Little et al. (2008)

Table 7 Mean, minimum (Min), maximum (Max) and standard deviation (SD) estimates for greenhouse gas emission intensity (kg CO_2 eq kg^{-1}carcass) (n=9 for each breed).

	A.Angus				Hereford				Charolais				Sig[a]
	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	
Enteric CH_4	12.95	9.98	16.09	1.86	13.16	11.90	14.66	0.83	12.26	11.44	13.57	0.67	ns
Manure CH_4	1.33	0.36	3.18	1.00	1.54	0.41	2.91	1.06	1.42	0.42	3.60	0.96	ns
Manure N_2O	2.96	1.88	3.63	0.60	3.76	2.69	4.99	0.69	2.67	1.66	3.16	0.45	**
Soil N_2O	3.53	2.64	4.11	0.45	3.70	3.10	4.22	0.32	3.80	3.05	6.16	0.95	ns
Soil C	3.14	-2.73	14.11	5.13	1.97	-2.08	7.84	3.75	-0.19	-2.37	3.58	2.19	ns
Off-farm barley	0.62	0.00	0.90	0.29	0.92	0.41	2.06	0.51	1.14	0.73	1.55	0.27	ns
Off-farm soya	0.71	0.00	1.10	0.35	0.75	0.52	1.34	0.27	1.19	0.75	1.51	0.26	*
Indirect energy	1.76	0.24	4.33	1.49	2.08	0.01	3.66	1.05	2.87	1.27	4.80	1.17	ns
Direct energy	3.00	1.13	5.29	1.64	1.93	0.03	3.38	1.09	2.56	1.26	4.73	1.13	ns
Total emissions	30.00	24.32	45.20	6.31	29.80	22.67	38.07	4.61	27.71	22.49	33.52	3.72	ns
Total emissions excluding soil C	26.86	21.45	31.09	3.27	27.83	24.39	32.28	2.97	27.90	24.38	34.07	2.76	ns

[a] Sig = significance: ns = non significant, * = $P \leq 0.05$, ** = $P \leq 0.01$.

Table 8 Mean greenhouse gas (GHG) emission intensities and proportion of total emissions (in parenthesis) from average herds of beef cattle in four regions of Norway (kg CO_2 eq kg^{-1}carcass).

	East (n=16)	Southwest (n=2)	Mid (n=4)	North (n=5)	Sig[a]
Enteric CH_4	12.76 (0.46)	13.95 (0.43)	13.41 (0.47)	11.93 (0.36)	ns
Manure CH_4	1.76 (0.06)	0.96 (0.03)	1.07 (0.04)	0.86 (0.03)	ns
Manure N_2O	3.19 (0.12)	4.51 (0.14)	3.06 (0.11)	2.44 (0.07)	**
Soil N_2O	3.65 (0.13)	3.87 (0.12)	3.56 (0.13)	3.77 (0.11)	ns
Soil C	0.06 (0.00)	3.36 (0.10)	1.40 (0.05)	6.18 (0.18)	*
Off-farm barley	0.95 (0.03)	0.58 (0.02)	0.87 (0.03)	0.86 (0.03)	ns
Off-farm soya	0.88 (0.03)	0.63 (0.02)	1.07 (0.04)	0.84 (0.03)	ns
Indirect energy	2.13 (0.08)	2.13 (0.07)	1.55 (0.05)	3.18 (0.09)	ns
Direct energy	2.30 (0.08)	2.08 (0.06)	2.26 (0.08)	3.48 (0.19)	ns
Total emission	27.67	32.06	28.26	33.55	ns
Total emission excluding soil C	27.61	28.70	26.85	27.36	ns

n = number of farms.

[a] Sig = significance: ns = non significant, * = P≤0.05, ** = P≤0.01.

Table 9 Ranking of farms with Aberdeen Angus (AA), Hereford (H) and Charolais (CH) in different regions in terms of GHG emission intensities including and excluding soil C balance.

East (n=16)		Southwest (n=2)		Mid (n=4)		North (n=5)	
Incl. soil C	Ex. soil C	Incl. soil C	Ex. soil C	Incl. soil C	Ex. soil C	Incl. soil C	Ex. soil C
H1	AA3	H17	H17	CH19	AA22	CH23	AA25
CH2	H11	H18	H18	AA20	CH21	H24	H26
AA3	H1			CH21	AA20	AA25	CH23
AA4	A10			AA22	CH19	H26	H24
CH5	CH2					AA27	AA27
H6	H6						

AA7	AA4
CH8	CH5
CH9	CH8
AA10	CH14
H11	AA7
H12	CH9
A13	AA13
CH14	H12
H15	H15
CH16	CH16

n = number of farms in each region.

Table 10 Least square means (LSM) of greenhouse gas (GHG) emission intensities and proportion of total emissions (in parenthesis) from average herds of Aberdeen Angus (AA), Hereford (H), and Charolais (CH) in four regions of Norway (kg CO_2 eq kg^{-1}carcass).

	East (n=16)			Southwest (n=2)	Mid (n=4)		North (n=5)			Location	Breed
	AA	H	CH	H	AA	CH	AA	H	CH	Sig[a]	Sig[a]
Enteric CH_4	13.07	13.13	12.19	13.95	14.23	12.58	11.35	12.45	12.05	ns	ns
Manure CH_4	1.85	1.77	1.67	0.96	0.99	1.15	0.40	1.53	0.45	ns	ns
Manure N_2O	3.12	3.71	2.80	4.51	3.36	2.77	2.15	3.14	1.66	**	**
Soil N_2O	3.39	3.61	3.90	3.87	3.70	3.42	3.71	3.74	3.94	ns	ns
Soil C	0.46	0.39	-0.53	3.36	2.31	0.50	10.68	4.55	3.36	*	ns
Off-farm barley	0.62	1.02	1.16	0.58	0.66	1.08	0.61	0.99	1.09	ns	ns
Off-farm soya	0.60	0.71	1.26	0.63	1.09	1.05	0.62	0.96	1.06	ns	ns
Indirect energy	1.79	1.90	2.60	2.13	0.36	2.73	3.07	2.49	4.80	ns	ns
Direct energy	2.06	1.89	2.84	2.08	3.10	1.43	5.25	3.14	1.88	ns	*
Total emission	26.94	28.13	27.89	32.06	29.80	26.72	37.84	31.71	28.63	ns	ns
Total emission excluding soil C	26.48	27.75	28.42	28.70	27.49	26.22	27.16	27.16	28.17	ns	ns

[a] Sig = significance: ns = non significant, * = P≤0.05, ** = P≤0.01.

Table 11 Sensitivity elasticities for the effect of 1% change in soil C change external factor ($r_w \times r_T$) and initial soil organic carbon (SOC) on the greenhouse gas (GHG) emission intensities CO_2 eq (kg carcass)$^{-1}$.

		East (n=16)		Southwest (n=2)		Mid (n=4)		North (n=5)		Sig[a]
	Response	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Initial soil organic carbon	Linear	0.17	0.09	0.20	0.14	0.10	0.24	0.23	0.15	ns
Soil C change external factor[b]	Non-linear	0.17	0.04	0.12	0.02	0.19	0.03	0.19	0.03	ns

[a] Sig = significance: ns = non significant
[b] Mean sensitivity elasticity (%) for the the change ±1% of $r_w \times r_T$

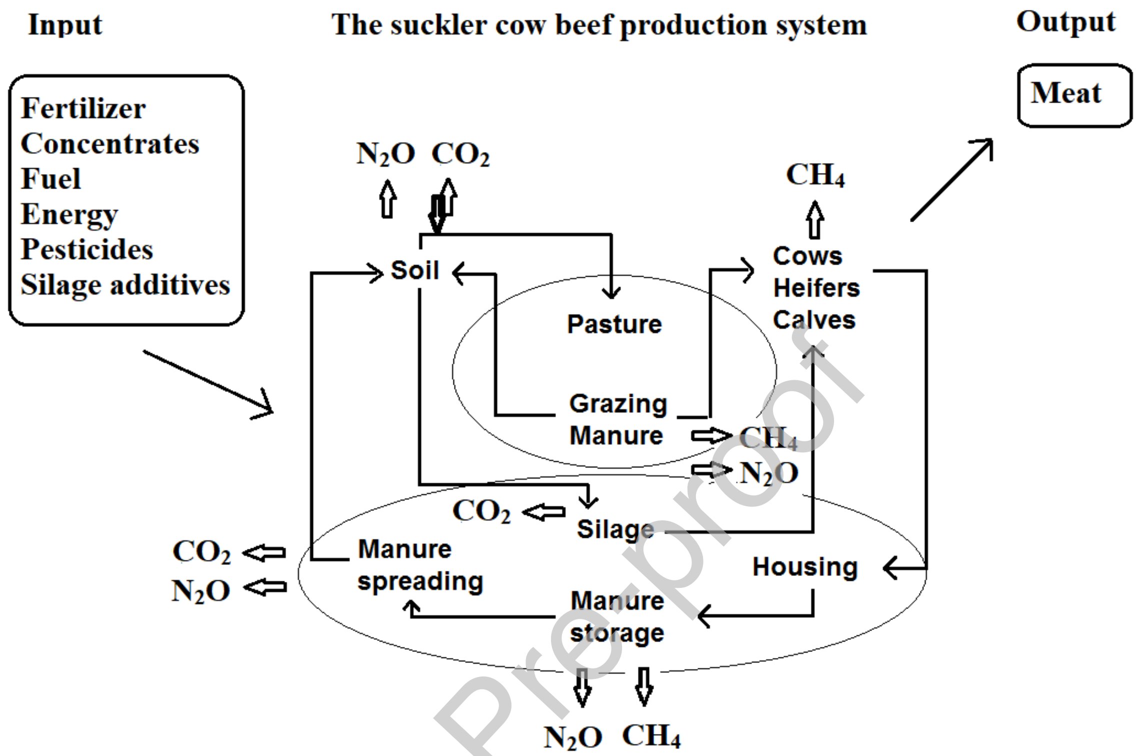

Figure 1 System boundaries of the suckler cow beef production system (Samsonstuen et al., 2019).

Author Statement

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Conflict of interest

The authors have no conflict of interest to disclose.