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Farm scale modelling of greenhouse gas emissions from semi-intensive suckler cow beef production

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ABSTRACT

A whole-farm model, HolosNorBeef was developed to estimate net greenhouse gas (GHG) emissions from suckler beef production systems in Norway. The model considers direct emissions of methane (CH_4), 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 leaching, volatilization and inputs used on the farm. The emission intensities from average beef cattle farms in Norway was estimated by considering typical herds of British and Continental breeds located in two different regions, flatlands and mountains, with different resources and quality of feed available. The flatlands was located at a low altitude in an area suitable for grain production and mountains was located at higher altitude in a mountainous area not suitable for grain production. The estimated emission intensities were 29.5 and 32.0 kg CO_2 equivalents (eq) kg^{-1} carcass for the British breeds and 27.5 and 29.6 kg CO_2 eq kg^{-1} carcass for the Continental breeds, for flatlands and mountains, respectively. Enteric CH_4 was the largest source accounting for 44–48% of total GHG emissions. Nitrous oxide from manure and soil was the second largest source accounting for, on average, 21% of the total emissions. Carbon sequestration reduced the emission intensities by 3% on average. When excluding soil C the difference between locations decreased in terms of GHG emission intensity, indicating that inclusion of soil C change is important when calculating emission intensities, especially when production of feed and use of pasture are included.

1. Introduction

The global population is expected to reach 9.73 billion by 2050 and it is estimated that global food production needs to increase by 50% compared with 2012 levels (FAO, 2017). Human population growth and climate change are exerting pressure on agricultural production systems to secure food production while minimizing greenhouse gas (GHG) emissions. In 2015, agriculture accounted for 10% of the total GHG emissions in Europe (European Environment Agency, 2017). It is a political goal to reduce total GHG emissions 40% by 2030 compared with 1990 levels (European Commission, 2014) and the agricultural sector is expected to contribute.

In compliance with policy commitments to reducing total GHG emissions, livestock supply chains have focused on decreasing GHG emission intensity, which is a measure of the quantity of GHG emissions generated in the production of a product. Focusing on emission intensity allows the industry to grow, but with less GHG emissions relative to the amount of product produced. In the case of beef, it is necessary to reduce emission intensities considerably, as global beef production is expected to increase by 72% when compared to 2000 levels (FAO, 2006). The emission intensity of beef production has been investigated in a number of studies (Beauchemin et al., 2010, 2011; Foley et al., 2011; Mogensen et al., 2015; Alemu et al., 2017) and varies widely, ranging from 17 to 37 CO_2 eq (kg^{-1} carcass) and 16.3–38.8 CO_2 eq (kg^{-1} live weight sold). The substantial variation in GHG emissions intensities for beef production systems are due to differences in farming systems (Nguyen et al., 2010), location (White et al., 2010) and farm management (Alemu et al., 2017). In terms of farm management, it has been shown that farm technical efficiency improvements have an important role to play in reducing GHG emissions intensity (Beauchemin et al., 2011; Zhang et al., 2013).

Whole farm systems models are useful for assessing the impact of

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improvements in technical efficiency and direct mitigation options on farm-level GHG emissions and emission intensity. In a review of farm-level modelling approaches by Schils et al. (2007) it was concluded that a whole-farm approach is a powerful tool for development of cost effective mitigation options, as interactions between farm components are revealed.

Previous studies have found substantial differences in emission intensities among continents (Gerber et al., 2013) and among farms within a country (Bonesmo et al., 2013), depending upon natural resources and farm management. Norway is a country with varying production conditions, with large areas suitable as pastures and only a small area (1%) suitable for grain production (Åby et al., 2014), limited by climate and topography. Most farm-level modelling studies assume that soil carbon (C) is at equilibrium. However, Soussana et al. (2007) concluded that European grasslands are likely to act as atmospheric C sinks. The net impact of including soil C in farm level modelling studies of beef production is not clear.

Thus, the aim of this study was to 1) develop a whole farm GHG model, HolosNorBeef, which includes changes in soil C and is adapted to the various production systems and feed resources in Norway, and 2) to use the model to evaluate the GHG emissions form typical suckler beef cow herds in two geographically different regions of Norway with different resources and quality of feed available.

2. Materials and methods

2.1. HolosNorBeef

The HolosNorBeef model was developed to estimate net GHG emissions from suckler beef production systems in Norway. It is an empirical model based on the HolosNor model (Bonesmo et al., 2013), BEEFGEM (Foley et al., 2011) and the methodology of the Intergovernmental Panel on Climate Change (IPCC, 2006) modified for suckler beef production systems under Norwegian conditions. The suckler cow beef production system in Norway is semi-intensive with extensive (low concentrate; approx. 0–10%) feeding of suckler cows, calves and heifer progeny and intensive (high concentrate; approx. 50%) finishing of male progeny as bulls for meat production (Åby et al., 2012). Suckler cows are kept indoors on during winter (approx. 8 months) during which time they are fed grass silage, hay or straw and minimal amounts of concentrates. During summer (approx. June to mid-September) they are kept on pasture with their calves. Mating season is during pasture and the calving season is from March to mid-June. Calves are weaned at 6 months of age, and the bull progeny are then fed a high concentrate diet (approx. 50%) until they are slaughtered at a relatively early age (average 16.7 months; Animalia, 2017a). Heifers are retained as replacements, sold or slaughtered. The cow-calf enterprise and finishing of bulls take place at the same farm. The most numerous breeds in Norway are: Charolais, Hereford, Limousin, Aberdeen Angus and Simmental (Animalia, 2017b). Data for the present study were obtained from The Norwegian Beef Cattle Herd Recording System that maintains individual data for animals from birth to slaughter, including weights, reproductive traits and carcass data. HolosNorBeef also includes the data for feed resources, diets and manure management, soil characteristics and weather.

HolosNorBeef was developed in Microsoft Excel (Microsoft Corporation, 2016) and is a two-step model where the first sub-model incorporates a detailed description of the farm to be used in the second sub-model (Section 2.1.1) that estimates on-farm GHG emissions (Section 2.1.2.) using a cradle to farm gate approach. The GHG sub-model considers direct emissions of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) from on-farm livestock production including soil 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 (Fig. 1). Direct emissions from animal production are calculated on a monthly basis, accounting for diet and weather differences. All GHG emissions are expressed as CO_2-equivalents (eq) to account for the global warming potential of the respective gases for a time horizon of 100 years: $CH_4(kg) \times 28 + N_2O(kg) \times 265 + CO_2(kg)$ (Myhre et al., 2013). Emissions intensities are expressed as GHG emissions (kg CO_2 eq) per kg beef carcass produced.

2.1.1. Input sub-model

The input sub-model gives a detailed description of the number of animals in each class of cattle, the animal live weights, energy requirements and feed intake on a monthly basis. The monthly live weights for each class of cattle are based on birth weights, weaning weights, yearling weights, slaughter weights and adult weights. The weight at the start of each month are calculated based on the starting live weight and live weight change for the previous month. The number of animals in each class of cattle at the start of each month is based on the number at the start of the previous month adjusted for the number of calvings, stillbirths, twin frequency, mortality rate and any sales and purchases in the previous month. The replacement rate is set to keep the farm size constant and kg beef carcass produced is calculated based on the number of animals sold to abattoirs, slaughter weights and dressing percentages.

Daily energy requirements of each class of cattle are estimated according to Refsgaard Andersen (1990) and are based on the animals' requirements for maintenance, growth, pregnancy and lactation. Dry matter intake (DMI) considers the energy requirements of the animal and the animals' intake capacity and is calculated for each animal group. Intake capacity is dependent on the fill value of the forage as well as the substitution rate of the concentrates (Refsgaard Andersen, 1990). Gross energy (GE) intake is estimated based on dry matter intake and the GE content of the diet. The nutrient content of the diet is determined from the chemical composition of commercial concentrates produced by the two largest feed mills in Norway (Felleskjøpet SA, Oslo Norway; Norgesfor AS, Oslo Norway) and forages (laboratory analysis information provided by Eurofins, Moss Norway).

2.1.2. GHG emissions sub-model

2.1.2.1. Methane emissions. HolosNorBeef estimates enteric CH_4 emissions for each class of cattle using an IPCC (2006) Tier 2 approach. Enteric CH_4 emissions are calculated from GE intake using an adjusted CH_4 conversion factor (Ym = 0.065; IPCC, 2006). The Ym is adjusted for the digestibility of the diet according to Bonesmo et al. (2013), as suggested by Beauchemin et al. (2010; Table 1). Manure CH_4 emissions are based on the production of volatile solids (VS) according to IPCC (2006), taking the GE content and digestibility of the diet into account. The VS production is multiplied by a maximum CH_4 producing capacity of the manure ($B_o = 0.18\,m^3\,CH_4\,kg^{-1}$) and a CH_4 conversion factor specific for the management practice used (Table 1).

2.1.2.2. Nitrous oxide emissions. The direct N_2O emissions from manure are calculated by multiplying the manure N content with an emission factor for the manure handling system; deep bedding or deposited on pasture (Table 1; IPCC, 2006). Manure N content is estimated based on DMI, crude protein (CP; CP = 6.25 × N) content of the diet and N retention by the animals based on IPCC (2006).

Direct N_2O emissions from soils are estimated based on N inputs, using the IPCC (2006) emission factor of 0.01 kg N_2O-N kg^{-1} N applied. Total N inputs include application of N fertilizer and manure, grass and crop residual N and mineralized N (Table 1). Straw from grain crop is left on the fields and is included in residue N. Residue N is calculated as the sum of above- and below ground residue, using the crop yields of Janzen et al. (2003). Mineralization of N inputs is calculated using the derived C:N ratio of organic soil matter of 0.1 (Little et al., 2008). To account for location specific effects of soil moisture and temperature, the relative effects of percentage water filled pore space (WFPS) of top soil and soil temperature at 30 cm depth (ts30 °C) are based on Sozanska et al. (2002) and included as described by Bonesmo et al.

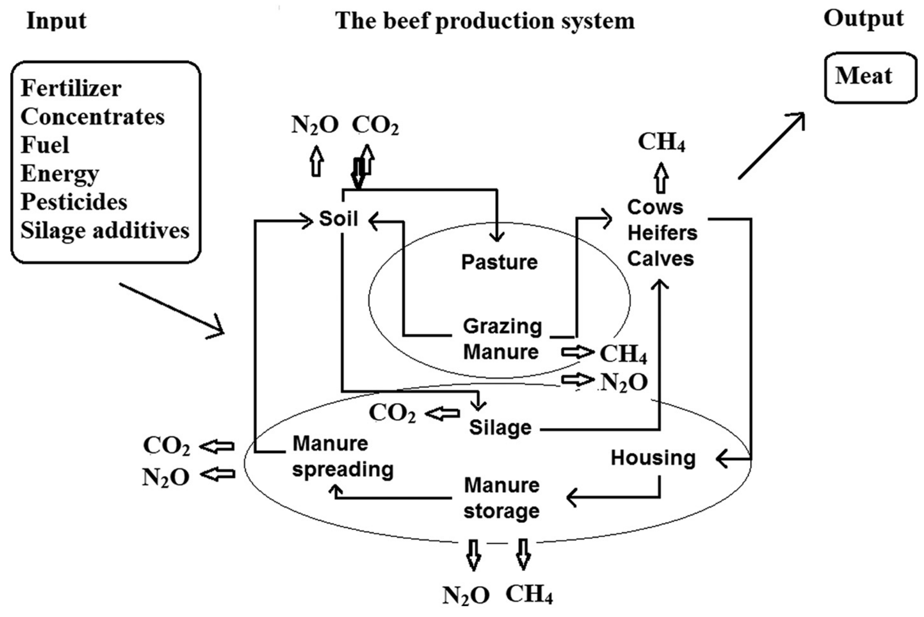

Fig. 1. The suckler cow beef production system.

(2012; Table 1). Seasonal variations were taken into account by including four seasons; spring (April–May), summer (June–August), fall (September–November) and winter (December–March). The "timing effect" of the application of N fertilizer and manure were calculated using a crop specific factor (Sozanska et al., 2002) and used to calculate the N_2O-N for each season based on WFPS and ts30 °C.

The indirect N_2O emissions emitted on farm from run-off, leaching and volatilization (Table 1) are estimated from assumed losses of N from manure, residues and fertilizer according to IPCC (2006). The emissions were estimated based on the assumed fraction of N lost adjusted for emission factors (0.0075 and 0.01 kg N_2O-N kg^{-1}) for leaching and volatilized ammonia-N, respectively (IPCC, 2006).

2.1.2.3. Soil C change. Estimates of soil C change are based on the Introductory Carbon Balance Model (ICBM) by Andrén et al. (2004). The model considers two soil C pools; young (Y) and old (O), accounting for 7% and 93% of the initial C content of the top soil, respectively. The change in Y and O soil C are estimated from total C inputs (i), a humification coefficient (h; Table 1), two decay constants (k_Y and k_O; Table 1) and the relative effect of soil moisture (r_W) and temperature (r_T). Total soil C inputs are calculated from crop residues and manure as described by Andrén et al. (2004). Similar to HolosNor (Bonesmo et al., 2013), regional differences are accounted for by including annual soil and climate data, which are based on the specific crop and soil type together with weather data from specific sites. The yearly C fluxes of Y and O soil C are given by the differential equations of Andrén and Kätterer (1997):

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

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

2.1.2.4. Carbon dioxide emissions. HolosNorBeef estimates CO_2 emissions from energy use. Direct emissions from use of diesel fuel and off-farm emissions from production and manufacturing of farm inputs (i.e. fertilizers and pesticides) are estimated using emission factors from Norway or Northern-Europe (Table 1). Indirect emissions related to purchased concentrates are estimated according to Bonesmo et al. (2013). The amount of purchased concentrates is estimated based on the concentrate deficit, determined as the concentrate required to meet the energy and CP requirements minus grain and oilseeds grown on the farm. The deficit is assumed to be supplied by barley and oats grown in Norway and soybean meal imported from South America (Table 1). On-farm emissions from production of field crops produced on the farm but not used in the beef enterprise (e.g. either sold or consumed by other classes of farm animals) are not included in the total farm emissions related to beef production.

2.2. Norwegian suckler beef production system

Four farms representative of beef production systems in Norway were modelled. The farms represent 'typical' Norwegian farms in term of scale, production results, feeding regimes and location within the country. The locations chosen for the study are areas with a large proportion of Norwegian suckler cow production and are referred to as flatlands and lowlands. The administrative center of flatlands (latitude/longitude 60.9/10.7) has an altitude of 246 m above sea level (m.a.s.l), whereas mountains (latitude/longitude 62.5/9.7) is located at 545 m.a.s.l. The locations have different resource bases and average temperatures (Table 2), and on a scale from 1 (good) to 8 (harsh) as compiled by Norwegian Meterological Insitute and Det norske hageselskap (2006), flatlands and mountains are within climatic zone 4 and 7, respectively. The locations differ in farm size and areas available for forage and crop production, which influence the use of different input factors.

The input data were average beef cattle production data (Åby et al., 2012; Animalia, 2017a,b), farm operational data from the Norwegian Institute of Bioeconomy Research (NIBIO, 2015) and soil and weather data (Skjelvåg et al., 2012) for the specific locations. The farm operational data are annual status reports based on tax results from a representative random sample of 81 Norwegian farms distributed across the country, whereas 21 and 11 were located in the flatland and mountains, respectively (NIBIO, 2015). In each location an average herd of British (Angus and Herford) and Continental (Limousin, Simmental and Charlolais) breeds were considered. The breed specific weights at different ages, proportion of stillborn calves, twin frequency and proportion dead before 180 days (Table 3) were obtained from Åby et al. (2012) and Animalia (2017a,b). The herd size and number of cattle in each class were based on average number of cows, average number of calvings and average number of heifers and calves (Table 4) obtained from NIBIO (2015). Estimates of proportion of concentrates

Table 1
Sources of GHG emissions, emission factors or equations used and reference source.

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	$0.1058 - 0.006 \times DE$	(Bonesmo et al., 2013)[a]
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)
Pasture manure	0.01 kg CH_4 (VS)$^{-1}$	(IPCC, 2006)
Direct nitrous oxide		
Soil N inputs[b]	0.01 kg N_2O-N (kg N)$^{-1}$	(IPCC, 2006)
Relative effect of soil water filled pore space (WFPS mm)	$0.4573 + 0.01102 \times \text{WFPS}$	(Sozanska et al., 2002)[c], (Bonesmo et al., 2012)[c]
Relative effect of soil temperature at 30 cm (ts30°C)	$0.5862 + 0.03130 \times \text{ts30}$	(Sozanska et al., 2002)[c],(Bonesmo et al., 2012)[c]
Deep bedding manure	0.01 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[b]	Leaching:	
	EF = 0.0075 kg N_2O-N (kg N)$^{-1}$, $Frac_{leach}$ = 0.3 kg N (kg N)$^{-1}$	(IPCC, 2006), (Little et al., 2008)[d]
	Volatilization:	
	EF = 0.01 kg N_2O-N (kg N)$^{-1}$, $Frac_{volatilization}$ = 0.1 kg N (kg N)$^{-1}$	(IPCC, 2006)
Deep bedding manure	Leaching:	
	EF = 0.0075 kg N_2O-N (kg N)$^{-1}$, $Frac_{leach}$ = 0 kg N (kg N)$^{-1}$	(IPCC, 2006)
	Volatilization:	
	EF = 0.01 kg N_2O-N (kg N)$^{-1}$, $Frac_{volatilization}$ = 0.3 kg N (kg N)$^{-1}$	(IPCC, 2006)
Pasture manure	Leaching:	
	EF = 0.0075 kg N_2O-N (kg N)$^{-1}$, $Frac_{leach}$ 0.3 kg N (kg N)$^{-1}$	(IPCC, 2006), (Little et al., 2008)[d]
	Volatilization:	
	EF = 0.01 kg N_2O-N (kg N)$^{-1}$, $Frac_{volatilization}$ = 0.2 kg N (kg N)$^{-1}$	(IPCC, 2006)
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., 2009)
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 30 cm; EF = emission factor; $Frac_{leach}$ = Leaching fraction; $Frac_{volatilization}$ = Volatilization fraction.

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

[b] Includes land applied manure, grass and crop residue, synthetic N fertilizer, mineralized N.

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

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

and time spent on pasture for each cattle class were available from Åby et al. (2012). The manure was assumed to be deposited on pasture during the grazing period and during housing the manure handling system was deep bedding. The areas (ha) and yields (kg ha^{-1}) of grass, barley, oats, winter wheat and summer wheat were obtained from NIBIO (2015; Table 4). The reduced tillage ratios for oats, barley, spring- and winter wheat were zero. The DM contents and nutritive values of the grass silages were estimated using data from Eurofins for the specific locations (Table 4). Use of energy, fuel and pesticides were available through the costs (NIBIO, 2015; Table 4). Cost of pesticides was distributed to the various crops according to Bonesmo et al. (2013) using relative weighting factors: barley, 1.00; oats, 0.51; spring wheat, 1.05; winter wheat, 1.71; and grass production, 0.15. The use of fertilizers was based on the Norwegian recommendations for N, P and K application levels for the specific crops (Table 4). Seasonal soil and weather data were available through Skjelvåg et al. (2012; Table 5).

2.3. Sensitivity analysis

A sensitivity analysis was performed to evaluate possible errors in the most important emission factors (EF): CH_4 conversion factor (Ym), manure N_2O (IPCC, 2006), soil N_2O (IPCC, 2006), manufacturing of N-fertilizer (DNV, 2010), and a combined indirect and direct EF for fuel (The Norwegian Environment Agency, 2017; Öko-Institut, 2010). In addition, the sensitivity of the yearly effect of temperature and soil moisture ($r_w \times r_T$), and initial soil organic carbon content was investigated. A farm with British breeds located in the flatlands were chosen as a baseline for the sensitivity analysis. Emission factors were changed 1%, and emission intensities were re-calculated and related to the baseline as a percentage change in emission intensities. The sensitivity of farm and herd size was tested based on variation in the farm operational data from NIBIO (2015) by evaluating a small and a large farm of British breeds located in the flatlands (Table 6).

Table 2

Average temperatures (C°) with min and max temperatures (in parenthesis) and land resources (ha) with proportion of total area (in parentheses) from two different locations (flatlands and mountains) in Norway.

	Flatlands	Mountains
Climatic zone[a]	4[*]	7[*]
Average temperatures		
Spring (C°)[a]	6.2 (-13.6;30.7)	5.3 (-15;20.7)
Summer (C°)[a]	14.4 (1.9;25.0)	11.1 (0.1;24.5)
Fall (C°)[a]	5.6 (-9.4;18.6)	4.1 (-17.6;18.4)
Winter (C°)[a]	-5.6 (-25.2;8.9)	-4.2 (-22;10.1)
Land resources		
Cultivated land/cropland (ha)[b]	16,466 (0.13[**])	4273 (0.02[**])
Cultivated pastures (ha)[b]	3288 (0.02[**])	3964 (0.02[**])
Forest (ha)[b]	70,333 (0.55[**])	36,627 (0.16[**])
Bare land (ha)[b]	7335 (0.06[**])	161,558 (0.71[**])
Rich vegetation (ha)[b]	3223 (0.44[***])	40,258 (0.25[***])
Medium rich vegetation (ha)[b]	734 (0.10[***])	39,369 (0.24[***])
Poor vegetation (ha)[b]	41 (0.01[***])	52,842 (0.33[***])
Bare mountain (ha)[b]	0 (0.00[***])	20,688 (0.13[***])
Unclassified (ha)[b]	3337 (0.45[***])	8400 (0.05[***])

[a] NRK and Norwegian Meterological Insitute (2018).

[b] Norwegian Institute of Bioeconomy Research (NIBIO, 2018).

[*] On a scale from 1 (good) to 4 (harsh).

[**] Do not sum up to 100% as area unrelated to agriculture are left out of the table.

[***] Proportion of bare land.

Table 3

Average animal data for Norwegian beef farms used to estimate GHG emission intensities in two locations.

Farm characteristics (unit)	British	Continental
Beef produced (kg carcass)[ab]	7699	9635
Cows, average weight (kg LW)[c]	600	800
Cows, carcass weight (kg)[c]	324	432
Cows, concentrate (proportion)[c]	0.25	0.17
Cows, time on pasture (proportion)[c]	0.36[*]	0.38[**]
Milk, yield (kg raw milk year^{-1})[c]	1100	1600
Twinning frequency (%)[a]	1.9	3.0
Still born (%)[a]	3.5	3.9
Dead before 180 days (%)[a]	3.6	4.1
Gender distribution (proportion heifers)[c]	0.5	0.5
Heifers, birth weight (kg LW)[c]	38	42
Heifers, weaning weight (kg LW)[c]	251	295
Heifers, yearling weight (kg LW)[c]	365	416
Heifers, carcass weight (kg)[c]	206	244
Heifers, age at slaughter (month) [a]	18.2	17.5
Heifers, age at first calving (month)[c]	26.5	28.9
Heifers, concentrate birth-slaughter (proportion)[c]	0.22	0.38
Heifers, time on pasture (proportion)[c]	0.19	0.13
Young bulls, birth weight (kg LW)[c]	40	45
Young bulls, weaning weight (kg LW)[c]	269	322
Young bulls, yearling weight (kg LW)[c]	445	547
Young bulls, carcass weight (kg)[a]	291	353
Young bulls, age at slaughter (month)[a]	17.5	16.8
Young bulls, concentrate birth-slaughter (proportion)[c]	0.53	0.50

LW = live weight.

[a] Animalia (2017a).

[b] Norwegian Institute of Bioeconomy Research (NIBIO, 2015).

[c] Åby et al. (2012).

[*] 42% cultivated pasture, 58% outfield pasture.

[**] 50% cultivated pasture, 50% outfield pasture.

Table 4

Average animal numbers, crop and fuel usage data for Norwegian beef farms used to estimate GHG emission intensities from two different locations (flatlands and mountains) in Norway.

Farm characteristics	Flatlands	Mountains
Animal system		
Cows (year^{-1})[a]	28	28
Calves born (year^{-1})[a]	28	28
Replacement heifers (year^{-1})[a]	10	10
Heifers slaughtered (year^{-1})[a]	4	4
Young bulls slaughtered (year^{-1})[a]	13	13
Input use		
Fuel (L year^{-1})[a]	3854	2947
Electricity (kWh year^{-1})[a]	26,300	29,100
Silage additive (kg CH_2O_2 year^{-1})[b]	803	416
Ley synthetic fertilizer (kg N ha^{-1})[b]	13	13
Ley pesticide (MJ ha^{-1})[a]	1.1	1.1
Barley synthetic fertilizer (kg N ha^{-1})[b]	9.5	9.5
Barley pesticide (MJ ha^{-1})[a]	29.8	29.1
Oats synthetic fertilizer (kg N ha^{-1})[b]	8.5	8.5
Oats pesticide (MJ ha^{-1})[a]	14.5	14.1
Spring wheat synthetic fertilizer (kg N ha^{-1})[b]	10	10
Spring wheat pesticide (MJ ha^{-1})[a]	34.1	33.2
Winter wheat synthetic fertilizer (kg N ha^{-1})[b]	12.1	12.1
Winter wheat pesticide (MJ ha^{-1})[a]	64.1	64.1
Land use		
Farm size (ha)[a]	44.6	41.5
Pasture and ley area (ha)[a]	38.9	40.1
Grass yield (FUm ha^{-1})[a]	3020	3190
Grass silage nutritive value (FUm)[c]	0.87	0.84
Barley area (ha)[a,d]	3.0	0.9
Barley yield (kg DM ha^{-1})[a,d,e]	4310	2840
Oats area (ha)[a,d]	1.5	0.1
Oats yield (kg DM ha^{-1})[a,d,e]	4030	2960
Spring wheat area (ha)[a,d]	1.1	0.0
Spring wheat yield (kg DM ha^{-1})[a,d,e]	4860	3870
Winter wheat area (ha)[a,d]	0.1	0.0
Winter wheat yield (kg DM ha^{-1})[a,d,e]	4860	3870

FUm = feed units milk.

[a] Norwegian Institute of Bioeconomy Research (NIBIO, 2015).

[b] Norwegian Institute of Bioeconomy Research (NIBIO, 2016).

[c] Eurofins (2015).

[d] Statistics Norway (2017).

[e] NMBU and Norwegian Food Safety Aguthority, (2008).

3. Results

The total emissions ranged from 227 to 284 t CO_2 eq. In both locations British breeds had less total net emissions than Continental breeds (Table 7). Enteric CH_4, manure CH_4 and manure N_2O emissions were greater for the Continental breeds in both locations. Soil N_2O emissions were greater for flatlands. Flatlands had greater soil C sequestration and greater energy CO_2 emissions.

Enteric CH_4 contributed most to the GHG emissions, accounting for 44–48% of the emissions (Table 7). Nitrous oxide from manure and soil were the second largest source, each accounting for on average 10% of the total emission. Direct CH_4 emissions from manure accounted for 10–12% of total emissions. Soil C balance was negative for Continental breeds in both locations and British breeds in flatlands, indicating C sequestration. However, British breeds had positive soil C in mountains, indicating a loss of soil C. The on-farm direct emissions from burning of fossil fuels accounted for 5–8% of the total emissions.

The emission intensities were greater for the British breeds (29.5 to 32.0 kg CO_2 eq kg^{-1} carcass) compared with the Continental breeds (27.5 to 29.6 kg CO_2 eq kg^{-1} carcass) in both locations (Table 8).

Enteric CH_4 conversion factor had the highest sensitivity elasticity, having a 0.45% change in emission intensities caused by one percentage change in Ym (Table 9). The estimated GHG were moderate sensitive to changes in manure N_2O EF, soil N_2O EF, N-fertilizer EF, and fuel EF ranging from 0.09 to 0.12%. The initial soil organic carbon and the yearly effect of soil temperature and soil moisture ($r_w \times r_T$) had a moderate linear and moderate non-linear response, respectively (Table 9). The total emissions increased with increasing farm and herd size. In terms of emission intensities, the changed farm and herd size increased the emission intensities for the small farm and reduced the emission the emission intensities for the large farm (Table 10).

Table 5
Natural resource data used to estimate GHG emission intensities from two different locations (flatlands and mountains) in Norway (Bonesmo et al., 2013; Skjelvåg et al., 2012).

	Flatlands		Mountains	
	Grassland	Field crops	Grassland	Field crops
Soil temperature at 30 cm depth, winter (°C)[a]	-0.68	-0.67	-0.39	0.90
Soil temperature at 30 cm depth, spring (°C)[a]	5.37	5.16	3.85	6.67
Soil temperature at 30 cm depth, summer (°C)[a]	13.79	13.80	10.81	13.93
Soil temperature at 30 cm depth, fall (°C)[a]	5.20	5.16	4.05	6.95
Water filled pore space, winter (%)[b]	65	65	74	68
Water filled pore space, spring (%)[b]	48	51	57	55
Water filled pore space, summer (%)[b]	43	48	45	51
Water filled pore space, fall (%)[b]	62	65	65	68
$r_w \times r_T$ yearly (dimensionless)[c]	0.94	1.06	0.65	1.29
Soil organic C (Mg ha^{-1})	6		8	

[a] Estimated according to Katterer and Andren (2009).
[b] Estimated according to Bonesmo et al. (2012).
[c] Estimated according to Andrén et al. (2004).

Table 6
Average animal numbers, carcass production, land use and farm inputs for small and large farms of British breeds located in the flatlands used to investigate the sensitivity to variation in farm size and corresponding impact on GHG emission intensities compared with the average farm[*].

Farm characteristics	Small farm	Large farm
Animal system		
Cows (year^{-1})[a]	14.4	38
Calves born (year^{-1})[a]	14.4	40
Replacement heifers (year^{-1})[a]	5	14
Heifers slaughtered (year^{-1})[a]	2	5
Young bulls slaughtered (year^{-1})[a]	7	19
Beef produced (kg carcass)[a,b]	3946	10,851
Input use		
Fuel (L year^{-1})[a]	2071	5729
Electricity (kWh year^{-1})[a]	18,300	38,200
Silage additive (kg CH_2O_2 year^{-1})[c]	323	593
Land use		
Farm size (ha)[a]	25.1	74.8
Pasture and ley area (ha)[a]	24.6	63.3
Barley area (ha)[a,d]	0.2	5.9
Oats area (ha)[a,d]	0.1	3.0
Spring wheat area (ha)[a,d]	0.1	2.1
Winter wheat area (ha)[a,d]	0.0	0.9

[*] Factors not included are similar to the baseline, British breeds located in the flatland.
[a] Norwegian Institute of Bioeconomy Research (NIBIO, 2015).
[b] Animalia (2017a).
[c] Norwegian Institute of Bioeconomy Research (NIBIO, 2016).
[d] Statistics Norway (2017).

Table 8
GHG emission intensities from average herds of British and Continental breeds in two different locations (flatlands and mountains) in Norway (CO_2 eq kg^{-1}carcass).

	Flatlands		Mountains	
	British	Continental	British	Continental
Enteric CH_4	14.03	13.26	14.07	13.29
Manure CH_4	3.22	3.17	3.25	3.20
Manure N_2O	3.01	2.79	3.04	2.81
Soil N_2O	3.27	3.02	3.08	2.81
Soil C	-1.76	-2.13	0.31	-0.32
Off-farm barley	0.85	1.23	1.64	1.90
Off-farm soya	1.38	1.74	1.89	2.10
Indirect energy	3.26	2.60	2.98	2.38
Direct energy	2.29	1.83	1.75	1.40
Total emissions	29.54	27.50	32.01	29.58
Total emissions ex. soil C	31.31	29.63	31.70	29.89

4. Discussion

The HolosNorBeef model is derived from IPCC methodology (2006) with modifications to accommodate Norwegian conditions, similar to the original HOLOS model developed for Canada (Little et al., 2008). Most whole-farm system models are based on IPCC methodology (Crosson et al., 2011), but adapting the methodology for local, regional or national conditions improves the sensitivity of the model to differences in production and environmental circumstances. The estimated emission intensities in the present study are comparable with the range of intensities for beef presented by Crosson et al. (2011). The range of

Table 7
Emissions and proportion of total emissions (in parenthesis) from average herds of British and Continental breeds in two different locations (flatlands and mountains) in Norway (kg CO_2 eq).

	Flatlands		Mountains	
	British	Continental	British	Continental
Enteric CH_4	108,011 (0.47)	127,729 (0.48)	108,307 (0.44)	128,091 (0.45)
Manure CH_4	24,814 (0.11)	30,532 (0.12)	25,054 (0.10)	30,823 (0.11)
Manure N_2O	23,176 (0.10)	26,835 (0.10)	23,384 (0.9)	27,068 (0.09)
Soil N_2O	25,145 (0.11)	29,059 (0.11)	23,713 (0.10)	27,108 (0.10)
Soil C	-13,574 (-0.06)	-20,524 (-0.08)	2381 (0.01)	-3046 (-0.01)
Off-farm barley	6526 (0.03)	11,895 (0.04)	12,638 (0.05)	18,266 (0.06)
Off-farm soya	10,658 (0.05)	16,772 (0.06)	14,516 (0.06)	20,229 (0.07)
Indirect energy	25,065 (0.11)	25,065 (0.09)	22,959 (0.09)	22,959 (0.08)
Direct energy	17,645 (0.08)	17,645 (0.07)	13,492 (0.05)	13,492 (0.05)
Total emissions	227,466	265,006	246,445	284,991
Total emissions ex. soil C	241,040	285,531	244,064	288,037

Table 9

Sensitivity elasticities for the effect of 1% change in the selected emission factors (EF) and initial soil organic carbon on the greenhouse gas (GHG) emission intensities CO_2 eq (kg carcass)$^{-1}$.

	Response	% change in CO_2 eq (kg carcass)$^{-1}$
Enteric CH_4 conversion factor, Ym	Linear	0.47
Manure N_2O EF	Linear	0.10
IPCC soil N_2O EF	Linear	0.09
Soil C change external factor[a]	Non-linear	0.16
Manufactoring fertilizer EF	Linear	0.10
Fuel combined EF	Linear	0.09
Initial soil organic carbon	Linear	0.12

[a] Mean sensitivity elasticity (%) for the change ± 1% of $r_w \times r_T$.

Table 10

The effect of farm and herd size on the greenhouse gas (GHG) emission intensities CO_2 eq (kg carcass)$^{-1}$.

	Small farm	Large farm
Enteric CH_4	14.52	13.50
Manure CH_4	3.31	3.12
Manure N_2O	3.14	2.88
Soil N_2O	3.34	3.31
Soil C	-1.49	-1.19
Off-farm barley	1.79	0.43
Off-farm soya	1.92	1.10
Indirect energy	3.63	3.75
Direct energy	2.40	2.42
Total emissions	32.57	29.31
Total emissions (% change from baseline[a])	10.12	0.88

[a] Baseline: average herd of British breeds located in the flatlands.

emission intensities across studies for different countries and production systems reflects the differences in assumptions, algorithms and approaches in addition to the differences in farm management, breed differences and natural resources. Direct comparisons across studies should therefore be done with caution.

The assessment in the present study used a cradle to farm gate approach, simulating both internal and external flows of the input factors to calculate the GHG emissions of beef production (Fig. 1). A whole-farm approach ensures that interactions are taken into account, and that the effects of changes in one factor are transferred throughout the system (Schils et al., 2007).

HolosNorBeef estimated emission intensities for average herds of British and Continental breeds in Norway of 27.5–32.0 CO_2 eq (kg carcass)$^{-1}$. This range of intensities is similar to the emission intensities reported for farming systems in Ireland: 23.1 CO_2 eq (kg carcass)$^{-1}$ (Foley et al., 2011), Denmark: 23.1-29.7 CO_2 eq (kg carcass)$^{-1}$ and Sweden: 25.4 CO_2 eq (kg carcass)$^{-1}$ (Mogensen et al., 2015). In those studies, emission intensities from enteric CH_4 varied depending upon the on feeding intensity (Ireland, 49.1% of total GHG emissions; Denmark/Sweden, 47.6–55.65% of total GHG emissions). In the present study, enteric CH_4 varied from 43.9 to 48.2% of total GHG emissions for the two breeds (Table 6). Mitigation strategies are often aimed at reducing enteric CH_4 emissions. The CH_4 conversion factor (i.e. Ym) had the highest sensitivity elasticity, thus a reliable Ym is crucial as a significant change in Ym due to feeding intensity would influence the emission intensities considerably. Comparisons between studies are challenging as there are differences in live weights and slaughter age between countries, leading to differences in feed requirements and dry matter intake. Suckler cows are feed a large proportion grass silage and pasture in both Norway and the other Scandinavian countries (Mogensen et al., 2015). Similar to the semi-intensive production system in Norway, the intensive system in Sweden and Denmark have an intensive finishing of bull calves with approx. 50% concentrates, whereas the proportion concentrates in heifer diets have more variation dependent on country and feeding intensity (Mogensen et al., 2015). The Irish and extensive beef production system in Denmark have a larger proportion pasture, and lower proportion of concentrates in the diet compared with average Norwegian beef production (Foley et al., 2011; Mogensen et al., 2015).

In flatlands for both breeds and mountains for the continental breeds, C sequestration had a mitigating effect on the emission intensity of beef production. The C mitigation was from the sequestration of manure, feed production and use of pasture. The British breeds produce less manure (due to lower DMI and body weight), which increases the use of synthetic fertilizer and reduces C sequestration. Soussana et al. (2007) concluded that European grasslands are likely to act as atmospheric C sinks, which underlines the importance of including C sequestration in the estimations of emission intensities from pastoral beef production systems.

Some whole-farm models, such as Irish BEEFGEM model (Foley et al., 2011), do not include C changes because the C sequestration in soils cannot continue indefinitely. As soil C builds, its decay also increases, and as rate of decay approaches rate of input, soil C reaches an approximate steady state (Guyader et al., 2016). By excluding the soil C change from our estimates, the emission intensities increase to 29.63–31.70 CO_2 eq (kg carcass)$^{-1}$ for the average farms (Table 8). When excluding soil C change the differences between locations decreased, which indicates that the inclusion of soil C in the calculation of emission intensities can have a marked effect on the outcome, especially for pastoral based beef production systems. The studies of beef production in Denmark and Sweden included the contribution from soil C changes based on the Bern Carbon Cycle Model of Petersen et al. (2013). The Bern Carbon Cycle Model quantifies the change in CO_2 in the atmosphere based on C added to the soil, the release of CO_2 from the soil and the decay of C. In Denmark and Sweden the contribution from C sequestration were from -1.8 to -2.4 CO_2 eq (kg carcass)$^{-1}$ (Mogensen et al., 2015). This is within the range of the level of C sequestration found in the present study of 0.31 to -2.13 CO_2 eq (kg carcass)$^{-1}$.

The Continental breeds are heavier, have a higher feed requirement, and thus produce more enteric CH_4. However, they also have a higher slaughter weight and produce more beef, thus emission intensity is lower. The location will dictate the use of pastures and can influence enteric CH_4 emissions through feed quality and C sequestration through soil, weather and use of inputs. In accordance with White et al. (2010), who reported average GHG emission intensities from beef production systems in New Zealand of 26.0 CO_2 eq (kg carcass)$^{-1}$ from lowlands and 34.0 CO_2 eq (kg carcass)$^{-1}$ in uplands, our estimates imply that location, farm size, resources and climatic conditions of the farm is important when estimating emission intensities. The locations in the present paper differ in both average temperatures and areas available for crop and silage production, cultivated pastures and outfield pastures (Table 2). The different climatic zones and altitudes influence the production conditions as well as crop and grass yields. By keeping the animal numbers and kg carcass produced constant within breed in the present paper, the emission intensities estimated can be interpreted in the context of location. Flatlands has higher soil N_2O and energy CO_2 emissions than mountains due to greater crop production and use of input factors such as fuel and fertilizer. However, greater crop and grass production in flatlands combined with favorable soil and weather conditions gives greater higher C sequestration compared with mountains. The sensitivity analysis indicate that the emission intensities are dependent on the farm and herd size within location in addition to resources and climatic condition as the emission intensities increase when farm size is reduced.

HolosNorBeef does not include aspects of sustainability beyond GHG emissions, which is important to consider in the climate debate. Suckler cow beef accounts for approx. 30% of the beef production in Norway (Animalia, 2018) and the remaining 70% are from dual purpose milk and beef production. The use of pastoral systems have several advantages (i.e., reduced feed costs, animal welfare, carbon sequestration, maintenance of landscape) and grazing preserves biodiversity (Luoto et al., 2003 as cited by Mogensen et al., 2015; Guyader et al., 2016) as well as increases the albedo effect (Kirschbaum et al., 2011). The ecosystems services provided by pastoral beef production systems are not captured by models estimating GHG intensities.

The scenarios examined in the present study estimate average emissions based on average farms and management practices, disregarding uncertainties associated with the input data as the use of average farms give a transparent evaluation of the model. Use of average farm scenarios for estimating GHG emissions has limitations, and does not account for the variation in production systems, choice of breed due to resource base, management practices, feeds and feed quality. Future uses of the model will estimate the emission intensities from actual farms distributed geographically across Norway.

5. Conclusions

The whole-farm approach estimated emission intensities of 27.5–32.0 CO_2 eq (kg carcass)$^{-1}$ from typical herds of British and Continental breeds in two geographically different regions. When excluding soil C the difference between locations decreased in terms of GHG emission intensity, which imply that geographical location is important to consider when estimating emission intensities. Soil C changes must be included in the model for a more a more complete assessment of GHG intensity of beef production from pastoral systems.

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