

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 (CH₄), nitrous oxide (N₂O) and carbon dioxide (CO₂) from on-farm livestock production and indirect N₂O and CO₂ 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 CO₂ equivalents (eq) (kg carcass)⁻¹. Enteric CH₄ 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 CO₂ 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.

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 CH₄ (Gerber et al., 2013). In Norway, enteric CH₄ accounts for 44–48% of total farm emissions from beef cattle production systems (Samsonstuen et al., 2019). The diet influences CH₄ emissions through

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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 CH₄ emissions (Sveinbjörnsson, 2006). Enteric CH₄ 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 CH₄ 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 et al., 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 (McCaughy 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 CH₄ and N₂O, 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 CO₂ eq kg⁻¹ carcass for British breeds, and 27.5 and 29.6 CO₂ 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 Meteorological Institute 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, 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

Table 1Average 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

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 N₂O 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 (CH₄) from enteric fermentation and manure, nitrous oxide (N₂O) and carbon dioxide (CO₂) from on-farm livestock production including soil carbon (C) changes, and indirect N₂O and CO₂ emissions associated with runoff, nitrate leaching, ammonia volatilization and from inputs used on the farm ([Figure 1](#); adopted by [Samsonstuen et al., 2019](#)). All emissions are expressed as CO₂ eq to account for the global warming potential (GWP) of the respective gases for a time horizon of 100 years: CH₄ (kg) × 25 + N₂O × 298 + CO₂ (kg) ([IPCC, 2007](#)). Emission intensities from suckler cow beef production are related to the on farm beef production and expressed as kg CO₂ eq (kg beef carcass)⁻¹.

2.2.1.1. Methane emissions. Enteric CH₄ 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

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).

Unit	Angus				Hereford				Charolais			
	DM %	FUm ^{ab}	CP g/kg DM	DE %	DM %	FUm	CP g/kg DM	DE %	DM %	FUm	CP g/kg DM	DE %
Concentrates ^c	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)
Silage ^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)
Straw, NH ₃ ^d	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, dry ^d	0.86	0.70	95	52	0.86	0.70	95	52	0.86	0.70	95	52
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
<i>Input use</i>												
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 ₂ O 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
<i>Land use</i>												
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

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 CH₄ was estimated from monthly GE intake using a diet specific CH₄ 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 – 0.0006 × DE) as suggested by Beauchemin et al. (2010; Table 6).

Manure CH₄ 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 CH₄ producing capacity of the manure (B₀ = 0.18 m³ CH₄ kg⁻¹), a CH₄ conversion factor (MCF = 0.01, 0.02, 0.17 kg CH₄ 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).

2.2.1.2. Nitrous oxide emissions. Direct manure N₂O 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 N₂O-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 N₂O emissions are estimated by multiplying the total N inputs with an emission factor of 0.01 kg N₂O-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 × WFPS; Sozanska et al., 2002) of top soil and soil temperature at 30 cm depth (ts30; 0.5762 + 0.03130 × ts30; Sozanska et al., 2002; Table 6).

Indirect N₂O 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 N₂O-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).

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 × r _r 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 Bonnesmo et al. (2012).

^c Estimated according to Andren et al. (2004).

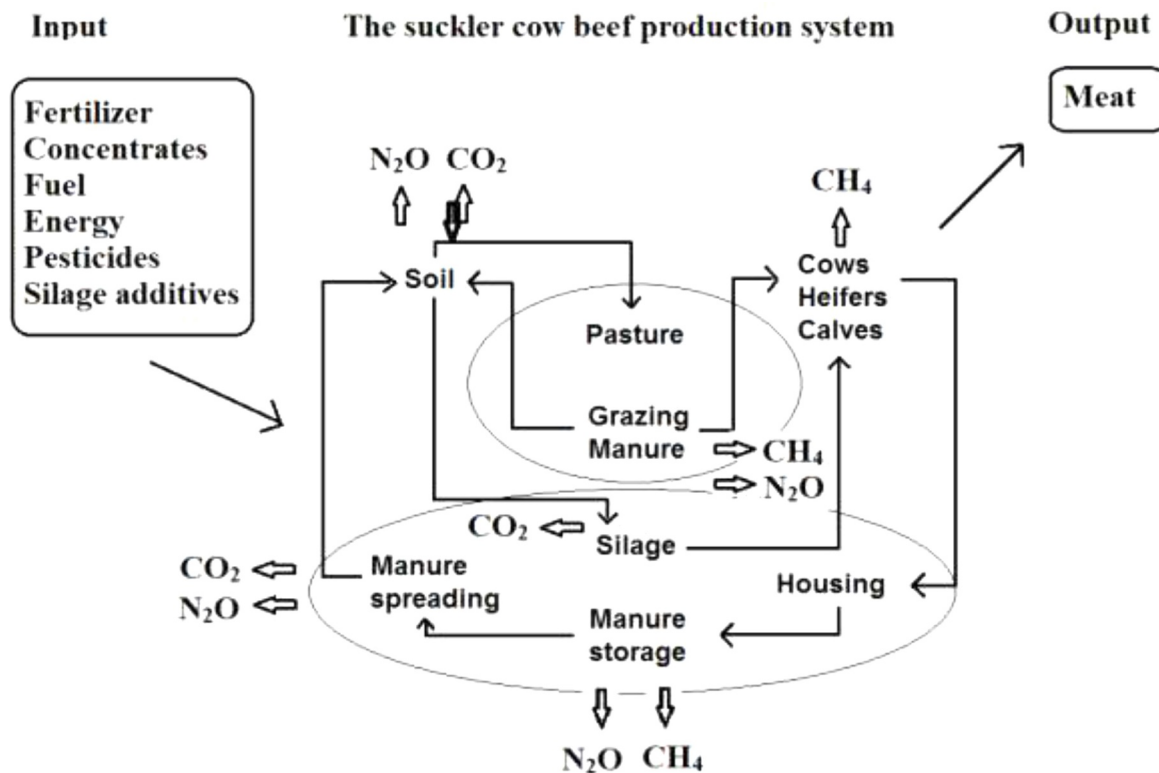


Figure 1. System boundaries of the suckler cow beef production system (Samsonstuen et al., 2019).

2.2.1.3. 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 ($k_y = 0.8 \text{ year}^{-1}$ 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):

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

$$\frac{dO}{dt} = h k_y rY - k_o rO$$

2.2.1.4. Carbon dioxide emissions. Direct CO₂ emissions are estimated from on-farm use of diesel fuel using an emission factor (2.7 kg CO₂ 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 CO₂ eq (MJ pesticide energy)⁻¹ (Audsley et al., 2014); electricity, 0.11 kg CO₂ eq (kWh)⁻¹ (Berglund et al., 2009); diesel fuel, 0.3 kg CO₂ eq (L)⁻¹ (Öko-Institut, 2010); silage additives, 0.72 kg CO₂ eq (kg CH₂O₂)⁻¹ (Flysjö et al., 2008); and N-based synthetic fertilizer, 4 kg CO₂ eq (kg N)⁻¹ (DNV, 2010; Table 6).

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 Cow Mean (SD)	Heifer* Mean (SD)	Bull** Mean (SD)	Hereford Cow Mean (SD)	Heifer* Mean (SD)	Bull** Mean (SD)	Charolais Cow Mean (SD)	Heifer* Mean (SD)	Bull** 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
<i>Methane</i>	$(0.065/55.64) \text{ kg CH}_4 \text{ (MJ GEI)}^{-1}$	(IPCC, 2006)
Enteric fermentation		
Relative effect of digestibility (DE%) of feed	$0.1058-0.0006 \times \text{DE}$	(Bonesmo et al., 2013)*
Max.CH ₄ producing capacity of manure (B ₀)	$0.18 \text{ m}^3 \text{ CH}_4 \text{ kg}^{-1}$	(IPCC, 2006)
Deep bedding manure	$0.17 \text{ kg CH}_4 \text{ (VS)}^{-1}$	(IPCC, 2006)
Solid storage manure	$0.02 \text{ kg CH}_4 \text{ (VS)}^{-1}$	(IPCC, 2006)
Pasture manure	$0.01 \text{ kg CH}_4 \text{ (VS)}^{-1}$	(IPCC, 2006)
<i>Direct nitrous oxide</i>		
Soil N inputs**	$0.01 \text{ kg N}_2\text{O-N (kg N)}^{-1}$	(IPCC, 2006)
Relative effect of soil water filled pore space (WFPS mm)	$0.4573 + 0.01102 \times \text{WFPS}$	(Sozanska et al., 2002)***, (Bonesmo et al., 2012)****
Relative effect of soil temperature at 30cm (ts30°C)	$0.5862 + 0.03130 \times \text{ts30}$	(Sozanska et al., 2002)***, (Bonesmo et al., 2012)****
Deep bedding manure	$0.01 \text{ kg N}_2\text{O-N (kg N)}^{-1}$	(IPCC, 2006)
Solid storage manure	$0.05 \text{ kg N}_2\text{O-N (kg N)}^{-1}$	(IPCC, 2006)
Pasture manure	$0.02 \text{ kg N}_2\text{O-N (kg N)}^{-1}$	(IPCC, 2006)
<i>Indirect nitrous oxide</i>		
Soil N inputs**	Leaching: $\text{EF} = 0.0075 \text{ kg N}_2\text{O-N (kg N)}^{-1}$, $\text{Frac}_{\text{leach}} = 0.3 \text{ kg N (kg N)}^{-1}$	(IPCC, 2006), (Little et al., 2008)**** (IPCC, 2006)
	Volatilization: $\text{EF} = 0.01 \text{ kg N}_2\text{O-N (kg N)}^{-1}$, $\text{Frac}_{\text{volatilization}} = 0.1 \text{ kg N (kg N)}^{-1}$	
Deep bedding manure	Leaching: $\text{EF} = 0.0075 \text{ kg N}_2\text{O-N (kg N)}^{-1}$, $\text{Frac}_{\text{leach}} = 0 \text{ kg N (kg N)}^{-1}$	(IPCC, 2006)
	Volatilization: $\text{EF} = 0.01 \text{ kg N}_2\text{O-N (kg N)}^{-1}$, $\text{Frac}_{\text{volatilization}} = 0.3 \text{ kg N (kg N)}^{-1}$	(IPCC, 2006)
Solid storage manure	Leaching: $\text{EF} = 0.0075 \text{ kg N}_2\text{O-N (kg N)}^{-1}$, $\text{Frac}_{\text{leach}} = 0 \text{ kg N (kg N)}^{-1}$	(IPCC, 2006)
	Volatilization: $\text{EF} = 0.01 \text{ kg N}_2\text{O-N (kg N)}^{-1}$, $\text{Frac}_{\text{volatilization}} = 0.45 \text{ kg N (kg N)}^{-1}$	(IPCC, 2006)
Pasture manure	Leaching: $\text{EF} = 0.0075 \text{ kg N}_2\text{O-N (kg N)}^{-1}$, $\text{Frac}_{\text{leach}} = 0.3 \text{ kg N (kg N)}^{-1}$	(IPCC, 2006), (Little et al., 2008)**** (IPCC, 2006)
	Volatilization: $\text{EF} = 0.01 \text{ kg N}_2\text{O-N (kg N)}^{-1}$, $\text{Frac}_{\text{volatilization}} = 0.2 \text{ kg N (kg N)}^{-1}$	
<i>Soil carbon</i>		
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)
<i>Direct carbon dioxide</i>		
Diesel fuel use	$2.7 \text{ kg CO}_2 \text{ L}^{-1}$	(The Norwegian Environment Agency, 2017)
<i>Indirect carbon dioxide</i>		
Manufacturing N-based synthetic compound fertilizer	$4 \text{ kg CO}_2\text{eq (kg N)}^{-1}$	(DNV, 2010)
Manufacturing pesticides	$0.069 \text{ kg CO}_2\text{eq (MJ pesticide energy)}^{-1}$	(Audsley et al., 2014)
Manufacturing silage additives	$0.72 \text{ kg CO}_2\text{eq (kg CH}_2\text{O}_2)^{-1}$	(Flysjö et al., 2008)
Production of diesel fuel	$0.3 \text{ kg CO}_2\text{eq L}^{-1}$	(Öko-Institut, 2010)
Production of electricity	$0.11 \text{ kg CO}_2\text{eq kWh}^{-1}$	(Berglund et al., 2009)
Purchased soya meal	$0.93 \text{ kg CO}_2\text{eq (kg DM)}^{-1}$	(Dalgaard et al., 2008)
Purchased barley grain	$0.62 \text{ kg CO}_2\text{eq (kg DM)}^{-1}$	(Bonesmo et al., 2012)

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

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 ($0.62 \text{ kg CO}_2 \text{ eq kg DM}^{-1}$; Bonesmo et al., 2012; Table 6) and soybean meal imported from South America ($0.93 \text{ kg CO}_2 \text{ eq kg DM}^{-1}$; 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 ($\text{CO}_2 \text{ eq (kg beef carcass)}^{-1}$) using the PROC GLM procedure of SAS® software, V9.4 (SAS Institute Inc., Cary,

Table 7Mean, minimum (Min), maximum (Max) and standard deviation (SD) estimates for greenhouse gas emission intensity (kg CO₂ eq kg⁻¹carcass) (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 ₂ O	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 ₂ O	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 ≤ 0.05

** = P ≤ 0.01.

NC, U. 2017).

3. Results

The total farm GHG emission intensities showed no significant difference across breeds (Table 7). However, N₂O emissions from manure (P ≤ 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 CO₂ eq (kg carcass)⁻¹ (median = 29.5, range 22.5 to 45.2; Table 7). Enteric CH₄ contributed most to the total GHG emissions, accounting for 44% of the total emissions. N₂O 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 CO₂ eq (kg carcass)⁻¹ depending on location. On-farm emissions from burning of fossil fuels accounted for 9% and the indirect CO₂ 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 CO₂ eq (kg carcass)⁻¹ of the total emissions in East and Mid, and 3.4 to 6.2 CO₂ 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

Table 8Mean greenhouse gas (GHG) emission intensities and proportion of total emissions (in parenthesis) from average herds of beef cattle in four regions of Norway (kg CO₂ eq kg⁻¹carcass).

	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 ₂ O	3.19 (0.12)	4.51 (0.14)	3.06 (0.11)	2.44 (0.07)	**
Soil N ₂ O	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.

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 CO₂ 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 CO₂ eq (kg carcass)⁻¹ and Sweden 25.4 CO₂ 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.

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 CO₂ eq kg⁻¹carcass).

	East (n=16)			Southwest (n=2)		Mid (n=4)		North (n=5)		Location CH	Sig ^a	Breed Sig ^a
	AA	H	CH	H	AA	CH	AA	H				
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 ₂ O	3.12	3.71	2.80	4.51	3.36	2.77	2.15	3.14	1.66	**	**	
Soil N ₂ O	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.

	Response	East (n=16)		Southwest (n=2)		Mid (n=4)		North (n=5)		Sig ^a
		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 $\pm 1\%$ of $r_w \times r_T$

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. HoloNorBeef 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. HoloNorBeef 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 CO₂ eq (kg carcass)⁻¹ (r_W × 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 × 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 CO₂ 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 CO₂ 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 CH₄ 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.

Author Statement

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Declaration of Competing Interest

The authors have no conflict of interest to disclose.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.livsci.2020.104091](https://doi.org/10.1016/j.livsci.2020.104091).

References

- Alemu, A.W., Amiro, B.D., Bittman, S., MacDonald, D., Ominski, K.H., 2017a. Greenhouse gas emission of Canadian cow-calf operations: A whole-farm assessment of 295 farms. *Agric. Syst.* 10.1016/j.agsy.2016.11.013.
- Alemu, A.W., Janzen, H., Little, S., Hao, X., Thompson, D.J., Baron, V., Iwaasa, A., Beauchemin, K.A., Kröbel, R., 2017b. Assessment of grazing management on farm greenhouse gas intensity of beef production systems in the Canadian Prairies using life cycle assessment. *Agric. Syst.* 10.1016/j.agsy.2017.08.003.
- Amon, T., Amon, B., Kryvoruchko, V., Zollitsch, W., Mayer, K., Gruber, L., 2007. Biogas production from maize and dairy cattle manure-Influence of biomass composition on the methane yield. *Agric. Ecosyst. Environ.* 10.1016/j.agee.2006.05.007.
- Andrén, O., Kätterer, T., 1997. ICBM: The introductory carbon balance model for exploration of soil carbon balances. *Ecological Applications* 7, 1226-1236.
- Andrén, O., Kätterer, T., Juston, J., Waswa, B., Rönig de Nowina, K., 2015. Soil carbon dynamics, climate, crops and soil type calculations using introductory carbon balance model (ICBM) and agricultural field trial data from sub-Saharan Africa. *African J. Agric. Res.* 10.5897/ajar12.205.
- Andrén, O., Kätterer, T., Karlsson, T., 2004. ICBM regional model for estimations of dynamics of agricultural soil carbon pools, in: *Nutrient Cycling in Agroecosystems*. 10.1023/B:FRES.0000048471.59164.ff.
- Animalia, 2017. *Norwegian Beef Cattle Recording System - Annual Report 2016*. Norwegian Meat and Poultry Research Centre, Oslo.
- Appahamy, J.A.D.R.N., Moraes, L.E., Wagner-Riddle, C., Casper, D.P., Kebreab, E., 2017. Predicting manure volatile solid output of lactating dairy cows. *J. Dairy Sci.* 10.3168/jds.2017-12813.
- Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G., 2014. Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use. *Cranf. Univ.* 10.1007/s13398-014-0173-7-2.
- Baron, V.S., Mapfumo, E., Dick, A.C., Naeth, M.A., Okine, E.K., Chanasyk, D.S., 2007. Grazing Intensity Impacts on Pasture Carbon and Nitrogen Flow. *J. Range Manag.* 10.2307/4003996.

- Beauchemin, K.A., Henry Janzen, H., Little, S.M., McAllister, T.A., McGinn, S.M., 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. *Agric. Syst.* 10.1016/j.agry.2010.03.008.
- Berglund, M., Cederberg, C., Clason, C., Henriksson, M., Törner, L., 2009. Jordbrukets klimatpåverkan- underlag för att bärekena växthusgasutsläpp på gårdsnivå og nulägesanalyser av exempelgårdar. Delrapport i JOKER-projektet. Hushållningsälskapet, Sweden. 117p (in Swedish).
- Bolinder, M.A., VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., Janzen, H.H., 2011. Modelling soil organic carbon stock change for estimating whole-farm greenhouse gas emissions. *Can. J. Soil Sci.* 10.4141/s05-102.
- Bonesmo, H., Beauchemin, K.A., Harstad, O.M., Skjelvåg, A.O., 2013. Greenhouse gas emission intensities of grass silage based dairy and beef production: A systems analysis of Norwegian farms. *Livest. Sci.* 10.1016/j.livsci.2012.12.016.
- Bonesmo, H., Skjelvåg, A.O., Henry Janzen, H., Klakegg, O., Tveito, O.E., 2012. Greenhouse gas emission intensities and economic efficiency in crop production: A systems analysis of 95 farms. *Agric. Syst.* 10.1016/j.agry.2012.04.001.
- Crosson, P., Shalloo, L., O'Brien, D., Lanigan, G.J., Foley, P.A., Boland, T.M., Kenny, D.A., 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. *Anim. Feed Sci. Technol.* 10.1016/j.anifeeds.2011.04.001.
- Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M., Pengue, W.A., 2008. LCA of soybean meal. *Int. J. Life Cycle Assess.* 10.1065/lca2007.06.342.
- de Vries, M., van Middelaar, C.E., de Boer, I.J.M., 2015. Comparing environmental impacts of beef production systems: A review of life cycle assessments. *Livest. Sci.* 10.1016/j.livsci.2015.06.020.
- Difford, G.F., Plichta, D.R., Løvendahl, P., Lassen, J., Noel, S.J., Højberg, O., Wright, A.D.G., Zhu, Z., Kristensen, L., Nielsen, H.B., Guldbrandtsen, B., Sahana, G., 2018. Host genetics and the rumen microbiome jointly associate with methane emissions in dairy cows. *PLoS Genet.* 10.1371/journal.pgen.1007580.
- DNV, 2010. Verification statement no. 76265-2010-OTH-NOR. Yara International ASA. Det Norske Veritas Certification, Høvik, Norway.
- DOW, I., 2012. Assessing On-Farm Dry Matter Losses in Silage Making. Eurofins, 2015. Feed analysis 2010-2015.
- FAO, 2017. The future of food and agriculture - Trends and challenges. Rome.
- Flajsjö, A., Cederberg, C., Strid, I., 2008. LCA-databas för konventionella fodermedel - miljöpåverkan i samband med produktion. SIK-Institutet för Livsmed, och Biotek.
- Foley, P.A., Crosson, P., Lovett, D.K., Boland, T.M., O'Mara, F.P., Kenny, D.A., 2011. Whole-farm systems modelling of greenhouse gas emissions from pastoral suckler beef cow production systems. *Agric. Ecosyst. Environ.* 10.1016/j.agee.2011.05.010.
- Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Faluccci, A., Tempio, G., 2013. Tackling Climate Change Through Livestock: A global Assessment of Emissions and Mitigation Opportunities. *Most.* 10.1016/j.anifeeds.2011.04.074.
- Hanigan, M.D., Appuhamy, J.A.D.R.N., Gregorini, P., 2013. Revised digestive parameter estimates for the Molly cow model. *J. Dairy Sci.* 10.3168/jds.2012-6183.
- Haque, M.N., 2018. Dietary manipulation: A sustainable way to mitigate methane emissions from ruminants. *J. Anim. Sci. Technol.* 10.1186/s40781-018-0175-7.
- Herd, R.M., Arthur, P.F., Donoghue, K.A., Bird, S.H., Bird-Gardiner, T., Hegarty, R.S., 2014. Measures of methane production and their phenotypic relationships with dry matter intake, growth, and body composition traits in beef cattle. *J. Anim. Sci.* 10.2527/jas.2014-8273.
- Edited by Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J., Oosting, S., 2013. Mitigation of greenhouse gas emissions in livestock production - A review of technical options for non-CO2 emissions. In: Gerber, Pierre J., Henderson, Benjamin, Makkar, Harinder P.S. (Eds.), *FAO Animal Production and Health Paper No. 177*. FAO, Rome, Ita.
- IPCC, 2006. Guidelines for National Greenhouse Gas Inventories. *Agric. For. other L. use.* 10.1016/j.phrs.2011.03.002.
- IPCC, 2007. Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.
- Janzen, H.H., Beauchemin, K.A., Bruisma, Y., Campbell, C.A., Desjardins, R.L., Ellert, B. H., Smith, E.G., 2003. The fate of nitrogen in agroecosystems: An illustration using Canadian estimates. *Nutr. Cycl. Agroecosystems.* 10.1023/A:1025195826663.
- Kätterer, T., Andersson, L., Andrén, O., Persson, J., 2008. Long-term impact of chronological land use change on soil carbon stocks on a Swedish farm. *Nutr. Cycl. Agroecosystems.* 10.1007/s10705-007-9156-9.
- Kätterer, T., Andrén, O., 2009. Predicting daily soil temperature profiles in arable soils in cold temperate regions from air temperature and leaf area index. *Acta Agric. Scand. Sect. B Soil Plant Sci.* 10.1080/09064710801920321.
- Kätterer, T., Andrén, O., 2001. The ICBM family of analytically solved models of soil carbon, nitrogen and microbial biomass dynamics - Descriptions and application examples. *Ecol. Modell.* 10.1016/S0304-3800(00)00420-8.
- Kröbel, R., Bolinder, M.A., Janzen, H.H., Little, S.M., Vandenbygaart, A.J., Kätterer, T., 2016. Canadian farm-level soil carbon change assessment by merging the greenhouse gas model Holos with the Introductory Carbon Balance Model (ICBM). *Agric. Syst.* 10.1016/j.agry.2015.12.010.
- Landbruks- og Matdepartementet., 2004. Forskrift om hold av storfe. <https://lovdata.no/dokument/SF/forskrift/2004-04-22-665> (In Norwegian).
- Lee, J.M., Sathish, P., Donaghy, D.J., Roche, J.R., 2010. Plants modify biological processes to ensure survival following carbon depletion: A Lolium perenne model. *PLoS One.* 10.1371/journal.pone.0012306.
- Legesse, G., Small, J.A., Scott, S.L., Crow, G.H., Block, H.C., Alemu, A.W., Robins, C.D., Kebreab, E., 2011. Predictions of enteric methane emissions for various summer pasture and winter feeding strategies for cow calf production. *Anim. Feed Sci. Technol.* 10.1016/j.anifeeds.2011.04.082.
- Limb, R.F., Hovick, T.J., Norland, J.E., Volk, J.M., 2018. Grassland plant community spatial patterns driven by herbivory intensity. *Agric. Ecosyst. Environ.* 10.1016/j.agee.2018.01.030.
- Little, S., Lindeman, J., Maclean, K., Janzen, H.H., 2008. HOLOS. A tool to estimate and reduce greenhouse gases from farms. Methodology and algorithms for version 1.1. Agriculture and Agri-Food Canada, Lethbridge, Canada. 162 p.
- LMD, 2018. Jordbruksavtale 2018-2019. https://www.regjeringen.no/no/dokument/dep/lmd/lover_regler/retningslinjer/2018/jordbruksavtale-2018-2019/id2606048/: Ministry of Agriculture and Food. 39pp.
- McCaughey, W.P., Wittenberg, K., Corrigan, D., 2010. Impact of pasture type on methane production by lactating beef cows. *Can. J. Anim. Sci.* 10.4141/a98-107.
- Merino, P., Ramirez-Fanlo, E., Arriaga, H., del Hiarro, O., Artetxe, A., Viguria, M., 2011. Regional inventory of methane and nitrous oxide emission from ruminant livestock in the Basque Country. *Anim. Feed Sci. Technol.* 10.1016/j.anifeeds.2011.04.081.
- Mogensen, L., Hermansen, J.E., Halberg, N., Dalgaard, R., Vis, J.C., Smith, B.G., 2012. Life Cycle Assessment Across the Food Supply Chain, in: Sustainability in the Food Industry. 10.1002/9781118467589.ch5.
- Mogensen, L., Kristensen, T., Nielsen, N.I., Spleth, P., Henriksson, M., Swensson, C., Hesse, A., Vestergaard, M., 2015. Greenhouse gas emissions from beef production systems in Denmark and Sweden. *Livest. Sci.* 10.1016/j.livsci.2015.01.021.
- Monteny, G.J., Groenestein, C.M., Hilhorst, M.A., 2001. Interactions and coupling between emissions of methane and nitrous oxide from animal husbandry. *Nutr. Cycl. Agroecosystems.* 10.1023/A:1012602911339.
- NIBIO, 2019. Muligheter og utfordringer for økt karbonbinding i jordbruksjord. Norsk institutt for bioøkonomi, Ås, Norway.
- NIBIO, 2016. Totalkalkylen for jordbruket. Jordbrukets totalregnskap 2014 og 2015. Budsjett 2016, in: Budsjettmemorandum for jordbruket (Ed.). (in Norwegian).
- NMBU, Norwegian Food Safety Authority, 2008. Førtabellen No Title.
- Norwegian Meteorological Insitute and Det norske hageselskap, 2006. Klimasonkart (In Norwegian).
- OECD/FAO, 2018. OECD-FAO Agricultural Outlook 2018-2027, Agricultural Outlook 2016-2025. 10.1787/agr_outlook-2018-en.
- Öko-Institut, 2010. E.V., Tankstelle/Diesel-DE-2010. <<http://www.probas.umweltbundesamt.de/php/volltextsuche.php?prozessid=%7b9F010C0D-A18D-4163-B86D-22E8656276F7%7d&id=1&step=1&search=Tankstelle/Diesel-DE&b=1#in-output>>. (in German).
- Ominski, K.H., Boadi, D.A., Wittenberg, K.M., 2011. Enteric methane emissions from backgrounded cattle consuming all-forage diets. *Can. J. Anim. Sci.* 10.4141/a05-051.
- Pelletier, N., Pirog, R., Rasmussen, R., 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. *Agric. Syst.* 10.1016/j.agry.2010.03.009.
- Reeder, J.D., Schuman, G.E., 2002. Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands, in: *Environmental Pollution*. 10.1016/S0269-7491(01)00223-8.
- Refsgaard Andersen, H., 1990. Ammekoens energibehov og foderoptagelseskapacitet. National Institute of Animal Science, Denmark.
- Rekdal, Y., 2014. Utmarksbeiteressurser i Norge. Ch. 4.3. Report 6, Agri Analyse et al. 95 pp. In Norwegian.
- Samsonstuen, S., Åby, B.A., Crosson, P., Beauchemin, K.A., Bonesmo, H., Aass, L., 2019. Farm scale modelling of greenhouse gas emissions from semi-intensive suckler cow beef production. *Agric. Syst.* 10.1016/j.agry.2019.10.2670.
- SAS Institute Inc., Cary, NC, U.S.A., 2017. SAS[®] 9.4. SAS Inst. Inc., Cary, NC, USA. 10.1016/0370-2693(82)91293-X.
- Schuman, G.E., Janzen, H.H., Herrick, J.E., 2002. Soil carbon dynamics and potential carbon sequestration by rangelands, in: *Environmental Pollution*. 10.1016/S0269-7491(01)00215-9.
- Skjelvåg, A.O., Arnoldussen, A.H., Klakegg, O., Tveito, O.E., 2012. Farm specific natural resource base data for estimating greenhouse gas emissions. *Acta Agric. Scand. A Anim. Sci.* 10.1080/09064702.2013.777092.
- Soussana, J.F., Allard, V., Pilegaard, K., Ambus, P., Amman, C., Campbell, C., Ceschia, E., Clifton-Brown, J., Czobel, S., Domingues, R., Flechard, C., Fuhrer, J., Hensen, A., Horvath, L., Jones, M., Kasper, G., Martin, C., Nagy, Z., Neftel, A., Raschi, A., Baronti, S., Rees, R.M., Skiba, U., Stefani, P., Manca, G., Sutton, M., Tuba, Z., Valentini, R., 2007. Full accounting of the greenhouse gas (CO₂, N₂O, CH₄) budget of nine European grassland sites. *Agric. Ecosyst. Environ.* <https://doi.org/10.1016/j.agee.2006.12.022>.
- Soussana, J.F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *animal.* 10.1017/s1751731109990784.
- Sozanska, M., Skiba, U., Metcalfe, S., 2002. Developing an inventory of N₂O emissions from British soils. *Atmos. Environ.* 10.1016/S1352-2310(01)00441-1.
- Statistics Norway, 2017. Cereal production <<https://www.ssb.no/jord-skog-jakt-og-fiskeri/statistikker/korn/aar>> .
- Sveinbjörnsson, J., 2006. Substrate levels, carbohydrate degradation rate and their effects on rumen end-product formation (Ph.D. thesis). Acta Universitatis Agriculturae Sueciae, SLU Service/Repro, Uppsala, Sweden.
- The Norwegian Environment Agency, 2017. Greenhouse Gas Emissions 1990-2015, National Inventory Report.
- Thornton, P.K., Herrero, M., 2010. Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proc. Natl. Acad. Sci. U. S. A.* <https://doi.org/10.1073/pnas.0912890107>.
- Tubiello, F.N., Salvatore, M., Córdor Golec, R.D., Ferrara, A., Rossi, S., Biancalani, R., Federici, S., Jacobs, H., Flammini, A., 2014. Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks, ESS Working Paper No.2 FAO. 10.

- 13140/2.1.4143.4245.
- Wang, T., Richard Teague, W., Park, S.C., Bevers, S., 2015. GHG mitigation potential of different grazing strategies in the United States Southern Great Plains. *Sustain.* 10.3390/su71013500.
- Wang, X., Vandenbygaart, A.J., McConkey, B.C., 2014. Land management history of Canadian grasslands and the impact on soil carbon storage. *Rangel. Ecol. Manag.* 10.2111/REM-D-14-00006.1.
- White, T.A., Snow, V.O., King, W.M.G., 2010. Intensification of New Zealand beef farming systems. *Agric. Syst.* 10.1016/j.agsy.2009.08.003.
- Wims, C.M., Deighton, M.H., Lewis, E., O'Loughlin, B., Delaby, L., Boland, T.M., O'Donovan, M., 2010. Effect of pregrazing herbage mass on methane production, dry matter intake, and milk production of grazing dairy cows during the mid-season period. *J. Dairy Sci.* 10.3168/jds.2010-3245.