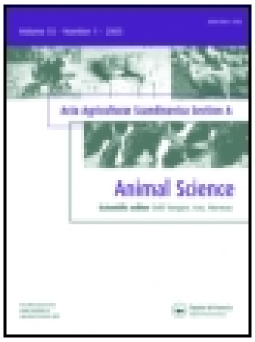

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Mitigation of greenhouse gas emissions from beef cattle production systems

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ABSTRACT
The whole-farm model HolosNorBeef was used to estimate the efficiency of GHG emission mitigation strategies in Norwegian beef cattle herds. Various mitigation scenarios, involving female reproductive performance (i.e. calf mortality rate and the number of calves produced per cow per year), production efficiency of young bulls for slaughter (i.e. age at slaughter and carcass weight), and supplementation of an inhibitor currently reported as promising for enteric methane (CH_4) inhibition (3-nitrooxypropanol; 3-NOP) was investigated in herds of British and Continental breeds. Reducing calf mortality and increasing the number of produced calves per cow per year both reduced emission intensities by 3% across breeds. Continental breeds showed greater potential of reducing emission intensities due to increased carcass production. Combining mitigation options in a best case scenario reduced the total emissions by 11.7% across breeds. The emission intensities could be further reduced by 8.3% with the use of 3-NOP.

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KEYWORDS
Beef production efficiency; farm scale model; methane inhibitor; mitigation options

Introduction

Beef consumption is expected to increase in both developed and developing countries as a consequence of global population growth (OECD/FAO, 2018). Thus, greenhouse gas (GHG) emissions from beef production are expected to increase. Beef has a large GHG emission intensity albeit with considerable variation among continents, countries (Gerber et al., 2013) and farms within a country (Bonesmo et al., 2013). The emission intensity of beef production depends upon breed (Hyslop, 2008), geographical location (White et al., 2010; Samsonstuen et al., 2019), farming system (Nguyen et al., 2010), and management practices (Alemu et al., 2017; Stanley et al., 2018). Hristov et al. (2013) showed potential long-term mitigation effects from ruminant production through improved reproductive performance, increased beef production and various management practices such as diet formulation, feed supplements, and manure management. Thus, the potential to reduce emission intensities is significant.

Animal productivity is important for beef farm profitability and is positively related to reductions in GHG emissions (Åby et al., 2014). The environmental impact of improved carcass production has been investigated by a number of studies (Thornton & Herrero, 2010; Desjardins et al., 2012; Legesse et al., 2016; Murphy et al., 2017; Legesse et al., 2018). Murphy et al. (2017) showed decreased emission intensity when reducing age at slaughter, while increased average daily gain (ADG) reduced the emission intensities of Irish beef production systems (Casey & Holden, 2006; Crosson et al., 2010). The emission intensities from Canadian beef production have decreased from 1981 to 2011 due to improved reproduction efficiency, increased ADG, increased slaughter weight, reduced age at slaughter, and use of high grain diets that enabled slaughtering at a younger age (Legesse et al., 2016, 2018).

The environmental impact of female fertility and calf survival is inadequate or absent in most studies, as research mainly focuses on carcass production efficiency. Poor fertility and low calf survival increases the number of animals to maintain production levels and a stable herd size, hence a greater proportion of the GHG emissions is produced by herd replacements (Garnsworthy, 2004; Wall et al., 2010; Bell et al., 2011). Calf survival is of great importance in beef production systems, as the calf is the main product from the enterprise. Improvements in calf survival and cow fertility are known to reduce the overall emissions from beef production, as well as improving animal welfare (Wall et al., 2010). Beauchemin et al. (2011) reported a 4% reduction in GHG emissions following practices that improved calf survival to weaning, and Navajas et al.

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(2010) reported reduction in emission intensities due to genetic improvement of fertility and calf survival.

Enteric CH_4 emissions account for approximately half the emissions from beef cattle production (Foley et al., 2011; Mogensen et al., 2015; Samsonstuen et al., 2019), hence various feed additives have been examined for their anti-methanogenic properties. These include various phyto-compounds (essential oils, oregano, garlic, green tea extract, condensed and hydrolysable tannins), microbials (live yeast, bacterial direct-fed probiotics), ionophores, dietary lipids, and chemical inhibitors (Hristov et al., 2013; Bayat et al., 2015, 2017; Kolling et al., 2018). However, many inhibitors have negative effects on feed intake (Hristov et al., 2013), organic matter fermentation in the rumen, digestibility (Johnson & Johnson, 1995), animal health and production (Hristov et al., 2013). However, the inhibitor 3-nitrooxypropanol (3-NOP, DSM Nutritional Products Ltd., Kaiseraugst, Switzerland) has shown promising long-term mitigation effects on enteric CH_4 emissions with no compromising effect on diet digestibility (Romero-Perez et al., 2014) or animal performance (Vyas et al., 2018).

The emission intensities from typical herds of British and Continental breeds in two geographically different regions in Norway were estimated by Samsonstuen et al. (2019). However, that study did not include GHG mitigation options such as improved cow efficiency, beef production efficiency or the effect of inhibitors. Furthermore, previous studies of calf survival (e.g. Beauchemin et al., 2011) and fertility (e.g. Bell et al., 2011) did not use nationally representative statistics or combinations of mitigation options. Additionally, pastoral systems have the potential to remove carbon (C) from the atmosphere through sequestration (Soussana et al., 2007), yet few studies have accounted for C sequestration when investigating mitigation options.

Thus, the aim of the study was to estimate the net mitigation potential in Norwegian beef cattle production systems using a whole-farm approach by investigating various scenarios, including variable cow and young bull beef production efficiency scenarios, as well as the mitigating effect of inhibitor (3-NOP) for enteric CH_4 reduction. The inhibitor evaluated was 3-NOP (DSM Nutritional Products Ltd., Kaiseraugst, Switzerland).

Materials and methods

This study was based on a previous study of GHG emissions from typical herds of British and Continental breeds in Norway (Samsonstuen et al., 2019). Fourteen mitigation scenarios were designed to reflect the variation in production efficiency among Norwegian beef cattle herds. The variable herd performances were compared to the typical herds to investigate GHG mitigation potentials. For each scenario, the amount of beef carcass (kg) produced was based on the number of animals sent to slaughter, body weights and dressing percentages for the specific breed and animal class. Production enterprises on the farm not related to the cattle operation, such as the use of farm inputs (i.e. area, fertilizer, and pesticides) for grain production, were excluded from the analysis as the grain crops are sold from the farm and not used as feed. All cattle manure was applied on the included grasslands.

Baseline scenarios

Baseline (BL) scenarios were developed to represent each typical herd; British (Angus and Hereford) and Continental (Limousin, Simmental, and Charolais) breeds with associated geographical location, management, and production levels as described by Samsonstuen et al. (2019). For both breeds the farms were located in the flatlands (average altitude 246 m above sea level) of Norway, with a land size ranging between 45.4 and 50.1 ha.

The Norwegian beef cattle production system is semi-intensive with the cow-calf enterprise and finishing of bulls at the same farm. The BL farms were stocked with 28 spring-calving cows with the replacement rate set at 36% to keep the herd size constant (NIBIO, 2015). All progeny were retained for slaughter with males finished as bulls at 17.5 and 16.8 months, and surplus heifers not required to replace culled cows finished at 18.2 and 17.5 months for British and Continental breeds, respectively (Åby et al., 2012). Amount of beef carcass (kg) produced was calculated based on the number of cattle slaughtered to remain a stable herd size, slaughter weights and dressing percentages. Estimates of proportion of energy from concentrates and forage in the diet were from Åby et al. (2012). From birth to age at slaughter female progeny was fed 22% and 38% concentrates, and male progeny was fed 53% and 50% concentrates for British and Contunental breeds, respectively. Cows were fed 25% (British) and 17% (Continental) concentrates throughout the year. Time spent on pasture for heifers were 19 and 13%, and for cows the time on pasture were 36 and 38% for British and Contunental breeds, respectively. Manure was assumed to be deposited on pasture during the grazing period (June 1 to Sept 15) and handled as deep bedding during the housing period (Sept 16 to May 31). Manure was applied on ley area during spring. Silage yield (3350 kg dry matter (DM) ha^{-1}), pesticide (1.1 MJ ha^{-1}), and silage additive (21 kg Formic acid (CH_2O_2) ha^{-1}) use for a typical farm in the flatlands were

Table 1. Animal performance, land use and farm inputs for cow efficiency scenarios used to estimate GHG emission intensities from beef cattle operations.

	Cow efficiency scenarios									
	British					Continental				
Scenario	BL	1 CML	2 CMH	3 CYL	4 CYH	BL	1 CML	2 CMH	3 CYL	4 CYH
Animal system										
Still born calves (%)	3.5[1]	0.0[2]	8.3[2]	3.5[1]	3.5[1]	3.9[1]	0.0[2]	6.2[2]	3.9[1]	3.9[1]
Dead calves < 180 days (%)	3.6[1]	0.0[1]	10.8[2]	3.6[1]	3.6[1]	4.1[1]	0.0[2]	10.9[2]	4.1[2]	4.1[2]
Calves cow^{-1} per year	1.0[1]	1.0[1]	1.0[1]	0.9[3]	1.1[3]	1.0[1]	1.0[1]	1.0[1]	0.9[3]	1.1[3]
Replacement heifers (year^{-1})	10	10	10	10	10	10	10	10	10	10
Heifers slaughtered (year^{-1})*	4	4	2	2	5	4	4	2	2	5
Young bulls slaughtered (year^{-1})*	13	14	12	12	15	13	14	12	12	15
ADG** heifers (g day^{-1})	645	645	645	645	645	784	784	784	784	784
ADG** young bulls (g day^{-1})	974	974	974	974	974	1212	1212	1212	1212	1212
Beef produced (kg carcass)[1,4]	7699	8190	6841	7004	8303	9635	10311	8862	8815	10362
Land use										
Farm size (ha)[5]***	45.4	47.5	45.3	45.5	47.8	50.1	52.5	50.0	50.2	52.8
Of which: Ley area (ha)[5]***	39.7	41.8	39.7	39.8	42.1	44.4	46.8	44.4	44.5	47.1
Input use										
Concentrates (kg DM year^{-1})	44300	46178	41266	41141	47037	61244	63527	58937	57938	64184
Fuel (L year^{-1})[5]***	3931	4138	3930	3947	4171	4394	4641	4394	4406	4668
Silage additive (kg CH_2O_2 year^{-1})[5]***	819	863	819	823	869	916	967	916	918	973

Note: BL = Baseline, typical beef cattle herd; CML = Calf mortality low; CMH = Calf mortality high; CYL = Calves cow^{-1} per year low; CYH = Calves cow^{-1} per year high; ADG = average daily gain.

[1]Animalia (2017).

[2]Animalia (2019).

[3]Animalia (2018).

[4]Norwegian Institute of Bioeconomy research (NIBIO, 2015).

[5]Norwegian Institute of Bioeconomy research (NIBIO, 2016).

*Heifers and young bulls available for slaughter varies across scenarios dependent on number of produced calves cow per year and calf mortality

**Average daily gain from birth to age at slaughter.

***Silage additives for conservation of grass by ensiling. Corresponds to the ley area required to cover the forage requirement.

obtained from Norwegian Institute of Bioeconomy Research (NIBIO, 2015). The ley area (ha) corresponded to the calculated forage requirements plus an additional 10% (DM basis) to account for losses due to ensiling according to Bonesmo et al. (2013). N-fertilizer application for conserved feed (13 kg N ha^{-1}) followed advisory based recommendations for forage production (NIBIO, 2016). Dry matter content and nutritive value (0.87 FU kg DM^{-1}) of forage was estimated for the flatlands based on laboratory analysis information (Eurofins, Moss, Norway). Use of electricity (26,300 kWh year^{-1}) and fuel (99 L ha^{-1}) for a typical farm in the flatlands was from operational farm data (NIBIO, 2015). Seasonal soil and weather data were available through Skjelvåg et al. (2012; supplemental Table S1).

Alternative scenarios

For each alternative scenario, the herd size and structure (number of cows and replacement heifers) were kept constant corresponding to the BL scenario. The ley area (ha) varied across scenarios and corresponded to the calculated forage requirements plus 10% loss (Tables 1 and 2). Forage yields (kg ha^{-1}), use of silage additives for conservation of grass through ensiling (kg CH_2O_2 ha^{-1}), fertilizers (kg N ha^{-1}), and fuel (L ha^{-1}) were kept constant per ha, yielding different total amounts for each scenario (Tables 1 and 2).

Cow efficiency scenarios (Table 1) were based on the observed variation in calf mortality and the number of calves born per cow per year from the Norwegian Beef Herd Recording System (NBS; Animalia, 2018, 2019). The calf mortality among Norwegian beef cattle production herds ranges from 0% to 20% with a positively skewed distribution. Scenarios were based on the observed proportion of stillborn and dead calves prior to 180 days among 95% of the herds with British and Continental breeds in the NBS (Scenario 1 (CML) and 2 (CMH)). The number of calves produced per cow per year was based on the observed production among the worst 1/3 and best 1/3 of Norwegian herds (Scenario 3 (CYL) and 4 (CYH)).

Young bull beef production efficiency scenarios (Table 2) were based on age at slaughter and carcass weight for young bulls among the worst and best 1/3 of the Norwegian herds from the annual report of NBS (Animalia, 2018; Scenario 5 (BPL) and 6 (BPH)). The proportion of concentrates in the diet and days on pasture were kept constant across scenarios, influencing the required ley areas (ha) to cover the animal requirements.

Table 2. Animal performance, land use and farm inputs for for young bull beef production efficiency, best case (BC) and worst case (WC) scenarios used to estimate GHG emission intensities from beef cattle operations.

	Young bull beef production efficiency scenarios						Best case/worst case scenarios			
		British			Continental		British		Continental	
Scenario	BL	5 BPL	6 BPH	BL	5 BPL	6 BPH	7 WC	8 BC	7 WC	8 BC
Animal system										
Still born calves (%)	3.5[1]	3.5[1]	3.5[1]	3.9[1]	3.9[1]	3.9[1]	8.3[2]	0.0[2]	6.2[2]	0.0[2]
Dead calves <180 days (%)	3.6[1]	3.6[1]	3.6[1]	4.1[1]	4.1[1]	4.1[1]	10.8[2]	0.0[2]	10.9[2]	0.0[2]
Calves cow^{-1} per year	1.0[1]	1.0[1]	1.0[1]	1.0[1]	1.0[1]	1.0[1]	0.9[3]	1.1[3]	0.9[3]	1.1[3]
Young bulls, age at slaughter (month)	17.5[4]	18.7[2]	16.1[2]	16.8[4]	18.1[2]	15.4[2]	18.7[2]	16.1[2]	18.1[2]	15.4[2]
Young bulls, carcass weight (kg)	291[1]	256[3]	334[3]	353[1]	317[3]	392[3]	256[3]	334[3]	317[3]	392[3]
Replacement heifers (year^{-1})	10	10	10	10	10	10	10	10	10	10
Heifers slaughtered (year^{-1})*	4	4	4	4	4	4	1	6	1	6
Young bulls slaughtered (year^{-1})*	13	13	13	13	13	13	10	16	10	16
ADG** heifers (g day^{-1})	645	645	645	784	784	784	645	645	784	784
ADG** young bulls (g day^{-1})	974	794	1227	1212	1002	1479	794	1227	1002	1479
Beef produced (kg carcass)[14]	7699	7232	8272	9635	9157	10159	5868	9509	7721	11700
Land use										
Farm size (ha)[5***]	45.4	45.6	47.9	50.1	51.5	50.8	43.6	44.9	49.1	53.0
Of which: Ley area (ha)[5***]	39.7	39.9	42.2	44.4	45.8	45.1	37.9	44.2	43.4	47.3
Input use										
Concentrates (kg DM year^{-1})	44300	40941	48299	61244	61554	58725	35688	53736	55987	63604
Fuel (L year^{-1})[5***]	3931	3951	4177	4394	4533	4472	3751	4375	4304	4683
Silage additive (kg CH_2O_2 year^{-1})[5***]	819	823	871	916	945	932	782	912	897	976

Note: BL = baseline, typical beef cattle herd; BPL = Young bull beef production efficiency, low; BPH = Young bull beef production efficiency, high; WC = Worst case, worst performing 1/3 of Norwegian beef cattle farms; BC = Best case, best performing 1/3 of Norwegian beef cattle farms; ADG = average daily gain.
[1]Animalia (2017).
[2]Animalia (2019).
[3]Animalia (2018).
[4]Norwegian Institute of Bioeconomy research (NIBIO, 2015).
[5]Norwegian Institute of Bioeconomy research (NIBIO, 2016).
[*] Heifers and young bulls available for slaughter varies across scenarios dependent on number of produced calves cow per year and calf mortality
*Average daily gain from birth to age at slaughter
** Silage additives for conservation of grass by ensiling. Corresponds to the ley area required to cover the forage requirements.

Unfavorable cow efficiency and young bull beef production efficiency scenarios scenarios were combined in a worst case (WC; Scenario 7) scenario. The corresponding best case (BC; Scenario 8) scenario was a combination of favorable scenarios (Table 2). The effect of feeding a low level of the inhibitor 3-NOP (100 mg/kg DM) on enteric CH_4 emissions was included in the BL scenario (BLinL; Scenario 9), the WC scenario (WCinL; Scenario 10), and BC scenario (BCinL; Scenario 11) for the two typical herds of British and Continental breeds (Table 2). The effect of feeding a high level of the inhibitor (237 mg/kg DM) was included in the BL scenario (BLinH; Scenario 12), the WC scenario (WCinH; Scenario 13), and corresponding BC scenario (BCinH; Scenario 14). Dietary supplementation of the inhibitor 3-NOP was based on the findings by Romero-Perez et al. (2014), Vyas et al. (2016) and Vyas et al. (2018). The inhibitor was fed during the housing period (8.5 months) for cows and backgrounding and finishing stock (6–24 months in age), respectively. It was assumed that on the days the inhibitor was fed, enteric CH_4 emissions expressed as a percentage of dry matter intake (DMI) were decreased by 7 (low) and 33% (high) with no negative effects on DMI or ADG.

Modeling GHG emissions

The GHG emissions were estimated using HolosNorBeef developed by Samsonstuen et al. (2019). HolosNorBeef is an empirical model specifically developed for beef cattle production systems under Norwegian conditions, using Tier 2 methodology of the Intergovernmental Panel on Climate Change (IPCC, 2006). The model estimated 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 estimated whole-farm GHG emissions by considering direct emissions of CH_4 from enteric fermentation and manure, 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. The sources of emmissions, emission factors, and equations used by the HolosNorBeef model are given in supplemental Table S2. All emissions were expressed as CO_2 eq to account for the global warming potential (GWP) of the respective gases for a time horizon of 100 years: CH_4

Table 3. Total greenhouse gas (GHG) emissions (kg CO_2 eq) and emission intensities (kg CO_2 eq kg^{-1} carcass) by source for cow efficiency scenarios from beef cattle operations.

	British					Continental				
		1	2	3	4		1	2	3	4
Scenario	BL	CML	CMH	CYL	CYH	BL	CML	CMH	CYL	CYH
Total GHG emissions	236,984	244,780	229,886	229,503	247,387	281,879	291,482	275,796	273,465	293,554
Emission intensities by source										
Enteric CH_4	14.03	13.50	15.20	14.82	13.45	13.24	12.70	14.03	13.95	12.73
Manure CH_4	3.22	3.11	3.47	3.40	3.09	3.17	3.05	3.34	3.33	3.05
Manure N_2O	3.01	2.89	3.28	3.20	2.87	2.78	2.66	2.96	2.95	2.66
Soil N_2O	3.03	2.94	3.33	3.25	2.93	2.86	2.77	3.05	3.06	2.77
Soil C*	−1.72	−1.62	−1.77	−1.74	−1.61	−1.85	−1.74	−1.90	−1.89	−1.74
Off-farm barley	1.94	1.90	2.04	1.98	1.91	2.15	2.08	2.25	2.22	2.09
Off-farm soy	1.89	1.85	1.98	1.93	1.86	2.09	2.02	2.18	2.16	2.03
Indirect energy	3.03	3.00	3.43	3.35	2.98	2.70	2.67	2.94	2.97	2.67
Direct energy	2.34	2.31	2.65	2.58	2.30	2.09	2.06	2.27	2.29	2.06
Total emission intensities	30.78	29.89	33.61	32.77	29.80	29.23	28.27	31.12	31.02	28.33
Total emission intensities excluding soil C	32.49	31.50	35.37	34.51	31.40	31.08	30.01	33.02	32.92	30.07

Note: BL: Baseline, typical beef cattle herd; CML: Calf mortality low; CMH: Calf mortality high; CYL: Calves cow^{-1} per year low; CYH: Calves cow^{-1} per year high.
*Negative values indicate carbon sequestration.

(kg) × 28 + N_2O (kg) × 265 + CO_2 (kg) (Myhre et al., 2013). Emission intensities were expressed as kg CO_2 eq (kg beef carcass)$^{-1}$.

Results

Total emissions

The total emissions per year for the BL scenario representing typical herds were 237 t CO_2 eq for British and 282 t CO_2 eq for Continental breeds (Tables 3–5). For both breeds, cow efficiency scenarios (Scenario 1–4) resulted in decreased total emissions when reducing the calf survival (CMH) and number of calves per year (CYL). Increased calf survival (CML) and number of calves per cow (CYH) increased the total emissions, compared with BL scenarios. The young bull carcass production scenarios (Scenario 5–6) differed across breeds. High age at slaugther and low carcass weight (BPL) reduced the total emission by 3.3% for the British breeds, whereas the scenario with low age at slaughter and high carcass weight (BPH) had a 1.6% lower total emissions for Continental breeds. In the combined scenarios (Scenario 7–8), high calf survival, high number of calves produced per cow and high young bull carcass production (BC) increased total emissions by 12.1 and 4.1% for British and Continental breeds, respectively. By including the effect of 3-NOP in the combined scenarios (Scenario 9–14), the total emissions were decreased with both supplementation rates for baseline (BLinL, BLinH) and worst case (WCinL, WCinH) scenarios compared with the BL scenarios. In the best case scenarios, a low supplementation rate (BCinL) increased the total emissions by 9.6 and 1.7%

Table 4. Total greenhouse gas (GHG) emissions (kg CO_2 eq) and emission intensities by source (kg CO_2 eq kg^{-1} carcass) for young bull beef production efficiency, worst case (WC) and best case (BC) scenarios from beef cattle operations.

	Young bull beef production efficiency scenarios						Best case/worst case scenarios			
	British			Continental			British		Continental	
		5	6		5	6	7	8	7	8
Scenario	BL	BPL	BPH	BL	BPL	BPH	WC	BC	WC	BC
Total GHG emissions	236,984	229,264	249,453	281,879	283,990	277,415	213,280	265,652	266,249	293,415
Emission intensities by source										
Enteric CH_4	14.03	14.34	13.60	13.24	13.94	12.28	16.47	12.58	15.51	11.27
Manure CH_4	3.22	3.29	3.14	3.17	3.36	2.91	3.76	2.92	3.72	2.68
Manure N_2O	3.01	3.08	2.91	2.78	2.91	2.59	3.58	2.67	3.27	2.36
Soil N_2O	3.03	3.14	2.97	2.86	3.05	2.68	3.64	2.73	3.41	2.45
Soil C*	−1.72	−1.67	−1.67	−1.85	−1.94	−1.63	−1.88	−1.57	−2.12	−1.51
Off-farm barley	1.94	1.91	1.97	2.15	2.27	1.95	2.05	1.91	2.45	1.84
Off-farm soy	1.89	1.86	1.92	2.09	2.21	1.90	2.00	1.86	2.38	1.79
Indirect energy	3.03	3.25	3.00	2.70	2.94	2.61	3.80	2.73	3.31	2.38
Direct energy	2.34	2.50	2.31	2.09	2.27	2.02	2.93	2.11	2.55	1.83
Total emission intensities	30.78	31.70	30.16	29.23	31.01	27.31	36.34	27.94	34.48	25.08
Total emission intensities excluding soil C	32.49	33.37	31.82	31.08	32.96	28.94	38.22	29.51	36.61	26.59

Note: BL: Baseline, typical beef cattle herd; BPL: Young bull beef production efficiency, low; BPH: Young bull beef production efficiency, high; WC: Worst case, poorest performing 1/3 of Norwegian beef cattle farms; BC: Best case, best performing 1/3 of Norwegian beef cattle farms.
*Negative values indicate carbon sequestration.

Table 5. Total greenhouse gas (GHG) emissions (kg CO_2 eq) and emission intensities by source (kg CO_2 eq kg^{-1} carcass) for worst case (WC) and best case (BC) scenarios with and without the reduction of enteric methane (CH_4) from low and high levels of the inhibitor 3-nitrooxypropanol (3-NOP).

	British							Continental						
Application level 3-NOP		100 mg (kg DM)$^{-1}$			237 mg (kg DM)$^{-1}$				100 mg (kg DM)$^{-1}$			237 mg (kg DM)$^{-1}$		
Scenario	BL	9 BLinL	10 WCinL	11 BCinL	12 BLinH	13 WCinH	14 BCinH	BL	9 BLinL	10 WCinL	11 BCinL	12 BLinH	13 WCinH	14 BCinH
Total GHG emissions	236,984	232,262	209,525	260,619	214,186	193,386	240,975	281,879	262,247	258,580	287,795	254,829	234,798	265,594
Emission intensities by source														
Enteric CH_4	14.03	13.29	15.67	11.95	10.77	12.71	9.74	13.24	11.11	14.40	10.70	10.15	11.85	8.66
Manure CH_4	3.22	3.22	3.76	2.92	3.22	3.76	2.92	3.17	3.17	3.72	2.68	3.17	3.72	2.68
Manure N_2O	3.01	3.01	3.58	2.67	3.01	3.58	2.67	2.78	2.78	3.27	2.36	2.78	3.27	2.36
Soil N_2O	3.03	3.03	3.64	2.73	3.03	3.64	2.73	2.86	2.86	3.41	2.45	2.86	3.41	2.45
Soil C*	−1.72	−1.72	−1.88	−1.57	−1.72	−1.88	−1.57	−1.85	−1.85	−2.12	−1.51	−1.85	−2.12	−1.51
Off-farm barley	1.94	1.94	2.05	1.91	1.94	2.05	1.91	2.15	2.15	2.45	1.84	2.15	2.45	1.84
Off-farm soy	1.89	1.89	2.00	1.86	1.89	2.00	1.86	2.09	2.09	2.38	1.79	2.09	2.38	1.79
Indirect energy	3.03	3.03	3.80	2.73	3.03	3.80	2.73	2.70	2.70	3.31	2.38	2.70	3.31	2.38
3-NOP**	0.00	0.12	0.16	0.10	0.30	0.38	0.25	0.00	0.10	0.12	0.09	0.29	0.36	0.22
Direct energy	2.34	2.34	2.93	2.11	2.34	2.93	2.11	2.09	2.09	2.55	1.83	2.09	2.55	1.83
Total emission intensities	30.78	30.16	35.70	27.41	27.82	32.95	25.34	29.23	27.19	33.49	24.60	26.42	31.19	22.70
Total emission intensities excluding soil C	32.49	31.88	37.58	28.98	29.53	34.83	26.91	31.08	29.04	35.61	26.11	28.27	33.31	24.21

Note: BL: baseline, typical beef cattle herd; BLinL: baseline with 7% reduction of enteric CH_4 emissions from the inhibitor; WCinL: Worst case farms with 7% reduction of enteric CH_4 emissions from the inhibitor; BCinL: Best case farms with 7% reduction of enteric CH_4 emissions from the inhibitor; BLinH: baseline with 33% reduction of enteric CH_4 emissions from the inhibitor; WCinH: Worst case farms with 33% reduction of enteric CH_4 emissions from the inhibitor; BCinH: Best case farms with 33% reduction of enteric CH_4 emissions from the inhibitor.

*Negative values indicate carbon sequestration.

**Emissions related to production and transport of 3-NOP.

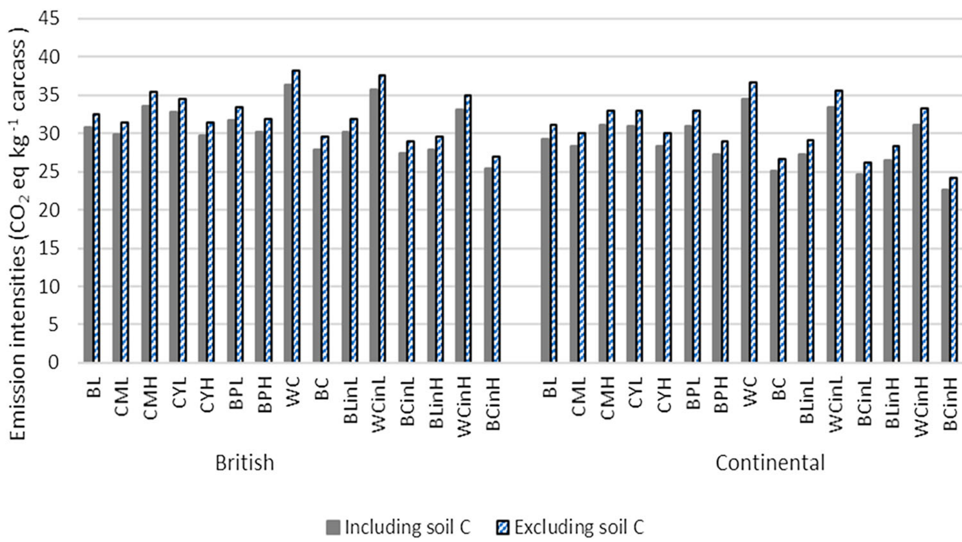

Figure 1. Emission intensities (CO_2 eq kg^{-1} carcass) for each scenario including and excluding soil carbon (C) balance. In all scenarios, the farm was located in the flatlands in Norway and stocked with 28 cows. BL: baseline; CML: calf mortality low; CMH: calf mortality high; CYL: calves per cow per year low; CYH: calves per cow per year high; BPL: young bull beef production efficiency low; BPH: young bull beef production efficiency high; WC: worst case; BC: best case; BLinL: baseline with inhibitor low; WCinL: worst case with inhibitor low; BCinL: best case with inhibitor low; BLinH: baselinge with inhibitor high; WCinH: worst case with inhibitor high; BCinH: best case with inhibitor high.

for British and Continental breeds, respectively. At high application level (BCinH) the total emissions increased 0.7% for the British breeds and decreased 5.8% for the Continental breeds.

Emission intensities

The emission intensities (Figure 1) for the BL scenario were greater for the British breeds (30.8 kg CO_2 eq (kg carcass)$^{-1}$) compared with the Continental breeds (29.2 kg CO_2 eq (kg carcass)$^{-1}$; Table 4). Enteric CH_4 contributed most to the GHG emissions, accounting for 45–46% of the total emissions. Nitrous oxide from manure and soil were the second largest source, accounting for 20–21% of the total emissions. Manure CH_4 accounted for 10–11% and soil C balance was negative for both breed types, indicating C sequestration. Emission intensities for the cow efficiency scenarios varied from 28.3 kg CO_2 eq (kg carcass)$^{-1}$ for the CML and CYH scenarios for Continental breeds to 33.6 kg CO_2 eq (kg carcass)$^{-1}$ for the CMH scenario for British breeds (Table 3). Across breeds, reduced calf mortality and increased number of calves per cow per year each reduced the emission intensities by 3.1% compared with the BL scenario, whereas CMH and CYL increased the emission intensities by 7.8 and 6.3%, respectively.

The Continental breeds demonstrated greater reduction in emission intensities with increased carcass

Table 6. Net reduction potential (t CO_2 eq) from implementing mitigation options by Norwegian from beef cattle operations assuming a constant production of 28,516 t carcass year^{-1}.

	Scenario	Net reduction potential (t CO_2 eq) Improving the 1/3 poorest performing herds to BL level	Net reduction potential (t CO_2 eq) Improving the BL level to the best performing level
Calf mortality	CML + CMH	−8,792	−26,377
Calves per cow year^{-1}	CYL + CYH	−8,935	−26,805
Young bull beef production	BPL + BPH	−12,072	−36,215
Combined*	WC + BC	−33,221	−99,662
BL inhibitor, low rate	BLinL	−12,642	−37,926
BL inhibitor, high rate	BLinH	−27,423	−82,268
Combined* inhibitor, low rate	WCinL + BCinL	−38,021	−114,063
Combined* inhibitor, high rate	WCinH + BCinH	−56,699	−170,096

Note: BL: baseline; (855,611 t CO_2 eq); CML: calf mortality low; CMH: calf mortality high; CYL: calves per cow per year low; CYH: calves per cow per year high; BPL: young bull beef production efficiency low; BPH: young bull beef production efficiency high; WC: worst case; BC: best case; BLinL: baseline with inhibitor low; BLinH: baselinge with inhibitor high; WCinL: worst case with inhibitor low; BCinL: best case with inhibitor low; WCinH: worst case with inhibitor high; BCinH: best case with inhibitor high.
*Combination of calf mortality, calves per cow year^{-1} and young bull beef production.

production compared to the British breeds (Table 4). Reduced carcass production and increased age at slaugther in the BPL scenario, increased the emission intensities by 3.0% and 6.1% for British and Continental breeds, respectively. Increased carcass weight (BPH) and reduced age at slaughter reduced the emission intensities by 2.0% for British and 6.6% for Continental breeds.

In the combined scenarios, larger effects on GHG intensities were observed. For the BC and WC scenarios, emission intensities varied from 27.9 to 36.3 kg CO_2 eq (kg carcass)$^{-1}$ for British breeds and from 25.1 to 34.5 kg CO_2 eq (kg carcass)$^{-1}$ for Continental breeds (Table 4). The BC scenario reduced the emission intensities by 11.7% on average. When the inhibitor 3-NOP was included during the housing period, the emission intensities were reduced by 4.5 and 9.6% across breeds for the BLinL and BLinH scenarios, respectively (Table 5). For the British breeds, the inhibitor reduced the emission intensities by 2.0 (BLinL) and 9.6% (BLinH) compared with the BL scenario, whereas the Continental breeds had 7.0 (BLinL) and 9.6% (BLinH) reductions. High supplementation rate of the inhibitor in the WCinH scenario offset more than half the increase in emission intensities in the WC scenario, resulting in only 6.9% greater emission intensity across breeds compared to the BL scenario (Table 5).

Improving cow efficiency and young bull carcass production among Norwegian beef cattle production herds reduced net emissions by 26,377 and 26,805 t CO_2 eq, respectively (Table 6). The largest net mitigation potential was obtained by combining both improved performance and feeding of the inhibitor 3-NOP at a high supplementation rate (Table 6).

Discussion

Our study investigated GHG mitigation options including cow efficiency, young bull beef production efficiency, combination of cow and bull efficiency, and use of CH4 inhibitor (3-NOP) for the typical beef herds of British and Continental breeds in Norway. The study adopted the unique approach of combining mitigation strategies because, individually, most mitigation strategies have low to moderate impact on decreasing emissions, whereas our study shows that combining strategies may help achieve the decreases in GHG emissions needed from the beef industry. 3-Nitrooxypropanol has been identified as a highly promising mitigation strategy for enteric CH_4 reduction. However the inhibitor 3-NOP is currently not approved by the Norwegian authorities, so the reduction potential from applying the inhibitor is theoretical at this point. Should the approval status of 3-NOP change in the near future (i.e. 3-NOP is undergoing review by authorities in the E.U.), the study demonstrates the possible implications for beef production in Norway. Unlike many previous farm scale studies for beef production (e.g. Foley et al., 2011), our analysis included changes in soil C in the model and demonstrates that forage-based beef production systems can offset some of the CH_4 emissions by preserving or enhancing soil C reserves. Differences in soil C cause differences across farms. However, as the yields and use of fertilizer are kept constant within a farm, the different scenarios causes a proportional change in soil C due to changes in animal manure.

HolosNorBeef estimated emission intensities from the BL scenarios of 29.2–30.8 kg CO_2 eq (kg carcass)$^{-1}$ for typical herds of British and Continental breeds. This range of emission intensities is similar to both other Nordic countries; Denmark 23.1–29.7 kg CO_2 eq (kg carcass)$^{-1}$ and Sweden 25.4 kg CO_2 eq (kg carcass)$^{-1}$ (Mogensen et al., 2015), and the typical herds of British and Continental breeds considered by Samsonstuen et al. (2019) (range: 27.5-32.01 kg CO_2 eq (kg carcass)$^{-1}$). The present study found that Norwegian beef production systems have potential to reduce emission intensities without substantial changes in the enterprise by adopting practices that improve female fertility and calf survival and increase carcass production. The risk of stillbirth could be reduced by supervision during calving, whereas ensuring colostrum and good hygiene could reduce mortality after calving. Good management and feeding of heifers to ensure optimal growth prior to mating help reduce calving difficulties and stillbirths. In addition to herd size and housing conditions, the on-farm calving management and workload is dependent on the length of the calving period (Murray et al., 2015). Seasonal calving could also ease the hygiene management and thus be beneficial to improving calf health and survival. Increased number of calves produced per cow per year through improved culling management, higher pregnancy rates, and fewer abortions and empty cycles is highly dependent on the individual farmers professional knowledge and experience and do not require additional resource input in the enterprice. Carcass production could also be increased by selecting breeding candidates with high genetic merit for feed efficiency that produce larger offspring (Arthur & Herd, 2005), or by dietary improvements such as higher forage quality from improved agronomic practices (Randby et al., 2010). Differences in GHG emissions were demonstrated between typical farm conditions (BL scenario). Across breeds, the alternative scenarios CML, CYH, BC, and BCinL resulted in greater total emissions, whereas scenarios CMH, CYL, BPL, WC, BLinL, WCinL, BLinH, and WCinH resulted in lower total emissions compared to BL. Scenarios BPH and BCinH were dependent upon breed. Higher levels of production were associated with higher levels of inputs (total use of pesticides, fertilizer, and fuel) resulting in greater total on-farm emissions compared with the BL scenarios. However, when expressed per kg carcass, the scenarios with increased cow and beef production efficiency reduced emission intensities (by 2.0–14.2%) compared with the BL scenarios.

In all scenarios, C sequestration had a mitigating effect on GHG emissions. Emission intensities vary due to location, resources, and climatic conditions (White et al., 2010; Samsonstuen et al., 2019). While most farm-level modeling studies assume that soil carbon is at equilibrium, Soussana et al. (2007) has shown that European grasslands act as atmospheric carbon sinks. In Denmark, Sweden and Norway, studies have also shown forage lands to be sequestering carbon (Mogensen et al., 2015; Samsonstuen et al., 2019). Those estimates of carbon sequestration are in the range of the level of C sequestration estimated in the present study. Bonesmo et al. (2013) reported variability in emission intensities from soil N_2O and soil C among Norwegian dairy farms. In the current study, a single location was considered with the initial SOC, temperature, and moisture held constant across scenarios. Forage production and application of N-fertilizer were also held constant per ha. Hence, differences in C sequestration were dependent upon the application of manure and the ley area (ha). As the ley area was a function of animal requirements and DMI, these relationships resulted in lower C sequestration (kg CO_2 eq kg^{-1} carcass) for scenarios where the production efficiency was increased (CML, CYH, BPH, BC) (Soil C; Tables 3 and 4).

Due to low reproductive rate, the impact of offspring survival is larger for cattle compared to pigs. Hence, offspring survival is of great importance for both economics (Azzam et al., 1993) and GHG emissions from beef cattle production (Wall et al., 2010). Calf mortality may be reduced by improving calving and maternal traits both through breeding (i.e. breeding for moderate birth weights) and improved management, such as providing colostrum, good hygiene at calving and navel dipping to reduce infections (Wall et al., 2010; Murray et al., 2015). The CML scenario had low calf mortality, which increased total forage requirements, area needed for forage production, and the total use of inputs (i.e. N-fertilizer and fuel). A larger number of heifer and bull calves were sent to slaughter, which increased the total beef production from the farm. Hence, the low calf mortality scenario (CML) lowered the emission intensities by 3.1% compared with the BL scenarios, which corresponded to the reported reduction in emission intensity (4%) from improved calf survival reported by Beauchemin et al. (2011). Improved female fertility may reduce both management costs and emissions (Wall et al., 2010). The best and worst 1/3 of the Norwegian beef cattle farms produce on average 1.1 and 0.9 calves per cow per year, respectively (Animalia, 2018). An increased number of calves produced per cow may be obtained by improved culling management, higher pregnancy rates, and fewer abortions and empty cycles, which may all be achieved through good management, health, and nutrition.

Production efficiency is essential for reducing the emission intensities from beef production systems (Hyslop, 2008). At low production levels, the number of cattle required to produce the same amount increases. Historically, the number of dairy cattle in Norway has decreased approximately 35% since 1990 as a consequence of increased milk yield (Statistics Norway, 2019). Thus, the number of beef cattle with a greater carcass production has increased to meet the increasing demand for domestic beef. Greater animal productivity through increased carcass production increases the gross efficiency by diluting the maintenance costs of the production animals (Wall et al., 2010). Intensive concentrate-based systems produce lowest emissions per kg beef (Hyslop, 2008) as such diets increase ADG and shorten the finishing period, thereby reducing enteric CH_4 emissions (Lovett et al., 2010). In the present study, the carcass output from the farms varied across scenarios (Tables 1 and 2) with a constant number of cows due to differences in female fertility, calf survival and animal productivity. In accordance with Veysset et al. (2014), the emission intensities decreased with greater animal productivity, due to reduced age at slaughter and increased carcass weights. Higher young bull efficiency (BPH) resulted in a larger reduction in emission intensities for the Continental breeds (6.6%) than the British breeds (2.0%) compared to BL, which reflects greater unexploited potential for increased carcass production for Continental breeds.

Enteric CH_4 accounts for 43.9–55.7% of total GHG emissions from beef cattle production (Foley et al., 2011; Mogensen et al., 2015; Samsonstuen et al., 2019) and is mainly related to variation in feed quality (Ominski et al., 2011) and DMI (Herd et al., 2014). Alemu et al. (2017) reported substantial variation in enteric CH_4 emissions among Canadian farms due to variation in diet composition and diet quality. Hence, reduced enteric CH_4 emissions through nutrition is often seen to be an ideal mitigation strategy. In the present study, differences in enteric CH_4 emissions were related to the number of animals, ADG, and age at slaughter, as the forage quality and proportion of concentrates/pasture were kept constant within breed across scenarios. The reduction in enteric CH_4 emissions from beef cattle by feeding 3-NOP in backgrounding diets varies from 4 to 59% dependent on diet composition and level of application (Romero-Perez et al., 2014; Vyas et al., 2016, 2018). The scenarios investigating the effect of 3-NOP assumed 7 or 33% reduction of enteric CH_4 emissions with no negative effects on performance or DMI. The effect of the inhibitor was only considered during the housing period as feeding supplements to cattle on pasture is challenging. At high supplementation rates, Vyas et al. (2016) reported reduced DMI ($P < 0.01$) during the backgrounding phase and a tendency ($P = 0.06$) for reduced DMI during the finishing phase, whereas Romero-Perez et al. (2014) showed no significant reduction of DMI. Hence, the emissions in the present study might be over-estimated as the inhibitor was assumed to have no effect on DMI. The reduction in emission intensities could potentially be greater if performance was improved or higher if DMI decreased with no influence on ADG. With 3-NOP, the reduction in enteric CH_4 emissions more than offset the increase in indirect energy emissions from manufacturing the inhibitor, regardless of level of supplementation. At high supplementation levels, 3-NOP offset more than half the increase in emission intensities of low production efficiency and poor management, as the WCin scenario had 6.9% greater CO_2 eq emissions across breeds compared with the BL scenario. Currently, the inhibitor (3-NOP) is only available for research purposes as the long-term effect of feeding the supplement needs further investigation for the inhibitor to be approved for use on commercial farms. Hence, the scenarios investigating the mitigation potential by feeding 3-NOP are highly theoretical. Additionaly, 3-NOP might influence other emission sources, such as cattle manure and corresponding soil C balance, which warrants further investigation of the inhibitor as a mitigation option.

The market demand for beef is a prerequisite for domestic production, and mitigation options to reduce the national GHG emissions from beef production need to be investigated in relation to the production level. Increased animal production efficiency could contribute to reduced national emissions both by reducing the total number of beef cows and by reducing emission intensities at the farm-level. The Norwegian beef cattle population produces approximately 28,516 t carcass year^{-1} (Nortura, 2019), corresponding to approximately 856,000 t CO_2 eq at BL level. By improving calf mortality, increasing the number of calves per cow per year, and increasing young bull carcass production of the poorest performing 1/3 herds to BL level, total emissions could be reduced by 8,792, 8,935 and 12,072 t CO_2 eq, respectively (Table 6). The results from this study indicate that the total potential for reducing GHG emissions from Norwegian beef cattle production ranges from 8,000 to 57,000 t CO_2 eq year^{-1} depending upon mitigation option. Over a 10 year period, the scenario combining improved performance and high 3-NOP supplementation rates (BCinH) exceeds the 5 mill ton reduction of GHG emissions required from the agricultural sector according to the agreement between the Norwegian Farmers Union and the Norwegian Government (Norwegian Farmers Union et al., 2019) while maintaining the same level of production.

Genetic improvement of livestock is cost effective and produces permanent and cumulative changes in performance, and can improve farm profitability and reduce emissions through improved animal productivity and efficiency, reduced wastage (i.e. reduced involuntary culling and empty reproductive cycles) and direct selection for low-emission animals (Wall et al., 2010; Åby et al., 2014). Other measures, such as the use of inhibitors are highly effective at reducing emissions, but increase input costs. A premise for farmers to implement on-farm mitigation options is that the extra efforts are considered profitable. Thus, adoption may require subsidy financing to encourage implementation unless a gain in production efficiency is also realized.

Conclusions

The baseline scenario estimated a farm gate GHG emission intensity of 30.8 and 29.2 kg CO_2 eq (kg carcass)$^{-1}$ for British and Continental breeds, respectively. Mitigation strategies that improve cow efficiency by reducing calf mortality and increasing the number of calves born per cow per year each reduced emission intensities by 3.1% across breeds. Improving young bull beef production efficiency had greater mitigation potential for Continental breeds (−6.6%) compared with British breeds (−2.0%). When mitigation options were combined, the emission intensities were reduced by 11.7% across breeds. Assuming no negative effect on performance or DMI, the inhibitor 3-NOP reduced the net GHG emissions from beef cattle production dependent on application level. At a constant national level of beef production, total national emissions can be reduced by implementing one or a combination of mitigation options aimed at improving female fertility, increasing carcass production or reducing enteric CH_4 production using an inhibitor. However, despite a decrease in emission intensity, the total emissions might increase as a consequence of increased production followed by annual population growth and/or increased demand for beef.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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