Norwegian University of Life Sciences
Faculty of Biosciences
Department of Animal and Aquacultural Sciences

Philosophiae Doctor (PhD)
Thesis 2019:93

Whole-farm modelling of greenhouse gas emissions from suckler cow beef production

Modellering av klimagassutslipp fra ammekuproduksjon

Stine Samsonstuen

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Ås, September 2019

Stine Samsonstuen

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Summary

The main objective of this thesis was to develop a whole-farm model adapted to the various production systems and natural resources in Norway, estimate the level and variation in greenhouse gas (GHG) emission intensities among Norwegian sucker cow herds, and investigate the effect of various mitigation options among Norwegian farms. Data from the Norwegian Beef Cattle Recording System and Account Results in Agriculture and Forestry were used for estimating emission intensities from average farms and for investigating GHG emission mitigation strategies. In addition, the data for estimating variability in GHG emission intensities were provided by the ongoing project "Optibeef – Increased meat production from beef cattle herds" (2014 -2019; Grant 233683/E50, Agriculture and Food Industry Research Funds), and consisted of comprehensive information about farm structure, herd management, animal production, and economics in Norwegian suckler cow farms.

The aim of paper I was 1) to develop a whole farm GHG model, including soil carbon (C) balance, adapted to the various production systems and natural resources in Norway, and 2) to use the model for estimating emission intensities from typical herds of sucker cow beef in two geographically distinct regions in Norway. HolosNorBeef is a deterministic model which considers direct emissions of methane (CH_4) from enteric fermentation and manure, nitrous oxide (N_2O) and carbon dioxide (CO_2) from on-farm beef production, and indirect N_2O and CO_2 emissions associated with run-off, nitrate leaching, ammonia volatilization, and inputs (e.g. diesel fuel) used on the farm. Herds of British and Continental breeds were considered in the flatlands and mountains. The flatlands were located at a low altitude in an area suitable for grain production, and mountains were located at a high altitude in a mountainous area not suitable for grain production. The emission intensities were 29.5 and 32.0 kg CO_2 equivalents (eq) (kg carcass)$^{-1}$ for British breeds, and 27.5 and 29.6 CO_2 eq (kg carcass)$^{-1}$ for Continental breeds for flatlands and mountains, respectively. Enteric methane (CH_4) was the largest source accounting for 44-48% of total GHG emissions and carbon (C) sequestration reduced the emissions by 3% on average. When excluding soil C balance, the difference

between locations decreased in terms of GHG emission intensity, indicating that the inclusion of soil C change is important when estimating emission intensities.

Variability in GHG emission intensity across Norwegian suckler cow herds was investigated in paper II. Emission intensities from 27 beef farms of Angus, Hereford, and Charolais breeds was estimated using the whole-farm model HolosNorBeef developed in paper I. The farms were distributed across Norway with varying climate and natural resource base, giving different feed resources and management practices. The emission intensities ranged from 20.9 to 44.2 CO_2 eq (kg carcass)$^{-1}$. Enteric CH_4 was the largest source, accounting for 50% of the emissions across breeds and location. The largest source of variation was soil C, which accounted for 6% of the total emissions on average. Ignoring soil C balance led to re-ranking of the farms in terms of GHG emission intensities and reduced the differences in GHG emissions among farms, with a range in emission intensities of 20.5 to 30.3 CO_2 eq (kg carcass)$^{-1}$. The estimation of soil C balance is sensitive to initial SOC content, which may indicate that further improvements and calibration of the model for estimating soil C balance in permanent grasslands are necessary.

Paper III investigated several mitigation strategies such as suckler cow efficiency (i.e. calf mortality rate and number of calves per cow per year), young bull beef production efficiency (i.e. age and weight at slaughter), a combination of suckler cow efficiency and young bull beef production efficiency and the effect of the inhibitor 3-nitrooxypropanol (3-NOP), which provides a chemical inhibition of the methanogenesis (i.e. CH_4 production). Herd size and structure (number of suckler cows constant and replacement heifers) were kept constant across scenarios, whereas the ley area and corresponding silage additives, N-fertilizer, and fuel varied across scenarios based on feed requirements. Improved suckler cow efficiency reduced the emission intensities by 3% on average. Continental breeds had a higher potential for reducing emission intensities from improved carcass production (-6.6%) compared with British breeds (-2.0%). Combining mitigation options in a best-case scenario reduced total emissions by 12% across breeds. At high supplementation rate, the inhibitor 3-NOP offset more than half the increase in emission intensities from low production and reduced the emission intensities 8.3% in the best case scenario.

Sammendrag

Hovedformålet med dette doktorgradsarbeidet var å utvikle en gårdsmodell for estimering av klimagassutslipp tilpasset de varierende produksjonssystemene og ressursgrunnlaget i Norge, estimere nivå og variasjon i klimagassutslipp fra norske ammekubesetninger, samt undersøke ulike tiltak for å redusere klimagassutslipp. Data fra Storfekjøttkontrollen og Driftsgranskningene i jordbruket ble benyttet både ved beregning av klimagassutslipp fra gjennomsnittsbesetninger og for å undersøke effekten av ulike reduksjonsstrategier. Datagrunnlaget for beregning av variasjon i klimagassutslipp var tilgjengelig gjennom det pågående prosjektet «Økt storfekjøttproduksjon fra ammekubesetninger» (Optibiff 2014-2019; Finansiert av Forskningsmidlene for jordbruk og matindustri), og bestod av omfattende informasjon om gårdsstuktur, management, produksjonsresultater og økonomi.

Hensikten med første artikkel var å 1) utvikle en gårdsmodell for beregning av klimagassutslipp, inkludert karbonbalanse i jord, tilpasset til de varierende produksjonssystemene og ressursgrunnlaget i Norge og 2) bruke modellen for å estimere klimagassutslipp fra gjennomsnittlige kjøttfebesetninger i to geografisk ulike regioner i Norge. HolosNorBeef er en deterministisk modell som inkluderer direkte utslipp av metan (CH_4) fra vomgjæring og gjødsel, lystgass (N_2O) og karbondioksid (CO_2) fra produksjon av storfekjøtt, samt indirekte N_2O og CO_2 utslipp forbundet med avrenning, fordampning og innkjøpt energi (eks. diesel). Besetninger med britiske og kontinentale raser ble undersøkt i lavlandet og høylandet. Lavlandet var lokalisert ved lav høyde i et område egnet for kornproduksjon, mens høylandet var lokalisert i ett fjellområde uegnet for kornproduksjon. Utslippsintensitetene var 29.5 og 32.0 kg CO_2 ekvivalenter (ekv) (kg slakt)$^{-1}$ for britiske raser, og 27.5 og 29.6 CO_2 ekv (kg slakt)$^{-1}$ for kontinentale raser. Enterisk CH_4 var den største utslippskilden og stod for 44-48 % av totalutslippet. Karbonlagring reduserte utslippene gjennomsnittlig 3 %. Ved å ekskludere karbonbalansen i jord ble forskjellen i utslippsintensitet mellom lokalitetene redusert, noe som indikerer at inkludering av jordkarbon er viktig når man estimerer klimagassutslipp på gårdsnivå.

Variasjon i klimagassutslipp fra norske ammekubesetninger ble undersøkt i artikkel II. Utslippsintensitet fra 27 ammekubesetninger med Angus, Hereford og Charolais ble estimert med gårdsmodellen HolosNorBeef. Gårdene var fordelt over hele Norge med varierende klima og ressursgrunnlag, noe som ga ulike fôrressurser og driftsmetoder. Utslippsintensitetene varierte fra 20.9 til 44.2 CO_2 ekv (kg slakt)$^{-1}$. Enterisk CH_4 var den største utslippskilden og stod i snitt for 50 % av totalutslippene. Jordkarbon stod i snitt for 6 % av totalutslippene og var den største kilden til variasjon. Ekskludering av jordkarbon reduserte variasjonen i klimagassutslipp og ga en omrangering av gårder. Uten jordkarbon varierte utslippsintensitetene fra 20.5 til 30.3 CO_2 ekv (kg slakt)$^{-1}$. Estimering av karbonbalansen i jord er følsom for det eksisterende karboninnholdet i jorda, noe som kan indikere at videreutvikling og kalibrering av jordkarbonmodellen for permanent grasmark og utmarksbeiter er nødvendig.

Artikkel III undersøkte effekten av ulike tiltak for å redusere klimagassutslipp på gårdsnivå. Reduksjonsstrategiene inkluderte ammekueffektivitet (dvs. redusert kalvetap og økt antall produserte kalver per ku), ungokseeffektivitet (dvs. alder ved slakt og slaktevekt), en kombinasjon av ammekueffektivitet og ungokseeffektivitet, samt effekten av et fôrtilsetningsstoff (3-nitrooxypropanol; 3-NOP) som hemmer metanogenesen (CH_4 produksjon). Besetningsstørrelsen og besetningsstrukturen (antall ammekyr og rekrutteringskviger) ble holdt konstant på tvers av scenarioer, mens engareal, ensileringsmiddel, N-gjødsel og diesel varierte på tvers av scenarioer avhengig av fôrbehov. Forbedret ammekueffektivitet reduserte utslippsintensiteten gjennomsnittlig 3 %. Kontinentale raser hadde høyere potensiale for å redusere utslippsintensiteten fra forbedret slakteproduksjon (-6.6 %) sammenliknet med britiske raser (-2.0 %). Et «beste fall»-scenario basert på kombinasjon av ulike tiltak reduserte totalutslippene 12 % på tvers av rase. Ved høy tilsetning kan 3-NOP kompensere for mer enn halvparten av økningen i utslippsitensitet fra lav produksjon, samt redusere utslippsintensiteten 8.3 % i «beste fall»-scenarioet.

List of abbreviations

3-NOP	3-nitrooxypropanol
ACLA	Attributional Life Cycle Assessment
ADG	Average daily gain
AFOLU	Agriculture, Forestry and Other Land Use
CH_4	Methane
C	Carbon
CLCA	Consequential Life Cycle Assessment
CO_2	Carbon dioxide
DM	Dry matter
DMI	Dry matter intake
ekv	Ekvivalenter
eq	Equivalents
EU	European Union
GE	Gross energy
GHG	Greenhouse gas
GWP	Global warming potential
ICBM	Introductory Carbon Balance Model
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
LCA	Life Cycle Assessment
N	Nitrogen
N_2	Dinitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO	Nitric oxide

NO_3^-	Nitrate
NR	Norwegian Red
NTNU	Norwegian University of Science and Technology
PEFCR	Product Environmental Footprint Category Rules
RFI	Residual feed intake
SOC	Soil organic carbon
UNFCCC	United Nations Framework Convention on Climate Change
VS	Volatile solids
Ym	Methane conversion factor

List of papers

The present thesis is based on the papers listed below. The papers will be referred to by their roman numbers throughout the thesis.

I. **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. *Agricultural Systems 176:102670*

II. **Samsonstuen, S.**, Åby, B. A., Crosson, P., Beauchemin, K. A., Wetlesen, M. S., Bonesmo, H., Aass, L. 2019. Variability in greenhouse gas emission intensity of semi-intensive suckler cow beef production systems. *Submitted to Livestock Science*

III. **Samsonstuen, S.**, Åby, B. A., Crosson, P., Beauchemin, K. A., Aass, L. 2019. Mitigation of greenhouse gas emissions from suckler cow beef production. *Submitted to Agricultural Systems*

1. General introduction

1.1 Climate and agriculture

The global population is expected to exceed 9.7 billion by 2050 and the food production needs to increase by 50% compared with 2012 levels (FAO, 2017). Human activities, such as food production and burning of fossil fuels, emit greenhouse gases (GHG) and cause global warming (IPCC, 2018). More than 100 countries have adapted a global warming limit of 2 °C or below as a guiding principle to reduce climate change risks, impacts, and damages (Council of the European Union, 2005; IPCC, 2007). However, limiting the global warming to 1.5 °C is expected to lower the impacts on terrestrial, fresh water and costal ecosystems. This requires a strict limitation of both carbon dioxide (CO_2) and non-CO_2 emissions (IPCC, 2018).

The food system produces GHG emissions, such as CO_2, nitrous oxide (N_2O) and methane (CH_4), through the farming process, retailing, food preparation and waste disposal (Garnett, 2011). Agriculture accounts for 11-12% of the global GHG emissions, whereas livestock production accounts for more than half (Tubiello et al., 2014) of these emissions. The livestock sector is competing with bio-energy production, food for humans, fiber for fabric, and conservation of forests and biodiversity for limited land and water resources (Flysjö et al., 2012; Lotze-Campen et al., 2008). Thus, livestock production should be as efficient as possible in utilizing resources. Erb et al. (2013) concluded that sustainable land-use intensification is crucial to cover the demand for land-based production without compromising the natural resource base.

By 2050, global demand for milk and meat is expected to increase by 73% and 58%, respectively, compared with 2010 levels (FAO, 2011). Worldwide, about 67 billion chickens, 1.5 billion pigs, 1 billion goat and sheep and around 304 million cattle are reared for meat production, whereas 278 million cows are used for milk production and 8.1 billion laying hens for egg production (FAOSTAT, 2017).

1.2 Norwegian agriculture

The Norwegian agricultural sector is diverse due to various and dispersed resources (LMD, 2016). Only 3% of the total Norwegian land area (0.98 mill. ha) is arable (NIBIO, 2018a) and the area suitable for cereal production is limited to 1/3 of the arable land due to climate and topography (Figure 1). Hence, the remaining 2/3 of the arable land is temporary and permanent grassland (Statistics Norway, 2019a). Adverse climatic conditions lead to lower crop yields compared to other European countries, whereas most crops are used for animal feed (NIBIO, 2017). On an energy basis, the Norwegian self-sufficiency is on average 50% (when including imported animal feed, else: 42% corrected for imported animal feed; LMD, 2016), and Norway rely on import of both food (e.g. grains, fruit, vegetables) and feed crops to meet the Norwegian populations requirement for food (Norwegian National Council of Nutrition, 2017).

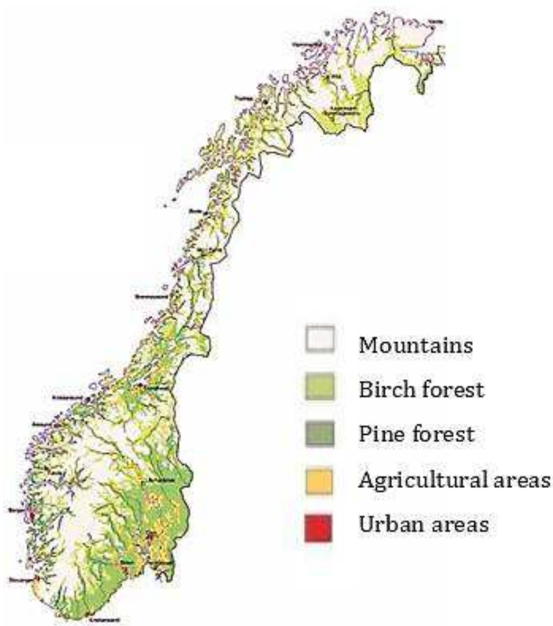

Figure 1 The Norwegian arable land corresponds to 3% of total land area (NIBIO, 2018a; Norwegian Mapping Authority, 2019)

Norway is considered to have good animal welfare (Norwegian Food Safety Authority, 2018), low use of antibiotics (European Medicines Agency, 2016), and animals with good health and fertility (Animalia, 2018). Since 1950, the number of farms have been reduced substantially, whereas the farm size and productivity (i.e. production of milk, meat, crop) have increased due to improved genetics, management and technological development (LMD, 2016; NIBIO, 2017).

1.2.1 Political regulation of Norwegian agriculture

The agricultural sector is influenced by available resources, technological development, national and international politics, economics, and general development of the society (NIBIO, 2017). The four main objectives of Norwegian agriculture policy is to ensure food security, maintain agriculture throughout the country, increase value creation and sustainable agriculture with lower GHG emissions (LMD, 2016). Norwegian agriculture is regulated through policies including border measures, budgetary payments and regulation of the domestic market (OECD, 2018). The farmers' organizations (i.e. Norges Bondelag and Norsk Bonde- og Småbrukarlag) have yearly negotiations with the Ministry of Agriculture and Food (LMD) and reach a commercial agreement (i.e. Agricultural agreement; Jordbruksavtalen), which includes target prices, financial subsidies and other measures to secure farmers' income. In return, the farmers commit to work towards political goals for Norwegian agriculture set by the parliament. The production of e.g. beef and milk is regulated by the target price. Corporations owned by the farmers act as market regulators and can reduce quotas and change the stock balance to avoid overproduction. If a product price exceeds target price for more than two weeks in a row, import restrictions can be eased to reestablish marked balance (LMD, 2018).

1.2.2 Norwegian beef production

Norwegian beef production is divided into two main production systems: 1) beef from culled cows and surplus calves from dual-purpose and specialized dairy and 2) beef from specialized beef breeds. Historically, the dual-purpose breed Norwegian Red (NR) met the demand for domestic beef. However, the increase in milk yield per cow of NR have decreased the number of dairy cattle in Norway approx. 35% since 1990 (Statistics Norway, 2019). As a result, the number of suckler cows has increased to meet the demand for beef (Figure 2). The beef consumption per capita has increased and the demand for beef was not met by the combined production of dual purpose- and suckler cow beef. Thus, Norway has relied on import to cover the shortfall of domestic beef (Nortura, 2019).

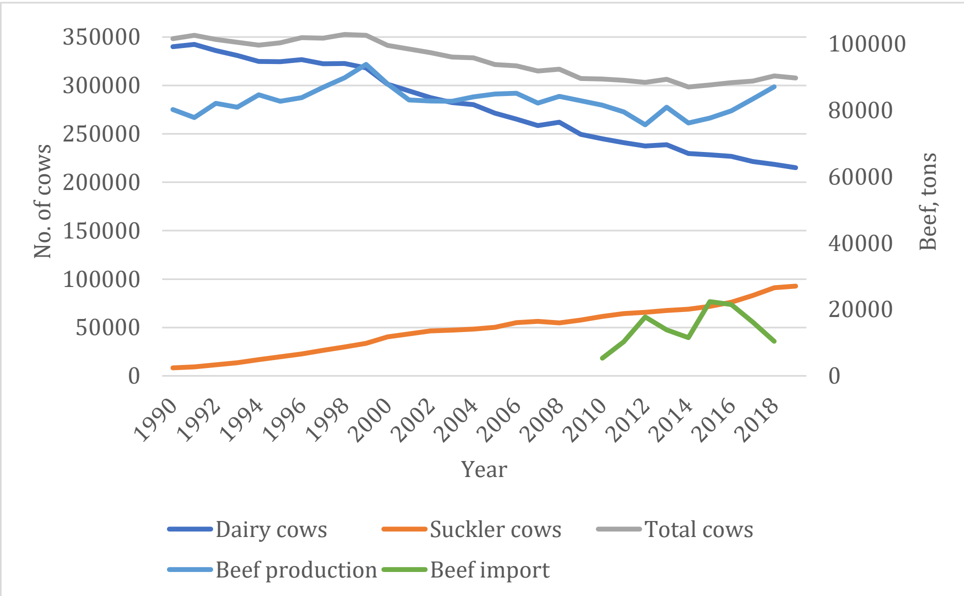

Figure 2 Dairy cow, suckler cow, and total cow population in Norway 1990-2019. Norwegian beef production and imported beef (Nortura, 2018; Statistics Norway, 2019b).

In 2018, the number of suckler cows in Norway was approximately 98 000 (Statistics Norway, 2019c), with an average stocking rate of approx. 24 suckler cows (Animalia, 2018). Norwegian suckler cow beef production is semi-intensive with extensive (low concentrate; approx. 0-10%) feeding of suckler cows and heifer progeny and intensive (high concentrate; approx. 50%) finishing of feeding of male progeny (Åby et al., 2012). Norway has a long housing period (approx. 8 months) due to climatic conditions and the suckler cows are typically kept indoors during winter, and out on pasture with their calves during summer. Farm revenues come from slaughtering of bulls, surplus heifers and cows in addition to subsidies. The major costs are related to feed and labor (Åby et al., 2012; NIBIO, 2018b).

1.3 Greenhouse gas emissions

The primary sources of GHG emissions from livestock production are CH_4 from enteric fermentation and manure storage, N_2O from manure, tillage and N-fertilizer, and CO_2 from transport, electricity and production of various input factors (e.g. pesticides, fuel). GHG emissions are expressed using a common metrics, CO_2 equivalents (eq), to account for the differing global warming potentials (GWP) of the respective gases. The GWP is calculated dependent on the lifetime and radiative forcing of the gas, and assume an equal environmental impact (IPCC, 2014). The non-CO_2 gases (i.e. CH_4 and N_2O) are weighed relative to CO_2, dependent on the contribution to global warming over time. The current GWP_{100} is based on a 100 year time horizon, whereas CH_4 is expected to have a lifetime of 28 years and N_2O is expected to have a lifetime of 265 years:

$\mathrm{CH_4(kg)} \times 28 + \mathrm{N_2O(kg)} \times 265 + \mathrm{CO_2(kg)}$ (Myhre et al., 2013).

In 2018, the agricultural sector accounted for about 8% of the total Norwegian GHG emissions, corresponding to 4.5 tons CO_2 eq (Statistics Norway, 2019a). CH_4 from enteric fermentation was the largest source and accounted for approx. 50% of total emissions from the agricultural sector (Statistics Norway, 2019d). Corresponding to European Union (EU) goals, Norway has committed to reduce the GHG emissions from agriculture (European Commission, 2014; Ministry of Climate and Environment, 2017). The Norwegian Government has commissioned several governmental agencies (e.g. the Norwegian Agricultural Agency, the Norwegian Environment Agency) to examine measures to reduce total GHG emissions 50% by 2030 compared with 2005 levels (The Norwegian Government, 2019).

The GHG emissions from livestock production can be calculated using different methodologies and approaches such as the Intergovernmental Panel on Climate Change (IPPC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), a whole-farm approach using a systems analysis approach, or a product-based approach using life cycle assessment (LCA). The IPCC methodology is transparent and provides a consistent inventory for national reporting at various times, whereas a whole-farm approach is useful to explore on-farm mitigation options or estimating the environmental impact of a product (Schils et al., 2007).

1.3.1 National inventory report and IPPC guidelines

According to Article 4 and 12 of the United Nations Framework Convention of Climate Change (UNFCCC), Norway is required to submit yearly national inventory reports with GHG emissions by source and removals by sinks (United Nations, 1992). The inventory report uses 1990 as the base year and the methodology is based on the IPPC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). National inventories are divided into five main sectors: Energy, Industrial Processes and Product Use (IPPU), Agriculture, Forestry and Other Land Use (AFOLU), Waste, and Other (IPCC, 2006). Upstream products from other countries (e.g. fuel, feed) is accounted for in the National inventory of the country of origin and distributed by sector. Hence, all emissions related to e.g. fuel is accounted for in the Energy sector regardless of use. The general method for calculating emissions is:

$$\text{Emissions (E)} = \text{Activity level (A)} \times \text{Emission Factor (EF)}$$

The IPCC methodology has different levels of complexity (tiers). The higher tiers are considered to be more accurate. Usually three tiers are provided: Tier 1) basic method with default emissions and stock change factors designed to be used with easily available national or international statistics, Tier 2) intermediate complexity with emissions and stock change factors based on regional- or country specific data, and Tier 3) high complexity based on country-specific methodologies, including models and measurement systems based on high resolution activity data (IPCC, 2006).

Emissions reported from agriculture include enteric fermentation, manure management, agricultural soils, field burning of agricultural residues, liming, and urea application (Norwegian Environment Agency, 2018). The Norwegian inventory report uses Tier 1 and Tier 2 approaches for reporting GHG emissions originated from the agricultural sector (Norwegian Environment Agency, 2018). A combination of Tier 1 and 2 is used for CH_4 from enteric fermentation and N_2O from manure management, a Tier 2 approach is used for CH_4 from cattle manure, whereas Tier 1 is used for the remaining categories. In 2016, the emissions from agriculture had a 6% decline compared with 1990 (Norwegian Environment Agency, 2018).

1.3.2 Whole-farm models

The complexity of the farm as a system, is a challenge when estimating GHG emissions from livestock production. The whole-farm approach was developed to describe and quantify the cycling of nutrients and materials between different farm components and the environment (Crosson et al., 2011). A whole-farm model is a systems analysis of the farm with the boundary of the model typically limited to within the farm gate. Most models include pre-farm emissions such as manufacturing of fuel and nitrogen (N)-fertilizer but do not include the emissions from post-farm processes such as slaughter and processing (Schils et al., 2007). It provides an estimate of the environmental impact of agriculture, management and resource utilization associated with farm activities (Schils et al., 2007). Processes occurring beyond the farm gate dependent on the farm production should be included for a complete assessment of the production, but are normally excluded (Schröder et al., 2003).

Whole-farm models are a mix of empirical and mechanistic modelling and different models have varying system boundaries and assumptions (Schils et al., 2007). The models are often developed by combining existing sub-models with different underlying methodologies, and the calculation procedures varies among models (Schils et al., 2007). A typical model of livestock production (Figure 3) includes the on-farm production of feed and the return of animal manure to the soils. The farm inputs are typically feed (e.g. concentrates), fuel, N-fertilizer, and pesticides, whereas the outputs are animal products such as milk and beef. Emissions occurring at different stages in the farm system are reflected in the model and the effects of management changes are transferred throughout the system (Schils et al., 2007). The whole-farm approach calculates the effect of several mitigation options. A number of models include economic submodels which permit the calculation of farm profitability thus ensuring that potential trade-offs between profit and GHG emissions are exemplified (Crosson et al., 2011; Gibbons et al., 2006; Janzen et al., 2011).

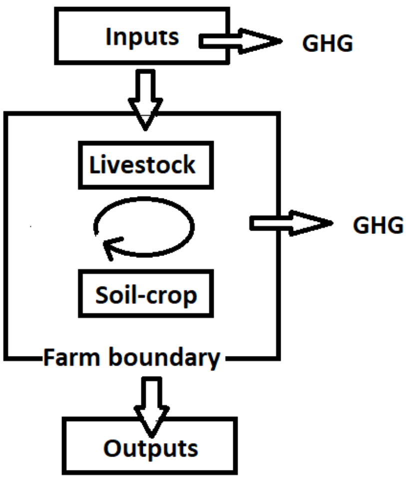

Figure 3 Basic elements of whole-farm modelling of greenhouse gas (GHG) emissions (adapted from Schils et al., 2007).

1.3.3 Life cycle assessment

The LCA is a scientific accepted approach to estimate the environmental sustainability of human activities (Baitz et al., 2013; Guinée et al., 2011) and is somewhat more formalized than whole-farm modeling using a system analysis approach (ISO, 2006). The European Commission have developed Product Environmental Footprint Category Rules (PEFCR) providing product specific guidelines on how to conduct a reliable and comparable LCA study (European Commission, 2013). LCA is widely used for documenting and evaluating the environmental impact of products such as fuel, N-fertilizer or feed crops (Hasler et al., 2015; Nanaki and Koroneos, 2012; Tricase et al., 2018; Zucali et al., 2018). In addition to GHG emissions, LCA models have additional impact categories including land use, energy use, acidification potential and eutrophication potential (Cederberg and Stadig, 2003; Nguyen et al., 2010; Ogino et al., 2004).

LCA models are cradle to grave assessments of the production chain, which estimates the environmental impact of a process over the full life cycle at the current level of production. Traditionally, LCA analysis had an attributional approach (ALCA) and considered the use of resources (e.g. material, energy) related to a unit of product when estimating the corresponding emissions (Earles and Halog, 2011). ACLA typically uses average data for each process within the life cycle to identify hot-spots in the production chain and allocates the emissions to the product. However, when modelling the consequence of a decision, the dynamic changes within the life cycle are modelled using a consequential LCA (CLCA) model. A CLCA approach requires system expansion to account for the corresponding changes in resource use and environmental impact (Zamagni et al., 2012). However, system expansion makes the CLCA more sensitive to uncertainties compared with ALCA (Thomassen et al., 2008).

1.3.4 Environmental impact of beef

The emission intensities (i.e. the GHG emissions generated per unit of product) of livestock products varies considerably across and within production systems due to different agro-ecological conditions, farming practices and supply chain management. Beef products are reckoned to have a large environmental impact compared to other livestock products and accounts for 41% of the total GHG emissions from the agricultural sector (Figure 4; modified after Gerber et al., 2013). The environmental impacts of suckler cow beef are greater than dairy beef as the emissions from dairy production are allocated to both milk and beef (de Vries et al., 2015). However, there is a large variation in emission intensities between continents (Gerber et al., 2013) and farms within a country (Bonesmo et al., 2013). Globally, the emission intensities from suckler cow beef varies from 17.0 to 67.6 CO_2 eq (kg carcass)$^{-1}$ (Alemu et al., 2017; Gerber et al., 2013; Legesse et al., 2018; Nguyen et al., 2010; White et al., 2010) dependent on differences in farming systems (Nguyen et al., 2010), location (White et al., 2010), breed (Hyslop, 2008), and farm management (Alemu et al., 2017; Stanley et al., 2018). Enteric CH_4 is the largest source of emissions from suckler cow beef production systems and account for 48-56% of total farm emissions (Beauchemin et al., 2010; Foley et al., 2011; Mogensen et al., 2015). Previous studies of GHG emissions from Norwegian suckler cow beef production have been based on the national inventory reports using coefficients (Grønlund, 2015), LCA (Refsgaard et al., 2012), and the Irish BEEFGEM model adapted to Norwegian conditions (Aass and Åby, 2018; Åby et al., 2016). The estimated emission intensities ranged from 26 to 34 CO_2 eq (kg carcass)$^{-1}$ (Aass and Åby, 2018; Grønlund and Harstad, 2014; Refsgaard et al., 2012).

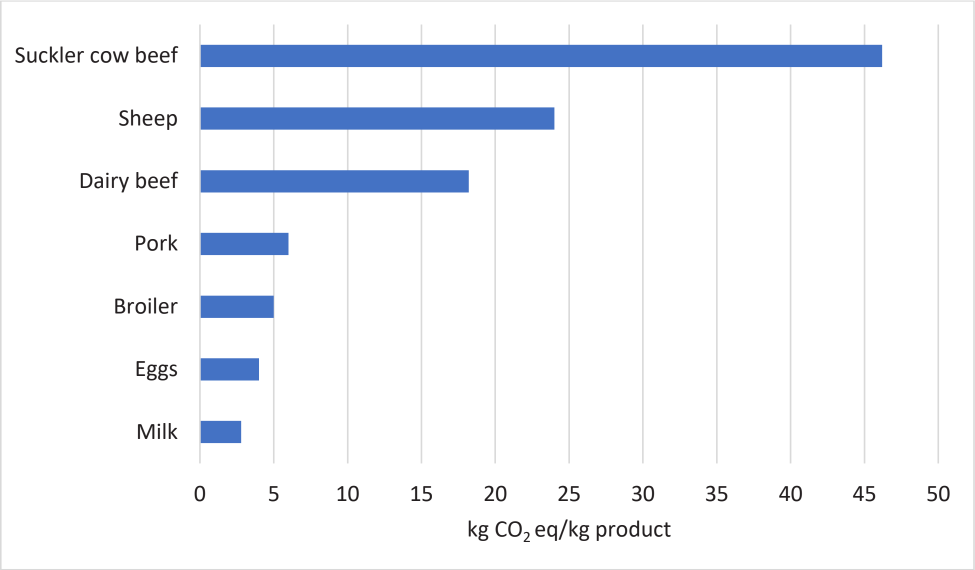

Figure 4 Average global emission intensities from livestock products (kg CO_2 equivalents (eq)/kg product; Gerber et al., 2013).

2. Aim and outline of the thesis

The main aim of this thesis was to develop a whole-farm model adapted to the various production systems and natural resources in Norway, estimate the level and variation in greenhouse gas (GHG) emissions among Norwegian suckler cow herds, and investigate the potential of GHG reduction through various mitigation options.

The thesis had three sub goals:

1. Develop a whole-farm GHG model and estimate emission intensities from average Norwegian suckler cow herds in different geographical regions.
2. Investigate the variability in emission intensities of suckler cow herds.
3. Investigate the GHG emission mitigation strategies following improved female reproductive performance, young bull beef production and supplementation of an inhibitor.

The aims were investigated through three studies. First, the model was developed and the level of GHG emission intensities of average Norwegian herds of British and Continental breeds in two geographical locations were estimated. Secondly, the variability in emission intensities was estimated from 27 suckler cow herds. Last, the model was used to investigate the net effect of varying suckler cow efficiency, young bull beef production efficiency, and the inhibitor 3-nitrooxypropanol (3-NOP) on emission intensities.

3. Paper I

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

Samsonstuen, S., Åby, B. A., Crosson, P., Beauchemin, K. A., Bonesmo, H., Aass, L.

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

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ABSTRACT

A whole-farm model, HolosNorBeef was developed to estimate net greenhouse gas (GHG) emissions from suckler beef production systems in Norway. The model considers direct emissions of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) from on-farm livestock production including soil carbon (C) changes, and indirect N_2O and CO_2 emissions associated with leaching, volatilization and inputs used on the farm. The emission intensities from average beef cattle farms in Norway was estimated by considering typical herds of British and Continental breeds located in two different regions, flatlands and mountains, with different resources and quality of feed available. The flatlands was located at a low altitude in an area suitable for grain production and mountains was located at higher altitude in a mountainous area not suitable for grain production. The estimated emission intensities were 29.5 and 32.0 kg CO_2 equivalents (eq) kg^{-1} carcass for the British breeds and 27.5 and 29.6 kg CO_2 eq kg^{-1} carcass for the Continental breeds, for flatlands and mountains, respectively. Enteric CH_4 was the largest source accounting for 44–48% of total GHG emissions. Nitrous oxide from manure and soil was the second largest source accounting for, on average, 21% of the total emissions. Carbon sequestration reduced the emission intensities by 3% on average. When excluding soil C the difference between locations decreased in terms of GHG emission intensity, indicating that inclusion of soil C change is important when calculating emission intensities, especially when production of feed and use of pasture are included.

1. Introduction

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

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

Whole farm systems models are useful for assessing the impact of

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

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

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

2. Materials and methods

2.1. HolosNorBeef

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

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

2.1.1. Input sub-model

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

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

2.1.2. GHG emissions sub-model

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

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

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

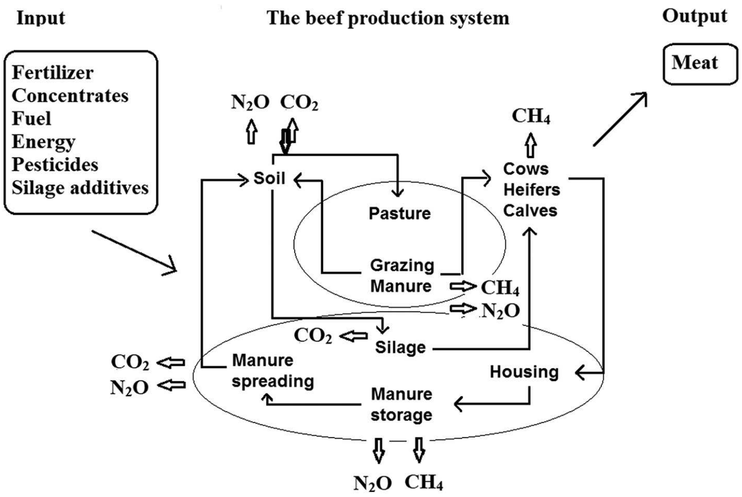

Fig. 1. The suckler cow beef production system.

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

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

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

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

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

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

2.2. Norwegian suckler beef production system

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

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

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

Gas/source	Emission factor/equation	Reference
Methane		
Enteric fermentation	(0.065/55.64) kg CH_4 (MJ GEI)$^{-1}$	(IPCC, 2006)
Relative effect of digestibility (DE%) of feed	$0.1058 - 0.006 \times DE$	(Bonesmo et al., 2013)[a]
Max.CH_4 producing capacity of manure (B_o)	0.18 m^3 CH_4 kg^{-1}	(IPCC, 2006)
Deep bedding manure	0.17 kg CH_4 (VS)$^{-1}$	(IPCC, 2006)
Pasture manure	0.01 kg CH_4 (VS)$^{-1}$	(IPCC, 2006)
Direct nitrous oxide		
Soil N inputs[b]	0.01 kg N_2O-N (kg N)$^{-1}$	(IPCC, 2006)
Relative effect of soil water filled pore space (WFPS mm)	$0.4573 + 0.01102 \times$ WFPS	(Sozanska et al., 2002)[c], (Bonesmo et al., 2012)[c]
Relative effect of soil temperature at 30 cm (ts30°C)	$0.5862 + 0.03130 \times$ ts30	(Sozanska et al., 2002)[c],(Bonesmo et al., 2012)[c]
Deep bedding manure	0.01 kg N_2O-N (kg N)$^{-1}$	(IPCC, 2006)
Pasture manure	0.02 kg N_2O-N (kg N)$^{-1}$	(IPCC, 2006)
Indirect nitrous oxide		
Soil N inputs[b]	Leaching:	
	EF = 0.0075 kg N_2O-N (kg N)$^{-1}$, $Frac_{leach}$ = 0.3 kg N (kg N)$^{-1}$	(IPCC, 2006), (Little et al., 2008)[d]
	Volatilization:	
	EF = 0.01 kg N_2O-N (kg N)$^{-1}$, $Frac_{volatilization}$ = 0.1 kg N (kg N)$^{-1}$	(IPCC, 2006)
Deep bedding manure	Leaching:	
	EF = 0.0075 kg N_2O-N (kg N)$^{-1}$, $Frac_{leach}$ = 0 kg N (kg N)$^{-1}$	(IPCC, 2006)
	Volatilization:	
	EF = 0.01 kg N_2O-N (kg N)$^{-1}$, $Frac_{volatilization}$ = 0.3 kg N (kg N)$^{-1}$	(IPCC, 2006)
Pasture manure	Leaching:	
	EF = 0.0075 kg N_2O-N (kg N)$^{-1}$, $Frac_{leach}$ 0.3 kg N (kg N)$^{-1}$	(IPCC, 2006), (Little et al., 2008)[d]
	Volatilization:	
	EF = 0.01 kg N_2O-N (kg N)$^{-1}$, $Frac_{volatilization}$ = 0.2 kg N (kg N)$^{-1}$	(IPCC, 2006)
Soil carbon		
Young (ky) soil C decomposition rate	0.8 year^{-1}	(Andrén et al., 2004)
Old (ko) soil C decomposition rate	0.007 year^{-1}	(Andrén et al., 2004)
Humification coefficient (h) of grass and crop residue	0.13	(Katterer et al., 2008)
Humification coefficient (h) of cattle manure	0.31	(Katterer et al., 2008)
Direct carbon dioxide		
Diesel fuel use	2.7 kg CO_2 L^{-1}	(The Norwegian Environment Agency, 2017)
Indirect carbon dioxide		
Manufacturing N-based synthetic compound fertilizer	4 kg CO_2eq (kg N)$^{-1}$	(DNV, 2010)
Manufacturing pesticides	0.069 kg CO_2eq (MJ pesticide energy)$^{-1}$	(Audsley et al., 2009)
Manufacturing silage additives	0.72 kg CO_2eq (kg CH_2O_2)$^{-1}$	(Flysjö et al., 2008)
Production of diesel fuel	0.3 kg CO_2eq L^{-1}	(Öko-Institut, 2010)
Production of electricity	0.11 kg CO_2eq kWh^{-1}	(Berglund et al., 2009)
Purchased soya meal	0.93 kg CO_2eq (kg DM)$^{-1}$	(Dalgaard et al., 2008)
Purchased barley grain	0.62 kg CO_2eq (kg DM)$^{-1}$	(Bonesmo et al., 2012)

GEI = Gross energy intake; VS = volatile solids; WFPS = water filled pore space; ts30 = soil temperature at 30 cm; EF = emission factor; $Frac_{leach}$ = Leaching fraction; $Frac_{volatilization}$ = Volatilization fraction.
[a] Equation derived by Bonesmo et al. (2013) based on IPCC (2006), Little et al. (2008) and Beauchemin et al. (2010).
[b] Includes land applied manure, grass and crop residue, synthetic N fertilizer, mineralized N.
[c] Equation derived by Bonesmo et al. (2012) using data from Sozanska et al. (2002)
[d] Value simplified from equation given by Little et al. (2008).

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

2.3. Sensitivity analysis

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

Table 2
Average temperatures (C°) with min and max temperatures (in parenthesis) and land resources (ha) with proportion of total area (in parentheses) from two different locations (flatlands and mountains) in Norway.

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

[a] NRK and Norwegian Meterological Insitute (2018).
[b] Norwegian Institute of Bioeconomy Research (NIBIO, 2018).
* On a scale from 1 (good) to 4 (harsh).
** Do not sum up to 100% as area unrelated to agriculture are left out of the table.
*** Proportion of bare land.

Table 3
Average animal data for Norwegian beef farms used to estimate GHG emission intensities in two locations.

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

LW = live weight.
[a] Animalia (2017a).
[b] Norwegian Institute of Bioeconomy Research (NIBIO, 2015).
[c] Åby et al. (2012).
* 42% cultivated pasture, 58% outfield pasture.
** 50% cultivated pasture, 50% outfield pasture.

3. Results

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

Table 4
Average animal numbers, crop and fuel usage data for Norwegian beef farms used to estimate GHG emission intensities from two different locations (flatlands and mountains) in Norway.

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

FUm = feed units milk.
[a] Norwegian Institute of Bioeconomy Research (NIBIO, 2015).
[b] Norwegian Institute of Bioeconomy Research (NIBIO, 2016).
[c] Eurofins (2015).
[d] Statistics Norway (2017).
[e] NMBU and Norwegian Food Safety Aguthority, (2008).

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

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

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

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

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

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

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

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

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

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

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

4. Discussion

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

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

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

Table 9
Sensitivity elasticities for the effect of 1% change in the selected emission factors (EF) and initial soil organic carbon on the greenhouse gas (GHG) emission intensities CO_2 eq (kg carcass)$^{-1}$.

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

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

Table 10
The effect of farm and herd size on the greenhouse gas (GHG) emission intensities CO_2 eq (kg carcass)$^{-1}$.

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

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

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

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

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

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

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

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

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

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

5. Conclusions

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

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4. Paper II

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

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

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Abstract

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

(N_2O) and carbon dioxide (CO_2) from on-farm livestock production and indirect N_2O and CO_2 emissions associated with inputs used on the farm. The corresponding soil carbon (C) emissions are estimated using the Introductory Carbon Balance Model (ICBM). The farms were distributed across Norway with varying climate and natural resource bases. The estimated emission intensities ranged from 23.1 to 46.1 kg CO_2 equivalents (eq) (kg carcass)$^{-1}$. Enteric CH_4 was the largest source, accounting for 47% 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 and North re-ranked in terms of emission intensities when soil C was excluded. Ignoring soil C, estimated emission intensities ranged from 21.7 to 35.5 kg CO_2 eq (kg carcass)$^{-1}$. High C loss from farms with high initial soil organic carbon (SOC) content warrants further examination of the C balance of permanent grasslands as a potential mitigation option for beef production systems.

Keywords

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

1. Introduction

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

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

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

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

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

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

2. Materials and methods

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

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

2.1 Farm characteristics

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

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

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

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

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

2.2. Modelling GHG emissions

2.2.1 The HolosNorBeef model

The GHG emissions were estimated using HolosNorBeef developed by Samsonstuen et al. (2019). HolosNorBeef is an empirical model based on the HolosNor model (Bonesmo et al., 2013), BEEFGEM (Foley et al., 2011), HOLOS (Little et al., 2008), and the Tier 2 methodology of the Intergovernmental Panel on Climate Change (IPCC, 2006) modified for suckler beef production systems under Norwegian conditions. The model estimates the GHG emissions on an annual time step for the land use and management changes and on a monthly time step for animal production, accounting for differences in diet, housing, and climate. HolosNorBeef estimates the whole-farm GHG emissions by considering direct emissions of methane (CH_4) from enteric fermentation and manure, nitrous oxide (N_2O) and carbon dioxide (CO_2) from on-farm livestock production including soil carbon (C) changes, and indirect N_2O and CO_2 emissions associated with run-off, nitrate leaching, ammonia volatilization and from inputs used on the farm (Figure 1; adopted by Samsonstuen et al., 2019). All emissions are expressed as CO_2 eq to account for the global warming potential (GWP) of the respective gases for a time horizon of 100 years: $\mathrm{CH_4(kg)} \times 28 + \mathrm{N_2O(kg)} \times 265 + \mathrm{CO_2(kg)}$ (Myhre et al., 2013). Emission intensities from suckler cow beef production are related to the on farm beef production and expressed as kg CO_2 eq (kg beef carcass)$^{-1}$.

Methane emissions

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

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

Nitrous oxide emissions

Direct manure N_2O emissions are calculated based on the N content of manure and an emission factor for the manure handling system (0.01, 0.02, 0.05 kg N_2O-N (kg N)$^{-1}$ for deep-bedding, pasture manure, and solid storage, respectively; IPCC, 2006). 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.

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

Indirect N_2O emissions from soil are estimated from the assumed losses of N from manure, crop residues, and fertilizer according to IPCC (2006). The emissions from run-off, leaching and volatilization are estimated based on the fraction of the loss for the manure handling system adjusted using emission factors (0.0075 and 0.01 kg N_2O-N kg^{-1}) for leaching and volatilized ammonia-N, respectively (IPCC, 2006). 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). 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).

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) and a humification coefficient of cattle manure (h= 0.31; Kätterer et al., 2008). The degradation of the pools is determined by the respective decomposition rates (k_y= 0.8 year^{-1} and k_o=0.007; Andrén et al., 2004). 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, as explained by Bonesmo et al. (2013).

Carbon dioxide emissions

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

2.3 Sensitivity analysis and comparisons

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

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

3. Results

The total farm GHG emission intensities showed no significant difference across breeds (Table 6). However, N_2O emissions from manure ($P \leq 0.01$) and emissions related to off-farm production of barley ($P \leq 0.05$) and soya ($P \leq 0.01$) 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 30.4 CO_2 eq (kg carcass)$^{-1}$ (median= 30.6, range 23.1 to 46.1; Table 6). Enteric CH_4 contributed most to the total GHG emissions, accounting for 47% of the total emissions. N_2O from soil and manure was the second largest source, accounting for 11% and 9%, respectively. Soil C balance accounted for 6% of the total emissions and had the largest variation across farms, ranging from -12% to 31% depending on location. On-farm emissions from burning of fossil fuels accounted for 8% and the indirect CO_2 emissions from manufacturing of farm inputs (i.e. N-fertilizers, fuels, electricity, pesticides) accounted for 8%.

Emission intensities differed regionally ($P \leq 0.05$; Table 7). East and Mid had lowest mean emission intensities, whereas Southwest and North had greatest mean emission intensities. Soil C differed across regions ($P \leq 0.01$) and was the largest source of variation, accounting for 0-5% of the total emissions in East and Mid, and 10-20% of the total emissions in Southwest and North. North had greater emissions from indirect and direct energy. By excluding the soil C balance, the variation between individual farms decreased and the emission intensity across all farms had a mean estimate of 28.6 CO_2 eq (kg carcass)$^{-1}$ (median= 28.4, range 21.7 to 35.5). Excluding soil C led to re-ranking of individual farms in terms of GHG emission intensity (Table 8).

Estimated GHG were moderately sensitive to changes in initial SOC and the yearly effect of soil temperature and soil moisture ($r_W \times r_T$). The sensitivity elasticity had a linear response ranging from 0.14 to 0.23 CO_2 eq (kg carcass)$^{-1}$ across region, caused by 1% change in initial SOC (Table 9). Changing the $r_W \times r_T$ 1%, caused a 0.12-0.19 CO_2 eq (kg carcass)$^{-1}$ across regions (Table 9).

4. Discussion

4.1 Animal production

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

4.2 Greenhouse gas emissions

Under the current conditions for beef production in Norway, HolosNorBeef estimated mean emission intensities, including soil C, of 30.4 CO_2 eq (kg carcass)$^{-1}$ (median= 30.6, range 23.1 to 46.1) for 27 herds of Angus, Hereford, and Charolais. This range of emission intensities is similar to reports for other Nordic countries; Denmark 23.1 to 29.7 CO_2 eq (kg carcass)$^{-1}$ and Sweden 25.4 CO_2 eq (kg carcass)$^{-1}$ (Mogensen et al., 2015). Emissions related to off-farm production of barley and soya differed in terms of emission intensities across breeds. Observed feed intake and use of concentrates showed variation both across breeds and between farms within breed as a consequence of diet composition and feed requirements. In general, farms with lower quality forage fed a larger proportion concentrates to the replacement heifers. Bulls were on average fed 33% concentrates and were usually fed good quality silage. However, as increased production follows increased feed intake, the observed variability did not cause differences in total emission intensities across breeds.

4.2.1 Methane emissions

Enteric CH_4 contributed most to the total GHG emissions, accounting for 47% of the total emissions on average. HolosNorBeef estimated enteric CH_4 emissions based on the GE intake while adjusting the Ym for the digestibility of the diet (i.e. DE%). Hence, as shown by Samsonstuen et al. (2019), variation in Ym would cause a linear change in emission intensities.

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

Manure CH_4 emissions varied from 2-9% of total emissions depending upon diet composition, housing conditions, and manure storage. HolosNorBeef calculated the manure CH_4 emissions on a monthly basis for each cattle class and determined the organic matter (i.e. VS) content of manure based on GE intake and the digestibility (i.e. DE%) of the diet. The DE% were variable, ranging from 59 to 71% among the farms leading to a large variation in manure CH_4 emissions between farms. This is similar to the range in DE% (49 to 81%) reported by Hanigan et al. (2013). Diet composition and DMI influence manure CH_4 emissions as increased organic matter (i.e., VS) content of manure increases the emissions from degradation (Monteny et al., 2001). Farms with low quality forage (e.g. straw or low quality silage) had lower manure CH_4 emissions as both the digestibility of the diet and the VS content of manure decreases. Crude protein (CP) and fiber content of the diet is significantly related to VS (Appuhamy et al., 2017), and Amon et al. (2007) showed that increased lignin and cellulose content in the manure reduces the CH_4 emissions as the digestibility decrease. However, manure management influence the manure CH_4 emissions as the CH_4 conversion is greater in deep bedding, compared with solid storage, due to anaerobic conditions. Thus, the greater CH_4 manure emissions were for farms using deep bedding during the housing period.

4.2.2 Regional variation

Both soil C (discussed in section 4.2.3) and total emissions 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 28.6 CO_2 eq (kg carcass)$^{-1}$ (median= 28.4, range 21.7 to 35.5). 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. However, unequal distribution of breeds and re-ranking of the individual farms within region when excluding soil C might imply that the regional resource base favor different breeds. 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. 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

Soil C balance accounted for 6% of the total emissions on average and had the largest variation across farms, ranging from -12% to 31% depending on location. HolosNorBeef estimated the C balance between the soil and atmosphere using the two-compartment ICBM model (Andrén et al., 2004). Soil C balance was influenced by 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 0-5% of the total emissions in East and Mid, whereas in Southwest and North the average C balance accounted for 10-20% 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., 2012). Hence, the estimated C loss from farms in Southwest and North is a result of high initial SOC. As the soil C content is difficult to measure, Andrén et al. (2015) suggested to modify the initial SOC if the changes between samplings are unrealistic. However, in the present study there is only a single estimate of the SOC content and modifying the initial SOC is not possible.

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

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

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

5. Conclusions

A whole-farm approach that included changes in soil C estimated GHG emission intensities of 23.1 to 46.1 CO_2 eq (kg carcass)$^{-1}$ from representative suckler cow beef farms in Norway with Angus, Hereford, and Charolais cattle. The variation in DMI and diet composition between farms influenced both enteric and manure CH_4 emissions, and contributed to variation in emission intensities between individual farms. Including soil C balance in the emission intensity of beef production increased variability in GHG emissions among individual farms. By excluding soil C balance, differences among locations, breeds, and individual farms were smaller, ranging from 21.7 to 35.5 CO_2 eq (kg carcass)$^{-1}$. The large initial SOC content in soils of some farms warrants further examination and additional measurement, as the ICBM model is sensitive to high initial SOC, which has a significant impact on estimated GHG intensity of beef production.

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Tables

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

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

LW= live weight

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

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

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

[a] 1FUm = 6.9 MJ net energy lactation

[b] Information from the farmer

[c] Forage analysis (Eurofins, 2015)

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

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

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

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

FUm= feed units milk

*outfield pasture areas are not included

[a] Farm accounts 2013/2014

[b] Information from the farmer

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

	East (n=16)			Southwest (n=2)			Mid (n=4)			North (n=5)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Soil temperature at 30 cm depth[a], winter (°C)	-0.3	-1.5	1.2	1.9	1.8	2.0	0.7	-0.5	1.6	0.8	-0.3	1.9
Soil temperature at 30 cm depth[a], spring (°C)	6.2	3.4	8.1	6.9	6.8	6.9	5.6	4.7	6.3	5.3	4.4	6.0
Soil temperature at 30 cm depth[a], summer (°C)	13.7	11.1	15.6	13.1	12.8	13.4	12.2	11.7	12.8	12.4	12.1	12.8
Soil temperature at 30 cm depth[a], autumn (°C)	5.5	2.8	8.4	8.1	8.0	8.1	6.0	4.6	7.4	6.1	4.5	7.4
Water filled pore space[b], winter (%)	71.2	51.5	85.5	65.9	64.5	67.4	51.2	43.4	56.7	66.4	44.6	92.6
Water filled pore space[b], spring (%)	56.7	41.7	68.4	55.0	53.9	56.1	41.4	35.3	46.5	59.6	35.3	90.2
Water filled pore space[b], summer (%)	47.0	31.1	62.5	50.9	49.1	52.7	35.7	29.2	40.6	45.2	21.7	56.7
Water filled pore space[b], autumn (%)	68.1	50.7	79.8	66.1	64.4	67.9	50.5	42.2	55.6	65.8	42.6	94.5
$r_w \times r_T$ yearly[c] (dimensionless)	1.0	0.6	1.4	1.4	1.4	1.4	1.0	0.8	1.2	1.1	0.7	1.4
SOC (Mg ha^{-1})	66.6	44.8	101.0	84.2	68.8	99.7	58.7	53.8	63.6	115.2	65.5	168.4

n= number of farms; SOC = soil organic carbon

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

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

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

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

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

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

* Birth to calving, milk intake not included

** Birth to slaughter, milk intake not included

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

Table 6 Mean, minimum (Min), maximum (Max) and standard deviation (SD) estimates for greenhouse gas emission intensity (kg CO_2 eq kg^{-1}carcass) (n=9 for each breed).

	A.Angus				Hereford				Charolais				Sig[a]
	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	
Enteric CH_4	14.74	13.01	18.02	1.74	14.54	13.13	16.16	0.94	13.69	12.75	15.20	0.79	ns
Manure CH_4	1.50	0.45	3.56	1.10	1.72	0.46	3.26	1.19	1.59	0.46	4.04	1.07	ns
Manure N_2O	2.64	1.97	3.23	0.46	3.26	2.23	4.36	0.63	2.35	1.42	2.81	0.41	**
Soil N_2O	3.20	2.35	3.66	0.43	3.27	2.72	3.73	0.29	3.37	2.71	5.48	0.85	ns
Soil C	3.88	-2.72	14.11	6.17	1.97	-2.08	7.85	3.75	-0.19	-2.37	3.59	2.19	ns
Off-farm barley	0.60	0.00	0.90	0.33	0.92	0.41	2.06	0.51	1.14	0.73	1.55	0.27	*
Off-farm soya	0.72	0.00	1.10	0.35	0.75	0.52	1.34	0.27	1.19	0.75	1.51	0.26	**
Indirect energy	2.03	0.24	4.33	1.71	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	32.31	24.62	46.08	7.77	30.43	23.05	38.56	4.62	28.57	23.45	34.91	3.84	ns
Total emissions excluding soil C	28.43	21.74	31.95	3.14	28.46	25.13	32.89	3.03	28.76	25.34	35.46	2.90	ns

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

Table 7 Mean greenhouse gas (GHG) emission intensities and proportion of total emissions (in parenthesis) from average herds of beef cattle in four regions of Norway (kg CO_2 eq kg^{-1}carcass).

	East (n=16)	Southwest (n=2)	Mid (n=4)	North (n=5)	Sig[a]
Enteric CH_4	14.18 (0.50)	15.43 (0.47)	15.00 (0.51)	13.80 (0.38)	ns
Manure CH_4	1.97 (0.07)	1.07 (0.03)	1.19 (0.04)	0.98 (0.03)	ns
Manure N_2O	2.78 (0.10)	3.91 (0.12)	2.72 (0.09)	2.20 (0.06)	**
Soil N_2O	3.23 (0.11)	3.42 (0.10)	3.16 (0.11)	3.47 (0.09)	ns
Soil C	0.06 (0.00)	3.36 (0.10)	1.41 (0.05)	7.52 (0.20)	**
Off-farm barley	0.95 (0.03)	0.58 (0.02)	0.87 (0.03)	0.81 (0.02)	ns
Off-farm soya	0.88 (0.03)	0.63 (0.02)	1.07 (0.04)	0.85 (0.02)	ns
Indirect energy	2.13 (0.07)	2.13 (0.07)	1.55 (0.05)	3.68 (0.10)	ns
Direct energy	2.30 (0.08)	2.08 (0.07)	2.26 (0.08)	3.48 (0.09)	ns
Total emission	28.48	32.61	29.23	36.79	*
Total emission excluding soil C	24.42	29.24	27.82	29.27	ns

n = number of farms.

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

Table 8 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	CH19	CH23	H25
CH2	H1	H18	H18	AA20	AA20	H24	CH23
AA3	H10			CH21	CH21	H25	H24
AA4	CH2			AA22	AA22	AA26	AA26
CH5	AA11					AA27	AA27
H6	H6						
AA7	AA4						
CH8	CH5						
CH9	CH8						
H10	CH14						
AA11	AA7						
AA12	CH9						
H13	AA12						
CH14	H13						
H15	H15						
CH16	CH16						

n = number of farms in each region.

Table 9 Sensitivity elasticities for the effect of 1% change in soil C change external factor ($r_w \times r_T$) and initial soil organic carbon (SOC) on the greenhouse gas (GHG) emission intensities CO_2 eq (kg carcass)$^{-1}$.

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

[a] Sig = significance: ns = non significant

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

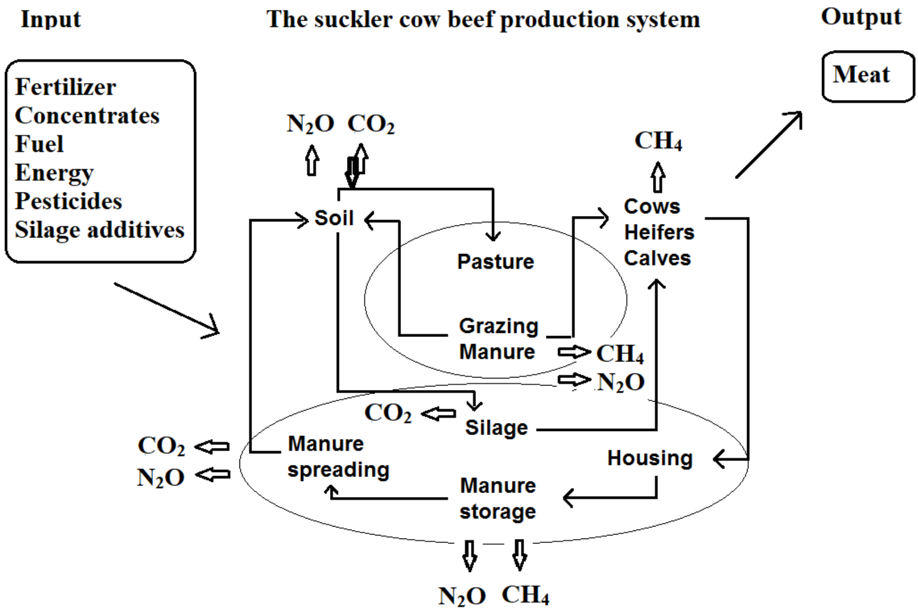

Figure 1 System boundaries of the suckler cow beef production system (Samsonstuen et al., 2019).

5. Paper III

Mitigation of greenhouse gas emissions from suckler cow beef production

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Mitigation of greenhouse gas emissions from suckler cow beef production

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Abstract

Numerous mitigation options have been suggested to reduce the environmental impact of suckler cow beef production, aimed at improving female reproductive performance, beef production efficiency and various management practices. Before implementing such practices, the net effect on greenhouse gas (GHG) emissions should be investigated. Thus, the whole-farm model HolosNorBeef, developed for Norwegian suckler cow herds, was used to estimate the effects of mitigation strategies on GHG emissions from two average farms of British and Continental breeds. The study included various mitigation scenarios, involving female reproductive performance (i.e. calf mortality rate and the number of calves produced per cow per year), young bull beef production efficiency (i.e. age at slaughter and carcass weight), and supplementation of a inhibitor currently reported as promising for enteric methane (CH_4) inhibition (3-nitrooxypropanol; 3-NOP). Additional scenarios included various combinations of these strategies. The baseline (BL) farms had 28 suckler cows and were located in the flatland area of Norway, with production results corresponding to average farms of the two breed categories. The BL farms had estimated emission intensities of 30.8 carbon dioxide equivalents (CO_2 eq) (kg carcass)$^{-1}$ and 29.2 CO_2 eq (kg carcass)$^{-1}$ for British and Continental breeds, respectively. Enteric CH_4 accounted for 45-46% of the total emissions. Reducing calf mortality from BL level (British, 3.5% stillborn and 3.6% dead before 180 days; Continental, 3.9 % stillborn and 4.1% dead before 180 days) to 0% and increasing number of calves per cow per year from BL level to 1.1 both reduced emission intensities by 3% across breeds. Continental breeds showed greater potential of reducing emission intensities due to increased carcass production from the BL level (-6.6%) compared to British breeds (-2.0%). 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, assuming it decreases CH_4 production by 33% during the housing period (Sept 15 to May 31). On a national level, the total emissions from suckler cow beef production can be reduced by improving female fertility and carcass production, especially on the poorest performing farms.

Keywords

Beef cattle; beef production efficiency; farm scale model; greenhouse gas emissions; methane inhibitor; mitigation options

1. 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 (Samsonstuen et al., 2019; White et al., 2010), 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 suckler 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 (Desjardins et al., 2012; Legesse et al., 2016, 2018; Murphy et al., 2017; Thornton and Herrero, 2010). 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 and 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).

Improved female fertility and calf survival have been identified as a potential strategies to reduce GHG emissions (Hristov et al., 2013), but only a few studies have included all sources of emissions (e.g. manure and enteric CH_4, manure and soil N_2O, pesticides, fuel, soil C) and explored the net impacts (Beauchemin et al., 2011; Navajas et al., 2010). 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 (Bell et al., 2011; Garnsworthy, 2004; Wall et al., 2010). Calf survival is of great importance in beef production systems, as the calf is the main product from the enterprise. High calf mortality is economically unfavorable for the farmer and reflects poor health, management and animal welfare (Mötus et al., 2018). Improvements in calf survival and suckler 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. (2010) reported reduction in emission intensities due to genetic improvement of fertility and calf survival.

Enteric methane (CH_4) emissions account for approximately half the emissions from suckler cow beef 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 (Bayat et al., 2015, 2017; Hristov et al., 2013; 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 and Johnson, 1995), animal health, and production (Hristov et al., 2013). However, the inhibitor 3-nitrooxypropanol (3-NOP) has shown promising long-term mitigation effects on enteric methane (CH_4) emissions with no compromising effect on diet digestibility (Romero-Perez et al., 2014) or milk production (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, this study did not include GHG mitigation options such as improved suckler cow efficiency, beef production efficiency or the effect of inhibitors.

Thus, the aim of the study was to estimate the mitigation potential in Norwegian suckler cow beef production by investigating various scenarios, including variable suckler cow and young bull beef production efficiency scenarios, as well as the mitigating effect of a inhibitor for enteric CH_4 reduction. The inhibitor evaluated was the promising 3-NOP (Romero-Perez et al., 2014).

2. 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 suckler cow herds. The variable herd performances were compared to the average herds to investigate GHG mitigation potentials. For each scenario, the beef carcass (kg) produced was based on the number of animals sent to slaughter, carcass weights and dressing percentages for the specific breed and animal class. Production enterprises on the farm not related to the cow-calf 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.

2.1. Baseline scenarios

Baseline (BL) scenarios was developed to represent each average 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, each with an area of 44.6 ha. 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 was retained for slaughter with males finished as bulls at 17.5 and 16.8 months, and surplus heifers not required to replace culled suckler cows finished at 18.2 and 17.5 months for British and Continental breeds, respectively (Åby et al., 2012). Estimates of proportion of concentrates and pasture in the diet were from Åby et al. (2012). 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). Silage yield (3020 feed units; FUm ha^{-1}), pesticide (1.1 MJ ha^{-1}), and silage additive (21 kg CH_2O_2 ha^{-1}) use for an average farm in the flatlands were 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 ensilaging (DOW, 2012). N-fertilizer application for conserved feed (13 kg N ha^{-1}) followed advisory based recommendations for forage production (NIBIO, 2016). Dry matter (DM) content and nutritive value (0.87 FUm kg DM^{-1}; feed units milk) of forage was estimated for the flatlands based on feed analyses (Eurofins, 2015). Use of energy (26300 kWh $year^{-1}$) and fuel (99 L ha^{-1}) for an average farm in the flatlands was from operational farm data (NIBIO, 2015). Seasonal soil and weather data were available through Skjelvåg et al. (2012; Table 1).

2.2. Alternative scenarios

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

Suckler cow efficiency scenarios (Table 2) 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) and the annual report of the NBS (Animalia, 2018, 2019). The calf mortality among Norwegian suckler cow herds varies from 0% to 20% for stillborn and dead prior to 180 days with positively skewed distribution, with approximately 95% of the herds with British and Continental breeds within the range 0 (CML; Scenario 1) to 8.3% stillborn and 10.9% dead prior to 180 days (CMH; Scenario 2) dependent on breed (Animalia, 2019). For both British and Continental breeds, the number of produced calves per cow per year in the annual report varies from 0.9 (CYL; Scenario 3) to 1.1 (CYH; Scenario 4) for the worst to the best 1/3 of the Norwegian herds, respectively (Animalia, 2018).

Young bull beef production efficiency scenarios are 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). The scenario investigating low beef production efficiency (BPL; Scenario 5) has high age at slaughter and low carcass weight, with lower ADG and feed requirements per day compared with the BL scenario. The scenario investigating high beef production efficiency (BPH; Scenario 6) has low age at slaughter and high carcass weight, with higher ADG and feed requirements per day relative to the BL scenario (Table 3). 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.

Scenarios CMH, CYL, and BPL were combined in a worst case (WC; Scenario 7) scenario. The corresponding best case (BC; Scenario 8) scenario was a combination of scenarios CML, CYH, and BPH. The effect of feeding a low level of the inhibitor 3-NOP 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 average herds of British and Continental breeds (Table 4). Whereas the effect of feeding a high level of the inhibitor 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 assumed fed at a rate of 100 (low) and 237 mg (kg DM)$^{-1}$ (high) during the housing period (8.5 months) to suckler cows, growing backgrounding and the finishing stock aged 6-24 months. It was assumed that the days the inhibitor was fed, the enteric CH_4 emissions was decreased by 7 (low) and 33% (high) as a percentage of DMI with no negative effect on DMI or ADG.

2.3. Modelling GHG emissions

2.3.1. The HolosNorBeef model

The GHG emissions were estimated using HolosNorBeef developed by Samsonstuen et al. (2019). HolosNorBeef is an empirical model specifically developed for suckler beef production systems under Norwegian conditions, using Tier 2 methodology of the Intergovernmental Panel on Climate Change (IPCC, 2006). 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 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. All emissions are expressed as CO_2 eq to account for the global warming potential (GWP) of the respective gases for a time horizon of 100 years: $\mathrm{CH_4(kg)} \times 28 + \mathrm{N_2O(kg)} \times 265 + \mathrm{CO_2(kg)}$ (Myhre et al., 2013). Emission intensities are expressed as kg CO_2 eq (kg beef carcass)$^{-1}$.

Methane emissions

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

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

Nitrous oxide emissions

Direct manure N_2O emissions are calculated based on the N content of manure and an emission factor for the manure handling system (0.01, 0.02, 0.05 kg N_2O-N $(kg\ N)^{-1}$ for deep-bedding, pasture manure, and solid storage, respectively; IPCC, 2006). 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.

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

Indirect N_2O emissions from soil are estimated from the assumed losses of N from manure, crop residues, and fertilizer according to IPCC (2006). The emissions from run-off, leaching and volatilization are estimated based on the fraction of the loss for the manure handling system adjusted using emission factors (0.0075 N_2O-N kg^{-1}) for leaching and (0.01 kg N_2O-N kg^{-1}) for volatilized ammonia-N, respectively (IPCC, 2006). For leaching, the emissions were based on the assumed fraction of N lost adjusted for emission factors for (0.0, 0.0, 0.3, 0.3 kg N (kg N)$^{-1}$ from 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). 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).

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) and a humification coefficient of cattle manure (h = 0.31; Kätterer et al., 2008). The degradation of the pools is determined by the respective decomposition rates (k_y = 0.8 year^{-1} and k_o= 0.007;

Andrén et al., 2004). 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, as explained by Bonesmo et al. (2013).

Carbon dioxide emissions

Direct CO_2 emissions are estimated from on-farm use of diesel fuel using an emission factor (2.7 kg CO_2 eq L^{-1}; The Norwegian Environment Agency, 2017). Off-farm emissions from production and manufacturing of farm inputs are estimated using emission factors for Norway or Northern-Europe; pesticides, 0.069 kg CO_2 eq (MJ pesticide energy)$^{-1}$ (Audsley et al., 2014); electricity, 0.11 kg CO_2 eq (kWh)$^{-1}$ (Berglund et al., 2009); diesel fuel, 0.3 kg CO_2 eq (L)$^{-1}$ (Öko-Instititut, 2010); silage additives, 0.72 kg CO_2 eq (kg CH_2O_2)$^{-1}$ (Flysjö et al., 2008); N-based synthetic fertilizer, 4 kg CO_2 eq (kg N)$^{-1}$ (DNV, 2010); and feed supplement, 47.9 kg CO_2 eq (kg 3-NOP)$^{-1}$. Emissions related to use of concentrates are estimated according to Bonesmo et al. (2013). The concentrates are assumed to be supplied by barley and oats grown in Norway (0.62 kg CO_2 eq kg DM^{-1}; Bonesmo et al., 2012) and soybean meal imported from South Africa (0.93 kg CO_2 eq kg DM^{-1}; Dalgaard et al., 2008), which is purchased commercially. Thus, on-farm produced field crops and straw are assumed sold from the farm and are not included in the farm emissions.

2.4. Sensitivity analysis

A sensitivity analysis was performed to evaluate the sensitivity of the different mitigation options to variation in the most important emission factor: CH_4 conversion factor (Ym). For all scenarios with British breeds, the Ym was changed 1% and emission intensities were re-calculated and related to the current level. In addition, the sensitivity of the mitigation options to the GWP methodology were tested by including the climate-carbon feedback in the GWP of the respective gases for a time horizon of 100 years: $CH_4(kg) \times 34 + N_2O(kg) \times 298 + CO_2(kg)$ (Myhre et al., 2013).

3. Results

3.1 Total emissions

The total emissions per year for the BL scenario representing average herds were 237 t CO_2 eq for British and 282 t CO_2 eq for Continental breeds (Figure 1). Suckler cow efficiency scenarios (Scenario 1-4) resulted in decreased total emissions for CMH and CYL and increased total emissions for CML and CYH for both breeds, compared with baseline scenarios. The young bull carcass production scenarios (Scenario 5-6) had lower total emissions for the BPL scenario for British breeds and the BPH scenario for Continental breeds compared with the BL scenario. The BC scenario increased total emissions by 12.1 and 4.1% for British and Continental breeds, respectively, compared to the BL scenarios. By including the effect of supplements (Scenario 9-14), the total emissions were decreased for scenarios BLinL, WCinL, BLinH, WCinH, compared with the BL scenario. The BCinL scenario increased the total emissions 9.6 and 1.7% for British and Continental breeds, respectively. At high application level, the BCinH scenarios gave a 0.7% increase in total emissions for the British breeds and a 5.8% reduction in total emissions compared with the BL scenarios.

3.2 Emission intensities

The emission intensities for the BL scenario were greater for the British breeds (30.78 CO_2 eq (kg carcass)$^{-1}$) compared with the Continental breeds (29.23 CO_2 eq (kg carcass)$^{-1}$; Table 5). 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 breeds, indicating C sequestration. Emission intensities for the suckler 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 5). Across breeds, both 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 production compared to the British breeds (Table 6). 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 CO_2 eq (kg carcass)$^{-1}$ for British breeds and from 25.1 to 34.5 CO_2 eq (kg carcass)$^{-1}$ for Continental breeds (Table 7). The BC scenario reduced the emission intensities by 11.7% on average. When the inhibitor 3-NOP with a 7 and 33 % reduction in enteric CH_4 emissions was included during the housing period, the emission intensities were reduced 4.5 and 9.6% across breeds for the BLinL and BLinH scenarios, respectively. For the British breeds, the the inhibitor reduced the emission intensities by 11.0 (BCinL) and 17.7% (BCinH) compared with the BL scenario, whereas the Continental breeds had a and 9.6 (BCinL) and 22.3% (BCinH) reduction. High application levels 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 8).

The sensitivity elasticity for the enteric CH_4 emission factor had a linear change in emission intensities caused by 1% change in Ym of 0.45 % change in emission intensities for for suckler cow efficiency scenarios (Scenario 1-4), young bull carcass production scenarios (Scenario 5-6) and the combined scenarios (Scenario 7-8). When including the effect of the inhibitor, the sensitivity elasticity decreased to 0.44 (low; BLinL, WCinL, BCinL) and 0.38% change in emission intensities (high; BLinH, WCinH, BCinH). In terms of emission intensities, inclusion of the climate-carbon feedback in the GWP increased the emissions 13.4-14.5% across scenarios (Table 9).

4. Discussion

Our study investigated the GHG emissions from typical beef herds of British and Continental breeds in Norway and accessed mitigation options of improving suckler cow efficiency, young bull beef production efficiency or a combination, with or without the effect of a CH_4 inhibitor included. As the inhibitor 3-NOP is currently not approved by the Norwegian authorities, the reduction potential from applying the inhibitor is theoretical at this point.

HolosNorBeef estimated emission intensities from the BL scenarios of 29.2 to 33.6 CO_2 eq (kg carcass)$^{-1}$ for average herds of British and Continental breeds. This range of emission intensities is similar to both other Nordic countries; Denmark 23.1 to 29.7 CO_2 eq (kg carcass)$^{-1}$ and Sweden 25.4 CO_2 eq (kg carcass)$^{-1}$ (Mogensen et al., 2015), and the average herds of British and Continental breeds considered by Samsonstuen et al. (2019) (range: 27.5-32.01 CO_2 eq (kg carcass)$^{-1}$). The present study founds that Norwegian beef production systems have potential to reduce emission intensities without substantial changes in the enterprise through improved female fertility, calf survival and inceased carcass production. Substantial differences in GHG emissions were demonstrated between average farm conditions (BL scenario) and the alternative scenarios (CML, CMH, CYL, CYH, WC, BC, BLinL, WCinL, BCinL, BLinH, WCinH, and BCinH). 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 suckler cow and beef production efficiency substantially reduced emission intensities (by 2.0 to 14.2%) compared with the BL scenarios.

In all scenarios, C sequestration had a mitigating effect on GHG emissions. Emission intensities varies due to location, resources, and climatic conditions (Samsonstuen et al., 2019; White et al., 2010). 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; Table 5, 6 and 7).

The offspring and culled breeding animals are the only product from most meat producing species (suckler cows, lamb, poultry and pigs), in contrast to dual purpose milk and beef production. 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 the economy (Azzam et al., 1993) and the GHG emissions from suckler cow beef production (Wall et al., 2010). The suckler cow is the most resource dependent and GHG emission intensive aspect of the beef production system (Foley et al., 2011; Morel et al., 2016; Pelletier et al., 2010). Higher calf mortality means more production resources directed to unproductive cows, and a larger proportion of the heifers are required to keep the herd size stable. 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 (Murray et al., 2015; Wall et al., 2010). The CML scenario had low calf mortality, which increased total forage requirements, areas needed for forage production, and the total use of input factors (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% CO_2 eq (kg carcass)$^{-1}$ 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). In addition to reducing calf mortality, improved fertility also influences the number of calves per cow per year. The best and worst 1/3 of the Norwegian suckler cow 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, 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). Higher animal productivity by 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 farm varies across scenarios (Table 2-4) with a constant number of suckler cows due to differences in female fertility, calf survival, and animal productivity. In accordance with Veysset et al. (2014), the emission intensities decreased with higher 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 a higher unexploited potential for increased carcass production for Continental breeds.

Enteric CH_4 accounts for 43.9 to 55.7 of total GHG emissions (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 are often aimed at by mitigation strategies. The sensitivity elasticity of the CH_4 conversion factor (i.e. Ym) shows a linear change in emission intensities across scenarios and scenarios investigated the effect of an inhibitor showed lower sensitivity elasticity. Thus, mitigation options aiming to change feeding intensity depend on a reliable Ym. In the present study, the 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 housing period as feeding supplements during pasture is challenging. At high application level 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 the as the inhibitor are assumed to have no effect on DMI. The reduction in emission intensities could potentially be lowered if the performance had been improved or higher if DMI decreased with no influence on ADG. Level of 3-NOP application influences the net reduction as the reduced enteric CH_4 emissions more than offset the increase in indirect energy emissions from manufacturing the inhibitor. At high application 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 (kg carcass)$^{-1}$ 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 is highly theoretical. However, 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 GWP transforms different greenhouse gases into a common unit as CO_2 eq by weighting the non-CO_2 gases relative to CO_2 according to the effects over time and assumes an equal environmental impact of the different gases (IPCC, 2014). The GWP value of 28 for CH_4 used in this study assumes CH_4 to have an impact 28 times greater than CO_2 over a time horizon of 100 years (Myhre et al., 2013). In the present study the various scenarios shows similar response to the changed GWP as the use of input factors, management and diet composition is kept constant across scenarios. Variation among individual farms increases the variability in emission intensities from different sources. Hence, the prevailing GWP methodology could be important for future mitigation options as the CH_4 emissions account for approx. half the emissions from suckler cow beef production systems (Foley et al., 2011; Mogensen et al., 2015; Samsonstuen et al., 2019). Implementation of the GWP* methodology or inclusion of the climate-carbon feedback yield a greater response from actions reducing the CH_4 emissions in relation to the base year, whereas changes increasing the CH_4 emissions lead to a high contribution to global warming.

Farm level mitigation options such as improved calf survival, the number of calves per cow per year and increased carcass production reduce the emission intensities but elevate the total beef production and the total emissions. On a national level, the market demand for beef is a prerequisite for the production level. Hence, mitigation options to reduce the national GHG emissions from beef production need to be investigated in relation to the desired production level. Increased animal production efficiency could also contribute by reducing the total number of suckler cows maintained in Norway, which combined with reduced emission intensities at the farm-level would reduce the total emissions from beef production. The Norwegian suckler cow population produces approx. 28,516 t carcass year^{-1} (Nortura, 2019), corresponding to 855,611 t CO_2 eq at BL level. By improving calf mortality to BL level from 8.3% stillborn and 10.8% dead prior to 180 days for British and 6.23% stillborn and 10.9% dead prior to 180 days for Continental breeds, total emissions could be reduced by 8,792 t CO_2 eq. Whereas, the potential reduction in emissions from improving the worst 1/3 herds in terms of number of calves per cow per year and young bull carcass production compared to the BL level is 17,965 and 12,832 t CO_2 eq, respectively.

Genetic improvement of livestock is cost effective and produces permanent and cumulative changes in performance, whereas improved management is non-permanent but changes emission intensities quickly. Genetic improvement 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 (Åby et al., 2014; Wall et al., 2010). A premise for farmers to participate in herd data recording systems and implement on-farm mitigation options is that the extra efforts are considered profitable. Other measures, such as the use of inhibitors are high effective at reducing emission, but increase input costs. Thus, adoption of CH_4 inhibitors, when commercially available to producers, may require subsidy financing to encourage implementation unless a gain in production efficiency is also realized. To date, such inhibitors are not commercially available, although 3-NOP is a promising experimental CH_4 inhibitor currently under evaluation in large-scale dairy and beef cattle studies to support licencing by government authorities.

5. Conclusions

The baseline scenario estimated GHG emission intensity of 30.8 and 29.2 CO_2 eq (kg carcass)$^{-1}$ for British and Continental breeds, respectively. Mitigation strategies that improve suckler 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 can reduce the net emissions from suckler cow beef production dependent on application level. Improvement of the poorest performing farms in terms of female fertility and carcass production can reduce the total emissions from beef production at a national level.

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Table 1 Natural resource data used to estimate GHG emission intensities from various scenarios based on average beef cattle herds located in the flatlands of Norway (Bonesmo et al., 2013; Skjelvåg et al., 2012).

	Flatlands
Soil temperature at 30 cm depth, winter (°C)[a]	-0.68
Soil temperature at 30 cm depth, spring (°C)[a]	5.37
Soil temperature at 30 cm depth, summer (°C)[a]	13.79
Soil temperature at 30 cm depth, fall (°C)[a]	5.20
Water filled pore space, winter (%)[b]	65
Water filled pore space, spring (%)[b]	48
Water filled pore space, summer (%)[b]	43
Water filled pore space, fall (%)[b]	62
$r_w \times r_T$ yearly (dimensionless)[c]	0.94
Soil organic C (Mg ha^{-1})	6

[a] Estimated according to Katterer and Andren (2009).
[b] Estimated according to Bonesmo et al. (2012).
[c] Yearly effect of temperature and soil moisture estimated according to Andrén et al. (2004).

Table 2 Animal performance, land use and farm inputs for suckler cow efficiency scenarios used to estimate GHG emission intensities

	Suckler cow efficiency scenarios									
	British					Continental				
Scenario		1	2	3	4		1	2	3	4
	BL	CML	CMH	CYL	CYH	BL	CML	CMH	CYL	CYH
Animal system										
Still born calves (%)	3.5[a]	0.0[b]	8.3[b]	3.5[a]	3.5[a]	3.9[a]	0.0[b]	6.2[b]	3.9[a]	3.9[a]
Dead calves < 180 days (%)	3.6[a]	0.0[a]	10.8[b]	3.6[a]	3.6[a]	4.1[a]	0.0[b]	10.9[b]	4.1[b]	4.1[b]
Calves cow^{-1} per year	1.0[a]	1.0[a]	1.0[a]	0.9[c]	1.1[c]	1.0[a]	1.0[a]	1.0[a]	0.9[c]	1.1[c]
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
Beef produced (kg carcass)[ad]	7699	8190	6841	7004	8303	9635	10311	8862	8815	10362
Land use										
Farm size (ha)[e**]	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)[e**]	39.7	41.8	39.7	39.8	42.1	44.4	46.8	44.4	44.5	47.1
Input use										
Fuel (L $year^{-1}$)[e**]	3931	4138	3930	3947	4171	4394	4641	4394	4406	4668
Silage additive (kg CH_2O_2 $year^{-1}$)[e**]	819	863	819	823	869	916	967	916	918	973

BL= Baseline, average 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

[a] Animalia (2017)

[b] Animalia (2019)

[c] Animalia (2018)

[d] Norwegian Insitite of Bioeconomy research (NIBIO, 2015)

[e] Norwegian Insitite of Bioeconomy research (NIBIO, 2016)

[*] Heifers and young bulls available for slaughter varies across scenarios dependent on number of produced calves cow^{-1} per year and calf mortality

[**] Corresponds to the ley area required to cover the forage requirements

Table 3 Animal performance, land use and farm inputs for young bull beef production efficiency scenarios used to estimate GHG emission intensities

	Young bull beef production efficiency scenarios					
		British			Continental	
Scenario		5	6		5	6
	BL	BPL	BPH	BL	BPL	BPH
Animal system						
Young bulls, age at slaughter (month)	17.5[a]	18.7[b]	16.1[b]	16.8[a]	18.1[b]	15.4[b]
Young bulls, carcass weight (kg)	291[c]	256[b]	334[b]	353[c]	317[b]	392[b]
Beef produced (kg carcass)[ac]	7699	7232	8272	9635	9157	10159
Land use						
Farm size (ha)[d*]	45.4	45.6	47.9	50.1	51.5	50.8
Of which: Ley area (ha)[d*]	39.7	39.9	42.2	44.4	45.8	45.1
Input use						
Fuel (L $year^{-1}$)[d*]	3931	3951	4177	4394	4533	4472
Silage additive (kg CH_2O_2 $year^{-1}$)[d*]	819	823	871	916	945	932

BL = Baseline, average beef cattle herd; BPL = Young bull beef production efficiency, low; BPH = Young bull beef production efficiency, high.

[a] Norwegian Insitite of Bioeconomy research (NIBIO, 2015)

[b] Animalia (2018)

[c] Animalia (2017)

[d] Norwegian Insitite of Bioeconomy research (NIBIO, 2016)

[*] Corresponds to the ley area required to cover the forage requirements

Table 4 Animal performance, land use and farm inputs for best case (BC) and worst case (WC) scenarios used to estimate GHG emission intensities

	Best case/worst case scenarios					
		British			Continental	
Scenario		7	8		7	8
	BL	WC	BC	BL	WC	BC
Animal system						
Still born calves (%)	3.5[a]	8.3[b]	0.0[b]	3.9[a]	6.2[b]	0.0[b]
Dead calves <180 days (%)	3.6[a]	10.8[b]	0.0[b]	4.1[a]	10.9[b]	0.0[b]
Calves cow^{-1} per year	1.0[a]	0.9[c]	1.1[c]	1.0[a]	0.9[c]	1.1[c]
Young bulls, age at slaughter (month)	17.5[d]	18.7[b]	16.1[b]	16.8[d]	18.1[b]	15.4[b]
Young bulls, carcass weight (kg)	291[a]	256[c]	334[c]	353[a]	317[c]	392[c]
Replacement heifers (year^{-1})	10	10	10	10	10	10
Heifers slaughtered (year^{-1})	4	1	6	4	1	6
Young bulls slaughtered (year^{-1})	13	10	16	13	10	16
Beef produced (kg carcass)[ad]	7699	5868	9509	9635	7721	11700
Land use						
Farm size (ha)[e*]	45.4	43.6	44.9	50.1	49.1	53.0
Of which: Ley area (ha)[e*]	39.7	37.9	44.2	44.4	43.4	47.3
Input use						
Fuel (L year^{-1})[e*]	3931	3751	4375	4394	4304	4683
Silage additive (kg CH_2O_2 year^{-1})[e*]	819	782	912	916	897	976

BL = baseline, average beef cattle herd; WC= Worst case; BC= Best case

[a] Animalia (2017)

[b] Animalia (2019)
[c] Animalia (2018)
[d] Norwegian Insitite of Bioeconomy research (NIBIO, 2015)
[e] Norwegian Insitite of Bioeconomy research (NIBIO, 2016)
[*]Corresponds to the ley area required to cover the forage requirements

Table 5 Emission intensities for suckler cow efficiency scenarios (CO_2 eq kg^{-1} carcass)

	British					Continental				
Scenario		1	2	3	4		1	2	3	4
	BL	CML	CMH	CYL	CYH	BL	CML	CMH	CYL	CYH
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 soya	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 emissions	30.78	29.89	33.61	32.77	29.80	29.23	28.27	31.12	31.02	28.33
Total emissions excluding soil C	32.49	31.50	35.37	34.51	31.40	31.08	30.01	33.02	32.92	30.07

BL= Baseline, average 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; WC= Worst case; BC= Best case

* Negative values indicate carbon sequestration

Table 6 Emission intensities for young bull beef production efficiency scenarios (kg CO_2 eq kg^{-1}carcass)

		British			Continental	
Scenario		5	6		5	6
	BL	BPL	BPH	BL	BPL	BPH
Enteric CH_4	14.03	14.34	13.60	13.24	13.94	12.28
Manure CH_4	3.22	3.29	3.14	3.17	3.36	2.91
Manure N_2O	3.01	3.08	2.91	2.78	2.91	2.59
Soil N_2O	3.03	3.14	2.97	2.86	3.05	2.68
Soil C*	-1.72	-1.67	-1.67	-1.85	-1.94	-1.63
Off-farm barley	1.94	1.91	1.97	2.15	2.27	1.95
Off-farm soya	1.89	1.86	1.92	2.09	2.21	1.90
Indirect energy	3.03	3.25	3.00	2.70	2.94	2.61
Direct energy	2.34	2.50	2.31	2.09	2.27	2.02
Total emissions	30.78	31.70	30.16	29.23	31.01	27.31
Total emissions excluding soil C	32.49	33.37	31.82	31.08	32.96	28.94

BL = Baseline, average beef cattle herd; BPL = Young bull beef production efficiency, low; BPH = Young bull beef production efficiency, high.

* Negative values indicate carbon sequestration

Table 7 Worst case (WC) and best case (BC) scenarios for estimating the emission intensities from Norwegian suckler cow herds (kg CO_2 eq kg^{-1}carcass)

	British			Continental		
Scenario		7	8		7	8
	BL	WC	BC	BL	WC	BC
Enteric CH_4	14.03	16.57	12.58	13.24	15.81	11.27
Manure CH_4	3.22	3.78	2.92	3.17	3.79	2.68
Manure N_2O	3.01	3.60	2.67	2.78	3.34	2.36
Soil N_2O	3.03	3.66	2.73	2.86	3.48	2.45
Soil C*	-1.72	-1.89	-1.57	-1.85	-2.16	-1.51
Off-farm barley	1.94	2.06	1.91	2.15	2.48	1.84
Off-farm soya	1.89	2.00	1.86	2.09	2.41	1.79
Indirect energy	3.03	3.82	2.73	2.70	3.38	2.38
Direct energy	2.34	2.95	2.11	2.09	2.60	1.83
Total emissions	30.78	36.56	27.94	29.23	35.13	25.08
Total emissions excluding soil C	32.49	38.45	29.51	31.08	37.29	26.59

BL = baseline, average beef cattle herd; WC= Worst case; BC= Best case

* Negative values indicate carbon sequestration

Table 8 Worst case (WC) and best case (BC) scenarios for estimating the emission intensities from Norwegian suckler cow herds with and without the reduction of enteric methane (CH_4) from low and high levels of the inhibitor 3-nitrooxypropanol (3-NOP) (kg CO_2 eq kg^{-1} carcass)

	British							Continental						
Application level 3-NOP		100mg (kg DM)$^{-1}$			237 mg (kg DM)$^{-1}$				100mg (kg DM)$^{-1}$			237 mg (kg DM)$^{-1}$		
Scenario		9	10	11	12	13	14		9	10	11	12	13	14
	BL	BLinL	WCinL	BCinL	BLinH	WCinH	BCinH	BL	BL	BLinL	WCinL	BCinL	BLinH	WCinH
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 soya	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	3.16	3.96	2.84	3.33	4.18	2.98	2.70	2.80	3.43	2.46	2.99	3.67	2.60
Direct energy	2.34	2.34	2.93	2.11	2.34	2.95	2.11	2.09	2.09	2.55	1.83	2.09	2.55	1.83
Total emissions	30.78	30.16	35.70	27.41	27.82	33.15	25.38	29.23	27.19	33.49	24.60	26.42	31.19	22.70
Total emissions excluding soil C	32.49	31.88	37.58	28.98	29.53	35.04	26.96	31.08	29.04	35.61	26.11	28.27	33.31	24.21

BL = baseline, average beef cattle herd; BLinL=baseline with 7% reduction of enteric CH_4 emissions from the inhibitor; WCinL= Worst case with 7% reduction of enteric CH_4 emissions from the inhibitor; BCinL= Best case 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 with 33% reduction of enteric CH_4 emissions from the inhibitor; BCinH= Best case with 33% reduction of enteric CH_4 emissions from the inhibitor.

* Negative values indicate carbon sequestration

Table 9 Sensitivity of the scenarios for the change in global warming potential (GWP) from CH_4 (kg) ×28+N_2O (kg) ×265+CO_2(kg) to CH_4 (kg) ×34+N_2O (kg) ×298+CO_2(kg), including the climate-carbon feedback in the GWP of the respective gases for a time horizon of 100 years (Myhre et al., 2013).

	Scenario	% change in CO_2 eq (kg carcass)$^{-1}$
BL		14.5
CML	1	14.3
CMH	2	14.4
CYL	3	14.4
CYH	4	14.3
BPL	5	14.4
BPH	6	14.3
WC	7	14.4
BC	8	14.3
BLinL	9	14.2
WCinL	10	14.2
BCinL	11	14.1
BLinH	12	13.5
WCinH	13	13.4
BCinH	14	13.4

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.

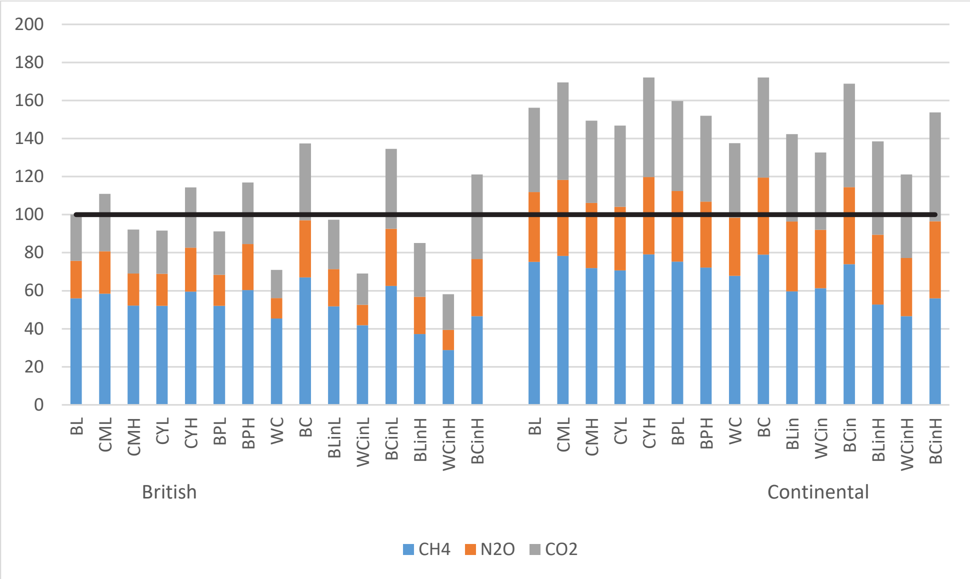

Figure 1 Total GHG emissions by gas for each scenario expressed relative to the baseline scenario of an average British farm stocked with 28 suckler cows, located in the flatlands in Norway with total emissions of 236,984 CO_2 eq (CH_4 132,825 CO_2 eq; N_2O, 46,499 CO_2 eq; CO_2, 57,660 CO_2 eq). BL= 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

6. General discussion

The expected human population growth and increasing concern of global warming calls for increasing the global food production, while minimizing the environmental impact of the production chain. In order to meet these challenges, measures such as reducing food waste, substitution towards lower meat diets, and increased production efficiency are likely to be important. The present study aims at measures taken by the agricultural sector to e.g. increase production efficiency through improved management, feeding, breeding for more efficient, healthier, and robust animals with higher yields.

6.1 Modelling of greenhouse gas emissions

Several approaches, such as national inventory reports, whole-farm modelling, and LCA have been used to quantify the level and investigate the potential for reducing GHG emissions from agriculture. Different modelling approaches have various levels of complexity, flexibility and system boundaries, giving different areas of application. National inventory reports are divided into five main sectors on national basis, of which the agricultural sector (e.g. AFOLU) is based on the IPCC methodology (IPCC, 2006). The emissions from AFOLU include enteric fermentation, manure management, agricultural soils, field burning of agricultural residues, liming, and urea application (Norwegian Environment Agency, 2018). Emissions related to e.g. imported feed are not accounted for (Crosson et al., 2011), whereas the emissions related to e.g. use of electricity and production of fertilizer are included in other sectors (IPCC, 2006). The IPCC emission factors are designed to aggregate the emissions to national level and lack the refinement to account for variation in emissions between individual farms (IPCC, 2006; Schils et al., 2007). The division of emissions to different sectors and exclusion of inputs to the livestock production in the inventory reports are not consistent with the agricultural production systems. Thus, total farm emissions are underreported when using an IPCC approach (Crosson et al., 2011). This approach is also less suitable for investigating the impact of improvements or alternative production strategies.

To overcome the limitations of the IPCC methodology, a whole-farm modelling approach can be used. Whole-farm models include all relevant sources of emissions related to livestock production and the interactions between farm components (Crosson et al., 2011; Schils et al., 2007). Thus, whole-farm models are suitable for estimating variability between farms. Paper 1 introduced the whole farm model HolosNorBeef which was developed based on the IPCC methodology, modified for suckler cow beef production under Norwegian condition. HolosNorBeef provides a system analysis of the suckler cow beef production by including all relevant sources of emissions. The adaption to local conditions improves the sensitivity of the model and provides a tool investigating the variability in emission intensities among individual farms and various mitigation options. However, HolosNorBeef does not include environmental impacts beyond GHG emissions (discussed in Section 6.5). The LCA approaches include additional impact categories (e.g. land use, energy use, acidification potential and eutrophication potential; Cederberg and Stadig, 2003; Nguyen et al., 2010; Ogino et al., 2004) to investigate the environmental impacts throughout a products life cycle (ISO, 2006). LCA is to some extent more formalized than whole-farm modelling using system analysis, with the main phases following the ISO standards of goal and scope definition, analysis and interpretation (ISO, 2006). Established databases such as EcoInvent (Weidema et al., 2013) or representative model farms provide the basis for the production chain and calculating the environmental impact. To understand the circular use of resources, LCA analysis can be increasingly important in the future as it has a wider aspect than the whole-farm modelling approach using a system analysis.

6.2 GHG emissions from suckler cow beef production

Paper I estimated the emission intensities from average herds of British and Continental breeds using HolosNorBeef. The objective was to evaluate the level of emission intensities from typical suckler cow herds in two distinct geographical regions in Norway. Estimated emission intensities ranged from 29.5 to 32.0 CO_2 eq (kg carcass)$^{-1}$ for British breeds and 27.5 to 29.6 CO_2 eq (kg carcass)$^{-1}$ for Continental breeds (Paper I; Table 8), within the range of emission intensities reported for farming systems in

Ireland, Denmark, and Sweden: 23.1-29.7 (kg carcass)$^{-1}$ (Foley et al., 2011; Mogensen et al., 2015). The use of average farm scenarios might be a concern as the average farm needs to be representative for the region or farming system it is designed to represent (Crosson et al., 2011). McAuliffe et al. (2018) demonstrates that the emission intensities estimated using pre-averaged data (e.g. simulated farms with average performance) may be underestimated up to 10% due to insufficient consideration given to poorly performing animals. In real farms, several years of data are required before you have a "steady state" farm system due to the nature of farming with variable herd size (e.g. buying, selling) and production cycles (Crosson et al., 2011). There is also an issue with data quality in real farms as registration of some data required for GHG emission estimation is voluntary or non-existent (Crosson et al., 2011). This can be mitigated by aggregating a number of years' data.

In a global perspective, Norwegian agriculture has extremely good data quality with individual records on health and production. The large stakeholders in the agricultural sector have joined and formed Landbrukets Klimaselskap SA (Agricultural Climate Company) and Landbrukets Dataflyt SA (Agricultural Dataflow). Landbrukets Klimaselskap SA aim to reduce the environmental impact of Norwegian agriculture through the project "Klimasmart Landbruk" (Climate Smart Agriculture). As a part of the project, the models for estimating GHG emissions from dual purpose milk and beef, grain production, and pig production (i.e. HolosNor; Bonesmo et al., 2012a, 2012b, 2013) have been further developed to become advisory tools for reducing emissions at farm level. The next step is to implement the HolosNorBeef model and estimate the emission intensities from commercial farms based on the data provided by Landbrukets Dataflyt SA to document the GHG emissions from livestock production and implement farm-specific measures for GHG mitigation.

6.3 Soil carbon – a source of variation

Most whole-farm models assume that soil C is at equilibrium and exclude soil C from the model. However, Soussana et al. (2007) reported that European grasslands are likely to act as atmospheric sinks. Thus, soil C is important to consider when estimating the environmental impact of beef production. Modelling of soil C balance is challenging as the decomposition and mineralization of added organic matter (e.g. manure, plant residues, increased crop yields) depend on the quality of the organic matter, the environmental conditions of the soil, and management practices (Conant et al., 2001). In a natural ecosystem, the release of CO_2 to the atmosphere through respiration, erosion and leaching is balanced by the input of C from plant residues. Whereas in managed soils the C content of the soil increases with added organic matter, and harvesting of crops and grass increases the C loss (Weil and Brady, 2017). Agricultural practices such as monoculture and extensive tillage lead to C loss and reduced diversity of soil organisms. Hence, grassland soils have a potential for C storage with improved management such as water management, controlling soil erosion and use of conservation tillage (i.e. no-till production system; Batjes, 2004) .

The HolosNorBeef model includes C balance in agricultural soils through the Introductory Carbon Balance Model (ICBM) calibrated to Norwegian conditions. In Paper I, the soil C was a sink in the flatlands for both breeds, while being a source of emissions for British breeds the mountains (Paper I; Table 7 and 8). Paper II showed variation emission intensities across regions when soil C was included in the model. On average, soil C accounted for 6% of the total emissions and was the largest source of variation ranging from -12% to 31% (Paper II; Table 7). In regions with more permanent grasslands (i.e. Southwest and North), soil C was a large source of emissions as the estimation of soil C balance is sensitive to both initial soil organic carbon (SOC) and the external factor of soil moisture and temperature ($r_W r_T$). This might imply that the model needs further calibration to soils with higher initial SOC content. However, the sensitivity elasticity does not show any difference between regions (Paper II, Table 9). By excluding the soil C balance, the difference between regions were reduced.

Outfield areas are currently excluded from HolosNorBeef as the potential for C storage in outfields and permanent pastures are unknown. Norwegian outfield areas (i.e. 14 mill ha) consist of good quality uncultivated pastures in the forest and mountains. Yearly, the outfields are grazed by 2.1 mill sheep and 0.3 mill cattle, utilizing only 50% of the available resources (Rekdal, 2014). In a Ph.D. project at the Norwegian University of Science and Technology (NTNU) they investigated the C storage in different heath, meadow, and shrub communities with low intensity sheep grazing in Dovre Mountains in Norway (Sørensen et al., 2018a, 2018b). The study showed that the shrub and meadow had greater C fluxes, and the total C content of the meadow was twice the C content of the shrub community due to larger below ground C content (Sørensen et al., 2018b). Most models (e.g. ICBM; Andrén et al., 2004) only include the top 30cm of the soil. However, Sørensen et al. (2018b) measured organic matter down to 51cm, implying that models calibrated for arable land does not include all changes in soil C in outfields and permanent grasslands. Applying the theory of organic matter down to 51cm and an increased below ground C content in the present study, the locations having large initial SOC are likely have C sequestrations rather than a C loss. Hence the estimated emission intensities might be overestimated for some locations in terms of soil C.

6.4 Mitigating GHG emissions

Numerous mitigation options have been suggested to reduce the environmental impact of beef production, of which many aimed at reducing enteric CH_4 emissions as it accounts for approx. 50% of the total emissions (Foley et al., 2011; Mogensen et al., 2015). The range of measures include breeding (e.g. improved performance; discussed in Section 6.4.1), dietary measures (e.g. dietary formulation; discussed in Section 6.4.2), improved management (e.g. manure management; discussed in Section 6.4.3), and alternative energy sources (e.g. biofuel; discussed in Section 6.4.4) (Hristov et al., 2013b). Reducing GHG emissions from farms are challenging due to interactions and feedback among practices. For example, reduced age at slaughter could reduce lifetime CH_4 emissions while increasing emission intensities (i.e. CO_2 eq (kg carcass)$^{-1}$) due to lower carcass production (Janzen et al., 2011). Thus, the net effect on total farm GHG emissions should be explored before implementing mitigating practices. Schils et al. (2007) concluded that a whole-farm model is a powerful tool to develop cost effective mitigation options as it estimates the net GHG emissions by including all sources of emissions and interactions.

Paper III investigated the net effect of several mitigation strategies in average farms of British and Continental breeds in the flatlands in Norway (discussed in Section 6.4.1, 6.4.2 and 6.4.3). Herd size and structure (number of suckler cows constant and replacement heifers) were kept constant across scenarios. Ley area and corresponding silage additives, N-fertilizer, and fuel varied across scenarios based on feed requirements, thereby increasing the required input when increasing performance. At farm level, increased carcass production reduces the emission intensities, whereas the total emissions increases. Ripple et al. (2014) stated that a reduced number of cows can reduce both enteric and manure CH_4 emissions. Increased animal productivity provides the ability to produce the same amount of beef from a lower number of cows, thereby yielding a larger reduction in both GHG emissions.

The use of pre-averaged data (i.e. assuming average performance) when investigating mitigation options call for careful interpretation as the emission intensities might be underestimated (McAuliffe et al., 2018). There is a concern related to investigating mitigation options on average farms as a statistical comparison is not possible. With small estimates, the variation among individual farms might be larger than the potential reduction from the mitigation option. However, McAuliffe et al. (2018) concluded that the opportunity to reduce the environmental impact is large as the benefit of selective breeding when using pre-averaged data is likely to be larger than currently thought.

6.4.1 Breeding for reduced GHG emissions

Animal breeding exploits natural variation between animals and provides a permanent, cumulative change in productivity (e.g. weight gain, milk yield), reproductive performance (e.g. age at first calving, calf survival), and health (e.g. longevity, disease resistance; Cassell, 2009). The improvement is permanent and is transferred to the next generation. Greater levels of productivity increase the proportion of the energy intake used for production (Pickering et al., 2015). However, increased productivity may also lead to greater production and a corresponding increase in GHG emissions.

The environmental impact of increased slaughter production have been investigated by a number of studies (Desjardins et al., 2012; Legesse et al., 2016, 2018; Murphy et al., 2017; Thornton and Herrero, 2010). Selection for growth traits or crossbreeding can improve average daily gain (ADG) and reduce the age at slaughter, thereby reducing the lifetime production of enteric CH_4 (Arthur et al., 2009). Several studies have shown that increased ADG and reduced age at slaughter reduce emission intensities from beef production (Casey and Holden, 2006; Crosson et al., 2010; Murphy et al., 2017). However, improved genetics also needs improved feeding (discussed in Section 6.4.2), and herd management (discussed in Section 6.4.3) to optimize the benefit. Paper III investigated the net effect of increased ADG by reducing age at slaughter and increasing carcass weight for young bulls. Emission intensities were reduced 2.0% for British and 6.6% for Continental breeds compared with average production levels (Paper III, Table 6).

Breeding for improved reproductive performance may reduce emissions through reduced age at calving, improved calf survival, less empty cycles and increased lifetime productivity (Wall et al., 2010). Calf survival is important for both economy (Azzam et al., 1993) and the GHG emissions from beef production (Wall et al., 2010). Paper III investigated the net effect of changed calf mortality for average herds of British and Continental breeds in Norway (Paper III, Table 5). The scenarios with 0% calf mortality lowered the net emission intensities 3.1% compared to the baseline level. This corresponded with the 4% reduction in emission intensities reported by (Beauchemin et al., 2011). However, obtaining 0% calf mortality is unlikely to occur over years in real farms as the calf survival is dependent on several factors such as genetics, health, and management.

Selecting for lower CH_4 emitting animals and more feed efficient animals can contribute to reduced global CH_4 emissions (Difford et al., 2018; Pickering et al., 2015). Enteric CH_4 is a relatively new trait in animal breeding with few studies on actual CH_4 emissions (Donoghue et al., 2016; Hayes et al., 2016). Large scale measurement of individual CH_4 emissions is practically impossible as it is challenging to measure. Thus, breeding for reduced emissions can be done based on indicator traits (e.g. dry matter intake; DMI, residual feed intake; RFI) as there is a strong relationship between feed intake and CH_4 production (Pickering et al., 2015) or indirectly through increased production. A Dutch study on dairy cattle suggest that selection for more efficient cows (i.e. low RFI) could reduce enteric CH_4 emissions by 11-26% in 10 years (De Haas et al., 2011). However, the net reduction is dependent on maintained production level. In terms of the young bull efficiency scenario with increased ADG (Paper III), improved feed efficiency could reduce both net emissions and feed costs by reducing the total feed intake at maintained production level.

6.4.2 Dietary mitigation options

Dietary strategies to reduce enteric CH_4 emissions have been of great interest and a number of studies have investigated the mitigating effect of improved forage quality (Jonker et al., 2016; Staerfl et al., 2012), forage to concentrate ratio (de Oliveira et al., 2007; Lovett et al., 2003), and dietary supplements (Hulshof et al., 2012; Romero-Perez et al., 2014; Tomkins et al., 2018). In a review of enteric CH_4 mitigation options, Hristov et al. (2013a) concluded that improving forage quality and nutrient use efficiency is an effective way of decreasing CH_4 emissions. Hence, at the same gross energy (GE) intake, the enteric CH_4 emissions would decrease with increased digestibility. The IPCC methodology calculates the CH_4 emissions as a fraction of GE intake converted to CH_4 based on a methane conversion factor (Ym), independent of diet digestibility (IPCC, 2006). Mitigation options aiming to increase diet digestibility would therefore cause no change in enteric CH_4 emissions when using the IPCC methodology. In HolosNorBeef, the Ym is adjusted for the digestibility of the diet as suggested by Beauchemin et al. (2010). Hence, HolosNorBeef is suitable for detecting investigating mitigation options aiming to increase diet digestibility.

Microbial fermentation of carbohydrates in the rumen produces CH_4 and CO_2 (Hristov et al., 2013a). Enteric CH_4 emissions represent a 2-12% energy loss of GE intake (Johnson et al., 1994) and is mainly related to variation in DMI (Herd et al., 2014) and feed quality (Ominski et al., 2011). Improved quality (i.e. energy content) and increased easily digested organic matter in the feed is associated with lower emissions (Difford et al., 2018; Wims et al., 2010). Diets with more starch and less fiber produce less CH_4 per kg dry matter (DM) (Haque, 2018), whereas a high proportion of fiber in the diet yields high acetic:propionic acid ratio in rumen fluid and lead to high enteric CH_4 emissions (Sveinbjörnsson, 2006). In addition to influencing enteric CH_4 emissions, the diet composition influences the manure CH_4 emissions through the organic matter content (i.e. VS; volatile solids) of manure. Crude protein and fiber content of manure is significant related to VS (Appuhamy et al., 2017).

Several studies have shown that intensive, concentrate based beef production have lower emission intensities compared with roughage-based production (de Vries et al., 2015; Hyslop, 2008; Pelletier et al., 2010). High concentrate diets increased ADG and reduced age at slaughter, thereby reducing lifetime enteric CH_4 emissions (Lovett et al., 2010). In a review of LCA of beef production systems, de Vries et al. (2015) showed that land occupation, GWP, and energy use was lower for concentrate based beef than forage based beef. However, grasslands less suitable for crop production might be preferred over high productive cropland for direct production of animal feed (de Vries et al., 2015). For example in Australia, grass fed beef cattle occupied small areas of arable land and were fed modest amounts of human edible protein compared to grain fed cattle (Wiedemann et al., 2015).

Improved forage quality reduces both enteric CH_4 emissions and total GHG emissions from beef production (Åby et al., 2019; Dick et al., 2015). Åby et al. (2019) showed that the emission intensities from young bull beef production could be reduced by 17% when replacing a normal harvest time silage and concentrates with early harvest silage. Feeding superior silage quality reduced emission intensities independent of concentrate level (Åby et al., 2019). Hence, the emission intensities could be further reduced with the use of high-quality silage in the young bull beef production scenario of Paper III.

The use of inhibitors can reduce enteric CH_4 emissions (Difford et al., 2018) and a number of dietary supplements including phyto-compounds (e.g. oregano, garlic, tannins), microbial (e.g. live yeast) supplements, ionophores, dietary lipids, and chemical inhibitors have been examined for their anti-methanogenic properties (Bayat et al., 2015, 2017; Hristov et al., 2013b; Kolling et al., 2018). Most supplements show promising short-term reduction of enteric CH_4 emissions if used at adequate concentrations. However, reducing CH_4 emissions are challenging as the rumen microbial population rapidly adapts to changes and returns to pre-treatment levels (Hristov et al., 2013a). As most studies apply the supplements for a limited period, long-term effects are often unknown. In addition to a long-term mitigating effect, the net reduction depends on maintained production level and diet digestibility. At the high administration levels needed to reduce CH_4, supplements can have negative effects on feed intake (e.g. dietary lipids, tannins; Hristov et al., 2013b; Jayanegara et al., 2012), digestibility (e.g. dietary lipids saponins, tannins; Goel and Makkar, 2012; Jayanegara et al., 2012; NRC, 2001; Patra, 2010), animal health (e.g. nitrates, tannins; Cockwill et al., 2000; Leng, 2008; Lowry et al., 1996) and performance (e.g. dietary lipids; Grainger and Beauchemin, 2011).

Paper III investigated the net effect of an inhibitor of enteric CH_4 represented by the 3-NOP, which at present is available for research purposes only. Thus, the scenario is indicative and only theoretical at this stage. The inhibitor was considered at two supplementation rates (i.e. 100 and 237 mg kg DM^{-1}) with different mitigation effects, assuming no negative effect on DMI and production. Supplementation rates and assumptions were based on previous studies by Romero-Perez et al. (2014), Vyas et al. (2016), and Vyas et al. (2018). Emission intensities (CO_2 eq (kg carcass)$^{-1}$) showed a net reduction of the baseline scenario of 4.5% and 9.6% across breeds at low and high supplementation rates, respectively (Paper III; Table 8).

The assumption of no negative influence of health and performance of 3-NOP is supported by a number of studies (Duin et al., 2016; Haisan et al., 2017; Lopes et al., 2016; Van Wesemael et al., 2019). However, due to release of N in the rumen, high 3-NOP application levels might have negative consequences at the same level of other nitrogen containing molecules (e.g. urea) with a surplus of nitrogen in the rumen resulting in nitrogen loss through urine (Harstad, 1994). Paper III investigated the mitigating effect of 3-NOP at two supplementation rates and assumed a reduction in enteric CH_4 yield of 7% (low) and 33% (high), within the range of reduction reported by studies of dairy and beef cattle (Haisan et al., 2014; Hristov et al., 2015a; Romero-Perez et al., 2014; Vyas et al., 2016). However, the decrease in CH_4 emissions is dependent on application level (Romero-Perez et al., 2014), application strategy (Hristov et al., 2015b), and forage to concentrate ratio (Romero-Perez et al., 2014; Vyas et al., 2016). Dijkstra et al. (2018) reported that the application rate for beef cattle was higher than dairy cattle to achieve the same effect. Thus, application rates and reduction potential should be related to the type of breed.

6.4.3 Improved management

Optimizing livestock performance through precision livestock farming and technical improvements reduces the environmental impact of livestock production (Beauchemin et al., 2011; Tullo et al., 2019; Zhang et al., 2013). Tullo et al. (2019) reported that enhancing productivity levels, reproduction, and health through precision livestock farming could reduce the environmental impact of livestock production. Emission intensities of Brazilian beef were reduced 2 to 57% through improved pasture and herd management (Mazzetto et al., 2015). Differences in management across countries yielded greater emission intensities for the Irish beef production system compared with the Australian system (Casey and Holden, 2006).

Livestock manure management accounts for almost 10% of the global GHG emissions from agriculture (Owen and Silver, 2015). Both CH_4 and N_2O emissions from manure depend on manure management, storage period, DM content, temperature, and application to land, in addition to the diet composition (Chadwick et al., 2011). Decomposition of manure under anaerobic conditions (i.e. absence of oxygen) during storage produces CH_4 (IPCC, 2006). Hence, liquid storage in lagoons or tanks yields larger manure CH_4 emissions than solid storage in piles or manure deposited on pasture. Direct N_2O emissions and indirect emissions from ammonia (NH_3) volatilization, runoff, and leaching varies significantly across management systems (IPCC, 2006). The difference in manure N_2O emissions between both breeds (Paper II; Table 6) and regions (Paper II; Table 7) is likely to occur due to differences in management systems and DMI. Animal manure typically have a N loss of 10 to 40% during storage (Chadwick, 2005; Eghball et al., 1997; Kirchmann, 1985; Larney et al., 2006; Petersen et al., 1998; Sommer, 2001; Sommer and Dahl, 1999). Nitrification of NH_3 from manure to nitrate (NO_3^-) occur under aerobic conditions, whereas anaerobic conditions causes a denitrification of NO_3^- to dinitrogen gas (N_2; Groenestein and Van Faassen, 1996; IPCC, 2006). Hence, both anaerobic and aerobic conditions can cause N emissions as nitric oxide (NO) and N_2O

are intermediate products of the nitrification and denitrification processes (Groenestein and Van Faassen, 1996).

Historically, the intensification of agriculture has come from increasing crop yields (i.e. per ha), increasing cropping intensity (i.e. number per unit), and increasing cropping value (i.e. higher marked value or better nutritional content; Pretty and Bharucha, 2014). The use of N fertilizer has been an important factor to increase crop yields (Smil, 2002). However, it can also have a negative impact on air, water, and biodiversity (Byrnes, 1990). White et al. (2010) reported increased GHG emissions per farm and per ha from beef production in New Zealand when increasing the N fertilizer application. However, expressed per kg beef, the emission intensities decreased (White et al., 2010). Stewart et al. (2009) reported corresponding results from Canada, where decreased intensification (i.e. reduced N fertilizer application) reduced the total farm GHG emissions and increased emission intensities.

6.4.4 Alternative energy sources

The on-farm use of energy can be replaced by renewable energy sources from e.g. biogas energy from manure and solar energy from panels placed on farm building roofs. Although the on-farm use of energy accounts for a relatively small proportion of the net emissions from beef production, a shift towards renewable energy is important to consider for a more sustainable beef production. Use of renewable energy sources mitigate energy-related GHG emissions (Panwar et al., 2011) and emissions from cattle production may be reduced through production of biogas by anaerobic digestion of manure (Banks et al., 2007; Clemens et al., 2006; Monteny et al., 2006). The net energy produced from biogas plants fluctuates throughout the year dependent on the type of substrate (e.g. type of manure, food waste) and ambient temperature (Fjørtoft et al., 2014b). Heating of substrates and thermal energy losses from the digester and pipes require energy (27-88% of energy produced), thereby reducing the net energy produced (Fjørtoft et al., 2014b). The long housing period in Norway provides access to livestock manure, however cold climate require isolation to minimize energy loss (Morken and Sapci, 2013). Small farm units favor cooperation between farms for optimizing energy production (Fjørtoft et al., 2014a). Optimizing the production of biogas energy have substantial mitigation potential (Arnøy et al., 2014; Holm-Nielsen et al., 2009; Morken and Sapci, 2013).

Installing solar panels on farm building roofs is an option for on-farm production of energy. Solar energy is directly converted to electricity using photovoltaic cells, reducing both GHG emissions and pollution (Panwar et al., 2011). Several studies have investigated the net reduction from solar energy showing variable energy accumulation across power stations and emissions caused by production of solar panels (Alsema, 2012; Pacca et al., 2007; Schaefer and Hagedorn, 1992). The net reductions from solar energy might increase following research and LCA studies of recycling processes of solar panels (Latunussa et al., 2016). In a review of renewable energy sources, Asdrubali et al. (2015) compared renewable energy sources (e.g. concentrated solar power, geothermal power, wind power). In terms of GHG emissions, all renewable energy sources had significant lower emissions (<100 g CO_2 eq kWh^{-1}) compared to natural gas (350-400 <100 g CO_2 eq kWh^{-1}) or hard cold plants with direct combustion (750-1050 g CO_2 eq kWh^{-1}) (Asdrubali et al., 2015).

6.5 Sustainability ≠ GHG emissions

Sustainability concerns have been on the global agenda since at least “The Brundtland Report” in 1987, which emphasizes the importance of not compromising the needs of future generations (World Commission on Environment and Development, 1987). This includes the possibility for food production, which are dependent on available area, soil quality, climatic conditions (i.e. temperature and rainfall), plant- and animal genetic resources, and knowledge among farmers and the society. When talking about sustainability of the food system, a lot of emphasis is given to GHG emissions, also in the public debate (Jones et al., 2016; Ridoutt et al., 2017). Considering only GHG emissions, ruminant products are often considered to be unsustainable (Garnett et al., 2017). However, sustainability involves other perspectives such as use of available renewable resources, use of water, energy and labor in addition to health and biodiversity.

Sustainability needs to be considered in all parts of a production chain and in connection with the resource base.

Dietary advices have increasingly focus on environmental impact for food production, consumption and food waste (Hendrie et al., 2016). Several reports have suggested common sustainable diet across countries or a global diet (e.g. Karlsson et al., 2017), ignoring the variability in resource base, production systems, and dietary challenges across regions. The food production in developing countries needs to increase and Gerber et al. (2015) stated that livestock production contributes to food production beyond the production of meat, milk and eggs as they act like a buffer against crises by producing high value products. Food security is a major concern with the increasing global population and it is stated that productive cropland should produce cereals for direct consumption rather than livestock feed (van Zanten et al., 2016). Hence, ruminants are important for developing countries as well as countries with large areas not suitable for production of food-crops or human-edible proteins. Increasing the efficiency and sustainability of livestock production therefore implies feeding livestock by-products from food production or utilizing human non-edible foods (e.g. grazing on marginal land; Eisler et al., 2014; Garnett, 2009). Some studies point out that livestock eat large quantities of concentrates and utilize the feed resources poorly compared with direct feeding of humans (Smil, 2002). However, a global study of cattle showed that 86% of the total feed were human non-edible (e.g. forages; Mottet et al., 2017). On average ruminants and non-ruminants were fed 2.8 and 3.2 kg human-edible food per kg produced, respectively (Mottet et al., 2017).

Emission intensities of forage-based beef production are higher than concentrate based beef production, chicken and pork (de Vries and de Boer, 2010). However, there are other aspects to consider as grazing animals compete less with humans for land resources that are suitable for arable production. The European countryside is characterized by a rich diversity of cultural landscapes shaped by traditional land-use (Plieninger et al., 2006). Grasslands cover more than one third of the agricultural area and besides supporting biodiversity, they are appreciated as they contribute to a regions' cultural heritage and recreation (Mitchell et al., 2000; Smit et al., 2008). The traditional land-use with pastures provide ecological services and have fostered habitat and species richness (Hampicke, 2006). Grazing also preserve biodiversity (Fjellstad et al., 2010; Guyader et al., 2016), increase C sequestration (Meyer et al., 2016), and increase the albedo effect (Kirschbaum et al., 2011; Rydsaa et al., 2017). Abandonment of traditional farming practices will lead to loss of hay meadows, lowland wet grasslands, heathlands, chalk and dry grasslands, moorlands (Henle et al., 2008) with corresponding loss of biodiversity, species, and cultural history.

The papers (Paper I, II, and III) evaluated the net GHG emissions of suckler cow beef production, using the whole-farm model HolosNorBeef. However, different beef systems could have trade-offs among environmental impact categories (Lupo et al., 2013; Ogino et al., 2016; Peters et al., 2010). Ogino et al. (2016) reported that increased productivity (i.e. larger carcass weight, reduced age at slaughter) of beef production in Thailand decreased the GHG emissions, while increasing impacts of energy consumption and acidification. In intensive farms, energy consumption increased from purchased concentrates, whereas the acidification increased due to purchased concentrates and greater NH_3 emissions from manure (Ogino et al., 2016). In the US, longer finishing time resulted in a 9.6-12% increase in freshwater eutrophication, marine eutrophication, terrestrial acidification, and terrestrial ecotoxicity compared with normal operations (Lupo et al., 2013). Grass fed calves had greater GHG emissions due to increased enteric CH_4, whereas the other environmental impacts (i.e. freshwater eutrophication, marine eutrophication, terrestrial acidification, and terrestrial ecotoxicity) were reduced (Lupo et al., 2013). Thus, inclusion of other environmental impacts such as acidification and eutrophication could influence the decision making when evaluating the sustainability of the beef production systems.

6.6 Future perspectives and suckler cow beef

Given that the global demand for food is increasing, reduced food production in one region will lead to an increase in other regions (Crosson et al., 2011; FAO, 2017). Hence, reduced food production could influence a country's food security without reducing the global GHG emissions. However, as food production needs to increase, reducing emission intensities does not necessarily mean reduced total emissions from the agricultural sector. Paper I showed that the emission intensities (CO_2 eq (kg carcass)$^{-1}$) from Continental breeds were lower compared with British breeds due to greater carcass production, whereas the total emissions (CO_2 eq) were lower for the British breeds (Paper I; Table 7 and 8). Correspondingly, Paper III showed that the mitigation options increasing the number of cattle (e.g. reduced calf mortality; Scenario CML) or increasing productivity (e.g. high carcass weight and low age at slaughter; Scenario BPH), decreased the emission intensities (CO_2 eq (kg carcass)$^{-1}$) (Paper III, Table 5 and 6) due to increased carcass production, while the total emissions (CO_2 eq) increased (Paper III; Figure 1).

Feeding the global population requires the utilization of all resources. Hence, suckler cow beef might be important for food security and self-sufficiency in the future due to the potential to utilize outfield pastures and marginal land. Cederberg and Stadig (2003) stated the importance of modelling and analyzing milk and beef production simultaneously when studying the environmental consequences of changing milk and beef production systems. Focus on optimizing milk production per cow as a mitigation option will have trade-offs for beef production (Vellinga and de Vries, 2018). Mitigation options reducing emission intensities from milk production, reduce the carcass produced from dairy breeds (Flysjö et al., 2012; Vellinga and de Vries, 2018) leading to a larger proportion of beef produced from specialized beef breeds, similar to the observed trend in Norway. The milk yield of dairy cows is expected to continue to increase as a result of genetic improvement and improved feeding management. In Norway, the dairy population is expected to have a further decrease as the milk quota regulates the total milk production. Hence, the demand for suckler cow beef will continue to increase. It is therefore apparent that sustainable beef production needs to be related to the corresponding milk production.

The methodology of the IPCC and the system boundaries of the model lays the foundation for the estimation of GHG emissions. At present, the GWP_{100} with a warming potential of 28 is used for CH_4. However, new methods accounting for the lifetime of CH_4 might be important in the future, as it influences the strategies to reduce the environmental impact of beef production. Continuous updates according to the prevailing methodology is crucial for the HolosNorBeef model, both as a research tool and an advisory tool. Further development is necessary to account for the entire environmental impact of the suckler cow beef production. The sustainability of production requires inclusion of other aspects than GHG emissions (e.g. eutrophication, acidification, biodiversity). Improvements in the model should also include calibration of ICBM model to outfield pastures and permanent grasslands. Development of the HolosNorBeef model into a climate calculator through "Klimasmart Landbruk" provides the opportunity for documenting the GHG emissions from the entire Norwegian suckler cow beef production.

7. Conclusions

- Emission intensities from Norwegian suckler cow beef is within the same range as the other Nordic countries.
- There is large variation in emission intensities between individual farms.
- Ignoring soil C reduces the variation in emission intensity between regions, breeds and individual farms
- The environmental impact of beef production can be reduced through breeding and management by improving suckler cow efficiency, increasing slaughter production and feeding supplements to reduce enteric CH_4 emissions
- Improvement of the soil C model is needed as the model is sensitive to initial SOC
- The mitigation potential in permanent grasslands and outfields may be higher than what is captured by the model, which is important to capture in a forage-based production
- The model should be further developed based on new knowledge and research, including other aspects of sustainability beyond GHG emissions.

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