UC Davis
UC Davis Previously Published Works

Title
Evaluation of greenhouse gas emissions from hog manure application in a Canadian cow–calf production system using whole-farm models

Permalink
https://escholarship.org/uc/item/0rq8s05f

Journal
Animal Production Science, 56(10)

ISSN
1836-0939

Authors
Alemu, Aklilu W
Ominski, Kim H
Tenuta, Mario
et al.

Publication Date
2016

DOI
10.1071/an14994

Peer reviewed

eScholarship.org Powered by the California Digital Library
University of California

CSIRO PUBLISHING

Animal Production Science
http://dx.doi.org/10.1071/AN14994

Evaluation of greenhouse gas emissions from hog manure application in a Canadian cow–calf production system using whole-farm models

Aklilu W. Alemu[A,D], *Kim H. Ominski*[A], *Mario Tenuta*[B], *Brian D. Amiro*[B] *and Ermias Kebreab*[C]

[A]Department of Animal Science, University of Manitoba, Winnipeg, MB, R3T 2N2, Canada.
[B]Department of Soil Science, University of Manitoba, Winnipeg, MB, R3T 2N2, Canada.
[C]Department of Animal Science, University of California, Davis, CA, 95616, USA.
[D]Corresponding author. Email: akliluwake@yahoo.com

Abstract. The development of beneficial management practices is a key strategy to reduce greenhouse gas (GHG) emissions from animal agriculture. The objective of the present study was to evaluate the impact of time and amount of hog manure application on farm productivity and GHG emissions from a cow–calf production system using two whole-farm models. Detailed model inputs (climate, soil and manure properties, farm operation data) were collected from a 3-year field study that evaluated the following three treatments: no application of hog manure on grassland (baseline); a single application of hog manure on grassland in spring (single); and two applications of hog manure as fall and spring (split). All three treatments were simulated in a representative cow–calf production system at the farm-gate using the following whole-farm models: a Coupled Components Model (CCM) that used existing farm component models and the Integrated Farm System Model (IFSM). Annual GHG intensities for the baseline scenario were 17.7 kg CO_2-eq/kg liveweight for CCM and 18.1 kg CO_2-eq/kg liveweight for IFSM. Of the total farm GHG emissions, 73–77% were from enteric methane production. The application of hog manure on grassland showed a mean emission increase of 7.8 and 8.4 kg CO_2-eq/kg liveweight above the baseline for the single and split scenarios, respectively. For the manured scenarios, farm GHG emissions were mainly from enteric methane (47–54%) and soil nitrous oxide (33–41%). Emission estimates from the different GHG sources in the farm varied between models for the single and split application scenarios. Although farm productivity was 3–4% higher in the split than in single application (0.14 t liveweight/ha), the environmental advantage of applying manure in a single or split application was not consistent between models for farm emission intensity. Further component and whole-farm assessments are required to fully understand the impact of timing and the amount of livestock manure application on GHG emissions from beef production systems.

Additional keywords: beef cattle, emissions intensity, single application, split application.

Received 8 December 2014, accepted 24 February 2015, published online 27 April 2015

Introduction

The environmental impact of animal agriculture has received increasing attention and, therefore, quantification and mitigation of greenhouse gas (GHG) emissions from the sector has been a focal point in agricultural research (O'Mara 2011). Globally, agriculture is estimated to contribute more than 10% of anthropogenic GHG emissions, with livestock accounting for about one-third of the methane (CH_4) emissions (Smith *et al.* 2007; O'Mara 2011). In 2012, the Canadian agricultural sector contributed ~8% of the total national GHG emissions, of which 57% was from the livestock sector where beef cattle were the main contributors (Environment Canada 2014).

Given the complex nature of livestock production systems, quantification of GHG emissions from the sector and evaluation of management practices to minimise GHG emissions at the farm scale have been challenging (Schils *et al.* 2005). As such, in an effort to quantify emissions and assess the whole-farm impact of management practices, various component-based (e.g. Dijkstra *et al.* 1992; Li *et al.* 1992; Kebreab *et al.* 2004) as well as integrated whole-farm models (e.g. Little *et al.* 2008; White *et al.* 2010; Rotz *et al.* 2011*a*) have been developed and implemented. Evaluation of management practices that reduce GHG emissions must be conducted at the farm scale using a whole-farm approach because implementation may yield synergistic and/or tradeoff effects among farm components, which impacts net farm GHG emissions (Janzen *et al.* 2006; Gerber *et al.* 2013). For example, a whole-farm simulation study by Hünerberg *et al.* (2014) on an average Canadian beef farm indicated that including high-fat dried distiller grain in the diet of feedlot cattle reduced enteric CH_4 emissions but increased nitrogen (N) excretion, which increased nitrous oxide (N_2O) emissions. As such, the intensity of GHG emissions increased by 6–9% on farms that fed dried distiller grain compared with the control average practice. Generally, whole-farm modelling provides a tool to inform policy decisions with respect

Journal compilation © CSIRO 2015

to estimated effectiveness of GHG mitigation practices associated with changes in farm management practices.

Application of manure as a substitute for synthetic fertiliser can potentially increase pasture productivity and reduce the carbon footprint of livestock products (Petersen *et al*. 2007; Hermansen and Kristensen 2011). For a cow–calf production system in a nutrient-poor landscape such as the Canadian prairie, where the largest proportion of the grazing land is unimproved (native) pasture (McCaughey *et al*. 1999; Manitoba Agricultural Review 2001), addition of external sources of manure to grassland is essential to maintain and improve productivity (Wilson *et al*. 2010; Bork and Blonski 2012). The use of animal manure as a source of N also provides a means to effectively utilise manure from intensive livestock operations and is a common practice in several parts of the world, including south-eastern Manitoba, Canada (Chadwick *et al*. 2000; Petersen *et al*. 2007; Wilson *et al*. 2010; Bork and Blonski 2012). Furthermore, application of animal manure reduces the use of synthetic fertilisers and, therefore, the GHG emissions associated with production and use (Bouwman *et al*. 2010). However, application of manure to grassland has a potential to increase soil N_2O emissions (Ellis *et al*. 1998; Chadwick *et al*. 2000; Rochette *et al*. 2008; Tenuta *et al*. 2010). Therefore, the challenge is to identify management practices, such as amount and time of application, that serve to improve productivity while decreasing gaseous emissions. In the Canadian Prairies, it is a common practice to apply manure on grassland once during the growing season, either in the spring, summer or fall; however, there is a lack of knowledge regarding its impact on net farm GHG emissions. Therefore, the objective of the present study was to evaluate the impact of timing and amount of hog manure application on farm productivity and total farm GHG emissions from a cow–calf production system by using whole-farm models.

Materials and methods

Data sources

Data for model inputs came from a 3-year field experiment in which manure was applied to grassland. Experiments were conducted for 3 years from 2004 to 2006 on the University of Manitoba La Broquerie Pasture and Manure Management Project site, La Broquerie, Manitoba, Canada (49°31′N, 96°30′W). The experimental site was divided into 12 paddocks, with hog manure applied to eight paddocks, as follows: four paddocks, as a split application in fall and spring, with 50% of the manure (70 kg available N/ha) applied in fall and the remaining 50% in spring (split); four paddocks, as a single application in spring (142 kg available N/ha, single); and the remaining four paddocks that did not receive hog manure served as a control (baseline). The paddocks were further subdivided such that they were used for either grazing or hay production (Wilson *et al*. 2010). The applied hog manure was sourced from the primary cell of a three-cell earthen manure storage at an adjacent commercial hog finishing operation. Manure was applied at a rate based on plant-available N content in the manure, assuming that 25% of manure ammonia and ammonium were lost by volatilisation on surface application to forage and 25% of organic N was available for plant use in the year of application (Tri-Provincial Manure Application and Use Guidelines 2006). Average total N applied over the 3-year period was 252 and 236 kg/ha for the single and split applications, respectively (Table 1). Hog manure was surface-applied using a splash-plate system without incorporation.

The quantity and composition of the applied hog manure, pasture and hay yield, and nutrient composition were measured throughout the experimental periods (Tables 1, 2). Soil properties were measured before the start of the experiment (Fall 2003) and throughout the trial in the fall of 2004, 2005 and 2006 before manure application (Table 1). Manure samples were collected and sent to a commercial laboratory for detailed analysis (Wilson *et al*. 2011). Rainfall at the site was monitored using a tipping bucket rain gauge and the normal annual precipitation was 541 mm. The growing-season total precipitation (April to October) during 2004, 2005 and 2006 was 611, 574 and 283 mm, respectively.

On the basis of the detailed information collected from the experimental site, the three management scenarios, namely (1) zero application of hog manure on grassland as baseline, (2) single full application of hog manure on grassland in spring and (iii) split application of hog manure on grassland in fall and spring, were used to simulate a cow–calf production system using whole-farm models to evaluate net GHG emissions associated with time and amount of manure application.

Description of the simulated cow–calf production system

The simulated system consisted of a cow–calf operation that maintained breeding animals, a backgrounding operation that raised weaned calves in preparation for finishing in a feedlot, as well as annual crop and forage production. The cow–calf production system was typical of the area and located in proximity to hog production facilities that provided hog manure to the land to enrich the nutrient content of the soil. The annual production cycle consisted of three major production periods, which began in late October when the animals were managed in confinement (Table 2). During the first period, 1 November to end of February, the operation consisted of 150 cows, 24 replacement heifers, seven bulls and 104 backgrounded animals. Animals were confined in a seasonal feeding area including pens and drylots and fed rations formulated on the basis of grass hay supplemented with barley grain and soybean meal. Beef cows were assumed to be in the third trimester of pregnancy. At the beginning of Period 1, culled cows were replaced by heifers from the previous year. Average cow-culling and mortality rate were 0.15 and 0.0125, respectively (Waldner *et al*. 2009). Replacement heifers (average daily gain (ADG) = 0.68 kg/day) were bred and calved at 15 and 24 months of age, respectively (Alemu *et al*. 2011). During the second period, 1 March to end of April, animals were also managed in confinement. Calves were born in late winter–early spring, with an average bodyweight (BW) of 44 kg. The gender ratio of calves was assumed to be 1 : 1 (MacNeil *et al*. 1994). At the age of weaning (7 months, average BW = 190 kg), calves were categorised as replacement heifers (24) and/or backgrounded animals (104). Backgrounded animals were fed a high forage diet containing 70–75% grass hay (ADG = 1.2 kg/day, Alemu *et al*. 2011) and shipped to market at the end of March (average BW = 433 kg for steers and 423 kg for heifers). Solid manure produced during Periods 1 and 2 was managed using a deep-bedding system, with barley straw as the bedding material,

Table 1. Average climate, soil and manure characteristics measured at the experimental site over 3 years (2004–2006) for the baseline and manured (single and split application of hog manure) treatments (mean ± s.e.)

Baseline, no application of hog manure on forage land; Single, application of hog manure in spring (100% spring application); Split, application of hog manure on forage land in fall and spring (50% of the manure is applied in fall and 50% in spring)

Item	Treatment		
	Baseline	Single	Split
	Climate		
Average daily solar radiation (MJ/m^2)[A]	13.53	13.53	13.53
Total precipitation from April to October (mm)[B]	489.33	489.33	489.33
Nitrogen in precipitation (mg/L)[C]	0.87	0.87	0.87
	Soil characteristics (0–30 cm)[D]		
Texture	Loamy sand	Loamy sand	Loamy sand
Type	Gleyed dark gray Chernozem	Gleyed dark gray Chernozem	Gleyed dark gray Chernozem
pH	7.6 ± 0.1	7.5 ± 0.1	7.5 ± 0.1
Field capacity (water filled pore space)	0.58	0.60	0.60
Total organic C (g C/kg)	18.7 ± 1.4	18.2 ± 1.2	18.3 ± 1.5
Total N (g N/kg)	1.5 ± 0.1	1.5 ± 0.1	1.4 ± 0.1
NO_3^- concentration (mg N/kg)	3.5 ± 1.2	4.5 ± 1.4	3.1 ± 0.8
NH_4^+ concentration (mg N/kg)	2.7 ± 0.2	3.1 ± 0.4	3.2 ± 0.3
Olsen-P (mg/kg)	12.1 ± 4.0	30.4 ± 8.4	27.6 ± 6.9
K^+ (mg/kg)	84.3 ± 19.2	131.7 ± 41.4	125.1 ± 32.4
Land topography	Nearly level (<2%)	Nearly level (<2%)	Nearly level (<2%)
	Imported hog manure[E]		
DM (%)	–	8.8 ± 1.9	6.0 ± 1.3
pH	–	7.0 ± 0.2	7.2 ± 0.1
C:N ratio	–	7.0 ± 0.2	7.2 ± 0.1
NH_4^+ (g N/L)	–	3.6 ± 0.2	3.4 ± 0.2
NO_3^- (g N/L)	–	0.002 ± 0.005	0.01 ± 0.01
Organic N, % total N	–	36.8 ± 3.1	27.3 ± 1.9
	Manure nutrient application rate[E]		
Application ('000 L/ha)	–	49.2 ± 8.0	48.7 ± 4.3
Total N (kg/ha)[F]	–	252.0 ± 27.8	235.8 ± 12.2
Organic N (kg/ha)	–	95.0 ± 40.1	39.0 ± 30.1
Ammonium-N (kg/ha)	–	120.0 ± 11.0	126.4 ± 4.2
Total P (kg/ha)	–	62.4 ± 3.3	44.0 ± 7.4

[A] Measured at the experimental site from 2005 to 2010.

[B] Rainfall at the site was monitored using a tipping bucket rain gauge. The total precipitation for the growing season (April–October) was 611, 574, 283 mm for the 2004, 2005 and 2006 growing year, respectively.

[C] Nitrogen in precipitation was obtained from Environment Canada (2012).

[D] Measured over 3 years (2004–2006), textural class was according to USDA classification. Information regarding soil characteristics was obtained from Tenuta *et al*. (2010), Wilson *et al*. (2011) and Coppi (2012). Soil characteristics for the 30–120 cm were reported in Wilson *et al*. (2011) and Coppi (2012).

[E] Average values for the composition and application rates of the imported hog manure applied in spring and fall (2003–2006) for the manured (split and single) treatments were obtained from Wilson *et al*. (2010, 2011) and Tenuta *et al*. (2010).

[F] The average (2004–2006) applied total N for the split and single hog manure applications were 240 and 252 kg/ha, respectively.

1.81 kg/animal unit.day, where one animal unit is equivalent to the weight of a mature cow (Manitoba Agriculture Food and Rural Development 2013). Measured soil parameters of the baseline scenario were used as model inputs to simulate barley production. On-farm produced solid cattle manure and synthetic urea N were applied in spring to the barley field on the basis of the recommendations in Manitoba (Tri-Provincial Manure Application and Use Guidelines 2006). During the third period, 1 May to 31 October, animals (cows, suckling calves, replacement heifers and bulls) were grazed on pasture continuously at a stocking rate of 0.56, 1.14 and 1.26 animal unit month per hectare for the control, single and split management scenarios, respectively. An average stocking rate of 0.59 animal unit month per hectare has been reported as an ecologically sustainable rate for mixed grass (wheat, needle and thread) native prairie pasture (Adams *et al*. 2013). Land area required for forage (pasture, hay) and barley grain production to support the nutritional needs of the animals was calculated on the basis of the total farm annual feed requirement, land productivity and losses related to harvest, storage and feeding (Table 3).

System boundary

The system boundary was defined by the GHG emissions associated with the simulated cow–calf production from 'cradle to farm-gate' (Fig. 1). The study used an International Organisation for Standardisation (ISO) partial lifecycle

Table 2. Characteristics of beef cattle populations in the simulated cow–calf production system for the individual periods within the annual production cycle

Cattle feed requirement and diets were formulated using CowBytes© software, a beef cattle ration balancer (Alberta Agriculture Food and Rural Development 2003). ADG, average daily gain; BW, bodyweight; DMI, dry matter intake

Animals	Period 1 (1 November – 29 February)				Period 2 (1 March – 30 April)				Period 3 (1 May – 31 October)				Diet
	No.	ADG (kg/day)	DMI (kg/day)	BW (kg)	No.	ADG (kg/day)	DMI (kg/day)	BW (kg)	No.	ADG (kg/day)	DMI (kg/day)	BW (kg)	
Cows	150	0	11.6	588	150	0.10	13.3	591	150	0.11	13.7	601	Grass hay supplemented with barley grain and soybean meal (6 months), pasture
Suckling calves[A]	0	–	–	–	128	1.20	0.44	81	128	1.20	2.8	190	Grass hay and milk (1.5 months), pasture (6 months)
Replacement heifers	24	0.68	8.0	351	24	0.68	9.8	372	24	0.68	10.9	434	Grass hay supplemented with barley grain (2 months), pasture (6 months)
Bulls	7	1.28	12.9	579	7	1.28	13.9	618	7	1.28	17.2	735	Grass hay supplemented with barley grain and soybean meal (6 months), pasture (6 months)
Backgrounded steers	64	1.20	10.4	383	64	1.20	10.5	411	0	–	–	–	High-forage backgrounding diet[B]
Backgrounded heifers	40	1.20	9.2	366	40	1.20	10.2	394	0	–	–	–	High-forage backgrounding diet[C]

[A] Average calving date was assumed as 15 March.

[B] Approximately 75% grass hay, 15% barley grain and 10% soybean meal during Periods 1 and 2 as well as 90% pasture and 10% barley grain during Period 3 for the baseline scenario; 80% grass hay and 20% barley grain during Periods 1 and 2 as well as 100% pasture during Period 3 for the split and single scenarios.

Table 3. Total land required for annual production cycle and expected yield, losses and nutrient composition of forage and barley grain used in the whole-farm analysis

Yield and composition of grass hay and pasture were obtained from the field experiment conducted between 2003 and 2006 (Wilson *et al*. 2010), barley grain yield for La Broquerie area was obtained from Manitoba Management Plus Program (MMPP 2012) and barley straw DM (89%) and straw crude protein (38 g/kg) were obtained from Narasimhalu *et al*. (1998). Harvest and storage loss for grass hay was based on Rotz (2003). Feed utilisation loss (trampling and wastage for pasture land) was according to Adams *et al*. (2013). Baseline, no application of hog manure on forage land; Single, application of hog manure in spring (100% spring application); Split, application of hog manure on forage land in fall and spring (50% of the manure is applied in fall and 50% in spring). Y, yes; N, no

Item	Yield (mg DM/ha)	DM (%)	Crude protein (g/kg)	Herbicide used	Harvest and storage loss (%)[C]	Feed utilisation loss (%)	Land required (ha)
				Baseline			
Barley grain[A]	2.02	88	127.3	Y	3	0	55
Grass hay	1.12	92	74.6	N	15	15	479
Pasture	1.52	38	97.5	N	0	25	414
				Single			
Barley grain[A]	2.02	88	127.3	Y	3	0	37
Grass hay	4.21	90	100.4	N	15	15	159
Pasture	3.45	31	181.7	N	0	25	205
				Split			
Barley grain[A]	2.02	88	127.3	Y	3	0	41
Grass hay	4.04	89	90.6	N	15	15	160
Pasture	3.69	32	162.5	N	0	25	186

[A] Nitrogen applied on the barley field was from solid on-farm produced manure as well as synthetic urea nitrogen.

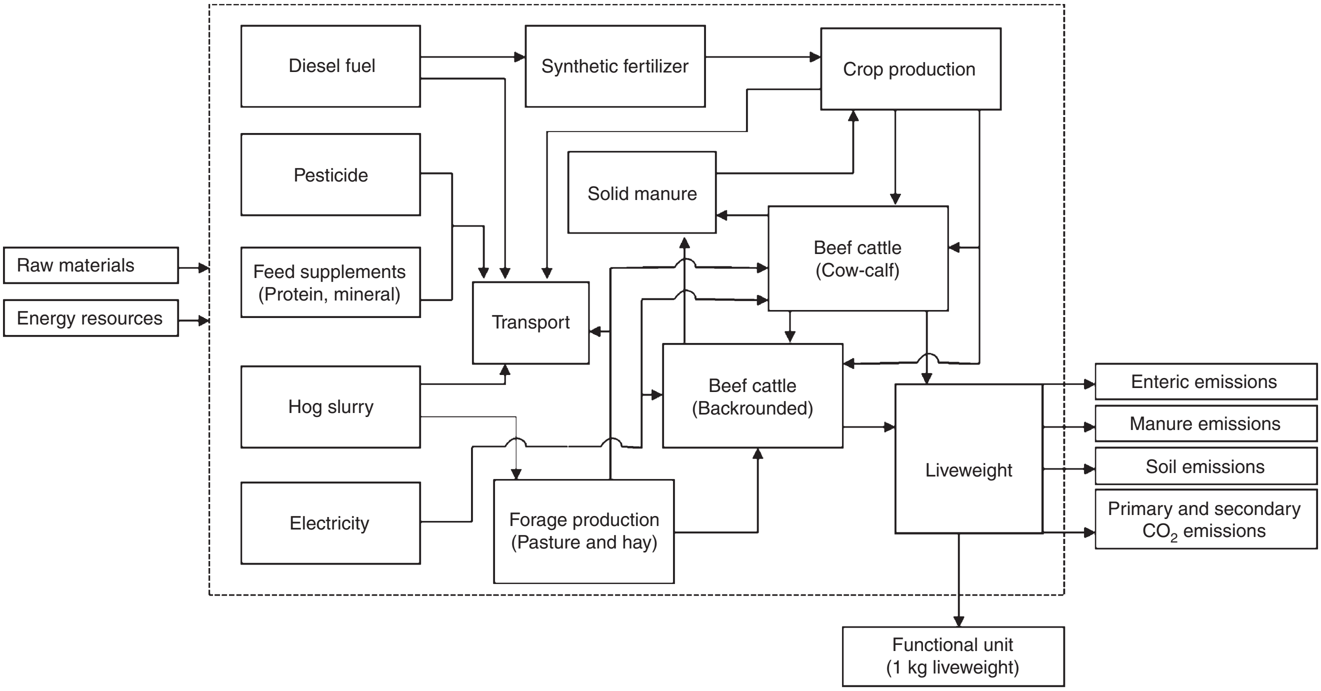

Fig. 1. System boundaries and processes of a Western Canadian cow-calf backgrounding production system from 'cradle to farm-gate'.

methodology (ISO 2006*a*, 2006*b*). The GHG emissions included were (1) direct emissions of CH_4 from enteric fermentation and manure, and N_2O from soil and manure, (2) indirect emissions of N_2O from N leaching, runoff and volatilisation, and (3) carbon dioxide (CO_2) emissions from primary (on-farm energy use) and secondary (production and transportation of farm inputs) sources (Fig. 1). On-farm energy use included diesel fuel for farm operations and electricity for housing and crop processing. Farm inputs included hog manure, soybean meal, herbicide and commercial urea-N fertiliser. GHG global-warming potentials for a 100-year time horizon were expressed as CO_2 equivalent units (CO_2 eq), where: CO_2 = 1, N_2O = 265 and CH_4 = 28 on a mass basis, without including climate-carbon feedbacks (Myhre *et al*. 2013). Total GHG emission of the cow–calf production system was the sum of all GHG emissions converted to CO_2-eq units.

Functional unit and allocation

The functional unit is the measure of the performance of the production system in which all inputs and outputs are related (ISO 2006*b*), and should be consistent to compare beef-production systems (Crosson *et al*. 2011). In our study, 1 kg of liveweight at the farm-gate was used as the functional unit (Fig. 1). Total liveweight at the farm-gate was calculated from the average weight of backgrounded steers and heifers as well as culled cows sold from the farm. Emissions were also expressed per unit land (t liveweight/ha) to consider the whole system as an integrated production unit. These functional units have been implemented in several previous studies (e.g. Phetteplace *et al*. 2001; Casey and Holden 2006*a*, 2006*b*; Beauchemin *et al*. 2010; Basarab *et al*. 2012; Bell *et al*. 2012).

Because hog manure was used as fertiliser in the cow–calf production system, emissions related to transport and application were included in the whole-farm GHG analysis; however, emissions associated with the storage and handling were allocated to the hog farm as described by Knudsen *et al*. (2010) and Whitman *et al*. (2011). Furthermore, emissions (N_2O, CO_2) related to the production, processing and transportation of the imported soybean meal were included in the whole-farm GHG analysis using an average emission factor of 0.46 kg CO_2-eq/kg dry soybean meal (Adom *et al*. 2012; Mc Geough *et al*. 2012; Table 4).

Mathematical models

Two models were used to analyse total farm GHG emissions from the simulated cow–calf production system, namely, the Coupled Components Model (CCM) and the Integrated Farm System Model (IFSM; Rotz *et al*. 2011*a*). Table 4 summarises the different approaches, assumptions and emission factors used in the models. A brief summary of each of the models is provided below.

Coupled Components Model

Several models developed for different components of the farm were coupled to estimate emissions from the cow–calf operation. The CCM included: Cowbytes$^{@}$ beef-cattle ration balancer (Alberta Agriculture Food and Rural Development 2003), COWPOLL (Dijkstra *et al*. 1992), Manure-DNDC (Li *et al*. 2012) and some aspects of the Intergovernmental Panel on Climate Change (IPCC 2006). These models were simulated separately for their respective farm components by maintaining the carbon (C) and N flows within the production system.

Dry matter intake and diet composition for a representative animal from each category during the annual production cycle (Table 2) in CCM were estimated using the Cowbytes$^{@}$ beef-cattle ration balancer (Version 4.6.8). These values were used as inputs for the COWPOLL model that was used to estimate enteric CH_4 emissions on the basis of predictions from rumen methanogenesis and hind-gut fermentation as described by Mills *et al*. (2001) and Reijs (2007), respectively. Excretion and composition (organic matter, C and N) of faeces and urine were estimated using an extended COWPOLL model based on static equations that describe intestinal and hind-gut digestion (Reijs 2007). For each component excreted in faeces and urine, a constant C and N fraction was adopted to estimate the amount of excretion. Urinary N balance was calculated by deducting the amount of N in faeces, milk (for lactating cows) and in the body (for growing animals) from the total N intake of the animal.

Emissions of N_2O and CH_4 from soil in CCM were estimated using a process-based model, manure–denitrification–decomposition (manure–DNDC) model (Version 2.0; Li *et al*. 2012). Manure–DNDC was simulated over 3 years (2004–2006 individually) to estimate N_2O (direct and indirect) and CH_4 emissions from soil, using the measured climate and soil characteristic data collected from the experimental site as an input to manure–DNDC (Tables 1, 3). The model simulated a 1-year production cycle and did not consider inter-year dynamics (Li *et al*. 2012). Indirect N_2O emissions were calculated from manure–DNDC estimates of N volatilised and leached and the IPCC (2006) emission factors for volatilisation (0.01 kg N_2O-N/kg gasses volatilised) and leaching (0.0075 kg N_2O-N/kg NO_3 leached; Table 4).

Emissions of CH_4 and N_2O (direct and indirect) from on-farm produced solid manure in CCM were estimated using IPCC Tier 2 methodology (IPCC 2006) because the virtual farm constructed in manure–DNDC contained only cow and veal animal categories and can accommodate only one animal category per simulation. However, the typical beef cow–calf operation in western Canada has cows, bulls, replacement heifers, backgrounded animals and calves (Basarab *et al*. 2005; Alemu *et al*. 2011). Manure management methods incorporated in the model were limited to compost, lagoon and anaerobic digester, which differ from the deep-bedding manure management system used in the majority of western Canadian beef operations (Beaulieu 2004). Methane emissions from fresh cattle faeces deposited on pasture during grazing were calculated using measured emission factors from the experimental site (0.085, 0.096 and 0.118 g CH_4/kg faeces for baseline, split and single scenarios, respectively (Tremorin 2009). The excreted urinary urea-like components (urea, uric acid and allantoin) estimated by COWPOLL were assumed to be converted into ammonium and ammonia during manure storage and used to estimate indirect N_2O emissions from on-farm solid manure storage by applying the default IPCC volatilisation fraction of 30% (Table 4). Emissions of CO_2 from direct on-farm fuel use were calculated as the product of the size of land area and a unique energy use value associated with each crop type (Table 4).

Integrated Farm System Model (Version 3.4)

The IFSM is a farm-simulation model that estimates the performance, environmental impact and economic sustainability of beef, dairy and crop farms (Rotz *et al*. 2011*a*). The model integrates nine major submodels that represent crop and soil, grazing, machinery, tillage and planting, crop harvest, crop storage, herd and feeding, manure management and economic analysis. The model parameters reflect the management strategies used in the beef industry in Manitoba. The formulated management scenarios (split and single) were simulated by adjusting the duration of manure storage in the IFSM. Manure-storage options in the model were 6 months when manure was applied to the field twice yearly (early April and late October; split application) and 12 months when manure was applied to the field once per year (early April; single application).

The model was simulated over 6 years (2005–2010) using environmental parameters (temperature, precipitation, solar radiation) measured at the experimental site. Initial conditions were reset each year as the model does not consider inter-year dynamics. In a given year, IFSM simulated a sequence in a daily time step that began with manure handling, tillage, planting, growth and harvest operations, feed storage, feed utilisation and herd production. Animal feed intake, performance and manure production were modelled using the herd and feeding components of the model. Feed allocation and animal responses were related to the nutritive value of available feed and nutrient requirements of the animal groups, estimated using the Cornell Net Carbohydrate and Protein System, level 1 (Rotz *et al*. 2005).

The IFSM tracked emissions of CH_4, N_2O and CO_2 from different sources in the production system (i.e. crop, animal, manure) as well as emissions related to production and transport of resources used on the farm (Table 4). Enteric CH_4 production was estimated using the non-linear equation developed by Mills *et al*. (2003) and CH_4 emissions from solid manure storage were estimated using IPCC Tier 2 methodology. However, CH_4 emissions from field-applied manure were based on manure volatile fatty acids, which were assumed to decline exponentially after application (Sherlock *et al*. 2002). A constant emission factor of 0.086 g CH_4/kg faeces (Sommer *et al*. 2004) was applied for CH_4 emission from fresh faeces deposited on pasture.

Direct N_2O emissions from forage- and crop-land were estimated using a simplified model based on DAYCENT (Chianese *et al*. 2009*a*). However, for direct N_2O emissions from manure storage, the model applied a constant emission factor of 0.005 kg N_2O-N/kg excreted N (Table 4). Indirect N_2O emissions were the product of default IPCC (2006) emission factors for volatilisation (0.01 kg N_2O-N/kg N) and leaching (0.0075 kg N_2O-N/kg N, Table 4) and model-estimated ammonia volatilisation (from animal housing, manure storage, field-applied manure, faecal- and urine-N deposited on the pasture) and soil N loss through leaching, respectively. The IFSM estimated CO_2 emissions from feed production and on-farm energy use, as well as secondary emissions from the production of machinery, fertiliser and pesticide (Chianese *et al*. 2009*b*).

Results

GHG emission estimates from the different sources (farm components) and annual emission-intensity estimates are reported in Table 5. The relative proportional contribution (% of total farm emissions) of the various GHG sources within the production system are indicated in Fig. 2, whereas Fig. 3 shows the proportional contribution of each animal category to the total CH_4 emissions from enteric fermentation.

Baseline scenario

Estimates of annual emission intensity for the baseline scenario were in close agreement, ranging from 17.7 kg CO_2-eq/kg liveweight using CCM to 18.1 kg CO_2-eq/kg liveweight using IFSM. When emission intensity was expressed per land basis, estimates were 1.06 t CO_2-eq/ha using CCM and 1.08 t CO_2-eq/ha using IFSM. Enteric CH_4 was the primary contributor to total farm emissions (73–77%) followed by soil N_2O (7.2–15.4%) and manure CH_4 (3.7–9.1%; Fig. 2). Methane emissions from enteric fermentation were mainly from beef cows (69%) followed by backgrounded steers and heifers (14%; Fig. 3). Of the total farm GHG emissions for the baseline scenario, direct emissions from animal husbandry (enteric CH_4, manure CH_4 and N_2O), accounted for 78% using IFSM and 90% using CCM.

Although the estimates of annual emission intensity for the two models varied on average by only 2%, their differences in estimating emissions from the different GHG sources were higher (Fig. 2). For example, the contribution of manure N_2O to the total farm emissions was 4.1% using CCM compared with 1.2% using IFSM. Conversely, soil N_2O contributed 7% of the total farm GHG emissions using CCM and 15% using IFSM. Of the total soil N_2O emissions, CCM estimated 20% from indirect sources, whereas IFSM estimated 19% from the same sources (Table 5).

Manured (single and split) scenarios

Annual estimated emission intensities for the manured scenarios were 40–47% higher for single and 38–56% higher for split scenarios than those for the baseline scenarios (Table 5). Expressed in land-based emissions, intensity estimates were 3.57 and 4.04 t CO_2-eq/ha for the single and split applications, respectively, using CCM, whereas IFSM estimated 3.64 and 3.66 t CO_2-eq/ha for the split and single applications, respectively (Table 5). Given the addition of N from the hog manure application in these scenarios, the observed increase in emission intensity was expected. In addition to the increased emissions intensity, application of hog manure also improved farm productivity, expressed as liveweight per unit land (Table 5). Compared with the baseline scenario (0.06 t liveweight/ha), farm productivity was on average 134% and 146% higher in single and split applications, respectively. The models differ in estimating farm emission intensity by 3% for single application, with the highest estimate from IFSM (26.1 kg CO_2-eq/kg liveweight), and by 11% for the split application, with the highest estimate from CCM (27.6 kg CO_2-eq/kg liveweight).

Addition of hog manure significantly increased soil N_2O emissions, to the point where the combination of direct and indirect N_2O emissions matched enteric CH_4 emissions (Fig. 2). For the manured scenarios, total farm emissions were mainly contributed by enteric CH_4 (47–54%) and soil N_2O (33–41%). For both the single and split hog manure-application scenarios, the greatest proportion of soil N_2O emissions were from direct emissions in CCM (19–24%) and indirect emissions in IFSM (23–24%; Table 5). Overall, the average contribution of direct emissions from animals (enteric CH_4, manure CH_4 and N_2O) were 61% in single and 57% in split scenarios.

Discussion

Baseline scenario

Given the differences in production systems, farm boundaries and assumptions, mathematical models used to estimate emissions and global-warming potential factors of GHGs (Myhre *et al*. 2013), comparison of emission-intensity estimates with previously reported values is challenging. However, some comparisons can still be made between model estimates and literature values for similar production systems. Estimates of farm GHG intensity for the baseline scenario (17.7–18.1 kg CO_2-

Table 4. Assumptions, equations and emission factors (EFs) used in the Coupled Components Model (CCM) and Integrated Farm System Model (IFSM) to estimate greenhouse gas emissions from the cow–calf production system

CF, conversion factor; EF_{liquid}, emission factor for liquid manure application; EF_{solid}, emission factor for solid manure application; MCF, methane conversion factor (by manure handling system); n.a., not applicable, NLEAP, nitrate leaching and economical analysis package model, VFA, volatile fatty acid

Greenhouse gases	CCM		IFSM	
	Models, equations and EFs used	Reference[A]	Models, equations and EFs used	Reference[A]
Methane (CH_4)				
Enteric fermentation	Based on rumen fermentation and rumen VFA stoichiometric models	9, 19	Non-linear Mitscherlich (Mits 3) equation	1
Deep-bedding manure[B]	Based on volatile solids and MCF	4	Based on volatile solids and MCF	2
Field applied manure	na		Linear Equation based on manure VFA concentration[C]	2
Fresh cattle faeces on pasture	EF = 0.085, 0.096 and 0.118 g CH_4/kg faeces for the baseline, split and single scenarios, respectively	21	EF = 0.086 g CH_4/kg faeces	2
Soil emission or uptake	Fermentation submodel of manure–DNDC	11	n.a.	
Nitrous oxide (N_2O)				
Direct N_2O				
Deep bedding manure	N excretion values were from COWPOLL; EF = 0.01 kg N/kg N	4, 22	EF = 0.02 kg N/kg excreted N (floor), EF = 0.005 kg N/kg excreted N (stacked manure)	4
Soil or cropping nitrogen	Denitrification and nitrification submodel of manure–DNDC	11	Simplified DAYCENT submodel	5
Indirect N_2O				
Deep bedding manure				
Volatilisation	Manure NH_4-N concentration was estimated using COWPOLL[D]; EF = 0.01 kg N_2O-N/kg N	4	Diffusion, dissociation, aqueous to gas partitioning and mass transport equations	2
Soil or cropping nitrogen				
Leaching	Hydrological submodel of manure–DNDC; EF = 0.0075 kg N_2O-N/kg NO_3 leached	12, 4	NLEAP submodel EF = 0.0075 kg N_2O-N/kg NO_3 leached	6
Volatilisation[E]	Decomposition submodel of Manure-DNDC; EF = 0.01 kg N_2O-N/kg gases volatilised	11, 4	NLEAP submodel; EF = 0.01 kg N_2O-N/kg gases volatilised	6, 4
Carbon dioxide (CO_2) – CO_2 from energy use (primary and secondary sources)				
On-farm energy use and cropping[F]	Unique energy use coefficients for different crops	14	Fuel consumption and CF of 2.637 kg CO_2/L	7
Manure application	EF_{liquid} = 0.42 kg CO_2/kg N; EF_{solid} = 0.27 kg CO_2/kg N	13	Fuel consumption and CF of 2.637 kg CO_2/L	2
Barley production	EF = 107 kg CO_2/ha	14	Fuel consumption and CF of 2.637 kg CO_2/L	2
Hay production	EF = 60.8 kg CO_2/ha	14	Fuel consumption and CF of 2.637 kg CO_2/L	3
Soybean meal production, processing and transportation	EF = 0.46 (for production and processing) and 0.0016 kg CO_2-eq/kg soybean meal DM basis (for transportation)	18, 23	n.a.	

Electricity	Annual use = 47.1 kWh/beef cow and CF of 0.22 kg CO_2/kWh	15, 16	Annual use = 80 kWh/beef cow and CF = 0.73 kg CO_2/kWh	7, 8
Energy to dry barley grain	0.001 kg CO_2/kg grain	17	Electric use factor is used to estimate electric consumption	2
Herbicide production	EF = 2.67 kg of CO_2/ha	14	2 kg/ha and EF = 22 kg of CO_2/kg pesticide	2
Nitrogen fertiliser	EF = 3.59 kg CO_2/kg N	20	EF = 3.307 kg CO_2/kg N	2
Machinery manufacturing	n.a.		3.54 CO_2-eq/kg of machinery	2, 7

[A] 1 = Mills *et al.* (2003), 2 = Rotz *et al.* (2011*a*), 3 = Rotz *et al.* (2010), 4 = IPCC (2006), 5 = Chianese *et al.* (2009*a*), 6 = Shaffer *et al.* (1991), 7 = Wang (2007), 8 = Ludington and Johnson (2003), 9 = Bannink *et al.* (2006), 10 = Yamulki *et al.* (1999), 11 = Li *et al.* (2012), 12 = Li *et al.* (2006), 13 = Wiens *et al.* (2008), 14 = Little *et al.* (2008), 15 = Dyer and Desjardins (2006), 16 = Environment Canada (2014), 17 = Vergé *et al.* (2007), 18 = Mc Geough *et al.* (2012), 19 = Mills *et al.* (2001), 20 = Nagy (2001), 21 = Tremorin (2009), 22 = Reijs (2007), 23 = Adom *et al.* (2012).

[B] The IPCC (2006) Tier 2 approach was implemented to estimate CH_4 emissions from deep bedding manure. For CCM, MCF = 0.17 kg CH_4/kg CH_4 and B_o = 0.19 m^3 CH_4/kg volatile solids. For IFSM, MCF = $7.11e^{0.0884(T)}$, where T = ambient barn temperature (°C) and methane producing capacity (B_o) = 0.24 m^3 CH_4/kg volatile solids. The B_o value used in IFSM was from Sommer *et al.* (2004).

[C] CH_4 (kg/day) = (0.17 × VFA + 0.026) × land area (ha) × 0.032; where VFA is the daily concentration of VFAs in the manure (mmol/kg manure) which is a function of initial concentration and time.

[D] Urinary urea-like compounds including urea, uric acid and allantoin estimated using COWPOLL were assumed to be converted to NH_4-N during manure storage and the IPCC (2006) default value for volatilisation fraction (30%) was applied.

[E] For CCM, 25% NH_4-N volatilisation loss from surface applied manure was assumed (Tri-Provincial Manure Application and Use Guidelines 2006). Fraction of NH_4-N loss through volatilisation from field applied mature in IFSM was estimated using formulae that consider ambient temperature and pH of the manure (Rotz *et al.* 2011*a*). Volatilisation loss was estimated until the manure was incorporated or for ~15 days after application assuming all surface NH_4-N is normally lost or infiltrated into the soil after this time.

[F] For IFSM, fuel consumption was estimated by using fuel use factor (average amount of fuel used to produce and deliver a unit of feed to the herd or remove a unit of manure) and total farm fuel use was calculated by summing the fuel use over all operations. Engine CO_2 emissions = fuel use (L/h) × 2.637. Fuel use is a function of fuel consumption rate (L/kWh), engine power (kW), fuel use efficiency, engine load and fuel use index (Rotz *et al.* 2011*a*).

eq/kg liveweight) were higher than previously reported estimates (11.6–15.4 kg CO_2-eq/kg liveweight) for Canadian beef production systems (Vergé *et al.* 2008; Beauchemin *et al.* 2010, 2011; Basarab *et al.* 2012; Hünerberg *et al.* 2014). Beauchemin *et al.* (2010) and Hünerberg *et al.* (2014) conducted a life-cycle analysis for cow–calf through to the feedlot production system by using the Holos model and reported an intensity estimate that ranged between 11.9 and 15.4 kg CO_2-eq/kg liveweight. Furthermore, for a similar production system, Vergé *et al.* (2008) and Basarab *et al.* (2012) used the IPCC Tier 2 approach to conduct the whole-farm analysis and reported an emissions intensity that ranged between 11.6 and 13.8 kg CO_2-eq/kg liveweight. The observed variation may be related to differences in model assumptions and production systems analysed. Previous studies examined emissions from cow–calf to the feedlot, whereas our analysis did not include a feedlot phase. The feedlot phase has higher efficiency (Johnson *et al.* 2002; Capper 2011); therefore, a whole-farm analysis that incorporates feedlot operation is expected to have lower total emissions per unit of production than does a cow–calf production system. Phetteplace *et al.* (2001), for example, reported a 33% higher emission intensity for conventional cow–calf production than for cow–calf to the feedlot production (15.5 kg CO_2-eq/kg liveweight gain).

Emission-intensity estimates expressed in land-based units (1.06–1.08 t CO_2-eq/ha) and farm productivity (0.06 t liveweight/ha) were smaller than values reported by Johnson *et al.* (2002) and Beauchemin *et al.* (2010). For beef production systems managed on pasture and fed mixed hay in North America, Johnson *et al.* (2002) reported an emissions intensity of 1.8 CO_2-eq/ha. For a beef production system in southern Alberta based on native pasture and dryland crop production, Beauchemin *et al.* (2010) reported a farm productivity of 0.18 t liveweight/ha. In the current study, the baseline scenario was based on native grassland with lower productivity, which increased the total land required to support the production cycle (948 ha, Table 3). Generally, even though the baseline scenario was used for comparison in the current study, the scenario is rarely recommended for long-term sustainability because the soil nutrient reserve will eventually be depleted, risking long-term productivity. As such, unless long-term implications are also considered, short-term estimates alone are not reliable as indicators of sustainability.

According to Johnson *et al.* (2003) and Vergé *et al.* (2008), proportional contribution of enteric CH_4 to total farm emissions in North American beef production systems ranged between 40% and 70%. These values were comparable to the contribution of enteric CH_4 (73–77%) in the current study for the baseline scenario, sourced mainly from beef cow and backgrounded animals (Fig. 3). However, the greater estimates using CCM (77%) can be attributed to the greater emission factor used in COWPOLL (7–8% of gross energy intake) than the default IPCC value (6% of gross energy intake) used in the previous studies. In a cow–calf backgrounding production system, Pelletier *et al.* (2010) and Lupo *et al.* (2013) reported that beef cows and backgrounded animals contributed 68–81% and 11–24% of the total farm GHG emissions, respectively. Furthermore, Beauchemin *et al.* (2010) indicated that beef cows and backgrounded animals contributed up to 79% and 7%, respectively, of farm CH_4 emissions from enteric fermentation.

Table 5. Greenhouse gas emissions from different sources in the farm and emissions intensity for baseline, single and split scenarios estimated using the Coupled Components Model (CCM) and Integrated Farm System Model (IFSM)

Baseline, no application of hog manure on forage land; Single, application of hog manure on forage land in spring (100% spring application); Split, application of hog manure on forage land in fall and spring (50% of the hog manure is applied in fall and 50% in spring). n.a., not applicable

Greenhouse gases	Emissions (t CO_2-eq)					
	Baseline		Single		Split	
	CCM	IFSM	CCM	IFSM	CCM	IFSM
Enteric CH_4	770.2	742.1	775.6	768.2	734.0	737.0
Manure CH_4	91.0	37.6	102.3	77.3	95.2	75.7
Manure N_2O	40.7	11.9	33.7	24.1	38.1	20.9
Direct N_2O	36.7	10.0	31.3	20.7	34.9	18.3
Indirect N_2O	4.0	1.9	2.4	3.4	3.3	2.6
Soil CH_4[A]	–8.3	n.a.	–3.4	n.a.	–4.8	n.a.
Soil N_2O	72.6	157.0	474.5	536.7	648.1	531.9
Direct N_2O	58.4	128.0	267.7	194.5	372.9	191.6
Indirect N_2O	14.2	29.0	206.8	342.2	275.2	340.3
Leaching and runoff	3.5	25.5	28.9	4.0	17.4	3.8
Volatilisation	10.7	3.5	177.9	338.2	257.7	336.5
CO_2 from farm energy use	39.0	71.2	47.9	63.4	53.8	42.7
Total farm GHG emissions	1005.3	1019.8	1430.6	1469.7	1564.4	1408.3
Farm emissions intensity (kg CO_2-eq/kg liveweight)	17.7	18.1	25.3	26.1	27.6	25.0
Farm emissions intensity (t CO_2-eq/ha)	1.06	1.08	3.57	3.66	4.04	3.64
Farm productivity (kg liveweight/ha)	60.0	59.5	146.2	145.4	141.1	140.5

[A] Negative values indicated consumption or uptake of CH_4 by the soils.

Overall, the close agreement between model-estimated enteric CH_4 values (0.4–4%) as well as between model estimates and previously reported literature values in the current study might suggest the current advances in enteric CH_4 prediction-model accuracy and the little opportunity for improvement.

Evaluation of the addition of hog manure

There is a paucity of information on the impact of animal-manure application on whole-farm GHG emissions from beef production systems (Petersen *et al*. 2007). As such, it is challenging to compare the estimated farm intensity values for single and split scenarios, with previously reported values. Casey and Holden (2006*a*, 2006*b*) examined application of on-farm cattle slurry twice per year at a rate of 50 t/ha, combined with synthetic fertiliser and reported emission intensities ranging from 8 to 11 kg CO_2-eq/kg liveweight. These values are lower than the intensity estimates for single and split scenarios in our study, in which all the required N in the farm for the forage field was sourced from imported hog manure. Higher soil N_2O emissions have been reported from soils that received livestock manure than from those that received synthetic fertiliser. Smith *et al*. (2008) reported 0.23 kg/ha of N_2O emissions for a maize field that received synthetic fertiliser (150 kg/ha) and 1.21 and 3.1 kg/ha for the field that received pig slurry at the rates of 60 and 120 t/ha, respectively. Therefore, the higher GHG-intensity estimates for split and single scenarios in our study could be associated with the use of hog manure on grassland causing increased soil N_2O emissions. Conversely, estimated emissions per unit land for single (3.6–3.7 t CO_2-eq/ha) and split (3.6–4.0 t CO_2-eq/ha) scenarios were comparable to values (3.3–5.9 t CO_2-eq/ha) reported by Flessa *et al*. (2002), Casey and Holden (2006*b*) and Foley *et al*. (2011) for European beef production systems that applied on-farm produced slurry to forage and crop land.

The addition of hog manure greatly increased soil N_2O emissions and had similar proportional contribution with enteric CH_4 to the total farm emissions (Fig. 2). Johnson *et al.* (2002) conducted a whole-farm analysis of GHG emissions for a cow–calf through to the feedlot production system in the USA, where on-farm-produced solid manure was deposited on pasture. In their study, enteric CH_4 contributed 36% and N_2O 52% of farm GHG-emission intensity. As much as 54% of the N_2O emissions were from manure application or manure deposition during grazing. Furthermore, Flessa *et al*. (2002) reported that N_2O emissions contributed 60% of emissions for a conventional beef farm that applied on-farm produced slurry to the cropland. Hence, our estimates of increased soil N_2O emission with the application of manure are consistent with these other studies.

Although the application of animal manure on grassland increases land productivity (Wilson *et al*. 2010; Bork and Blonski 2012), it is apparent that the concurrent increase in emissions of soil N_2O occur through enhanced nitrification and denitrification (Ellis *et al*. 1998; Chadwick *et al*. 2000; Tenuta *et al*. 2010). Therefore, the sustainability of manure application requires implementation of management practices that reduce soil N_2O emissions. One of the management strategies is timing of manure application to favour plant uptake of N (Chadwick 1997; Rochette *et al*. 2004). Furthermore, application of manure at two different times of the year (i.e. spring and fall) has also been practiced (Tenuta *et al*. 2010). This practice provides the same total amount of N and may have the potential to reduce the large flush of ammonium and nitrate in the soil that leads to increased soil N_2O emissions. In the current study, although annual emission intensity was higher for both single and split applications than was the baseline, there was disagreement between models regarding which scenario has lower emissions. However, farm productivity was smaller in the single than split scenario by 3–4%. Variation in

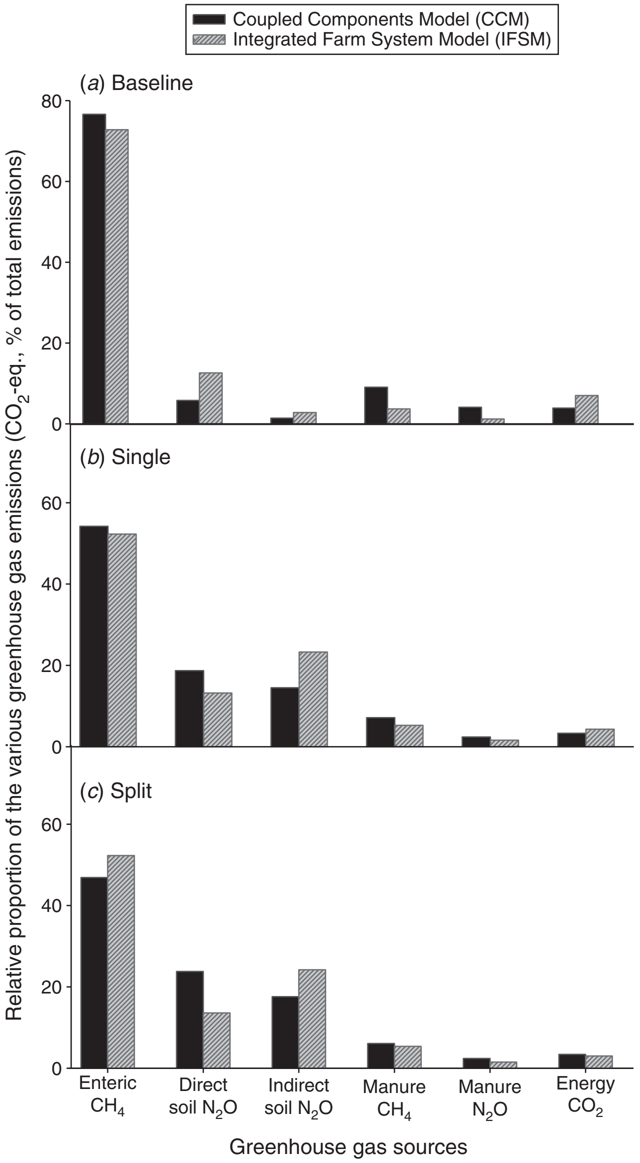

Fig. 2. Proportional contribution of the various GHG emission sources (CO_2-eq, % of total emissions) in *a*) baseline, *b*) single and *c*) split scenarios estimated using the Coupled Components Model (CCM) and Integrated Farm System Model (IFSM).

pasture quality and dry matter productivity is reported for pastureland that received hog manure (Wilson *et al.* 2010). The increased pastureland productivity in split applications (Table 3) reduced the total land required to support the production cycle (387 ha) compared with the single application (401 ha), which may contribute to the observed higher farm productivity for the split scenario.

The observed inconsistency between models in estimating emission intensity for the single and split applications may partly be attributed to their difference in estimating soil N_2O emissions. Direct emissions of soil N_2O were quantified using manure–DNDC in CCM and the simplified DAYCENT model in IFSM (Rotz *et al.* 2011*a*). The major proportion of the total soil N_2O emissions was contributed from direct emissions using CCM and indirect (ammonia volatilisation loss from field-applied manure) emissions using IFSM for both single and split scenarios (Fig. 2, Table 5). Several local- and global-scale studies have compared DNDC and DAYCENT models and observed differences in estimated N loss (Del Grosso *et al.* 2006, 2009; Smith *et al.* 2008; Abdalla *et al.* 2010). Furthermore, on a farm-component scale, inconsistencies have been reported in field studies designed to measure the impact of timing and amount of manure application on GHG emissions. Allen *et al.* (1996) reported greater soil N_2O emissions for animal manure applied on grassland in the UK during fall than during spring application, whereas Chadwick *et al.* (2000) reported greater soil N_2O and CH_4 emissions for slurry applied on grassland in spring than for those applied in fall and summer. Similarly, Rochette *et al.* (2004) reported a two-fold increase in soil N_2O emissions for spring application of hog slurry on maize compared with fall application (1.74% of total hog slurry-applied N). Rochette *et al.* (2000) observed an increase in N loss as N_2O (from 1.23% to 1.65%) when the application rate of hog slurry was doubled. Combining rate and time of application, Tenuta *et al.* (2010) reported a 0.51% loss of total hog slurry-applied N when applied on grassland in a single spring application, compared with 0.29% loss when applied as a split application. Generally, the observed inconsistencies may indicate the need for further component and whole-farm assessments to fully understand the impact of time and amount of livestock manure application on farm GHG emissions from beef production system.

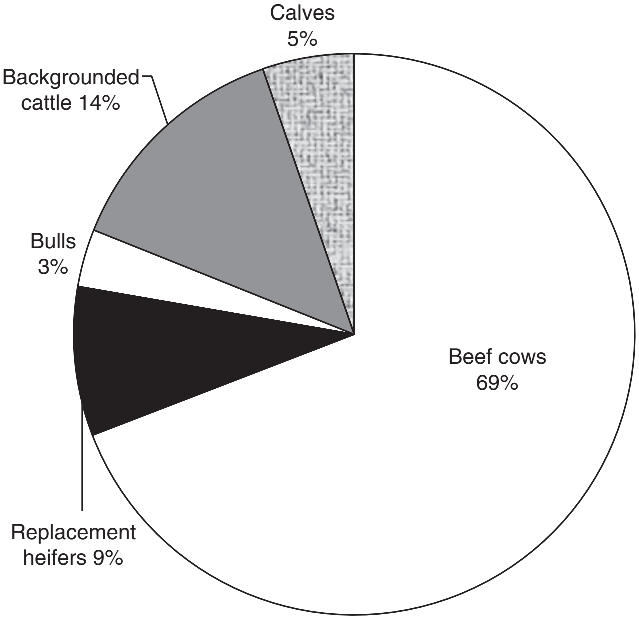

Fig. 3. Breakdown of average enteric CH_4 emissions (CO_2-eq) by animal category for baseline, single and split scenarios estimated using the Coupled Components Model (CCM). The outputs from Integrated Farm System Model (IFSM) were average values and difficult to breakdown by animal categories.

Implications and future study

Various mitigation strategies have been proposed and implemented to minimise GHG from animal agriculture (Beauchemin *et al.* 2009; Eckard *et al.* 2010). However, often the strategies are applied to a single farm component (e.g. animal, soil) and, therefore, it is difficult to evaluate their impact from a whole-farm perspective. A whole-farm modelling approach is a powerful tool for the development of cost-effective GHG mitigation options because relevant interactions among farm components are revealed (Schils *et al*. 2007). In the current study, the two models used to analyse the whole-farm GHG emissions from the cow–calf operation are not consistent in estimating GHG-emission intensity from the split and single scenarios (Table 5). Although differences among models were expected as a result of their difference in approaches, assumptions and algorithms used to estimate GHG emissions, there was general agreement in the baseline scenario. However, the observed difference in manured scenarios may indicate the need for further model improvement.

Estimated emissions contributed by the different farm components identified the sources that should be targeted in developing beneficial management practices to reduce the carbon footprint of the beef operations. For the baseline scenario, total emissions were mainly contributed from direct emissions of livestock enteric CH_4, whereas for the manured scenarios, enteric CH_4 and soil N_2O were the main contributors (Fig. 2). Thus, strategies to minimise emissions might best be aimed at targeting these farm components.

The simulated cow–calf production system in the current study followed a common practice in those areas with high livestock density where hog manure was applied to forage land without incorporation, which may have increased N loss through volatilisation (Rochette *et al*. 2008). Incorporation or injection of hog manure may reduce N loss through volatilisation (Rotz *et al*. 2011*b*) and increase N_2O and CH_4 emissions from soil (Velthof *et al*. 2003; Rodhe *et al*. 2006), which may result in a greater difference between the application scenarios.

In the current study, beef cattle were assumed to be managed in confined lots during the winter period (Period 2). However, the trend in the past decade indicates that cow–calf farmers in western Canada are moving away from overwintering cows in a confined lot to an in-field wintering system, in which beef cattle are fed on pasture with manure deposited directly in the field (Agriculture and Agri-Food Canada 2011; McCartney 2011). This management practice reduces the contribution of emissions from manure management, by avoiding accumulation of manure in the confined lots. It also reduces enteric CH_4 emissions because animals managed outdoors under cold temperatures produce less enteric CH_4 (Kennedy and Milligan 1978; Takahashi *et al*. 2002; Bernier *et al*. 2012), there is increased nutrient recycling efficiency (Jungnitsch *et al*. 2011; Kelln *et al*. 2012) and a reduction in winter feeding costs (Kelln *et al*. 2011). Therefore, integration of management practices such as in-field overwintering management of beef cattle with amount and timing of hog manure application on grassland needs to be evaluated, so as to assess their impact on the total farm GHG emissions.

Conclusions

The use of a whole-farm approach to analyse GHG emissions from a beef production system is essential in evaluation of a beneficial management practice. In the current study, farm productivity and environmental impact (GHG emissions) of the timing and amount of hog manure application on forage land (i.e. in spring or in spring and fall) in a cow–calf operation were assessed using whole-farm models. Farm emission-intensity estimates for a baseline scenario ranged between 17.7 and 18.1 kg CO_2-eq/kg liveweight. The application of hog manure on grassland showed a mean emission increase of 7.8 and 8.4 kg CO_2-eq/kg liveweight above baseline for single and split scenarios, respectively. The baseline scenario would rarely be recommended, regardless of the low GHG-emission intensity, because the soil nutrient reserves in this scenario would eventually be depleted, challenging its long-term productivity and sustainability. Conversely, farm productivity, expressed as liveweight per unit land, was higher (134–146%) in manured scenarios than in baseline scenario. The advantage of applying manure during a single spring application compared with split applications was not conclusive because of the inconsistency between model estimates, where CCM estimated a higher emission intensity for the split and IFSM for the single scenario. Given their higher proportional contribution to the total farm GHG emissions, management strategies designed to minimise emissions need to target enteric CH_4 emissions in the baseline scenario and enteric CH_4 and soil N_2O emissions in the manured scenarios. Generally, further whole-farm analyses are required to evaluate the environmental impacts of livestock manure application in beef production systems and to identify best management practices that minimise the environmental footprint of these systems.

Acknowledgements

We acknowledge Dr C. Alan Rotz for his assistance on IFSM, Drs Changsheng Li and William Salas for providing manure–DNDC and assistance with the model and Dr J. Dijkstra for his assistance with COWPOLL. This research received funding from the Agriculture and Agri-Food Canada Agricultural Greenhouse Gas Program, University of Manitoba Graduate Fellowship, MITACS ACCELERATE and the Sesnon Endowed Chair Program (UC Davis).

References

Abdalla M, Jones M, Yeluripati J, Smith P, Burke J, Williams M (2010) Testing DayCent and DNDC model simulations of N_2O fluxes and assessing the impacts of climate change on the gas flux and biomass production from a humid pasture. *Atmospheric Environment* **44**, 2961–2970. doi:10.1016/j.atmosenv.2010.05.018

Adams BW, Richman J, Poulin-Klein L, France K, Moisey D, McNeil RL (2013) 'Rangeland plant communities and range health assessment guidelines for the mixed grass natural subregion of Alberta. Second approximation. Lethbridge, Pub. No. T/03940.' (Rangeland Management Branch, Policy Division, Alberta Environment and Sustainable Resource Development: Lethbridge, AB, Canada)

Adom F, Maes A, Workman C, Clayton-Nierderman Z, Thoma G, Shonnard D (2012) Regional carbon footprint analysis of dairy feeds for milk production in the USA. *The International Journal of Life Cycle Assessment* **17**, 520–534. doi:10.1007/s11367-012-0386-y

Agriculture and Agri-Food Canada (2011) Sustainable management on nutrients on the landscape for in-field livestock winter feeding system. Available at http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1294669298001&lang=eng [Verified 15 May 2012]

Alberta Agriculture, Food and Rural Development (2003) 'CowBytes©, beef cattle ration balancer (V. 4. 6. 8).' (Agriculture and Rural Development: Alberta, Canada)

Alemu AW, Ominski KH, Kebreab E (2011) Estimation of enteric methane emissions trends (1990–2008) from Manitoba beef cattle using empirical and mechanistic models. *Canadian Journal of Animal Science* **91**, 305–321. doi:10.4141/cjas2010-009

Allen A, Jarvis S, Headon D (1996) Nitrous oxide emissions from soils due to inputs of nitrogen from excreta return by livestock on grazed grassland in the UK. *Soil Biology & Biochemistry* **28**, 597–607. doi:10.1016/0038-0717(95)00186-7

Bannink A, Kogut J, Dijkstra J, France J, Kebreab E, Van Vuuren AM, Tamminga S (2006) Estimation of the stoichiometry of volatile fatty acid production in the rumen of lactating cows. *Journal of Theoretical Biology* **238**, 36–51. doi:10.1016/j.jtbi.2005.05.026

Basarab JA, Okine EK, Baron VS, Marx T, Ramsey P, Ziegler K, Lyle K (2005) Methane emissions from enteric fermentation in Alberta's beef cattle population. *Canadian Journal of Animal Science* **85**, 501–512. doi:10.4141/A04-069

Basarab J, Baron V, López-Campos Ó, Aalhus J, Haugen-Kozyra K, Okine E (2012) Greenhouse gas emissions from calf- and yearling-fed beef production systems, with and without the use of growth promotants. *Animals* **2**, 195–220. doi:10.3390/ani2020195

Beauchemin KA, McAllister TA, McGinn SM (2009) Dietary mitigation of enteric methane from cattle. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* **4**, 18–27. doi:10.1079/PAVSNNR20094035

Beauchemin KA, Janzen HH, Little SM, McAllister TA, McGinn SM (2010) Life cycle assessment of greenhouse gas emissions from beef production in Western Canada: a case study. *Agricultural Systems* **103**, 371–379. doi:10.1016/j.agsy.2010.03.008

Beauchemin KA, Janzen HH, Little SM, McAllister TA, McGinn SM (2011) Mitigation of greenhouse gas emissions from beef production in western Canada: evaluation using farm-based life cycle assessment. *Animal Feed Science and Technology* **166–167**, 663–677. doi:10.1016/j.anifeedsci.2011.04.047

Beaulieu MS (2004) 'Manure management in Canada. Catalogue no. 21-021-MIE-No. 002.' (Statistics Canada, Farm Environmental Management in Canada, Agricultural Division: Ottawa, Canada) Available at http://publications.gc.ca/collections/Collection/Statcan/21-021-M/21-021-MIE2004001.pdf [Verified 3 March 2012]

Bell MJ, Eckard RJ, Cullen BR (2012) The effect of future climate scenarios on the balance between productivity and greenhouse gas emissions from sheep grazing systems. *Livestock Science* **147**, 126–138. doi:10.1016/j.livsci.2012.04.012

Bernier JN, Undi M, Plaizier JC, Wittenberg KM, Donohoe GR, Ominski KH (2012) Impact of prolonged cold exposure on dry matter intake and enteric methane emissions of beef cows overwintered on low-quality forage diets with and without supplemented wheat and corn dried distillers grain with solubles (DDGS). *Canadian Journal of Animal Science* **92**, 493–500. doi:10.4141/cjas2012-040

Bork EW, Blonski LJ (2012) Short-term native grassland compositional responses following liquid hog manure application. *Canadian Journal of Plant Science* **92**, 55–65. doi:10.4141/cjps2011-105

Bouwman AF, Stebfest E, van Kessel C (2010) Nitrous oxide emissions from the nitrogen cycle in arable agriculture. In 'Nitrous oxide and climate change'. (Ed. K Smith) pp. 85–106. (Earthscan LLC: Washington, DC)

Capper JL (2011) Replacing rose-tinted spectacles with a high-powered microscope: the historical vs. modern carbon footprint of animal agriculture. *Animal Frontiers* **1**, 26–32. doi:10.2527/af.2011-0009

Casey JW, Holden NM (2006*a*) Quantification of GHG emissions from sucker-beef production in Ireland. *Agricultural Systems* **90**, 79–98. doi:10.1016/j.agsy.2005.11.008

Casey JW, Holden NM (2006*b*) Greenhouse gas emissions from conventional, agri-environmental scheme, and organic Irish suckler-beef units. *Journal of Environmental Quality* **35**, 231–239. doi:10.2134/jeq2005.0121

Chadwick DR (1997) Nitrous oxide and ammonia emission from grassland following applications of slurry: potential abatement practices. In 'Gaseous nitrogen emission from grassland'. (Eds SC Jarvis, BF Pain) pp. 257–264. (CAB International: Wallingford, UK)

Chadwick D, Pain B, Brookman S (2000) Nitrous oxide and methane emissions following application of animal manures to grassland. *Journal of Environmental Quality* **29**, 277–287. doi:10.2134/jeq2000.00472425002900010035x

Chianese DS, Rotz CA, Richard TL (2009*a*) Simulation of nitrous oxide emissions from dairy farms to assess greenhouse gas reduction strategies. *Transactions of the ASABE* **52**, 1325–1335. doi:10.13031/2013.27782

Chianese DS, Rotz CA, Richard TL (2009*b*) Simulation of carbon dioxide emissions from dairy farms to assess greenhouse gas reduction strategies. *Transactions of the ASABE* **52**, 1301–1312. doi:10.13031/2013.27780

Coppi L (2012) Nitrogen and phosphorus in soil and groundwater following repeated nitrogen-based swine slurry applications to a tame grassland on coarse textured soil. PhD Thesis, University of Manitoba, Canada. Available at http://mspace.lib.umanitoba.ca/handle/1993/14417. [Verified 13 September 2014]

Crosson P, Shalloo L, O'Brien D, Lanigan GL, Foley PA, Boland TM, Kenny DA (2011) A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. *Animal Feed Science and Technology* **166–167**, 29–45. doi:10.1016/j.anifeedsci.2011.04.001

Del Grosso SJ, Parton WJ, Mosier AR, Walsh MK, Ojima DS, Thornton PE (2006) DAYCENT national-scale simulations of nitrous oxide emissions from cropped soils in the United States. *Journal of Environmental Quality* **35**, 1451–1460. doi:10.2134/jeq2005.0160

Del Grosso SJ, Ojima DS, Parton WJ, Stehfest E, Heistemann M, DeAgelo B, Rose S (2009) Global scale DAYCENT model analysis of greenhouse gas emissions and mitigation strategies for cropped soils. *Global and Planetary Change* **67**, 44–50. doi:10.1016/j.gloplacha.2008.12.006

Dijkstra J, Neal HD, Beever DE, France J (1992) Simulation of nutrient digestion, absorption and outflow in the rumen: model description. *Journal of Nutrition* **122**, 2239–2256. doi:02–316/92

Dyer JA, Desjardins RL (2006) An integrated index of electrical energy use in Canadian agriculture with implications for greenhouse gas emissions. *Biosystems Engineering* **95**, 449–460. doi:10.1016/j.biosystemseng.2006.07.013

Eckard RJ, Grainger C, de Klein CAM (2010) Options for the abetment of methane and nitrous oxide from ruminant production: a review. *Livestock Science* **130**, 47–56. doi:10.1016/j.livsci.2010.02.010

Ellis S, Yamulki S, Dixon E, Harrison R, Jarvis SC (1998) Denitrification and N_2O emission from a UK pasture soil following the early spring application of cattle slurry and mineral fertilizer. *Plant and Soil* **202**, 15–25. doi:10.1023/A:1004332209345

Environment Canada (2012) Precipitation product samples. Available at http://www.ec.gc.ca/natchem/default.asp?lang=En&n=B385159B-1. [Verified 11 April 2012]

Environment Canada (2014) National inventory report 1990–2012 (Parts 1, 2 and 3): greenhouse gas sources and sinks in Canada. The Canadian Government's Submission to the UN Framework Convention on Climate Change. Greenhouse Gas Division. Environment Canada, Gatineau, QC. Available at http://www.ec.gc.ca/ges-ghg/ [Verified 5 September 2014]

Flessa H, Ruser R, Dörsch P, Kamp T, Jimenez MA, Munch JC, Beese F (2002) Integrated evaluation of greenhouse gas emissions (CO_2, CH_4, N_2O) from two farming systems in southern Germany. *Agriculture, Ecosystems & Environment* **91**, 175–189. doi:10.1016/S0167-8809(01)00234-1

Foley PA, Crosson P, Lovett DK, Boland TM, O'Mara FP, Kenny DA (2011) Whole-farm systems modelling of greenhouse gas emissions from pastoral suckler beef cow production systems. *Agriculture, Ecosystems & Environment* **142**, 222–230. doi:10.1016/j.agee.2011.05.010

Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A, Tempio G (2013) 'Tackling climate change through livestock. A global assessment of emissions and mitigation opportunities.’ (Food and Agriculture Organization of the United Nations (FAO): Rome). Available at http://www.fao.org/docrep/018/i3437e/i3437e.pdf. [Verified 25 June 2014]

Hermansen JE, Kristensen T (2011) Management options to reduce the carbon footprint of livestock products. *Animal Frontiers* **1**, 33–39. doi:10.2527/af.2011-0008

Hünerberg M, Little SM, Beauchemin KA, McGinn SM, O’Connor D, Okine EK, Harstad OM, Kröbel R, McAllister TA (2014) Feeding high concentrations of corn dried distillers’ grains decreases methane, but increases nitrous oxide emissions from beef cattle production. *Agricultural Systems* **127**, 19–27. doi:10.1016/j.agsy.2014.01.005

Intergovernmental Pannel on Climate Change (IPCC) (2006) Guidelines for national greenhouse gas inventories. In ‘Intergovernmental Panel on Climate Change’. (Eds S Eggleston, L Buendia, K Miwa, TK Ngara, H Tanabe) (Prepared by the National Greenhouse Gas Inventories Programme, IGES: Japan)

ISO (2006*a*) ‘Environmental management: life cycle assessment: principles and framework. (ISO 14040:2006).’ (European Committee for Standardization: Brussels)

ISO (2006*b*) ‘Environmental management: life cycle assessment: requirements and guidelines. (ISO 14044:2006).’ (European Committee for Standardization: Brussels)

Janzen HH, Angers DA, Boehm M, Bolinder M, Desjardins RL, Dyer JA, Ellert BH, Gibb DJ, Gregorich EG, Helgason BL, Lemke R, Massé D, McGinn SM, McAllister TA, Newlands N, Pattey E, Rochette P, Smith W, VandenBygaart AJ, Wang H (2006) A proposed approach to estimate and reduce net greenhouse gas emissions from whole farms. *Canadian Journal of Soil Science* **86**, 401–418. doi:10.4141/S05-101

Johnson DE, Phetteplace HW, Seidl AF (2002) Methane, nitrous oxide and carbon dioxide emissions from ruminant livestock production systems. In ‘Greenhouse gases and animal agriculture’. (Eds J Takahashi, BA Young) pp. 77–86. (Elsevier: Amsterdam, The Netherlands)

Johnson DE, Phetteplace HW, Seidl AF, Schneider UA, McCarl BA (2003) Management variations for US beef production systems: effects on greenhouse gas emissions and profitability. In ‘The 3rd international methane and nitrous oxide mitigation conference’. pp. 953–961. (Coal Institute: Beijing, China) Available at http://www.coalinfo.net.cn/coalbed/meeting/2203/papers/agriculture/index.html [Verified 10 October 2014]

Jungnitsch PF, Schoenau JJ, Lardner HA, Jefferson PG (2011) Winter feeding beef cattle on the western Canadian prairies: Impacts on soil nitrogen and phosphorus cycling and forage growth. *Agriculture, Ecosystems & Environment* **141**, 143–152. doi:10.1016/j.agee.2011.02.024

Kebreab E, Mills JAN, Crompton LA, Bannink A, Dijkstra J, Gerrits WJJ, France J (2004) An integrated mathematical model to evaluate nutrient partition in dairy cattle between animal and environment. *Animal Feed Science and Technology* **112**, 131–154. doi:10.1016/j.anifeedsci.2003.10.009

Kelln B, Lardner HA, McKinnon JJ, Campbell JR, Larson K, Damiran D (2011) Effect of winter feeding system on beef cow performance, reproductive efficiency, and system cost. *The Professional Animal Scientist* **27**, 410–421.

Kelln B, Lardner H, Schoenau J, King T (2012) Effects of beef cow winter feeding systems, pen manure and compost on soil nitrogen and phosphorous amounts and distribution, soil density, and crop biomass. *Nutrient Cycling in Agroecosystems* **92**, 183–194. doi:10.1007/s10705-011-9480-y

Kennedy PM, Milligan LP (1978) Effects of cold exposure on digestion, microbial synthesis and nitrogen transformation in sheep. *British Journal of Nutrition* **39**, 105–117. doi:10.1079/BJN19780017

Knudsen MT, Yu-Hui Q, Yan L, Halberg N (2010) Environmental assessment of organic soybean (*Glycine max*) imported from China to Denmark: a case study. *Journal of Cleaner Production* **18**, 1431–1439. doi:10.1016/j.jclepro.2010.05.022

Li CS, Frolking S, Frolking TA (1992) A model of nitrous oxide evolution from soil driven by rainfall events: 1. model structure and sensitivity. *Journal of Geophysical Research* **97**, 9759–9776. doi:10.1029/92JD00509

Li CS, Farahbakshazad N, Jaynes DB, Dinnes DL, Salas W, McLaughlin D (2006) Modeling nitrate leaching with a biogeochemical model modified based on observations in a row-crop field in Iowa. *Ecological Modelling* **196**, 116–130. doi:10.1016/j.ecolmodel.2006.02.007

Li CS, Salas W, Zhang R, Krauter C, Rotz A, Mitloehner F (2012) Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. *Nutrient Cycling in Agroecosystems* **93**, 163–200. doi:10.1007/s10705-012-9507-z

Little S, Linderman J, Maclean K, Janzen H (2008) ‘Holos: a tool to estimate and reduce greenhouse gases from farms. Methodology and algorithms for versions 1.1.x.’ Cat. No. A52-136/2008E-PDF (Agriculture and Agri-Food Canada: Lethbridge, AB, Canada)

Ludington D, Johnson EL (2003) ‘Dairy farm energy audit summary.’ (FlexTech Services, New York State Energy Research and Development Authority, Albany, NY). Available at http://www.nyserda.ny.gov/Publications/Research-and-Development/~/media/Files/Publications/Energy/Audit/Reports/dairy-farm-energy.ashx [Verified 2 December 2011]

Lupo CD, Clay DE, Benning JL, Stone JJ (2013) Life-cycle assessment of the beef cattle production system for the Northern Great Plains, USA. *Journal of Environmental Quality* **42**, 1386–1394. doi:10.2134/jeq2013.03.0101

MacNeil MD, Newman S, Enns RM, Stewart-Smith J (1994) Relative economic values for Canadian beef production using specialized sire and dam lines. *Canadian Journal of Animal Science* **74**, 4ll–417. doi:10.4141/cjas94-059

Manitoba Agricultural Review (2001) Agriculture statistics. (Program and Policy Analysis Branch, Manitoba Agriculture and Food: Winnipeg, Canada) Available at http://digitalcollection.gov.mb.ca/awweb/pdfopener?smd=1&did=10622&md=1 [Verified 10 September 2012]

Manitoba Agriculture, Food and Rural Development (2013) ‘Guidelines for estimating beef backgrounding costs‘. Available at http://www.gov.mb.ca/agriculture/business-and-economics/financial-management/pubs/cop_beef_backgrounding.pdf [Verified 12 February 2014]

Manitoba Management Plus Program (MMPP) (2012) MMPP variety yield. Available at http://www.mmpp.com/mmpp.nsf/mmpp_index. html [Verified 11 November 2012]

McCartney D (2011) ‘Country pasture/forage resource profiles.’ (Agriculture and Agric.-Food Canada, Lacombe, Alberta). Available at http://www.fao.org/ag/AGP/AGPC/doc/Counprof/Canada/Canada.html [Verified 13 May 2012]

McCaughey WP, Wittenberg K, Corrigan D (1999) Impact of pasture type on methane production by lactating beef cows. *Canadian Journal of Animal Science* **79**, 221–226. doi:10.4141/A98-107

Mc Geough EJ, Little SM, Janzen HH, McAllister TA, McGinn SM, Beauchemin KA (2012) Life-cycle assessment of greenhouse gas emissions from dairy production in eastern Canada: a case study. *Journal of Dairy Science* **95**, 5164–5175. doi:10.3168/jds.2011-5229

Mills JAN, Dijkstra J, Bannink A, Cammell SB, Kebreab E, France J (2001) A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: model development, evaluation, and application. *Journal of Animal Science* **79**, 1584–1597.

Mills JAN, Kebreab E, Yates CM, Crompton LA, Cammell SB, Dhanoa MS, Agnew RE, France F (2003) Alternative approaches to predicting methane emissions from dairy cows. *Journal of Animal Science* **81**, 3141–3150.

Myhre G, Shindell D, Breon F-M, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque J-F, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, Zhang H (2013). Anthropogenic and Natural Radiative Forcing. In ‘Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the

Intergovernmental Panel on Climate Change'. (Eds TF, Stocker D, Qin GK, Plattner M, Tignor SK, Allen J, Boschung A, Nauels Y, Xia V, Bex PM, Midgley) pp. 661–731. (Cambridge University Press: Cambridge, UK)

Nagy CN (2001) Energy and greenhouse gas emission coefficients for inputs used in agriculture. In 'Report to prairie adaptation research collaborative (PARC)'. Centre for Studies in Agriculture, Law and the Environment, Saskatoon, Canada. Available at http://www.parc.ca/ [Verified 12 September 2014]

Narasimhalu P, Kong D, Choo TM (1998) Straw yields and nutrients of seventy-five Canadian barley cultivars. *Canadian Journal of Animal Science* **78**, 127–134. doi:10.4141/A97-020

O'Mara FP (2011) The significance of livestock as a contributor to global greenhouse emissions today and in the near future. *Animal Feed Science and Technology* **166–167**, 7–15. doi:10.1016/j.anifeedsci.2011.04.074

Pelletier N, Pirog R, Rasmussen R (2010) Comparative life cycle environmental impacts of three beef production strategies in the upper midwestern United States. *Agricultural Systems* **103**, 380–389. doi:10.1016/j.agsy.2010.03.009

Petersen SO, Sommer SG, Béline F, Burton C, Dach J, Dourmad JY, Leip A, Misselbrook T, Nicholson F, Poulsen HD, Provolo G, Sørensen P, Vinnerås B, Weiske A, Bernal MP, Böhm R, Juhász C, Mihelic R (2007) Recycling of livestock manure in a whole-farm perspective. *Livestock Science* **112**, 180–191. doi:10.1016/j.livsci.2007.09.001

Phetteplace HW, Johnson DE, Seidl AF (2001) Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States. *Nutrient Cycling in Agroecosystems* **60**, 99–102. doi:10.1023/A:1012657230589

Reijs J (2007) Improving slurry by diet adjustments. A novelty to reduce nitrogen losses from grassland based dairy farms. PhD Thesis, Wageningen University, Wageningen, The Netherlands.

Rochette P, van Bochove E, Prevost D, Angers DA, Cote D, Bertrand N (2000) Soil carbon and nitrogen dynamics following application of pig slurry for the 19th consecutive year: II. Nitrous oxide fluxes and mineral nitrogen. *Soil Science Society of America Journal* **64**, 1396–1403. doi:10.2136/sssaj2000.6441396x

Rochette P, Angers DA, Chantigny MH, Bertrand N, Cote D (2004) Carbon dioxide and nitrous oxide emission following fall and spring applications of pig slurry to an agricultural soil. *Soil Science Society of America Journal* **68**, 1410–1420. doi:10.2136/sssaj2004.1410

Rochette P, Guilmette D, Chantigny MH, Angers DA, MacDonald JD, Bertrand N, Parent L-É, Côte' D, Gasser MO (2008) Ammonia volatilization following application of pig slurry increases with slurry interception by grass foliage. *Canadian Journal of Soil Science* **88**, 585–593. doi:10.4141/CJSS07083

Rodhe L, Pell M, Yamulki S (2006) Nitrous oxide, methane and ammonia emissions following slurry spreading on grassland. *Soil Use and Management* **22**, 229–237. doi:10.1111/j.1475-2743.2006.00043.x

Rotz CA (2003) How to maintain forage quality during harvest and storage. In 'Western Canadian Dairy Seminar 2003'. pp. 227–236. (Advanced Dairy Technology: Canada) Available at http://www.wcds.ca/proc/2003/ [Verified 12 August 2012]

Rotz CA, Buckmaster DR, Comerford JW (2005) A beef herd model for simulating feed intake, animal performance and manure excretion in farm systems. *Journal of Animal Science* **83**, 231–242.

Rotz CA, Montes F, Chianese DS (2010) The carbon footprint of dairy production systems through partial life cycle assessment. *Journal of Dairy Science* **93**, 1266–1282. doi:10.3168/jds.2009-2162

Rotz CA, Corson MS, Chianese DS, Montes F, Hafner SD, Jarvis R, Coiner CU (2011a) 'The integrated farm system model. Reference manual, Version 3.4.' (Pasture Systems and Watershed Management Research Unit, Agricultural Research Service, USDA: PA, USA)

Rotz CA, Kleinman PJA, Dell CJ, Veith TL, Beegle DB (2011*b*) Environmental and economic comparisons of manure application methods in farming systems. *Journal of Environmental Quality* **40**, 438–448. doi:10.2134/jeq2010.0063

Schils RLM, Verhagen A, Aarts HFM, Šebek LBJ (2005) A farm level approach to define successful mitigation strategies for GHG emissions from ruminant livestock systems. *Nutrient Cycling in Agroecosystems* **71**, 163–175. doi:10.1007/s10705-004-2212-9

Schils RLM, Olesen JE, del Prado A, Soussana JF (2007) A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. *Livestock Science* **112**, 240–251. doi:10.1016/j.livsci.2007.09.005

Shaffer MJ, Halvorson AD, Pierce FJ (1991) Nitrate leaching and economic analysis package (NLEAP): model description and application. In 'Managing nitrogen for groundwater quality and farm profitability'. (Eds RF Follett, DR Deeney, RM Cruse) pp. 285–298. (Soil Science Society of America Journal: Madison, WI)

Sherlock RR, Sommer SG, Khan RZ, Wood CW, Guertal EA, Freney JR, Dawson CO, Cameron KC (2002) Ammonia, methane and nitrous oxide emission from pig slurry applied to a pasture in New Zealand. *Journal of Environmental Quality* **31**, 1491–1501. doi:10.2134/jeq2002.1491

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O (2007) Agriculture. In 'Climate change 2007: mitigation. Contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel on Climate Change'. (Eds B Metz, OR Davidson, PR Bosch, R Dave, LA Meyer) pp. 499–540. (Cambridge University Press: Cambridge, UK)

Smith WN, Grant BB, Desjardins RL, Rochette P, Drury CF, Li C (2008) Evaluation of two process-based models to estimate soil N_2O emissions in eastern Canada. *Canadian Journal of Soil Science* **88**, 251–260. doi:10.4141/CJSS06030

Sommer SG, Petersen SO, Møller HB (2004) Algorithms for calculating methane and nitrous oxide emissions from manure management. *Nutrient Cycling in Agroecosystems* **69**, 143–154. doi:10.1023/B:FRES.0000029678.25083.fa

Takahashi T, Suzuki Y, Horiguchi K (2002) Effect of heat exposure on methane emission from expiratory gas in sheep fed with high concentrate diets. In 'Proceeding of the 1st international conference on greenhouse gases and animal agriculture'. (Eds J Takahashi, BA Young, CR Soliva, M Kreuzer) pp. 7–11. (Elsevier: Obihiro, Japan)

Tenuta M, Mkhabela M, Tremorin D, Coppi L, Phipps G, Flaten D, Ominski K (2010) Nitrous oxide and methane emission from a coarse-texture grassland soil receiving hog slurry. *Agriculture, Ecosystems & Environment* **138**, 35–43. doi:10.1016/j.agee.2010.03.014

Tremorin DA (2009) Greenhouse gas emissions from grassland pasture fertilized with liquid hog manure. MSc Thesis, University of Manitoba, Canada.

Tri-Provincial Manure Application and Use Guidelines (2006) Manitoba version. Prepared by Prairie Provinces Committee on Livestock Development and Manure Management Committee. Available at http://www.gov.mb.ca/agriculture/livestock/beef/pdf/baa08s01a.pdf [Verified 20 March 2014]

Velthof G, Kuikman P, Oenema O (2003) Nitrous oxide emission from animal manures applied to soil under controlled conditions. *Biology and Fertility of Soils* **37**, 221–230. doi:10.1007/s00374-003-0589-2

Vergé XPC, Dyer JA, Desjardins RL, Worth D (2007) Greenhouse gas emissions from the Canadian dairy industry in 2001. *Agricultural Systems* **94**, 683–693. doi:10.1016/j.agsy.2007.02.008

Vergé XPC, Dyer JA, Desjardins RL, Worth D (2008) Greenhouse gas emissions from the Canadian beef industry. *Agricultural Systems* **98**, 126–134. doi:10.1016/j.agsy.2008.05.003

Waldner CL, Kennedy RI, Rosengren L, Clark EG (2009) A field study of culling and mortality in beef cows from western Canada. *The Canadian Veterinary Journal. La Revue Veterinaire Canadienne* **50**, 491–499.

Wang M (2007) 'GREET version 1.8a.' (Argonne National Laboratory) Available at http://www. transportation.anl.gov/publications/transforum/v8/v8n2/greet_18b.html. [Verified 10 June 2012]

White TA, Snow VO, King WMcG (2010) Intensification of New Zealand beef farming systems. *Agricultural Systems* **103**, 21–35. doi:10.1016/j.agsy.2009.08.003

Whitman T, Yanni SF, Whalen JK (2011) Life cycle assessment of corn stover production for cellulosic ethanol in Quebec. *Canadian Journal of Soil Science* **91**, 997–1012. doi:10.4141/cjss2011-011

Wiens MJ, Entz MH, Wilson C, Ominski KH (2008) Energy requirements for transport and surface application of liquid pig manure in Manitoba, Canada. *Agricultural Systems* **98**, 74–81. doi:10.1016/j.agsy.2008.03.008

Wilson C, Undi M, Tenuta M, Wittenberg KM, Flaten D, Krause DO, Entz MH, Holley R, Ominski KH (2010) Pasture productivity, cattle productivity and metabolic status following fertilization of a grassland with liquid hog manure: a three-year study. *Canadian Journal of Animal Science* **90**, 233–243. doi:10.4141/CJAS09037

Wilson C, Undi M, Tenuta M, Tremorin D, Coppi L, Flaten D, Wittenberg KM, Ominski KH (2011) Utilization of liquid hog manure to fertilize grasslands in southeast Manitoba: impact of application timing and forage harvest strategy on nutrient utilization and accumulation. *Nutrient Cycling in Agroecosystems* **91**, 155–171. doi:10.1007/s10705-011-9453-1

Yamulki S, Jarvis SC, Owen P (1999) Methane emission and uptake from soils as influenced by excreta deposition from grazing animals. *Journal of Environmental Quality* **28**, 676–682. doi:10.2134/jeq1999.00472425002800020036x