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Greenhouse gas emissions of Canadian beef production in 1981 as compared with 2011

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Abstract. The present study compared the greenhouse gas (GHG) emissions, and breeding herd and land requirements of Canadian beef production in 1981 and 2011. In the analysis, temporal and regional differences in feed types, feeding systems, cattle categories, average daily gains and carcass weights were considered. Emissions were estimated using life-cycle assessment (cradle to farm gate), based primarily on Holos, a Canadian whole-farm emissions model. In 2011, beef production in Canada required only 71% of the breeding herd (i.e. cows, bulls, calves and replacement heifers) and 76% of the land needed to produce the same amount of liveweight for slaughter as in 1981. Compared with 1981, in 2011 the same amount of slaughter weight was produced, with a 14% decline in CH_4 emissions, 15% decline in N_2O emissions and a 12% decline in CO_2 emissions from fossil fuel use. Enteric CH_4 production accounted for 73% of total GHG emissions in both years. The estimated intensity of GHG emissions per kilogram of liveweight that left the farm was 14.0 kg CO_2 equivalents for 1981 and 12.0 kg CO_2 equivalents for 2011, a decline of 14%. A significant reduction in GHG intensity over the past three decades occurred as a result of increased average daily gain and slaughter weight, improved reproductive efficiency, reduced time to slaughter, increased crop yields and a shift towards high-grain diets that enabled cattle to be marketed at an earlier age. Future studies are necessary to examine the impact of beef production on other sustainability metrics, including water use, air quality, biodiversity and provision of ecosystems services.

Additional keywords: beef cattle, environmental footprint, greenhouse gases.

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Introduction

Canada produces ~2% of the world's beef and is the 5th-largest global exporter of beef in the world, producing 1.41 million tonnes in 2014 (Canfax Research Services 2015; Statistics Canada 2015*a*). Beef production also contributes an estimated CA$33 billion annually in the sales of goods and services either directly or indirectly to the Canadian economy (Kulshreshtha *et al*. 2012). Traditionally, economic returns have been the primary driver of decision processes in the beef industry, but, recently, the environmental footprint of beef production is under increasing scrutiny from industry groups, consumers, retailers and non-governmental organisations (Grebitus *et al*. 2013). Beef producers are looking for science-based information to provide a more accurate assessment of the environmental impact of the industry and strategies to increase consumer confidence through the implementation of improved and environmentally friendly production practices. The footprint of the beef industry is far reaching with implications for greenhouse gas (GHG) emissions, nutrient cycling, water and air quality, carbon storage, and the management of grassland and wetland ecosystems. The three major GHGs associated with Canadian beef production are methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2).

The amount of beef produced per animal in Canada, like in other industrialised countries, has increased significantly as a consequence of improvements in production efficiency over the past 30 years. Despite a 2% reduction in slaughter numbers, total beef production (kg) in 2011 increased by 32% as compared with 1981 (Statistics Canada 2015*a*). Whether environmental sustainability has increased simultaneously with production has been questioned (Koneswaran and Nierenberg 2008; Weis 2013; Lee *et al*. 2014), but studies in the United States (Capper 2011) and Australia (Wiedemann *et al*. 2015) have reported a reduction in GHG emissions associated with beef production over the past three decades.

The objective of the present study was to compare the GHG emissions and resource use asscociated with Canadian beef production in 2011 with that in 1981.

Materials and methods

System boundaries

For the current comparative analysis, 1981 and 2011 were selected as the two reference years, as 30 years was deemed an adequate time period to capture potential differences. Both years were Canadian census years, with 2011 being the most recent year in which detailed census data were collected.

The model system and the boundaries used for the comparative analysis of GHG emissions associated with beef production in Canada in 1981 and 2011 are presented in Fig. 1. In this model, we included relevant inputs for (e.g. fertilisers and pesticides associated with feed production; surplus dairy calves) and outputs from (e.g. beef and GHG) the beef production system.

Description of cattle categories and feeding scenarios

The Canadian beef industry may be broadly divided into the following three segments: cow–calf operations where producers breed cows to produce calves; backgrounding operations where producers put additional weight on weaned calves through pasture or other high-forage diets; and feedlot operations where the cattle are fed grain-based diets before slaughter. Across the country, production systems are diverse in terms of numbers of cattle per operation, feeds and feeding management practices employed (Sheppard *et al*. 2015).

Beef cattle production in Canada can be depicted as shown in Fig. 2*a*. Beef heifers are typically bred as yearlings and calve at 2 years of age (Mathison 1993), a point at which they have achieved 85% of their mature bodyweight. Calving typically occurs in the winter–spring (January through May), with 1 April taken as the average time of calving (Mathison 1993; Sheppard *et al*. 2015). Canadian beef cows have a calving interval of ~1 year (McCartney *et al*. 2004), with an average milk yield of 7 kg/head.day (Butson and Berg 1984; Rahnefeld *et al*. 1990). Calves are typically weaned in the fall (October or November), with 31 October selected as the average weaning date in the present study. On average, this resulted in calves being 7 months old at weaning. Cows and pre-weaned calves grazed natural or tame/seeded pastures during the summer–early fall in both 1981 and 2011. Tame/seeded pastures are defined as grazeable land that has been improved from its natural state by seeding, draining, irrigating, fertilising or weed control. Extended grazing strategies (e.g. swath, stockpiled and bale grazing) were more prevalent in the beef herd in 2011 (Sheppard *et al*. 2015) than in 1981.

Cattle destined to slaughter

Three main categories of Canadian cattle destined to slaughter were defined as (1) calf-fed: weaned steers or heifers that were placed directly in a feedlot and fed a finishing diet; (2) yearling-fed (backgrounded in confinement only): weaned steers or heifers that were backgrounded in confinement and feedlot finished; and (3) yearling-grass fed (backgrounded in confinement and on pasture): weaned steers or heifers that were backgrounded first in confinement then on pasture and feedlot finished. The number of days required for steers and heifers to reach slaughter weight was comparable in 1981 and 2011. The only difference was slightly longer periods on pasture in 1981, as yearlings were backgrounded in confinement (November–April, 6 months) and typically pastured the following spring–summer (May–September, 5 months; instead of 4 months, as shown in

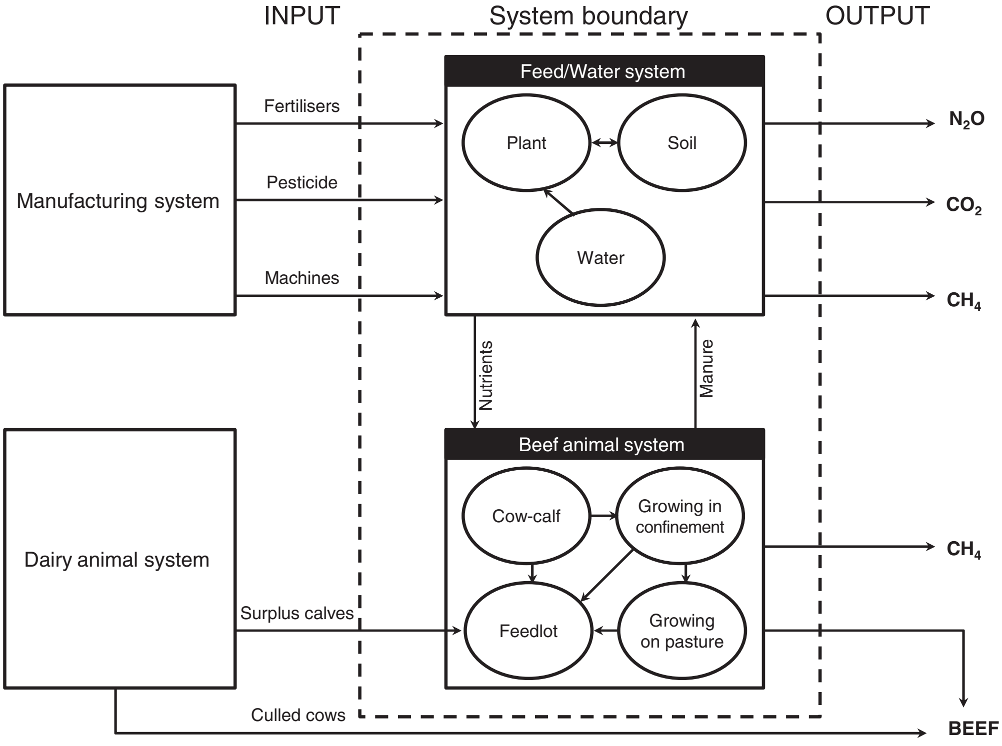

Fig. 1. System boundaries and components considered in the life-cycle analysis of Canadian beef production in 1981 versus 2011.

Fig. 2*b* for 2011), and sold as feeder cattle in the fall at ≈18 months of age (Mathison 1993).

On the basis of available literature (Agriculture Canada 1981*a*) and expert opinion (Canadian Roundtable for Sustainable Beef, pers. comm.) in 1981, 20% of weaned calves were assumed to be directly placed in feedlots on finishing diets. Half of the weaned calves that were not directly placed on finishing diets were assumed to be finished immediately after backgrounding in confinement (40% of weaned calves), while the other half (40% of weaned calves) were assumed to be further backgrounded on pasture before finishing in a feedlot. In 2011, it was assumed that one-third of weaned calves were finished directly after weaning, one-third were fed backgrounding diets in confinement before being provided a finishing diet, and one-third of calves were backgrounded first in confinement then on pasture before finishing in a feedlot (Canfax Research Services 2014). Starting weight, ending weight, days on feed and average daily gain of steers and heifers destined to slaughter are presented in Table 1.

Average weaning weights for 1981 and 2011 were based on values reported by Schaeffer *et al.* (1981) and Sheppard *et al.* (2015), respectively. Reports indicated that weaned calves from early maturing breeds are best suited for backgrounding, while heavier calves of continental genetics (later maturing) are more suited to a high-energy diet after weaning (Mathison 1993). The average weaning weight of continental calves was ~10% greater than the average of all other breeds (Schaeffer *et al.* 1981). For the present study, the weaning weights of calf-fed and yearling-grass fed (backgrounded in confinement and on pasture) for both years were assumed to be 10% heavier and 10% lighter, respectively, than average. Yearling steers or heifers that were weaned, backgrounded in confinement and finished were considered to be of moderate bodyweight at weaning (Table 1).

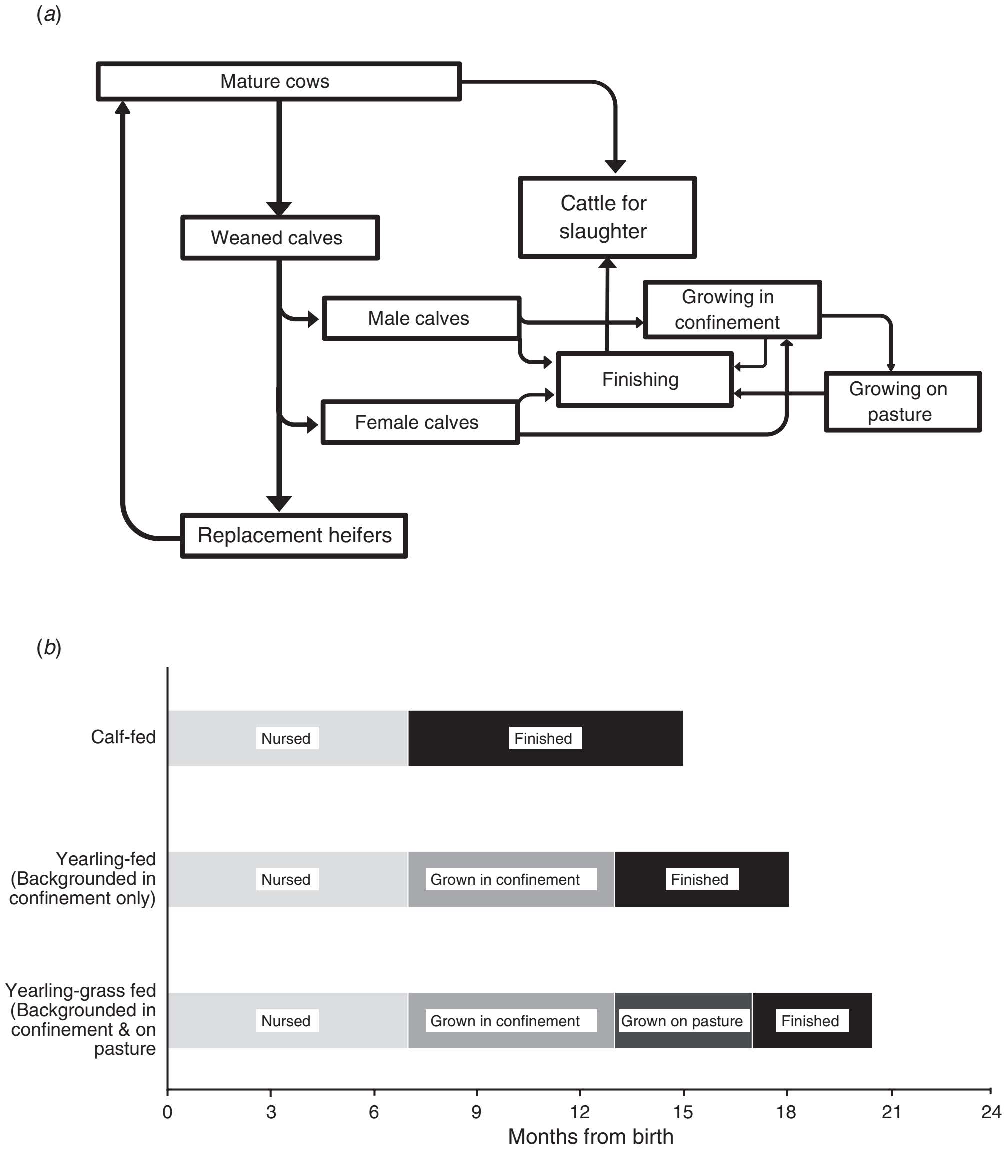

Fig. 2. (*a*) Generalised flow diagram of beef cattle production in Canada, (*b*) with a timeline for beef cattle destined to slaughter from birth to finish in 2011.

Table 1. Production parameters and feeding system of post-weaning steers and heifers destined to slaughter in 1981 and 2011

The ratios of calf-fed : yearling-fed (backgrounded in confinement only) : yearling-grass fed (backgrounded in confinement and on pasture) animals in 1981 and 2011 were assumed to be 20% : 40% : 40% and 33.3% : 33.3% : 33.3 of weaned calves not retained as replacements, respectively

Cattle type	Parameter	Feeding system		
		Growing in confinement	Growing on pasture	Finishing
1981 – steers				
Calf-fed	Starting weight (kg)	–	–	249
	Ending weight (kg)	–	–	499
	Duration (day)	–	–	240
	Daily gain (kg/day)	–	–	1.04
Yearling-fed (backgrounded in confinement only)	Starting weight (kg)	226	–	370
	Ending weight (kg)	370	–	533
	Duration (day)	180	–	150
	Daily gain (kg/day)	0.80	–	1.09
Yearling-grass fed (backgrounded in confinement and on pasture)	Starting weight	203	327	431
	Ending weight	327	431	541
	Duration (day)	180	150	100
	Daily gain (kg/day)	0.69	0.70	1.10
1981 – heifers				
Calf-fed	Starting weight (kg)	–	–	234
	Ending weight (kg)	–	–	393
	Duration (day)	–	–	240
	Daily gain (kg/day)	–	–	0.67
Yearling-fed (backgrounded in confinement only)	Starting weight (kg)	212	–	322
	Ending weight (kg)	322	–	426
	Duration (day)	180	–	150
	Daily gain (kg/day)	0.61	–	0.69
Yearling-grass fed (backgrounded in confinement and on pasture)	Starting weight (kg)	191	283	361
	Ending weight (kg)	283	361	433
	Duration (day)	180	150	110
	Daily gain (kg/day)	0.51	0.51	0.66
2011 – steers				
Calf-fed	Starting weight (kg)	–	–	299
	Ending weight (kg)	–	–	623
	Duration (day)	–	–	240
	Daily gain (kg/day)	–	–	1.35
Yearling-fed (backgrounded in confinement only)	Starting weight (kg)	271	–	454
	Ending weight (kg)	454	–	666
	Duration (day)	180	–	145
	Daily gain (kg/day)	1.01	–	1.47
Yearling-grass fed (backgrounded in confinement and on pasture)	Starting weight (kg)	243	390	508
	Ending weight (kg)	390	508	676
	Duration (day)	180	120	100
	Daily gain (kg/day)	0.82	0.98	1.68
2011 – heifers				
Calf-fed	Starting weight (kg)	–	–	281
	Ending weight (kg)	–	–	562
	Duration (day)	–	–	240
	Daily gain (kg/day)	–	–	1.17
Yearling-fed (backgrounded in confinement only)	Starting weight (kg)	255	–	408
	Ending weight (kg)	408	–	609
	Duration (day)	180	–	160
	Daily gain (kg/day)	0.85	–	1.25
Yearling-grass fed (backgrounded in confinement and on pasture)	Starting weight (kg)	229	361	462
	Ending weight (kg)	361	462	619
	Duration (day)	180	120	110
	Daily gain (kg/day)	0.73	0.84	1.43

Heifer calves were assumed to be 6% lower in weaning weight than steers (McKay *et al*. 1990; Newman *et al*. 1994; Basarab *et al*. 2012). Slaughter weights for 2011 were calculated on the basis of monthly carcass data obtained from Canfax and converted to slaughter bodyweights (Canadian Beef Grading Agency 2014). Slaughter weight of steers and heifers in 1981 were 20% and 30% less than the slaughter weight of steers and heifers in 2011, respectively (Agriculture Canada 1981*b*; Canadian Beef Grading Agency 2014).

Feeding scenarios

With few exceptions, it was assumed that the same feeds were available in 1981 and 2011. However, cows were predominantly offered mostly conserved forage during the winter of 1981, whereas extended grazing of cows through the winter was a more common practice in 2011. In both reference years, corn was the preferred grain and silage crop for beef cattle in eastern Canada, while barley was the commonly fed grain and silage crop for beef cattle in western Canada (Hironaka and Freeze 1992; Sheppard *et al*. 2015). The chemical composition of feedstuffs (Table S1, available as Supplementary material for this paper) was primarily based on Canadian sources (Abouguendia 1998; Stewart 1999; Lardner *et al*. 2011; Legesse *et al*. 2012; Lardner 2013; Saskatchewan Forage Council 2014), while nutrient requirements of various cattle categories within the beef production system were derived using NRC-based diet formulation software (NRC 1996; AARD 2011).

The major cattle categories considered for the analysis were cows (lactating and dry), beef calves, replacement heifers (weaning to 1 year, 1–2 years), breeding bulls, backgrounding steers and heifers, and feedlot cattle. Criteria used to develop feeding scenarios included sex, the physiological condition (age, pregnancy status) of the animal, feeding season and regional differences in feed types. In total, 46 and 49 feeding scenarios were used to describe the cattle feeding practices employed by the Canadian beef industry in 1981 and 2011, respectively (Tables S2–S5, available as Supplementary material for this paper).

Lactating cows were assumed to be fed to meet their nutrient requirements for maintenance (not for growth) with an average milk yield of 7 kg/day (Butson and Berg 1984; Rahnefeld *et al*. 1990). Grain supplementation (i.e. barley in the west; corn in the east) for breeding animals (i.e. cows, replacement heifers, bulls and calves) was considered only when forage sources did not satisfy nutrient requirements. The most common type of conserved forage used by cow–calf producers in western Canada was baled perennial hay. Kaliel (2004) reported that over 90% of cow–calf enterprises in Alberta used baled forages as the primary source of roughage during the winter.

Dry cows were assumed to be fed to meet their nutrient requirements for maintenance and gestation. The proportion of Canadian beef farms practising extended grazing was 39% in 2011 (Statistics Canada 2013), a level that was found to be even higher (58%) in a more recent survey (Sheppard *et al*. 2015). Of those that practiced extended grazing, 44% grazed forages unrolled behind a tractor or processed with a bale processor in the field, 42% grazed bales, 29% grazed stockpiled forages and 25% grazed annual swathed cereal crops (Sheppard *et al*. 2015). The two related winter grazing strategies (i.e. bale grazing and grazing processed/unrolled forages) were practiced by ~50% of beef farmers. Hence, feeding scenarios for dry cows were designed to reflect the winter grazing practice for a part of the winter (3 months) in 2011 (i.e. 50% grazed perennial forage bales, 30% grazed stockpiled perennial forages, and 20% grazed swathed annual cereal crops).

Replacement heifers from weaning to calving and breeding bulls were assumed to be fed to meet growth and maintenance requirements. Calves younger than 4 months were assumed to consume only milk and, therefore, as recommended by IPCC (2006) the emission factor for CH_4, Y_m, was set to zero. Diets to meet the requirements of growing calves aged 4–7 months were assumed to consist of 80% or more of non-milk feeds (on a DM basis).

Nutrient requirements of backgrounding cattle were determined with consideration of sex and bodyweight of the animal, feeding season and regional differences in diets. Backgrounding cattle in confinement were assumed to have been fed a forage : grain diet at 60 : 40, while for finishing feedlot diets this ratio was 10 : 90 on a DM basis (Beauchemin *et al*. 2010).

Cattle population and beef carcass production

For beef cows, calves and breeding bulls, population data were derived from the census of agriculture conducted every 5 years by statistics Canada (Statistics Canada 2014*b*; Table 2). In addition, a more detailed inventory of beef and dairy cattle conducted bi-annually via telephone surveys of agricultural producers by statistics Canada was consulted when the data for a particular category of cattle were not differentiated between beef and dairy cattle in the census (Statistics Canada 2014*a*). Population inventories were considered from 1 July rather than 1 January, as this date was closer to the census date. The number of dairy breeding bulls in 1981 was approximated on the basis of the ratio of dairy bulls to dairy cows between 2000 and 2011. The values were further verified using the registrations of dairy cattle from artificial insemination sires in Canada (CDIC 2014). For 1981, the number of calves less than 1 year of age on beef and dairy farms was estimated from the number of beef and dairy cows reported in the census, with the assumption that only half of the dairy calves (i.e. the heifer calves) entered the dairy production supply chain with a 50% : 50% sex ratio of male to female calves at birth (Armstrong *et al*. 1990).

Splitting the total number of calves in the census into beef and dairy farms for 2011 was done on the basis of the proportion of calves reported on beef and dairy operations in the 1 July Statistics Canada livestock inventory (Statistics Canada 2014*a*).

The number of cattle produced on Canadian farms was estimated by subtracting the number of live cattle imports from the total slaughter of domestic cattle and live exports. Total beef carcass production was estimated by multiplying thte number of cattle produced on Canadian farms by carcass weight. As our analysis was a life-cycle approach, estimates of marketed cattle needed to correspond to the breeding herd numbers. Since the number of slaughtered animals in a given year was also influenced by the breeding herd inventories and associated production decisions in the previous 1 or 2 years, the estimates were standardised to ensure that the probable effects of other factors that might have affected meat production and cattle demography

Table 2. Population of live and slaughtered cattle and beef carcass data in 1981 and 2011 used as model inputs

Category	1981	2011
Breeding herd population		
Beef cows[A]	3 517 286	3 849 368
Calves on beef operations[A]	3 113 788	3 661 604
Breeding beef bulls[A]	230 723	215 346
Beef heifers for replacement[B]	522 840	498 154
Slaughter parameters		
Number of slaughtered animals		
Steers	1 737 987	1 950 832
Heifers	766 099	1 119 623
Beef cows	386 901	423 430
Dairy cows[C]	323 825	226 944
Breeding beef bulls	46 145	43 069
Breeding dairy bulls	28 930	10 444
Bodyweight at slaughter[E] *(kg)*		
Steers	503	647
Heifers	410	593
Cows	518	619
Breeding bulls	643	821
Carcass weight[F] *(kg)*		
Steers	302	388
Heifers	246	356
Cows	254	303
Breeding bulls	354	452
Total carcass output (kg)		
Steers	525 033 634	757 460 515
Heifers	188 343 442	398 156 669
Beef cows	98 277 625	128 491 527
Dairy cows	82 255 374	68 866 852
Breeding bulls	26 561 720	24 176 057

[A] Derived from census/biannual inventory.

[B] Heifer retention rates (as percentage of female calves) of 40% and 30% were estimated using 74% (Rahnefeld *et al.* 1991) and 85% (Western Beef Development Centre 2015) of reproductive efficiency (i.e. number of calves weaned per 100 cows exposed) values in 1981 and 2011, respectively. Our model also took into account two groups of replacement heifers (i.e. weaning to 1 year and 1–2 years).

[C] The slaughter data for cows did not discriminate between beef and dairy cows; therefore, it was necessary to estimate the number of slaughtered beef cows. The number of slaughtered beef cows was estimated from the culling rate of beef cows in a given year, with the remaining number of cows assumed to be culled dairy cows.

[D] The slaughter data for bulls did not discriminate between beef and dairy bulls. The number of slaughtered beef bulls was estimated from the estimated beef bull culling rate, with the remaining number of bulls assumed to be culled dairy bulls.

[E] Estimated on the basis of the reported carcass weights and carcass-to-liveweight conversion factors for cattle (AAFC 2013).

[F] Source: Brenna Grant, Canfax Research Services; pers. comm. Referencing the Canadian Beef Grading Agency data.

(e.g. the position of the year in the cattle cycle) did not bias the data. Such standardisation is particularly important for comparative analyses that involve non-consecutive time points over decades.

The values were standardised on the basis of the size of breeding herd within the reference year rather than on the number of cattle slaughtered (Table 2). The production systems in the reference year (*t*) and its adjacent years (*t*–1, *t*+1) were assumed to be at a demographic steady-state (i.e. the national herd assumed to have been in equilibrium). This is defined as a system where the calving, weaning, replacement and culling rates and, thus, the size of the breeding herd remained constant. This assumption was made to estimate the number of cattle that either entered or exited the herd within the reference year (i.e. *t*). Weaning rate for the cow herd (i.e. number of calves weaned per 100 cows exposed) was assumed to be 74% in 1981 (Rahnefeld *et al.* 1991) and 85% in 2011 (Western Beef Development Centre 2015). All the calves in the census beyond the estimated weaning rates were assumed to be male calves from dairy farms. All male beef cattle (apart from the 3% that were left intact to serve as breeding bulls) were assumed to be fed and slaughtered as steers. All heifers that were not kept as replacements were assumed to be slaughtered. Preweaning death losses of cows and calves were included in the census estimates. Preweaning cow and calf mortalities that were not captured in the census or the weaning rate estimates were assumed to be insignificant and to not differ between 1981 and 2011. A historical average culling rate of 11% and a 98.4% post-weaning survival rate of steers and heifers (Canfax Research Services 2009) were used for both years. Mature cows and breeding bulls were assumed to be shipped directly from pasture to slaughter without a finishing period (Hawrysh and Price 1981; Hironaka and Freeze 1992).

The proportion of natural and tame/seeded pastures used by beef cattle in 2011 and 1981

To our knowledge, the proportion of natural and tame/seeded pastures grazed by beef cattle in Canada has not been previously estimated. GIS mapping data were also not available to define the land allocation to the various grazing groups for our comparative analysis across both reference years. The area of pasture available for grazing cattle for the two reference years was obtained from Statistics Canada, Census of Agriculture data (Statistics Canada 2014*c*). The amount of natural pasture and tame/seeded pastureland available for grazing was standardised on the basis of an average stocking rate (Table 3). Stocking rate was defined as the number of animals grazing a unit of land for a specified time period and expressed as animal-unit months (AUMs) per unit area. The animal unit (AU) is a standard unit that can be used in calculating the relative grazing impact of different classes of cattle. Estimated provincial average stocking rates range from 0.91 to 2.47 AUMs/ha for natural pastures and from 3.34 to 7.41 AUMs/ha for tame/seeded pastures (Yungblut 2012). For the current calculation, stocking rates of 1.5 and 5.25 AUMs/ha were assumed for natural and tame/seeded pastures, respectively.

The proportion of breeding stock (i.e. cows, pre-weaning calves, replacement heifers and bulls) grazing natural and tame/seeded pastures was assumed to reflect the grazing capacity of each of the pasture types. In 2011, 43% and 57% of the breeding stock were assumed to have grazed natural and tame/seeded pastures, respectively, on the basis of the relative availability of these pasture types. In 1981, 51% of the breeding stock grazed natural pastures and 49% grazed tame/seeded pastures (Table 3). Yearling-grass fed cattle were assumed to

Table 3. Estimated natural and tame/seeded pastureland available for grazing in 1981 and 2011
AUM, animal-unit month

Pasture type	Pasture available for grazing[A] (ha)	(%)	Stocking rate (AUMs/ha)	Adjusted grazing capacity (AUMs)[B]	(%)
		1981			
Natural pasture	16 216 823	79	1.50	24 325 522	51
Tame or seeded pasture	4 404 727	21	5.25	23 124 837	49
		2011			
Natural pasture	14 703 330	73	1.50	22 055 017	43
Tame or seeded pasture	5 532 652	27	5.25	29 046 453	57

[A] According to the Glossary of the 2011 Census of Agriculture, natural land for pasture is defined as areas used for pasture that have not been cultivated and seeded, or drained, irrigated or fertilised. This includes native pasture/hay (indigenous grass suitable as feed for livestock and game); rangeland (land with natural plant cover, principally native grasses or shrubs valuable for forage); grazeable bush (forest land and bushy areas used for grazing, not land cultivated for crops or with dense forest). Tame or seeded pasture is grazeable land that has been improved from its natural state by seeding, draining, irrigating, fertilising or weed control. This does not include areas of land harvested for hay, silage or seed (http://www.statcan.gc.ca/eng/ca2011/gloss; accessed 12 February 2015). Prior to the 1986 census, 'unimproved land for pasture, grazing or hay' was not separated from 'all other unimproved land'. For the current approximation, unimproved land for pasture in 1981was estimated by subtracting unimproved woodland from total unimproved land.

[B] Adjusted based on the estimated stocking rates of the pastures. Stocking rates were assumed to be the same in 2011 and 1981 for the respective pasture types.

mostly graze tame/seeded pastures (85%), while only 15% grazed natural pastures in both reference years.

The pastureland required for grazing beef cattle was not only a function of the stocking rate, but also of bodyweight and days on pasture. For our calculations, 1 AU was defined as a 454 kg of beef cow with or without a nursing calf (up to 3 months of age), with the pastureland required for calves of 4 months or older calculated separately. Animal-unit equivalents (AUE) were calculated for the various sizes of cattle. For example, a 580 kg cow was 1.28 AUE, whereas a 310 kg replacement heifer was 0.68 AUE. The amount of pastureland required for grazing cattle was estimated as follows:

$$\mathrm{Pastureland_i} = \mathrm{AUE_i} \times \mathrm{AUD_i} \times \mathrm{GrazingPeriod_i} \times \mathrm{CattleNumber_i},$$

where $\mathrm{Pastureland_i}$ was the amount of land required for a given group of grazing cattle (ha), $\mathrm{AUE_i}$ was the AUE for a given group of grazing cattle, $\mathrm{AUD_i}$ was the amount of pastureland (ha) required to meet the nutrient requirements of 1 AU for a day and was calculated by dividing the amount of pastureland required for an AU for 1 month by 30. Pastureland required for an AU for a month was estimated as the inverse of the stocking rate of the pasture in AUMs. Accordingly, the amount of natural and tame/seeded pastureland required to support 1 AU/month was 0.67 ha and 0.19 ha, respectively. $\mathrm{GrazingPeriod_i}$ was the number of days on pasture for a given grazing group. $\mathrm{CattleNumber_i}$ was the estimated number of cattle in a given grazing group.

Estimating GHGs

Greenhouse gas emissions from Canadian beef production were assessed using the methods and algorithms of the Holos model, a whole-farm modelling program developed by Agriculture and Agri-Food Canada (Janzen *et al.* 2006; Little *et al.* 2013). The GHG sources considered in our analysis included CH_4 emissions from cattle and manure, N_2O emissions from manure and soils, N_2O emissions from N leaching, runoff and volatilisation (indirect N_2O emissions) and CO_2 emissions from on-farm use of fuel energy (e.g. cropping) and their use in manufacturing of fertilisers and herbicides. Ammonia emissions were not estimated in our study. Sources of GHG emissions, equations and emission factors are presented in Table 4. Carbon stocks in Canadian agricultural lands were assumed to be near equilibrium and were excluded from analysis. Electricity-related emissions were also assumed to be negligible, owing to the low consumption of electricity by Canadian beef farms (CRA 2010). Energy associated with drying feed grains was also not included as most grains in Canada are harvested at low moisture (Vergé *et al.* 2008). Carbon dioxide emissions from transporting feed were deemed negligible as it was assumed that all feed was grown on the farm.

Emissions associated with culled dairy cows for 2011 were estimated using relevant coefficients developed for the allocation of GHG emissions to meat and milk in Canada (McGeough *et al.* 2012). According to Dyer *et al.* (2008), between 1981 and 2001, Canadian milk production increased by 48%, while GHG emission intensity decreased by 35%. On the basis of this, the coefficients derived from McGeough *et al.* (2012) were multiplied by a factor of 1.04 for slaughtered dairy cows in 1981.

Manure in confined cattle production is most commonly stockpiled (Aklilu Alemu, pers. comm.) and this method of manure handling was assumed to be used at both reference years. Commercial fertilisers and manure were assumed to have been applied at a rate to meet the N requirements of the crop. For 2011, the manure and fertiliser application rates were used from the recent survey results (Sheppard *et al.* 2015) and relevant reports (Beauchemin *et al.* 2010; McGeough *et al.* 2012; Little *et al.* 2013), but similar data were not available for 1981. As a result, methods and rates of application were assumed to be the same in both reference years. Manure N in excess of that required for crop production was assumed to have been spread on tame/seeded pastureland.

Table 4. Sources and equations or emission factors (EF) used to estimate greenhouse gas emissions

Gas	Emission factor/equation[A]
CH_4	
Enteric fermentation	Y_m ranges from 3% to 7% (i.e. cows, 7%; replacement heifers and backgrounding cattle, 6.5%; finishing cattle, 3.5%)
Pasture/range[B]	0.01 kg of CH_4
Solid storage manure handling[C]	0.02 kg of CH_4
N_2O (direct)	
Pasture/range	0.02 kg of N_2O-N/kg of N
Solid storage manure handling	0.005 kg of N_2O-N/kg of N
Soil/cropping nitrogen inputs[D]	$EF_{EasternCanada}$[E] = 0.017 kg of N_2O-N/kg of N $EF_{WsternCanada}$[E] = 0.004 kg of N_2O-N/kg of N
N_2O (indirect)	
Pasture/range[B]	Leaching: EF = 0.0075 kg of N_2O-N/kg of N; $Frac_{leach}$[F] = 0.11 kg of N; Volatilisation: EF = 0.01 kg of N_2O-N/kg of N; $Frac_{volatilisation}$[G] = 0.20 kg of N
Solid storage manure handling[C]	Leaching: EF = 0.0075 kg of N_2O-N; $Frac_{leach}$ = 0 kg of N; Volatilisation: EF = 0.01 kg of N_2O-N; $Frac_{volatilisation}$ = 0.45 kg of N
Soil/cropping nitrogen inputs	Leaching: EF = 0.0075 kg of N_2O-N/kg of N; $Frac_{leach}$ (west)[F] = 0.11 kg of N; $Frac_{leach}$ (east)[F] = 0.30 kg of N; Volatilisation[H]: EF = 0.01 kg of N_2O-N/kg of N; $Frac_{volatilisation}$: 0.1 kg of N_2O-N
CO_2[I]	
Energy to crop corn (grain and silage) (kg/ha)	230
Energy to crop soybean (kg/ha)	218
Energy to crop barley(kg/ha)	156
Energy to hay (kg/ha)	100
Energy from manure application (kg/kg of N)	0.347
Nitrogen fertiliser production (kg/kg of N)[J]	3.59
Phosphorous fertilisr production (kg/kg of P_2O_5)[J]	0.5699
Herbicide production (barley) (kg/ha)	0.93
Herbicide production (corn and soybean) (kg/ha)	0.46

[A] Unless indicated otherwise, emission factors or equations were sourced from IPCC (2006) or Little *et al.* (2013).

[B] All grazing animals.

[C] All non-grazing cattle.

[D] Includes land applied manure, crop residue, synthetic nitrogen fertiliser, and mineralised nitrogen.

[E] Emission factor were approximated on the basis of regional differences in growing season precipitation to potential evapotransporation (P/PE) (Basarab *et al.* 2012; Duke 2006).

[F] Leaching fraction. Approximated on the basis of Rochette *et al.* (2008).

[G] Volatilisation fraction.

[H] Indirect emissions due to volatilisation were calculated on the basis of nitrogen inputs from land applied manure and synthetic nitrogen fertiliser.

[I] As needed, regional or crop-related differences in soil type and tillage system was considered.

[J] Source: Nagy (2000).

According to Dorff and Beaulieu (2014), Canadian cropland expanded between 1981 and 2011 from 31 million to 35.4 million ha, while the area of land applied with synthetic fertilisers increased from 18.5 million to 24.9 million ha over this time period. Consequently, the proportion of land fertilised with commercial N for crop production in 1981 was assumed to be 14% lower than 2011.

Carbon dioxide equivalent (CO_2e) is the metric used to standardise GHG emissions according to the global warming potential (GWP) of individual gases. Hence, to report GHG intensity, emissions were expressed as CO_2e/kg beef (liveweight), assuming GWP values of 28 kg of CO_2e/kg for CH_4 and 265 kg of CO_2e/kg for N_2O (Myhre *et al.* 2013). As estimated GWP values from Intergovernmental Panel on Climate Change or other climate modellers have changed over time, GHG intensities of beef production derived using different GWP values in other studies were standardised to enable meaningful comparisons.

Most calculations were performed at a regional scale (east/west), accounting for differences in cattle distribution, feed utilisation and crop production. Soil N mineralisation was assumed to be balanced by immobilisation, so that root-zone soil organic N was in a steady-state. Both harvest and feeding losses were considered in estimating the amount of land required to produce feeds. However, emissions associated with wasted feed were not included in CH_4 and N_2O emissions from manure.

Crop coefficients used to determine GHG emissions from feed crops and pastures are presented in Table 5. The total feed required was calculated on the basis of the daily DM intake for each class of animal, the percentage of the dietary DM represented by the individual feeds, the number of days cattle were on feed, and the field and feeding losses.

Field losses during harvest were assumed to be 12% for hay and silages and 3% for grains, while feed wastage was estimated to be 20% for hay, 5% for silage and 0% for grain (Rotz and Muck

Table 5. Crop coefficients used in each reference year

Item	Barley grain	Barley silage	Corn grain	Corn silage	Soy-bean	Grass hay	Grass-legume hay	Tame pasture	Bale grazing	Stockpiled forages	Swath grazing
1981											
% of land fertilised with synthetic nitrogen (N)	59	51	59	51	77	19	19	13	n.a.	n.a.	n.a.
% of land fertilised with synthetic phosphorus (P_2O_5)	100	100	100	100	100	0	0	0	n.a.	n.a.	n.a.
% of land fertilised with manure	31	31	31	31	10	19	19	43	n.a.	n.a.	n.a.
% of irrigated land	2	2	2	2	2	2	2	0	n.a.	n.a.	n.a.
% of herbicide applied land	49	49	49	49	49	0	0	0	n.a.	n.a.	n.a.
Synthetic N application rate (kg N/ha)	54	64	120	120	20	50	50	51	n.a.	n.a.	n.a.
Synthetic P application rate (kg P_2O_5/ha)	35	35	50	50	40	0	0	0	n.a.	n.a.	n.a.
Manure N application rate (kg N/ha)	54	64	120	120	20	50	50	51	n.a.	n.a.	n.a.
DM yield (kg/ha)[A]	2295	3970	5304	8883	2215	4230	4230	1446	n.a.	n.a.	n.a.
2011											
% of land fertilised with synthetic N	69	59	69	59	90	19	19	13	19	19	28
% of land fertilised with synthetic P (P_2O_5)	100	100	100	100	100	0	0	0	0	0	100
% of land fertilised with manure	31	31	31	31	10	19	19	35	19	19	31
% of irrigated land	2	2	2	2	2	2	2	0	2	2	2
% of herbicide applied land	76	76	76	76	76	0	0	0	0	0	76
Synthetic N application rate (kg N/ha)	54	64	120	120	20	50	50	51	50	50	64
Synthetic P application rate (kg P_2O_5/ha)	35	35	50	50	40	0	0	0	0	0	35
Manure N application rate (kg N/ha)	54	64	120	120	20	50	50	51	50	50	64
DM yield (kg/ha)[A]	2820	4878	8520	11 599	2820	3894	3894	1343	4306	4860	8073
For both years[B]											
Above-ground residue N (kg N/kg)	0.007	0.007	0.005	0.013	0.006	0.016	0.015	0.015	0.015	0.015	0.007
Below-ground residue N (kg N/kg)	0.010	0.010	0.007	0.007	0.010	0.010	0.015	0.015	0.015	0.015	0.010
Relative DM allocation											
Yield ratio	0.38	0.72	0.47	0.72	0.30	0.18	0.40	0.40	0.40	0.40	0.72
Above-ground residue ratio	0.47	0.13	0.38	0.08	0.45	0.12	0.10	0.10	0.10	0.10	0.13
Below-ground residue ratio	0.15	0.15	0.15	0.20	0.25	0.70	0.50	0.50	0.50	0.50	0.15
Length of perennial stand (years)	n.a.	n.a.	n.a.	n.a.	n.a.	5	5	5	5	5	n.a.

[A] DM Yield referred to crop yield on DM basis at harvest and was sourced primarily from Statistics Canada (2015*b*). Crop yield averages for the respective year and the two adjacent years were used. A DM percentage of 90% was assumed for both corn and grain yields. DM percentages of 30% and 90% were assumed for silages and hay, respectively. Additional sources for yield estimates were barley silage (Alberta Agriculture 2013), bale grazing/stockpiled forages (Lardner 2013), and swathed crops (Lardner *et al*. (2011).

[B] Unless indicated otherwise, Little *et al*. (2013) was the source.

1994). A feed loss of 20% was assumed for stockpiled and swath-grazed forages on the basis of Hutton *et al*. (2004). The area of land required to produce each crop was estimated from average regional Canadian yields.

Co-product allocation

Greenhouse gas emissions related to surplus dairy calves that joined beef operations as feeder calves were estimated and entirely attributed to beef production, but veal calves were not included in the analysis as their contribution to Canadian cattle meat production is less than 3% (Statistics Canada 2015*a*), and their enteric CH_4 emissions are negligible (McGeough *et al*. 2012). Canadian veal is meat produced primarily from young male dairy calves that are slaughtered at 5–7 months of age (Farm and Food Care Ontario 2015) at a carcass weight of 180 kg or less (Canadian Food Inspection Agency 1992). In practice, dairy calves can enter the beef production system at various ages; for the present analysis, they were assumed to enter the beef production system immediately after birth. Thus, all emissions associated with the growth of dairy animals for meat production were accounted for in the analysis. The environmental footprint associated with culled dairy cows and surplus dairy calves (before entering the beef system) was approximated on the basis of relevant coefficients compatible with ISO (2006; Standard 14044) for the allocation of GHG emissions to meat and milk (McGeough *et al*. 2012). According to the cited Canadian-based study, economic allocation resulted in 91% of emissions being assigned to milk. To overcome variability associated with fluctuations in commodity prices over time, the researchers averaged commodity prices over a 5-year period. The allocation of emissions on the basis of economic value was also the procedure favoured by the BSI (2008).

Any necessary live-to-carcass weight conversions were undertaken using factors recommended for Canadian cattle (steers and heifers, 60%; cows, 49%; breeding bulls, 55%; AAFC 2013). In our study, the boundary was set at the farm gate; as a result, emissions associated with the processing of the carcass or the various by-products that arise from it were not estimated.

Results and discussion

Total Canadian beef production in 1981 was 1.05 billion kg from 3.80 million slaughtered cattle. A total of 1.35 billion kg of beef was produced from 3.72 million cattle slaughtered in 2011. The average carcass weights of steers, heifers, cows and breeding bulls slaughtered in 2011 were 29%, 45%, 19% and 28% heavier, respectively, than those of animals slaughtered in 1981. The steer carcass weights represented 1.19 and 1.28 times of the cow carcass weights in 1981 and 2011, respectively.

Approximately, 83% of all the feed in 1981 and 78% of all the feed in 2011 required by the Canadian beef cattle herd was forage, which aligns with a previous estimate of it accounting for 80% of the feed for the Canadian cattle herd (Beef Cattle Research Council 2012). Cows grazed two-thirds of available natural pastures in both reference years.

Support population and land requirement

Our analysis showed that 29% less breeding stock (i.e. cows, preweaning calves, replacement heifers and bulls) was required to produce the same amount of beef in 2011 than in 1981 (Fig. 3). The slaughter population required to produce a given amount of Canadian beef was also reduced by 24%.

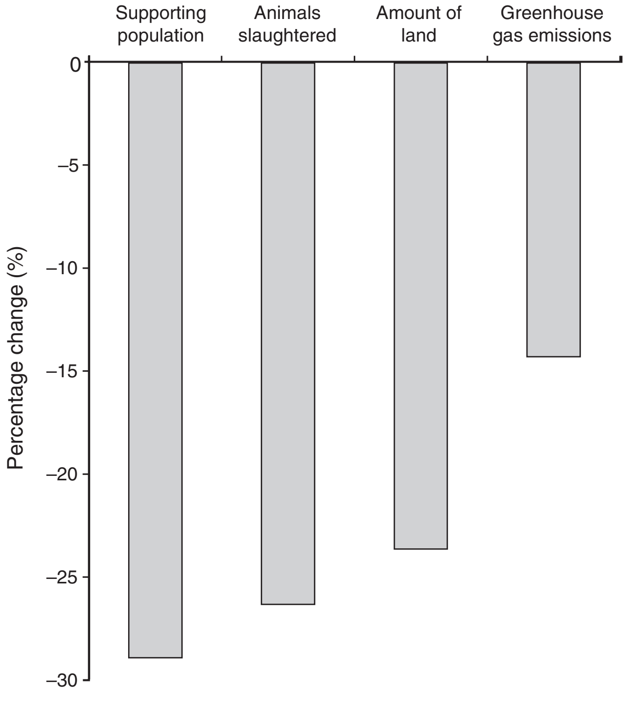

Fig. 3. Percentage reduction in resource requirements and greenhouse gas emissions (CO_2e) to produce a given amount of Canadian beef in 2011 relative to 1981.

Between 1981 and 2011, the land use to produce a given amount of Canadian beef was reduced by 24% (i.e. 5.6×10^6 ha per billion kg of beef), with pasturelands constituting more than 76% of this land base. Estimated land requirements associated with a kilogram of beef liveweight in 1981 and 2011 were 136.5 m^2 and 104 m^2, respectively. Our land-use estimate for 2011 was comparable to a least-cost baseline scenario of a US production system parametrised using national average production data (White *et al*. 2015) and to values reported for beef cattle production systems in southern Australia (Ridoutt *et al*. 2014). However, they were greater than estimates for other production scenarios in the USA and Europe (Nguyen *et al*. 2010; Capper 2011; White *et al*. 2015) and smaller than the values derived for extensive production system in southern Brazil (Dick *et al*. 2015). The amount of land estimated in our study could be higher than the actual values under producer control, as the stocking-rate assumptions in our analysis were close to the recommended ecologically sustainable rates for Canadian pasturelands. Employing different approaches to estimate land use may result in different values, but similar trends. For example, if we assume that the average national tame-hay yield was comparable to the improved pasture yield average (i.e. a 3894 DM yield/ha for improved pasture; and 1113 DM yield/ha for natural pastures in 2011, with additional 32% field and feeding losses for both pastures), the land-use estimate associated with a kilogram of liveweight would be roughly 62 m^2/kg liveweight, a 22% decline from 1981. Similarly, if the average DM yields of 3000 kg/ha and 6800 kg/ha used by Nguyen *et al*. (2010) for European low-productive and moderately productive grasslands, respectively, were assumed for natural and improved pastures in the current study (with additional 32% field and feeding losses), the land use associated with a kilogram of liveweight would be ~40.4 m^2/kg liveweight, a 23% decline from 1981. Hence, irrespective of the methods used to estimate the land use, it required 22–24% less land to produce the same amount of liveweight for slaughter in 2011 than in 1981.

Greenhouse emissions associated with beef cattle production

Total GHG emissions from the production of Canadian beef cattle were 28% higher in 2011 than they were 1981 (28.3 Tg CO_2e vs 22.1 Tg CO_2e). However, on an intensity basis, CO_2e per kilogram of liveweight (culled dairy cows excluded) decreased in 2011 by 18%, to 12.7 CO_2e, as compared with CO_2e 15.6 in 1981. This decline arose as a result of declines of 18% in CH_4, 19% in N_2O and 16% in CO_2 emissions.

Taking into account beef from culled dairy cows, our analysis yielded an estimated GHG intensity of 12.0 kg CO_2e per kg liveweight for 2011 and 14.0 kg CO_2e per kg liveweight for 1981, a 14% decline (Fig. 3). Using the same GWP coefficient for CH_4, an estimate of emissions per kilogram of beef (beef from dairy cows included) in 2011 was similar to that reported for US beef in 2007 (Capper 2011), a result that likely reflects the similarities in the production systems in the two countries.

Approximately 73% of total GHG emissions in both reference years arose from enteric CH_4 emissions, while

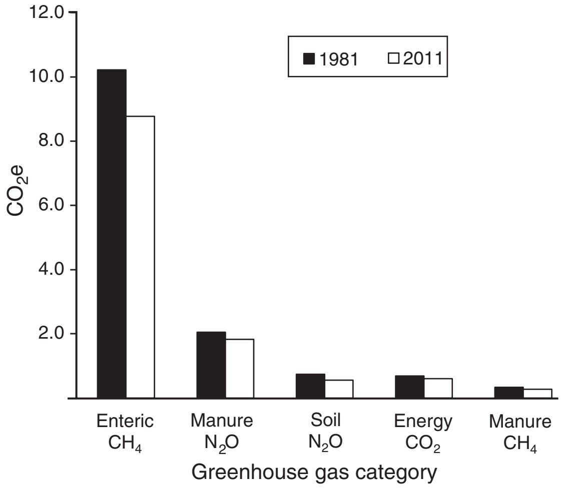

Fig. 4. The contribution of different sources of greenhouse gases to the total emissions associated with production of a kilogram of Canadian beef in 1981 versus 2011.

enteric CH_4, manure N_2O and soil N_2O accounted for more than 92% of the total GHG emissions (Fig. 4). Life-cycle analysis of a simulated western Canadian beef production system also found that these GHGs accounted for 90% of CO_2e emissions per kilogram of carcass weight (Beauchemin *et al.* 2010).

The reduction in GHG emissions over a 30-year timeframe has been partially attributed to a dilution in the amount of energy that beef cattle require for maintenance (Capper 2011; Dijkstra *et al.* 2013; Wiedemann *et al.* 2015). The considerable increase in reproductive efficiency, average daily gain and slaughter weights, and the resulting improvement in beef production per breeding herd over the study period led to the dilution of maintenance costs of the herd and overall nutrient demand. Advancements in reproductive efficiency and productive performance imply that the cow–calf producers adopted improved genetics and management practices and, as a result, overall weaning weights have increased by ~20% over the past 30 years (Schaeffer *et al.* 1981; Sheppard *et al.* 2015). Growth-promoting technologies, such as hormonal implants and β-agonists, were also more readily available in 2011 than in 1981. Growth-promoting implants, in themselves, have been shown, on average, to improve the average daily gain of feedlot cattle by 18%, feed efficiency by 8% and carcass weight by 5% (Duckett and Pratt 2014). The improvement in reproductive efficiency and productive performance can also be partly due to improved health management (e.g. management of digestive upsets, vaccines, antibiotics) increasing conception and survival rates and lowering the effects of morbidity on growth efficiency. All the health and management improvements made in reducing respiratory and digestive disorders have direct implications for improving feed intake and bodyweight gain. Other reasons for the notable decline in GHG intensity over the past three decades include a reduced time from birth to slaughter and improvement in annual crop yields.

If the reproductive efficiency (i.e. number of calves weaned per 100 cows exposed) in 2011 was unchanged from 1981, the current reduction in GHG intensity, breeding herd and land requirements would be lowered by 7%, 6% and 8%, respectively. The lower intensity of CO_2 emissions from an on-farm use of fuel energy (e.g. cropping, manure spreading) and their use in manufacturing of fertilisers and herbicides are due to improvements in crop and animal productivity. If the yields of feed crops had not been improved, the estimated decline in energy CO_2 intensity would have not been realised. Similarly, if the reproductive efficiency in 2011 were unchanged from 1981, the current reduction in energy CO_2 intensity would be 4% lower. In 1981, we estimated that it required an additional month for backgrounded steers and heifers to reach sufficient weight for finishing. Marketing more cattle at an earlier age also contributed to the lower GHG emissions per unit of liveweight that left the farm in 2011. A larger proportion of calves was sent to feedlots immediately after weaning in 2011 than in 1981. Basarab *et al.* (2012) compared the GHG emissions from feedlot cattle slaughtered at earlier (11–16 months) versus later (17–23 months) age, and found that those slaughtered at an older age produced 6.3–7.5% more GHG emissions.

After using the latest GWP coefficients (Myhre *et al.* 2013), our estimate of GHG intensity in 2011 was slightly lower than that of Beauchemin *et al.* (2010) (14.6 kg CO_2e per liveweight), and within the range of that reported by others (Beauchemin *et al.* 2009). The life-cycle analysis conducted by Beauchemin *et al.* (2010) was based on a simulated western Canadian beef production system, while we followed a nation-wide industry level approach, taking into account temporal and/or regional differences in feed types, feeding systems, cattle categories, average daily gain and carcass weights. Vergé *et al.* (2008) reported 18 kg CO_2e per liveweight for 1981 and 11.7 kg CO_2e kg liveweight for 2001. The 1981 estimate reported in Vergé *et al.* (2008) was greater than the current estimate for the same year, while the 2001 estimate was comparable with our 2011 estimate (beef from culled dairy cows included). One source of variation could be differences in emission factors used in the two studies. Methane-conversion factors used in our analysis were based on IPCC (2006) and relevant Canadian studies (Little *et al.* 2013). Vergé *et al.* (2008) estimated enteric CH_4 emissions on the basis of a single emission factor. The approaches employed to estimate resource requirements were also different in the two studies. Further, energy-derived CO_2 associated with the manufacture of farm machinery was included in Vergé *et al.* (2008), but excluded from the current analysis. However, owing to the extensive nature of cow–calf production, CO_2 associated with machinery manufacture is generally insignificant for ruminants (LEAP 2015). Our estimate of GHG intensity in 2011 was lower than the 14.8–19.2 kg of CO_2e per kg liveweight estimated for three beef-finishing scenarios in the upper Midwestern United States (Pelletier *et al.* 2010). A recent study on the GHG intensity of Australian beef over 30 years from 1981 to 2010 showed a 14% decline from 15.3 to 13.1 kg CO_2e per kg liveweight (Wiedemann *et al.* 2015).

In the past decade, several studies have estimated the carbon footprint of beef. Most of these studies simulated individual farms and have not taken the same nation-wide approach as in the present study. Direct comparison of results across different studies can be difficult in view of differences in production systems, system boundaries, assumptions, algorithms and other methodological inconsistencies. With consideration of these methodological differences, our study substantiated the reported trends in the USA (Capper 2011) and Australia (Wiedemann *et al.* 2015), where improvements in production efficiency over the past three decades have reduced the environmental footprint per kilogram liveweight (Fig. 5). For the US study, GHG intensity was expressed in terms of carcass weight. Thus, the GHG intensity per kilogram carcass weight was converted to per kilogram liveweight, assuming a 60% dressing percentage. In all three studies, the GHG intensity of beef over the past three decades showed 14–17% decline per kilogram liveweight.

At both reference years, the cow–calf system accounted for the majority of total enteric CH_4 emissions (Fig. 6), with feedlot production accounting for only 6% and 9% of total emissions in 1981 and 2011, respectively. Feedlot production represents a relatively small proportion of enteric CH_4 from beef production systems, an outcome attributable to the short feeding duration and the use of grain-based finishing diets which lower CH_4 emissions. Comparatively, the lower fraction of GHG emissions for feedlot cattle in 1981 was due to more days required for the backgrounding of cattle. Other studies have also clearly confirmed that the cow–calf system is the primary source of GHG emissions (Beauchemin *et al.* 2010; Basarab *et al.* 2012). In western Canada, Beauchemin *et al.* (2010) found that 84% of enteric CH_4 was from the cow–calf system, with the majority of these emissions arising from mature cows. In the present study, it was assumed that all preweaning calves grazed either natural or tame/seeded pastures with their dams. Knowing that a small proportion of calves likely received concentrate at both reference years, enteric CH_4 emissions might be slightly overestimated in our study, but these differences are expected to be small.

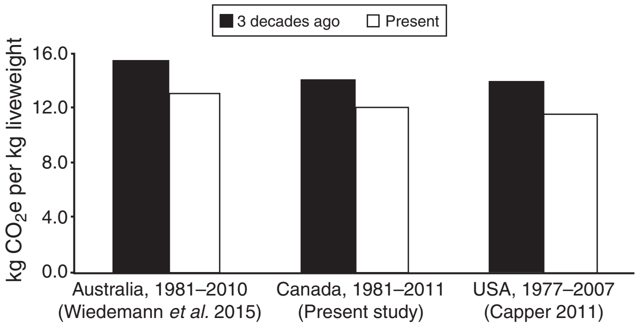

Fig. 5. Change in greenhouse gas emissions per kilogram of liveweight from Australian, Canadian and American beef sectors over the past three decades.

It was not possible to acquire reliable data regarding transportation of cattle and feeds among and within provinces. Although we have not included emissions associated with transportation of feeds and cattle in our GHG estimates, transport emissions from cattle in Canada have been surmised to be small, with a minor effect on GHG intensity (Desjardins *et al.* 2012). After conducting a cradle-to-gate life-cycle assessment of beef production, Stackhouse-Lawson *et al.* (2012) estimated that transportation was responsible for less than 2% the total GHG emissions in California, while Roop *et al.* (2013) reported that transportation accounted for ~6% of total emissions in the Palouse region of the north-western USA.

Effects of feed crop production on environmental footprint of beef

The efficiency of the Canadian beef sector is both directly and indirectly associated with the efficiency of crop production. Estimating the environmental impact of beef production using a life-cycle approach does not only include emissions associated with feeding the animals, but also the production of feeds at their place of origin. Hence, concerted research efforts that make

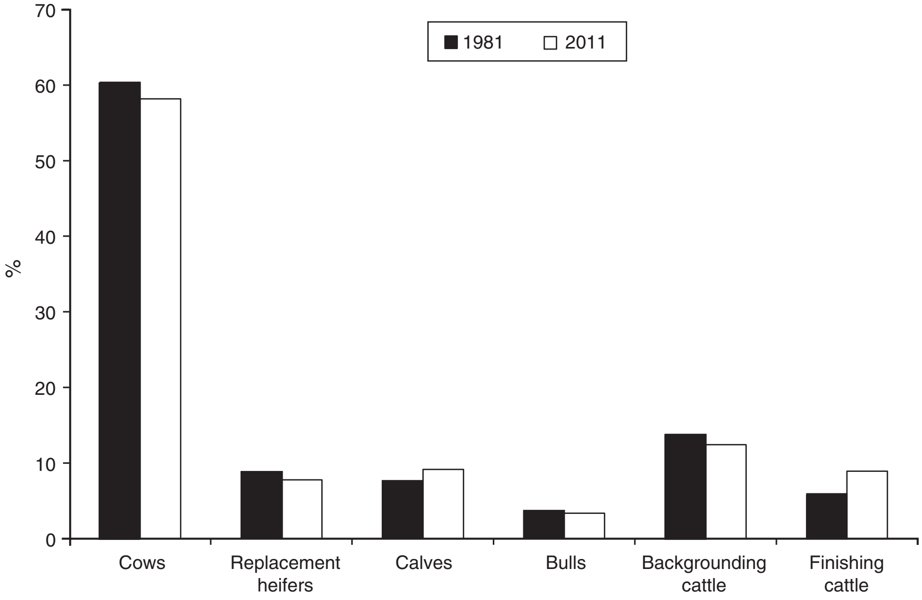

Fig. 6. Breakdown of enteric methane (CH_4) emissions by cattle category in 1981 and 2011. The backgrounding cattle category in the figure contains animals backgrounded in confinement, as well as those backgrounded in confinement and on pasture.

improvements in the yield and quality of feed crops may possibly provide not only increased economic returns, but also environmental benefits. In the present study, the improvements in yield of corn and barley reduced the land and production inputs required to produce beef and, thereby, lowered the overall intensity of GHG emissions. For instance, if the yields of corn and barley had not been improved, the estimated decline in GHG intensity and land requirement would have been lower by 1% and 2%, respectively. Between 1981 and 2011, the Canadian hay yield per unit area showed a 10% decline (Statistics Canada 2015*b*), while the hay yield per unit area in the USA was found to remain virtually constant (USDA 2014). This decrease may be partly attributable to a decline in funding for forage research and technology transfer, and to an increasing pattern of growing forages on marginal lands, with more fertile land being used to grow annual cash crops (Canadian Cattlemen's Association 2008). As a result of this change, ~10% more land was required to produce hay for the Canadian beef industry in 2011 than in 1981.

There has been a significant increase in the number of hectares dedicated to corn production, particularly in the Prairie Provinces (Stanton *et al.* 2007). For example, between 1971 and 2011, the seeded area of corn for grain in Manitoba increased 23-fold, from 3678 ha to 85 499 ha (Hamel and Dorff 2014). Corn grain and silage are primarily used for livestock feed, with this northern expansion being mainly due to the development of earlier-maturing varieties (Hamel and Dorff 2014). Moreover, a Canadian study showed that CH_4 emissions per kilogram of DM intake and as a percentage of gross energy intake were less for corn grain than for barley grain during the finishing phase (Beauchemin and McGinn 2005). This makes corn one potential crop that may further reduce the GHG intensity of Canadian beef.

The impact of including beef from dairy systems on GHG intensity

In Canada, the beef herd is significantly larger than the dairy herd (3.85 million beef cows and 0.962 million dairy cows in 2011; Statistics Canada 2014*b*). Resource use and GHG emissions from surplus dairy calves that joined the beef production cycle were included in the beef production system in our study, lowering the number of beef breeding stock relative to the amount of Canadian beef produced. Including slaughter weight from dairy cows in the analysis resulted in 6–11% decline in GHG intensity, as compared with values derived exclusively from liveweight from slaughtered beef cattle.

Consumer demand has been evolving to consider the environmental impact of products in their purchasing decisions, a trend that could influence the nature of future production systems. Unlike in most European countries, the major source of beef in Canada is non-dairy cattle, consisting primarily of European and continental beef breeds. Considering the current Canadian dairy-supply management system, it is unlikely that the use of dairy breeds for beef production will notably increase in the foreseeable future (McGeough *et al*. 2012).

Data limitations

By its very nature, this type of historical analysis of cattle production systems relies very much on disparate datasets and assumptions for its input parameters such as feed types, feeding practices, herd structure and growth rates, all of which have direct implications on GHG emissions and resource use. Despite efforts to ensure the use of relevant data and realistic assumptions, uncertainties are inevitable, warranting some caution in the interpretation of our results. However, the trend of GHG intensity and resource use over the study period is valid and a true indicator of the effects of improved efficiency. As we employed a life-cycle approach, estimates of marketed cattle were standardised on the basis of the size of the breeding herd within the reference year, to ensure that the probable effects of other factors that might have affected meat production and cattle demography did not bias the analysis. The GHG emission sources identified in the present study serve to provide a foundation for the development of GHG policy for the Canadian beef industry into the future.

Conclusions

The present study compared GHG emissions and resource (i.e. land and animal) requirements of Canadian beef production in 2011 to 1981, considering growth efficiency, crop yields and management practices. The GHG intensity of Canadian beef in 2011 (12.0 kg CO_2e/kg liveweight) was 14% lower than that in 1981(14 CO_2e/kg liveweight). Increases in reproductive efficiency, average daily gain, slaughter weight and crop yields were among the factors that contributed to the decrease in emission intensity over time. Enteric CH_4 was responsible for 73% of total GHG emissions per kilogram liveweight, with more than 78% of enteric CH_4 arising from the cow–calf sector. Consequently, the greatest opportunities for mitigation lie within this portion of the beef cycle. To produce the same amount of liveweight for slaughter in 2011 required only 71% of the breeding herd and 76% of the land as compared with 1981. The present study adds to a growing body of evidence for a significant decrease in resource use and GHG emissions per unit of beef produced in several developed countries in the past three decades. Further studies are necessary to assess the impact of the Canadian beef production on other sustainability indicators such as water use, air quality, biodiversity and provision of ecosystems services.

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