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Research article

Assessment of regional greenhouse gas emission from beef cattle production: A case study of Saskatchewan in Canada

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ABSTRACT

The beef cattle production has been considered as one of the largest sources of greenhouse gases (GHGs) emission. A large amount of GHGs including N_2O and CH_4 from enteric fermentation and manure are discharged to atmosphere during beef-production process. In addition, a substantial amount of GHGs is also emitted from many other related processes such as feed production, transportation, and energy consumption. In this study, an emission assessment model was developed to quantify the amount of regional GHGs produced from the beef cattle production process. A case study was conducted based on the beef production in Saskatchewan, Canada. The results demonstrated that the GHG emissions from the annual marketed beef cattle in Saskatchewan in 2014 were 8.52×10^9 kg CO_2-eq in total and the cattle-source GHGs (enteric CH_4, manure CH_4, and manure N_2O emission) accounted for more than 90% of the total emission. Sensitivity analysis showed that the most critical factors influencing the GHG emission included feedlot manure handling system, cattle diet, feed additives, maximum methane producing capacity (B_o), and climate (temperature, precipitation, and potential evapotranspiration). The potential impacts of climate change on GHG emission from beef cattle production in Saskatchewan were also investigated. An overall decrease in the GHG emission can be observed due to the climate change, which are 3.67%, 4.96%, and 6.63% for 2020–2039, 2040–2059, and 2060–2099, respectively.

1. Introduction

Due to a rapid increase in the world population, there has been a significant growth in the meat demand and corresponding livestock industry over the past 30 years. The production of beef, one of the main meat sources of human being, is expected to reach 62.6 million tonnes worldwide in 2019 (USDA, 2019). However, the high consumption of natural resources associated with livestock production can lead to a series of environmental concerns (Loyon et al., 2016; Song et al., 2018). For example, about 8% of human water use and about 30% of world land were used for the livestock production (Evans et al., 2015; Panunzi, 2008; Steinfeld et al., 2006). Moreover, since beef cattle are ruminant, a large amount of greenhouse gases (GHGs) including N_2O and CH_4 from enteric fermentation and manure are discharged to atmosphere during beef production process (Zhuang et al., 2019). According to the report from United Nations, the beef cattle source has accounted for approximately one third of the world anthropogenic CH_4 emission (Steinfeld et al., 2006). In addition, a substantial amount of GHGs is also emitted from many other related processes such as feed production, transportation, and energy consumption. With the rising concern over climate change, much attention has been paid to the development of low-carbon emission strategy for beef livestock production (Tauseef et al., 2013; Zhang et al., 2019).

Some efforts have been made to evaluate the GHG emission from livestock production. IPCC (2006) developed a guideline for the estimation of national GHG inventories which has been widely used to estimate GHG emission from livestock production. Based on this method, a study conducted by Herrero et al. (2016) reported 5.6 and 7.5 Gt CO_2-eq were produced from livestock industry during 1995–2005. It accounted for 18% of the global GHG emission according to the estimation by Food and Agriculture Organization (Steinfeld et al., 2006). To better evaluate the GHG emission from livestock production and look for the possible

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mitigation measures in a certain area, the regional GHG assessment is also required. Lesschen et al. (2011a) assessed the GHG emission from various types of livestock in Europe. It was found that the amount of GHGs generated by dairy cows or beef cattle was more than twice as much as that for pigs. Also, a GHG emission assessment showed that the dairy cows and beef cattle accounted for 60% of the total emission from EU-27 livestock sector in 2007 (Bellarby et al., 2013). Dyer et al. (2010) evaluated the livestock GHG emission intensities by products in Canada. The beef product has the highest average emission intensity (119 kg CO_2-eq/kg protein) compared with milk (31.7 kg CO_2-eq/kg protein), pork (24.9 kg CO_2-eq/kg protein), broilers (10.6 kg CO_2-eq/kg protein), and eggs (21.9 kg CO_2-eq/kg protein). However, the assessment of regional GHG emission from beef production for providing customized mitigation strategies is still limited and the significance of factors affecting regional livestock GHG emission are still not clear (Cai et al., 2019; Chen et al., 2019a; Huang et al., 2018).

The aim of this study is to develop an emission assessment model to quantify the amount of regional GHGs produced from the beef cattle (including feeder and slaughter cattle) production process. A case study based on the beef production in Saskatchewan, Canada will be conducted. The sensitivity of modeling results will be analyzed to identify the most critical factors affecting the GHG emission, and thus the potential mitigation measures will be discussed. Also, the impact of climate change on the GHG emission from beef cattle production system will be investigated.

2. Methodology

2.1. Study area

Beef production is one of the major agricultural industries in Canada. About 9.5 million cattle were fed in Canada in 2019, accounting for 1% of the total beef production in the world (Statistics Canada, 2019b). Saskatchewan is a prairie province in Canada, with a total area of 651, 900 km^2. In Canada, 23% of the cattle in beef operation was produced in Saskatchewan, which is the second largest beef production province (Statistics Canada, 2019b). The amount of GHGs generated from beef cattle industry in Saskatchewan was quantified in this study to assess its potential risks on climate change (Hauer et al., 2016). The beef cattle population and environmental conditions can affect the amount of corresponding GHG emission. Therefore, the GHG emission was evaluated for each crop district in Saskatchewan.

2.2. Components of GHGs emission in beef production process

Saskatchewan has several kinds of beef production processes according to the operation modes in the farms. A typical beef production process in Saskatchewan was defined in this study to identify the GHG sources within system boundary. GHGs generated from on-farm sources (e.g. enteric fermentation and cattle manure), off-farm sources (feed production), and other sources from energy used (e.g. transportation, housed beef, production of fertilizer and herbicide) were taken into consideration. Various factors can affect the amount of GHG emission from these sources. Regarding GHGs generated from enteric fermentation and manure, the amount directly relates to the attributes of cattle (gender, age, and weight), feed quality, and manure management. The GHG emission from feed production can be affected by crop type, crop area, usage of tillage, and regional climate. Although the carbon sequestrated by green land could also affect GHG emission (Salvador et al., 2017; Viglizzo et al., 2019), this effect was not taken into consideration in this study. The system boundary considered for GHG emission from beef production in Saskatchewan is shown in Fig. 1.

2.2.1. Description of general process of beef cattle production in Saskatchewan

The cattle in beef production can be divided into two major groups, beef cattle and breeding cattle. Fig. 2 indicates the life cycles of different types of beef cattle used for the estimation of GHG emission in this study. The cows are assumed to give birth to calves on April 1, and all the claves need to stay with their mother and be fed by mixed diet (milk and forage) for seven months until October 31. After weaning, the feeder heifers and steers are fed by backgrounding diets for 110 days. In contrast, the breeding cattle need longer period (151 days) for backgrounding diets. The feeder cattle after backgrounding stage are typically sold and transported to feedlot (finishing diets) for 170 days to finish before slaughter. However, the breeding heifers and bulls would still be grazed in farm for one year to ensure they reach breeding age. The breeding heifers normally give birth to the first calf at the age of two and the bulls can be used for breeding at the same age. These cows and bulls are replaced by the new breeding cattle when they reach 9 years old (at the end of eighth year) due to the decline in fertility, and replaced cattle are sent to slaughterhouse. The breeding cattle are assumed to stay

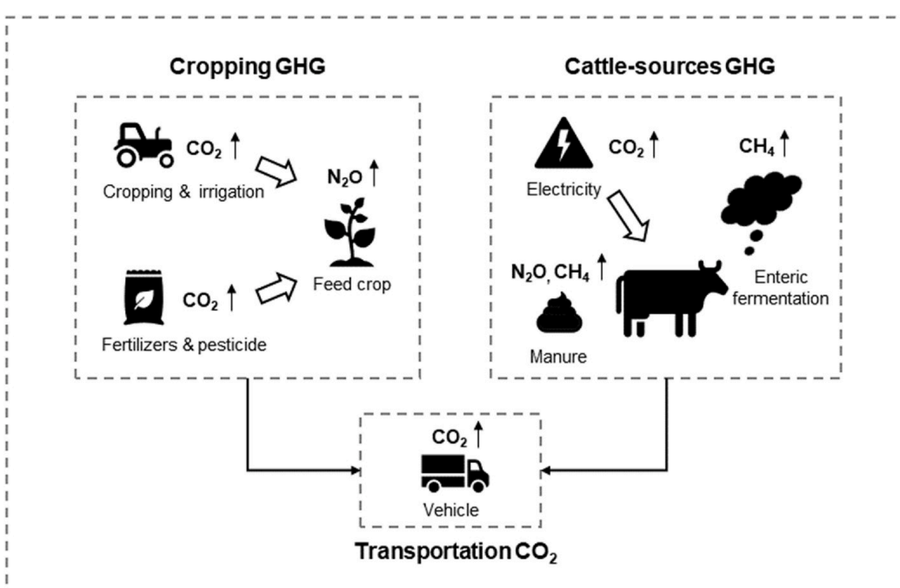

Fig. 1. Boundary of greenhouse gas emission from beef production.

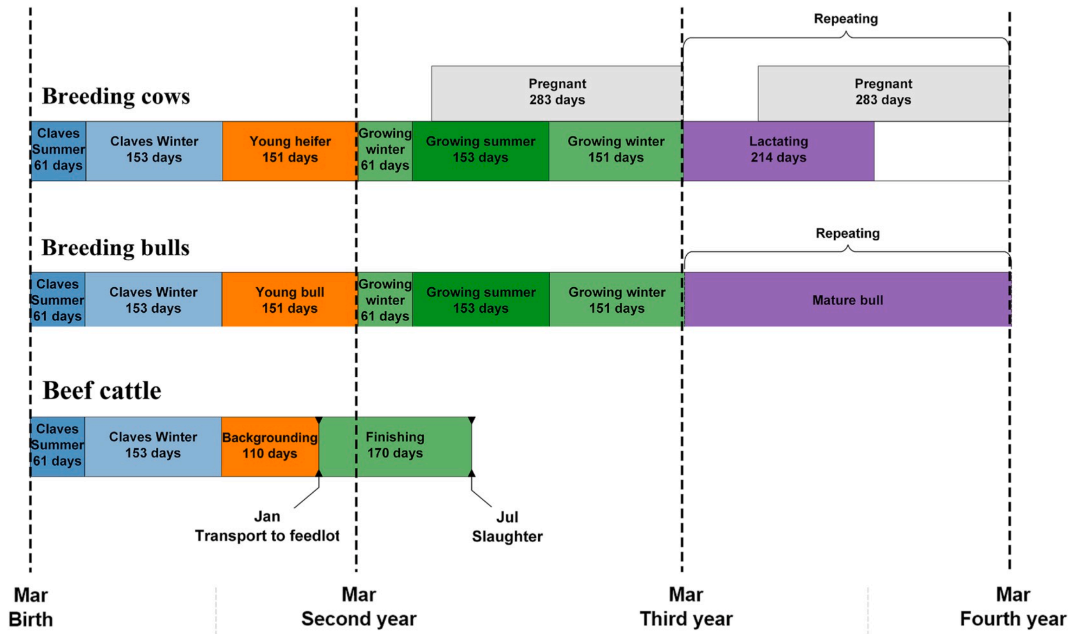

Fig. 2. Life cycle by types of cattle.

on farm throughout their whole life cycle and beef cattle are kept on farm until they are sent to feedlot at the end of backgrounding phase.

The operating modes of beef cattle farm differ from the seasons. All the cattle are fed by hay indoors in winter (from November 1 to April 30) and grazing is the major method of feeding for most types of cattle in summer (from May 1 to October 31). However, those beef cattle which are at the backgrounding and finishing stages are placed in the feedlot and fed by special diets. Table 1 shows the parameters for each growing stage of beef cattle used in the GHG estimation, including weight, diet, and duration.

Table 1
Parameters of beef cattle by categories.

Cattle category	Initial weight (kg)	Final weight (kg)	Duration (Days)	Diet
Feeder cattle				
Heifer calves	40	225	214	Milk and hay (winter); Milk and pasture (summer)
Backgrounding heifers	225	350	110	Backgrounding
Finishing heifers	325	575	170	Finishing
Bull calves	40	225	214	Milk and hay (winter); Milk and pasture (summer)
Backgrounding steers	225	350	110	Backgrounding
Finishing steers	350	625	170	Finishing
Breeding cattle				
Calves	40	225	214	Milk and hay (winter); Milk and pasture (summer)
Young heifers	225	390	151	Backgrounding
Growing heifers	390	600	365	Hay (winter); Pasture (summer)
Cows	600	600	365 × 6	Hay (winter); Pasture (summer)
Lactating cows	600	600	214	Hay (winter); Pasture (summer)
Calves	40	225	214	Barley
Young bulls	225	390	151	Backgrounding
Growing bulls	390	820	365	Hay (winter); Pasture (summer)
Bulls	820	820	365 × 6	Hay (winter); Pasture (summer)

Only the GHG emission caused by the beef cattle fed in Saskatchewan was taken into account in this regional study. The amount of GHG emission was estimated based on the annual marketed beef cattle, including feeder and slaughter, in Saskatchewan. The slaughter cattle are those cattle which have been finished and can be directly sent to the slaughterhouse. All GHGs generated within the life cycle of the beef cattle before slaughter are included. For feeder cattle, they normally are traded after the backgrounding stage at farms and then transported to feedlot for the further finishing. But for feeder cows and bulls, the average age when they are sold are assumed to be 4 years old. In this assessment, only the GHG emission before the cattle are marketed are considered.

2.2.2. Cattle-sources GHG emission

Enteric and manure emissions are the primary GHG sources, which are directly caused by cattle. Enteric CH_4 is the by-product of digestive process of cattle and is eliminated from the body by burping. This process lasts throughout the life cycle of beef cattle. Apart from types of cattle and feed, the amount of emissions largely depends on manure handling system. Various systems have been implemented in the cattle farms of Canada. In Saskatchewan, cows, calves, and bulls are on the pasture and their manure are usually left there to rich pasture in summer. However, the manure from cattle in feedlot (including backgrounding cattle, finishing cattle, and other types of cattle in winter) is deep-bedded over the production cycle of 6–12 months. Cattle manure can cause the release of CH_4 and N_2O due to the bacteria activity (Liu et al., 2019). In addition, the CO_2 emission caused by the electricity consumption for cattle was also taken into account in this study.

2.2.3. Cropping GHG emission

Feed production is also one of the most important sources of GHG emission from beef production. The major feeds for beef cattle consist of barley grain, barley silage, hay, and pasture in western Canada. In this assessment, the barley crops are assumed to be planted in commercial farm. The harvested barley is transported to feedlot and made into feed for backgrounding and finishing cattle. Pasture planted without fertilizers in cattle farm is used for grazing and haymaking. The produced hay serves as the forage for grazing cattle (breeding cattle and calves) in winter. The GHG sources from cropping include soil N_2O emissions due to N inputs (fertilizer application and crop residue) and energy CO_2 emission (tillage, seeding, spraying, harvesting, irrigation, and fertilizer use).

2.2.4. Transportation

Transportation account for 24% of the Canada's GHG emission in 2017 (Environment Canada, 2019), which is also an indispensable source of GHGs generated in the process of beef cattle production. Three main transportation routes during beef cattle production process including (1) Feeder cattle to feedlot, (2) cattle feed to feedlot, and (3) finisher cattle to feedlot were considered in this assessment.

2.3. GHGs emission assessment model

2.3.1. Cattle-source GHG emission

The enteric and manure emission can be calculated according to the method from IPCC (2006) and the input of the beef cattle production is required (Table 2). The enteric CH_4 from each type of cattle can be estimated using gross energy intake (by body weight, activity, growth, ambient temperature, and diet) and CH_4 conversion factors (Y_m) (by diet). The emission rate of manure CH_4 can be determined by the amount of volatile solid excreted by beef cattle, which is affected by the gross energy intake, ash content of manure, and digestibility. To estimate the amount of manure CH_4, the maximum methane producing capacity (B_o) and methane conversion factor (by manure handling system, region, and season of application) will also be considered.

Manure can also lead to the direct and indirect N_2O emission, which can be estimated based on N excretion rate. The N excretion rate can be calculated by Eq. (1) considering protein intake from diet and protein retained.

$$N_{excretion} = \frac{PI}{6.25} - \left(\frac{PR_{fetal}}{6.25} + \frac{PR_{lactation}}{6.38} + \frac{PR_{gain}}{6.25}\right) \quad (1)$$

Table 2
Emission factors for the cattle-source GHG emission.

Gas sources	Equation/emission factor	References
Enteric CH_4	GE × Y_m/55.65 × (1 - AR/100) [kg CH_4 head^{-1} day^{-1}]	IPCC (2006)
Manure CH_4	VS × B_o × MCF × 0.67 [kg CH_4 head^{-1} day^{-1}]	IPCC (2006)
Manure direct N_2O		
Pasture	EF_{direct} = 0.02 [N_2O–N (kg N)$^{-1}$]	IPCC (2006)
Deep-bedding	EF_{direct} = 0.01 [N_2O–N (kg N)$^{-1}$]	IPCC (2006)
Manure indirect N_2O		
Pasture	Leaching:	
	EF = 0.075 [N_2O–N (kg N)$^{-1}$]	IPCC (2006)
	$Frac_{leach}$ = 0.3247 P/PE – 0.0247	Rochette et al. (2008)
	Volatilization:	
	EF = 0.01 [N_2O–N (kg N)$^{-1}$]	IPCC (2006)
	$Frac_{volatilization}$ = 0.01	IPCC (2006)
Deep-bedding	Leaching:	
	EF = 0.075 [N_2O–N (kg N)$^{-1}$]	IPCC (2006)
	$Frac_{leach}$ = 0	Rochette et al. (2008)
	Volatilization:	
	EF = 0.03 [N_2O–N (kg N)$^{-1}$]	IPCC (2006)
	$Frac_{volatilization}$ = 0.01	IPCC (2006)
Energy CO_2		
Beef housing	EC_{cattle} × $EF_{electricity}$ [kg CO_2-eq year^{-1}]	Dyer and Desjardins (2006)

GE: gross energy intake (MJ head^{-1} day^{-1}); AR: additive reduction factor (%); VS: Volatile solids (kg head^{-1} day^{-1}); B_o: methane producing capacity (0.19); EF: emission factor; $Frac_{leach}$ = Leaching fraction; $Frac_{volatilization}$ = Volatilization fraction; P = Growing season (May–October) precipitation; PE = Growing season (May–October) evapotranspiration; EC_{cattle}: Annual electricity consumption per cattle (KWh head^{-1} year^{-1}); $EF_{electricity}$: emission factor of electricity consumption (kg CO_2-eq KWh^{-1}).

where $N_{excretion}$ is N excretion rate (kg head^{-1} day^{-1}); *PI* is protein intake (kg head^{-1} day^{-1}); PR_{fetal} is protein retained for pregnancy (kg head^{-1} day^{-1}); $PR_{lactation}$ is protein retained for lactation (kg head^{-1} day^{-1}); PR_{gain} is protein retained for gain (kg head^{-1} day^{-1}).

Direct N_2O emission can be estimated by multiplying emission factor of specific manure handling system by N excretion rate. Indirect N_2O emission from manure is mainly caused by volatilization, leaching, and runoff, which is significantly affected by the manure handling system and the regional climate (Table 2). Thus, IPCC (2006) provided emission factors regarding different scenarios. As mentioned in section 2.2, deep-bedding system is assumed to be applied in all feedlot in Saskatchewan and the manure on pasture from grazing cattle is not managed.

The energy CO_2 emission due to housing of beef cattle was also calculated by multiplying annual electricity consumption per cattle by emission factor of grid electricity in this model. According to the report by Southwell and Rothwell (1977), a beef cattle can consume 65.7 KWh electricity per year in Canada. The regional emission factor of grid electricity can be obtained from Environment Canada (2019).

2.3.2. Cropping GHG emission

The GHGs generated by feed production is mainly composed of soil N_2O emission from the N inputs due to fertilizer and manure application, and crop residue after harvesting. The input parameters for main cattle feed (barley grain, barley silage, and pasture) are shown in Table 3. The amount of feed required by these cattle can be estimated based on the forage intake rate of cattle (Table 4). Thus, the feed crop area by crop types can be calculated by the average yield and feed demands. The forage intake rate of cattle depends on the body condition of cattle and forage quality. Lactating cows have to eat more feed to produce milk. Cattle would eat more when their forage has high grain or component which is easier to digest. To ensure the rapid growth of body weight, finishing diet has a higher proportion of barley grain compared with backgrounding diet. The grain and silage account for 90% and 10% of the finishing diet, compared with 40% and 60% for backgrounding diet, respectively (Beauchemin et al., 2010).

The amount of soil N_2O emission is mainly determined by the nitrogen inputs and affected by some other factors, including crop types, soil texture, tillage, irrigation, leaching, runoff, and volatilization (Table 5). In addition, some agricultural activities such as chemical use (nitrogen, phosphorus fertilizers, and herbicide) and fuel consumption of agricultural machineries (for cropping and irrigation) can lead to the energy CO_2 emission (Table 5).

2.3.3. Transportation

The fuel consumption for transportation is another source of CO_2 emissions in the beef cattle production system. The transportation of beef cattle in Canada is mainly carried by highway (Flint et al., 2014), and road transportation is assumed for feed and cattle in this study. To estimate the amount of fuel consumed throughout the transportation

Table 3
Input parameters for crop properties.

Item	Barley grain	Barley silage	Pasture
DM Yield (kg ha^{-1} year^{-1})	2900	7410	3220
Moisture Content	0.12	0.55	0.13
N application rate (kg ha^{-1} year^{-1})	64	77	–
P_2O_5 application rate (Kg ha^{-1} year^{-1})	64	77	–
Herbicide applied	Yes	Yes	No
Above ground residue ration - N	0.007	0.007	0.015
Below ground residue ration - N	0.01	0.01	0.015
Irrigation rate (%)	1	1	–
Relative DM allocation			
Yield ratio	0.38	0.72	0.4
Above ground residue ratio	0.47	0.13	0.1
Below ground residue ratio	0.15	0.15	0.5

Table 4
Daily intake rate by diets.

Diet	Daily intake rate[a] (%)	
	Non-lactating cattle	*Lactating cow*
Hay	2.0%	2.3%
Pasture	2.5%	2.7%
Backgrounding or finishing	2.5%	2.7%

[a] Intake rate is the ratio of daily dry matter (DM) intake to the body weight of cattle.

Table 5
Emission factors for the cropping-source GHGs.

Gas sources	Equation/emission factor	References
Direct Soil N_2O		
Soil N inputs	EF_{eco} = 0.022 P/PE – 0.0048 [N_2O–N (kg N)$^{-1}$]	Rochette et al. (2008)
Tillage	(RF_{till} – 1) EF_{eco} [N_2O–N (kg N)$^{-1}$]	Rochette et al. (2008)
Soil texture	(RF_{text} – 1) EF_{eco} [N_2O–N (kg N)$^{-1}$]	Rochette et al. (2008)
Irrigation	(0.017- EF_{eco})/EF_{eco} × F_{irrig} [N_2O–N (kg N)$^{-1}$]	Rochette et al. (2008)
Indirect Soil N_2O		
Leaching	EF = 0.0075 [N_2O–N (kg N)$^{-1}$]	IPCC (2006)
	$Frac_{leach}$ = 0.3247 P/PE – 0.0247	Rochette et al. (2008)
Volatilization	EF = 0.1 [N_2O–N (kg N)$^{-1}$]	IPCC (2006)
	$Frac_{volatilizationcrop}$ = 0.01	IPCC (2006)
Energy CO_2		
Cropping fuel use	E_{fuel} × 75 [kg CO_2 ha^{-1} year^{-1}]	Little et al. (2008)
Herbicide use	$E_{herbicide}$ × 5.8 [kg CO_2 ha^{-1} year^{-1}]	Dyer and Desjardins (2007)
Fertilizer use	Nitrogen fertilizer: 3.59 [kg CO_2 (kg N fertilizer)$^{-1}$];	Nagy (2000)
	Phosphorus fertilizer: 0.5699 [kg CO_2 (kg P_2O_5 fertilizer)$^{-1}$]	Nagy (2000)
Irrigation	370 [kg CO_2 ha^{-1} year^{-1}]	Little et al. (2008)

EF_{eco}: Ecodistrict emission factor; RF_{till}: ratio factor for tillage (by province, soil type, tillage) (Little et al., 2008); RF_{text}: ratio factor for soil texture (by province, soil texture) (Little et al., 2008); F_{irrig}: fraction of agricultural land under irrigation; E_{fuel}: energy from fuel use (GJ ha^{-1}); $E_{herbicide}$: energy for herbicide use (GJ ha^{-1}).

process, the types of vehicle used and the average travel distance for three routes (feeder cattle to feedlot, cattle feed to feedlot, and finisher cattle to feedlot) are required (Table 6).

The total energy CO_2 generated from the transportation activities during the process of beef cattle production can be calculated by Eq. (2):

$$\sum E_{fuel,i} \times d_j \times TW_{i,j} \times \mathrm{EF}_{diesel} \quad (2)$$

where, $E_{fuel,i}$ is the fuel consumption rate for truck classification i (L/1000t-km); d_j is the average distance for transportation of j (100 km); $TW_{i,j}$ is the weight of fully loaded truck (for truck classification i and transportation of j); EF_{diesel} is the emission factor for diesel fuel (2.71 g CO2-eq/L diesel fuel) (Environment Canada, 2019).

Table 6
Average travel distance for feeding cattle, slaughter cattle, and cattle feed.

Route	Average distance (km)	Truckload	Weight of loaded truck (kg)
Feeding cattle to feedlot	149.7	75 cattle	41,659
Cattle feed to feedlot	22.3	22,000 kg	42,409
Slaughter cattle to slaughterhouse	153.7	45 cattle	37,409

* Data from (Kannan et al., 2016).

2.4. Data acquisition and analysis

A case study was conducted to quantify the GHG emissions due to the annual marketed cattle of Saskatchewan in 2014. The number of marketed beef cattle by classes and by crop districts was obtained from the marketing report of Saskatchewan Ministry of Agriculture (2014). Their statistic data include all beef cattle traded in Saskatchewan, including cattle bred in other provinces and counties. However, this study only focuses on the cattle fed within Saskatchewan boundary; the foreign cattle is excluded in this simulation.

The input parameters related to cattle, including body weight, maintenance coefficient, feeding activities coefficient, milk production, and fat content of milk, came from IPCC (2006) and Holos (Little et al., 2008). The duration of different growing stages was obtained from the studies by Beauchemin et al. (2010) and Legesse et al. (2016). Winter temperature (from November to April) can also affect the GHG emission because of its impacts on energy requirement for cattle maintenance. The Canadian climate normal from 1981 to 2010 collected by weather station in each crop district of Saskatchewan was used (ECCC, 2019). The diet coefficients, such as digestibility (DE), crude protein content (CPC), and methane conversion factor (Y_m), used in this simulation for various diets came from Holos (Little et al., 2008).

Barley silage and grain are the main ingredients of backgrounding and finishing diet, which are planted in commercial crop farm. Pasture and hay are the main diets for grazing cattle in summer and winter, respectively. The crop area required to supply these feeds can be calculated by the number of cattle, feed intake rate, and crop yield. The DM yield of barley grain, barley silage, and pasture are sourced from Statistics Canada (2019a), McCartney et al. (2004), and Legesse et al. (2016). The N and P_2O_5 fertilizer application rates used are obtained from official crop planning guide by Saskatchewan Ministry of Agriculture (2018). The fraction of 1% for the crop land in Saskatchewan is obtained from a report prepared by Clifton Associates Ltd. (2008). The climate data required by this model include precipitation (P) and potential evaporations (PE) in the growing season (from May to October), which can also affect the soil N_2O emission due to volatilization and leaching. In the terms of transportation, the default vehicle information and average distance for each route are sourced from Bai et al. (2007) and Kannan et al. (2016). The empty weight of default trucks plus trailer for feed and cattle transportation is 15,409 kg, and its fuel consumption rate is 16.65 L/1000 t-km.

The sensitivity analysis was conducted using Tornado analysis tool in Crystal Ball (Oracle, US) which is the spreadsheet-based application for predictive modeling, forecasting, simulation, and optimization (Oracle Crystal Ball, 2013). The aim is to determine the significant factors affecting GHG emission from beef cattle production, and thus assist the development of mitigation measures (Zhou et al., 2016a, 2016b, 2019). The range for those factors which have available data is set according to literature and ±20% variation range is used for others (Table 7). The input parameters of DE, CPC, and Y_m for diets, are obtained from Holos (Little et al., 2008). Also, the impacts of predicted climate changes on the GHG emission from beef cattle production in Saskatchewan are assessed based on the modeling results by Zhou et al. (2018) and Wang (2019). The temperature and precipitation changes were predicted dynamically-downscaled using Providing Regional Climates for Impacts Studies (PRECIS) model.

3. Results and discussion

3.1. GHG emission from beef production in Saskatchewan

The GHG emissions from the annual marketed beef cattle in Saskatchewan in 2014 were 8.52 × 10^9 kg CO_2-eq in total. Specific parameters, such as cattle number and climatic conditions, were defined

Table 7
Input parameters for factors affecting GHG emission from beef cattle production.

Factor	Default	Range [Min, Max]	References
Finishing diet			
Digestibility, DE (%)	81	[75, 85]	(IPCC, 2006; Little et al., 2008)
Crude protein content, CPC	0.125	[0.1, 0.14]	(IPCC, 2006; Little et al., 2008)
Methane conversion factor, Y_m	0.04	[0.02, 0.04]	(IPCC, 2006; Little et al., 2008)
Backgrounding diet			
Digestibility (%)	70	[65, 75]	(IPCC, 2006; Little et al., 2008)
Crude protein content, CPC	0.12	[0.1, 0.14]	(IPCC, 2006; Little et al., 2008)
Methane conversion factor, Y_m	0.065	[0.055, 0.075]	(IPCC, 2006; Little et al., 2008)
Pasture diet			
Digestibility (%)	60	[57, 70]	(IPCC, 2006; Little et al., 2008)
Crude protein content, CPC	0.12	[0.06, 0.18]	(IPCC, 2006; Little et al., 2008)
Methane conversion factor, Y_m	0.065	[0.06, 0.075]	(IPCC, 2006; Little et al., 2008)
Hay diet			
Digestibility (%)	55	[52, 65]	(IPCC, 2006; Little et al., 2008)
Crude protein content, CPC	0.12	[0.06, 0.18]	(IPCC, 2006; Little et al., 2008)
Methane conversion factor, Y_m	0.07	[0.065, 0.08]	(IPCC, 2006; Little et al., 2008)
Manure handling system			
Feedlot handling system	Deep bedding	Intensive windrow; Passive windrow; Solid storage	Little et al. (2008)
Cattle			
Milk production (kg day^{-1})	8	[5.5, 11.5]	Day et al. (1987)
Milk fat content (%)	4	[3, 5]	IPCC (2006)
Manure ash content, Ash (%)	8	[6.4, 9.6]	IPCC (2006)
Maximum methane producing capacity, B_o	0.19	[0.17, 0.21]	IPCC (2006)
Additive reduction factor, AR (%)	0	[0, 30]	(Little et al., 2008; Wang et al., 2018)
Climate			
Winter temperature (°C)	−7.1	[-8.6, −5.7]	ECCC (2019)
Growing season precipitation, P (mm)	306.1	[244.88, 267.31]	ECCC (2019)
Growing season potential evapotranspiration, PE (mm)	841.74	[673.4, 1010.09]	ECCC (2019)
Crop - Barley grain			
DM yield (kg ha^{-1})	2900	[1800, 3800]	(Statistics Canada, 2019a)
N application rate (kg ha^{-1})	64	[51, 77]	(Saskatchewan Ministry of Agriculture, 2018)
P_2O_5 application rate (kg ha^{-1})	64	[51, 77]	(Saskatchewan Ministry of Agriculture, 2018)
Irrigation rate (%)	1	[0, 2]	(Clifton Associates Ltd., 2008)
Crop - Barley silage			
DM yield (kg ha^{-1})	7330	[5421, 11,352]	(Saskatchewan Ministry of Agriculture, 2012)
N application rate (kg ha^{-1})	77	[62, 93]	(Saskatchewan Ministry of Agriculture, 2018)
P_2O_5 application rate (kg ha^{-1})	77	[62, 93]	(Saskatchewan Ministry of Agriculture, 2018)
Irrigation rate (%)	1	[0, 2]	(Clifton Associates Ltd., 2008)
Energy			
E_{fuel} (GJ ha^{-1})	1.88	[1.5, 2.25]	Little et al. (2008)
$E_{herbicide}$ (GJ ha^{-1})	0.28	[0.23.0.34]	Little et al. (2008)
$EF_{electricity}$ (kg CO_2-eq KWh^{-1})	0.77	[0.62, 0.92]	Little et al. (2008)
Vehicle fuel consumption rate (L/1000t-km)	16.65	[13.32, 20]	Kannan et al. (2016)

for each district in this assessment and the GHG emission by crop districts is shown in Fig. 3. The uneven distribution of beef cattle industry resulted in the difference in the level of GHG emission in each crop district. 9 b was the district which produced the largest number of beef cattle, accounting for 9.6% of the total number in Saskatchewan. The developed beef cattle market in 9 b also led to the largest amount of GHG emissions (1.03×10^9 kg CO_2-eq) compared with other districts. In contrast, the least-producing district 8 b only contributed to 1.13×10^8 kg CO_2-eq GHG emission. The GHG emission from beef cattle in most other districts ranged from 2.92×10^8 to 7.27×10^8 kg CO_2-eq. The uneven distribution of beef cattle industry and its GHG emission can be explained by the traffic routes in Saskatchewan. The districts with the higher number of beef cattle are basically around the two main highways, Highway 16 (5 A, 5 B, 6 A, 6 B, 9 A, and 9 B) and Trans-Canada Highway 1 (1 B, 2 B, 3AN, 3BN, 4 A, and 4 B).

The GHG emission from beef cattle production in Saskatchewan was categorized by their sources as shown in Fig. 4. The majority of GHG emission such as enteric CH_4, manure N_2O, and manure CH_4 was directly caused by the cattle activities. They contributed to the 63.12%, 18.73%, 13.38% of the total emission respectively. In contrast, the soil N_2O (1.39%) and energy CO_2 (3.39%) only resulted in minor parts of total GHG emission from beef cattle production. The sources of energy CO_2, including electricity consumption for beef housing, herbicide and fertilizer use, and fuel consumption for cropping, irrigation, and transportation, are shown in Fig. 4. The electricity consumption from housing beef accounted for the largest proportion (50.19%) of total GHG emissions for this sector. The emission factor of grid electricity of 2014 in Saskatchewan was 0.77 kg CO_2-eq KWh^{-1}, which was much higher than then the average level (0.15 kg CO_2-eq KWh^{-1}) in Canada (Environment Canada, 2019). The N fertilizer use is the second most-significant source, which contributed 26.06% of the total energy CO_2 emission. The figures for cropping, P_2O_5 fertilizer use, transportation, herbicide use, and irrigation in energy consumption were 14.99%, 4.14%, 3.39%, 0.84% and 0.39%, respectively.

Enteric fermentation was the most GHG-producing source in the beef production system. Legesse et al. (2016), Alemu et al. (2017), and Beauchemin et al. (2010) analyzed the beef production GHG emissions in Canada respectively, and their results are similar with this study. In their studies, the enteric CH_4 accounted for 73%, 65%, and 63% of the total emission, respectively. The cattle-source GHG emission, including enteric CH_4, manure CH_4, and manure N_2O, led about 90% of emission in the whole production system according to their assessment results.

3.2. Sensitivity analysis

The sensitivity analysis can be used to determine the critical factors affecting the GHG emission and develop corresponding mitigation strategies (Hu et al., 2018; Li et al., 2019; Lu et al., 2019). All the

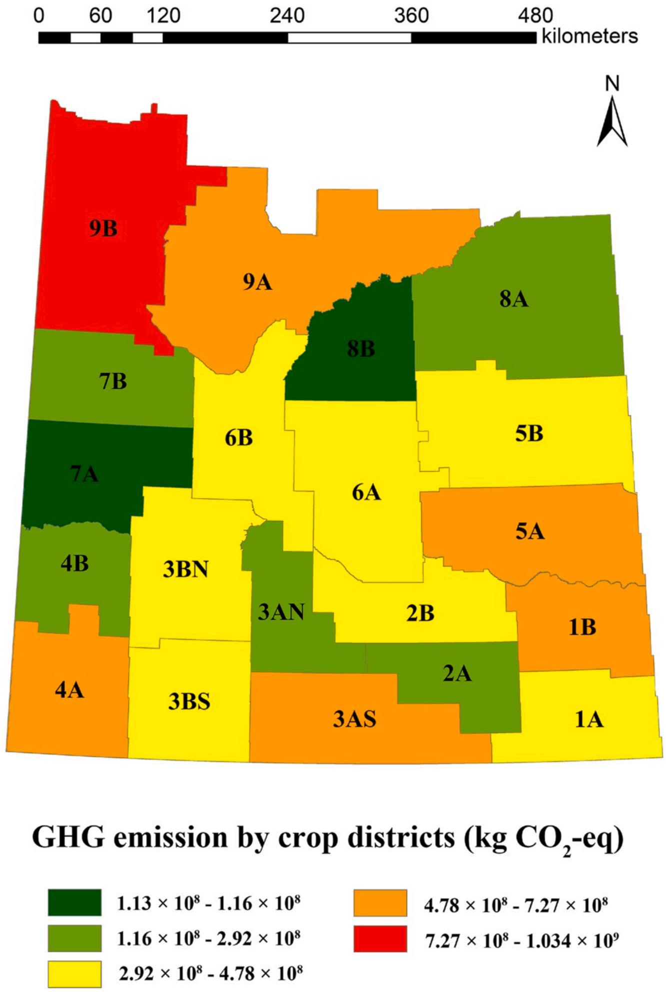

Fig. 3. The GHG emission from beef cattle production in 2014 by crop districts of Saskatchewan.

parameters used in the sensitivity analysis and their range are shown in Table 7. The Tornado charts (Fig. 5), for total GHG emission, enteric CH_4 emission, manure GHG emission, and cropping GHG emission are modified and produced based on the calculation results from Crystal Ball. The sensitivity of factors can be calculated by Eq. (3):

$$\beta = (U_f - D_f)/B_f \tag{3}$$

where β is the sensitivity; U_f, D_f, and B_f are the upside, downside, and baseline of the forecasting variable. Only those main factors with sensitivity more than 1% for each forecasting target are listed in these charts (Fig. 5). According to the results, the most critical factors influencing the GHG emission included feedlot manure handling system, cattle diet, feed additives, maximum methane producing capacity (B_o), and climate (temperature, precipitation-P, and potential evapotranspiration-PE). The effects of these factors on the GHG emission and their potential mitigation measures in the beef cattle production were further discussed in the following sections.

3.3. *Roles of feedlot manure handling system*

When the deep-bedding method was widely applied in feedlot of Saskatchewan, 18.73% and 13.38% of GHG emission were caused by N_2O and CH_4 emission from feedlot cattle manure respectively. Even though the manure handling system can only affect the generation of manure-source GHGs, it is the most sensitive factor for GHG emission from beef cattle production system according to the sensitivity analysis (Fig. 5). The sensitivity for the total emission and manure emission were 44.93% and 155.52%, respectively. Five variables (MCF, EF_{leach}, $Frac_{leach}$, $EF_{volatilization}$, and $Frac_{volatilization}$) involved in this factor can determine the direct and indirect N_2O emission caused by cattle manure. The default parameters for four manure handling system shown in Holos (Little et al., 2008) were used in this analysis. The deep-bedding was assumed as default method in all feedlot of Saskatchewan. In this scenario, 2.73×10^9 kg CO_2-eq GHG could be generated from cattle manure. According to the results, composting - intensive windrow and solid storage are the most and least GHG-producing manure handling system, which can increase 55% and reduce 19% of manure GHG emission respectively, compared with the deep-bedding.

These differences in the manure GHG production were mainly due to the different oxygen supply levels on manure. The N_2O emission from manure is primarily contributed by the nitrification under aerobic conditions (Hao et al., 2001). Even though the denitrification under anaerobic conditions can also produce N_2O, it only occurs in the later stages of manure storage when the oxygen is used up inside, and only have low level of reaction rate (Pattey et al., 2005). However, the anaerobic conditions are favorable for the production of CH_4 caused by fermentation and anaerobic respiration (Hao et al., 2001). The composting with intensive windrow method requires the regular turning for mixing and aeration. The adequate oxygen supply enhances the NO_2

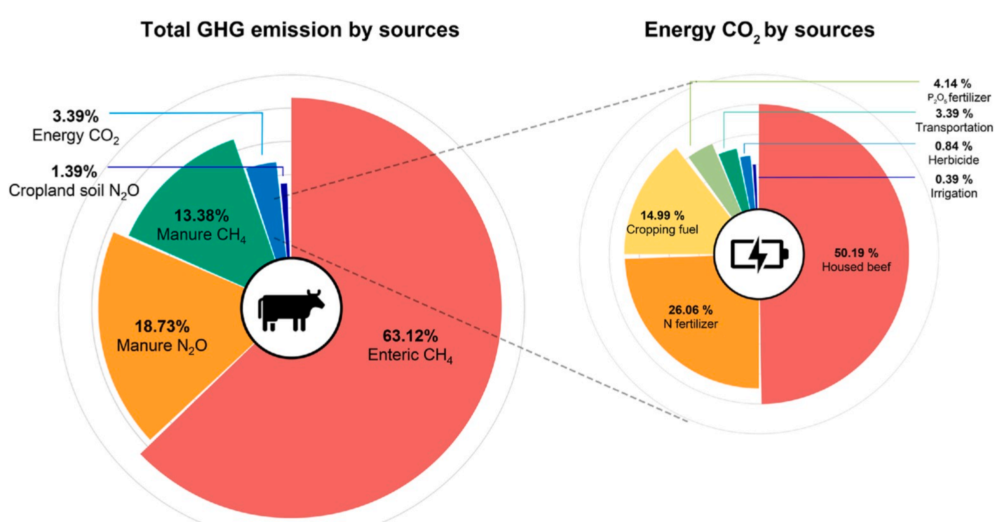

Fig. 4. The GHG emission from beef cattle production by sources.

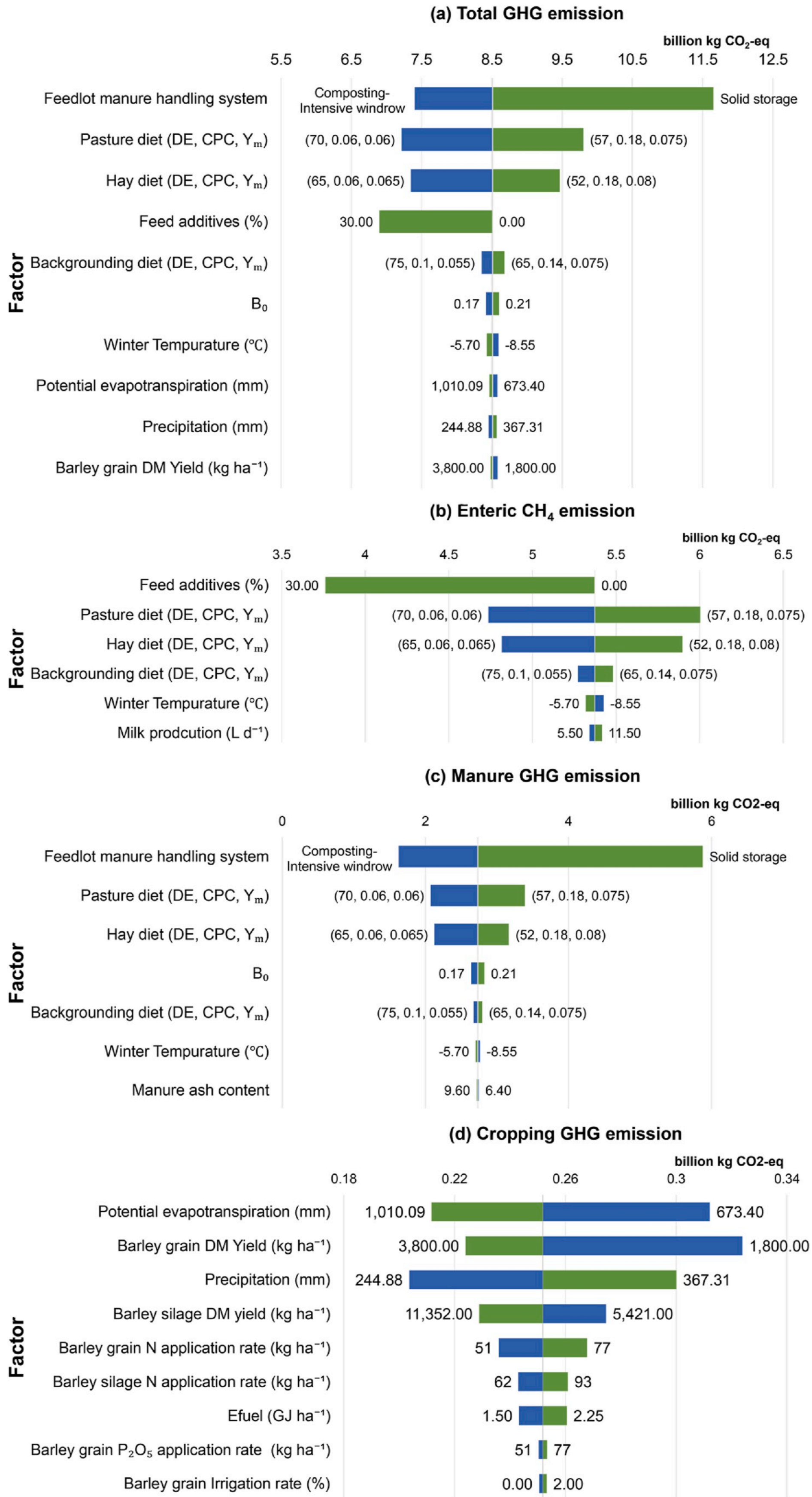

Fig. 5. The Tornado charts for (a) total GHG emission, (b) Enteric CH_4 emission, (c) Manure GHG emission, and (d) Cropping GHG emission.

production from nitrification, which is the reason why this method has the largest GHG emission in comparison with others.

As previously described, the processes for CH_4 and N_2O production mainly occurred under anaerobic and aerobic conditions respectively; thus, it is hard to prevent their generation at the same time (Clemens et al., 2006). Limited research has been done to optimize the handling system for diminishing the manure GHG emission. Using livestock manure to generate biogas from anaerobic fermentation can be the potential mitigation measure (Wang et al., 2018). It is not only an effective measure to mitigate the impacts of manure methane emission but also provide the renewable energy (Chen et al., 2019b; Feng et al., 2018). However, the GHG production caused by the application of biogas generator and other manure handling systems was not compared in previous studies.

3.4. Effects of cattle diets

Cattle diets were the one of the most crucial factors for the GHG emissions from beef cattle production industry in Saskatchewan, especially for pasture and hay diets which were feed for grazing cattle in summer and winter, respectively. The sensitivity of these two factors for the total GHG emission were 30.38% and 18.84% respectively, but the corresponding figures for backgrounding diets and finishing diets were only 3.85% and 0.4%, respectively. The Tornado charts (Fig. 5b and c) demonstrated that change in diets could be an efficient way to alter the total GHG emission from beef production system. The cattle diets vary by the types of cattle and growing stages, which have been discussed in section 2.1.1. The high-grain diets are only available for backgrounding and finishing cattle in feedlot. Thus, the amount of grain feeds consumed is much less than that for hay and pasture grass because the main GHG contributor, cattle-calf operation, is generally conducted on pasture instead of feedlot. In addition, less fiber contained in the high grain diets can result in less GHG emission from enteric fermentation and manure; thus, the lower default values cause their lower variation range. These are the reasons why pasture and hay diets show higher significance than those for high-grain (backgrounding and finishing) diets on GHG production in the sensitivity analysis.

The feed components provide the substrate for rumen fermentation and thus determine the level of methane production. The rumen microbes can assist cattle to access the energy from fiber, but methane is generated during this process at the same time. Reducing the component of fiber by increasing the grain feeds ratio can effectively reduce the production of enteric CH_4. The methane conversion factor (Y_m) can decrease by about half when the grain feed ratio reaches 90% or more (Wang et al., 2018). However, the high-grain diets are easier to be digested by cattle; more residual feed intake can benefit the enteric methane production. Thus, even though the results show that using high-grain diets can mitigate GHG emission in the beef cattle production, it is not an economical and efficient strategy.

Although it is hard to mitigate the methane production by adjusting cattle diet, it is possible to use some strategies to reduce the N excretion rate and associated manure N_2O emission (Dijkstra et al., 2011). The major mitigation approach for N excretion reduction is to apply the low crude protein diet. Applying the minimum amount of N fertilizers which would not extend the harvesting cycle can help reduce the concentration of crude protein of plant (Dijkstra et al., 2011). It was reported 12.8% and 3.5% reduction on the N excretion and N_2O emission could be achieved respectively if the low crude protein diets were used for beef cattle (Wang et al., 2018).

3.5. Effects of feed additives

Food additives can reduce total GHG emissions by mitigating enteric methane production. It ranked the fourth and first most-significant factor which can affect total GHG emission and enteric CH_4 emission, respectively. Adding additives into feed can at most reduce 30.00% of enteric CH_4 emission and 18.94% of total GHG emission in comparison with the default conditions. Two types of feed additives, ionophore and fat, are considered in Holos (Little et al., 2008), but more chemicals are being developed to mitigate the enteric CH_4 production of ruminants in recent years.

Ionophore such as monensin, lasalocid, salinomycin, narasin, maduramicin, laidlomycin, and semduramycin is a species of chemicals, which is commonly used as antibiotics in the beef and dairy cattle production industry to improve the cattle health and feed efficiency (Beauchemin et al., 2008; Novilla et al., 2017). The ionophore has an effective and short-term reduction on the rumen methanogenesis (Bayat and Shingfield, 2012). According to the report by Guan et al. (2006), adding monensin to cattle feed decreased up to 30% of CH_4 emission from enteric fermentation at the first two weeks; however, its effects were reduced over time. Such effects are caused by the inhibition mechanism of ionophore. It can inhibit the rumen protozoal numbers and adjust the ratio of various ruminal bacteria to reduce the rumen methanogens. These microorganisms can gradually adapt to this chemical in their living environment and restore to the former status.

Lipid additives, as an extensively-used enteric CH_4 mitigation strategy in the livestock production industry, have attracted increasing attention. The model in Holos applied the opinion from experts and used 20% as the value of the enteric methane reduction for lipid supplementation. However, the effects on the CH_4 mitigation vary by the categories and sources of lipids. The lipid can suppress the rumen protozoal and reduce fermentable substrate (Knapp et al., 2014). Thus, the methane generation can be decreased by 10–40% by lipid supplementation (Beauchemin et al., 2008). Some negative impacts of lipid were also observed by some researchers (Martin et al., 2010). For example, a meta-analysis conducted by Eugène et al. (2008) showed that lipid could reduce 9% methane production but there was also 6.4% decrease in DMI. Beauchemin et al. (2007) tested the effects of lipid on 16 growing Angus heifers and found that the digestibility decrease ranged from 12% to 20% by categories of lipids. However, there was still average 17% reduction on methane emission while this decrease in the digestible energy intake was considered.

Recently, there are also some studies on the use of other chemical additives including electron receptor category, halogenated CH_4 analogues, and plant bioactive compounds for the mitigation of methane. The mean reduction on enteric CH_4 production by using electron receptor category, such as nitrate, fumaric, and malic acids, was 15.2% according to the meta-analysis by Wang et al. (2018). Halogenated CH_4 analogues, such as hloroform, CCl_4, chloral hydrate, bromochloromethane, and bromoethanesulphonic acid, can also inhibit the activity of rumen methanogens (Sejian et al., 2011). The experimental results of Tomkins et al. (2009) demonstrated that adding bromochloromethane into feed could reduce 93.7% of methane production of cattle in the first 90 days, and 40% of effect remained in the following 30 days although there was a declining trend over the time. In addition, the potential use of plant compounds such as tannins, saponins, and essential oils for enteric methane reduction were also studied. Martin et al. (2010) reported that the enteric methane generation rate of various ruminants was decreased by 0–30% when using different plants extract additives.

Even though the effects of methane production mitigation by a variety of chemicals have been confirmed in *vitro* and in *vivo*, studies demonstrated that some additives could have potential negative effects on ruminants and human health (Russell and Houlihan, 2003). Thus, most of the additives mentioned in the previous studies were not applied in large scale, and some were even banned in some areas. For instance, the use of ionophores has been prohibited in Europe since 2006 (Bayat and Shingfield, 2012). However, dietary lipids would be the most recommended feed additive to mitigate the CH_4 production if both health and efficiency considerations were taken into account (Wang et al., 2018).

3.6. GHG emission from beef cattle production under changing climate

Human activities resulted in the climate change and changing climate also responded to the anthropogenic GHG emission (Li et al., 2018; Xie et al., 2019). Considering the impacts of climate change in the assessment of GHG emission could contribute to the better understanding of their relationship; therefore, the scenario for the future climate was discussed in this study. The climatic factors considered in this model included winter temperature, growing season P, and growing season PE. The mean sensitivities of these three factors for the total GHG emission were 1.94%, 1.37%, and 1.31%, respectively.

Winter temperature can affect feed intake due to the changes in the required maintenance energy (Gonyou et al., 1979) and thus alter the GHG emission from enteric fermentation and manure (IPCC, 2006). In addition, Christopherson (1976) observed in the field tests that the lower DM digestibility of cattle could be caused by the lower environment temperature, resulting in the increase in the enteric methane production. The open farm conditions were assumed in this study; therefore, the same value as average air temperatures were used for the barn. In fact, farmers would also apply some methods such as installing insulation layer in the external wall of barn, adding extra bedding for cattle, and providing blankets with young claves to keeping warm in extreme cold weather and ensure the safety of cattle (Mitch Wertlieb and Bodette, 2018).

The growing season P and PE are the most critical factors for soil N_2O emission (Little et al., 2008). Soil moisture is strongly correlated with P and PE, affecting the oxygen content in soils (Rochette et al., 2018). The water in void can block the exchange of air between porous media and atmosphere, providing the anaerobic environment for the N_2O production due to nitrification (Lesschen et al., 2011b; Zhao et al., 2015). Other environmental conditions such as soil pH, temperature, and organic carbon content can also alter soil N_2O emission factors (Lesschen et al., 2011b; Rochette et al., 2018). Many studies have been conducted to explore the relationship between soil N_2O emission and these factors (Lesschen et al., 2011b; Rochette et al., 2008, 2018; Zhang and Han, 2008), which can be used in the further development of GHG emission assessment model.

The climate change affects the weather pattern worldwide, which can also alter the amount of GHG produced during the process of beef cattle production. The impacts of climate change (2020–2099) on GHG emission from the system were predicted according to the climate forecasting data (Wang, 2019; Zhou et al., 2018). The predicted climate data at the same location of the climate stations were used and other parameters were set same as the default values to ensure the results are comparable.

Fig. 6 shows the changes of GHG emission by districts in 2020–2039, 2040–2059, and 2060–2099, compared with the baseline in 2014 shown in Fig. 3. An overall decrease in the GHG emission can be observed due to the climate change, which are 3.67%, 4.96%, and 6.63% for 2020–2039, 2040–2059, and 2060–2099, respectively. It can be explained by the increase in the winter temperature climate change and the reduction in the precipitation. The rising temperature can result in the decrease in feed intake rate and thus the enteric and manure emission; the reducing precipitation can benefit the aeration of subsoil and thus mitigate the soil N_2O emission due to nitrification. It should be noted that this prediction can only give the views in terms of emission factors; it could have much more complicated impacts on GHG emission from beef production due to climate change.

4. Conclusions

In this study, a new framework for the assessment of reginal GHG emission from cattle production was established. This framework was used for assessment of GHG emission from the marketed beef cattle of Saskatchewan. The results showed that the cattle-source GHGs (enteric CH_4, manure CH_4, and manure N_2O emission) accounted for more than 90% of the total emission from beef cattle production. In addition, the electricity consumption by cattle housing has accounted for more than half for the energy CO_2 emission during beef cattle production.

The sensitivity analysis indicated the main factors affecting the total GHG emission from beef cattle production system were feedlot manure handling system, cattle diets, and feed additives. Various mitigation measures such as applying advanced manure handling system, high-grain diets, and appropriate additives can reduce 10–20% of total GHG emission. The changing climate in Saskatchewan can lead to an overall decreasing trend on the regional GHG emission by beef cattle production due to the increase in temperature and the decrease in precipitation. The results of this study can be used to provide authority a scientific guideline to establish the policy and strategy for mitigating GHG emission during the cattle production process. Some limitations of the present study can also be further improved in the future research. The data used in the model were obtained from related papers and reports. For example, some assumptions can be better adapted to the situation in Saskatchewan. In addition, this study assessed the potential impact of climate change on GHG emissions from beef production mainly based on the consideration of climatic parameters. However,

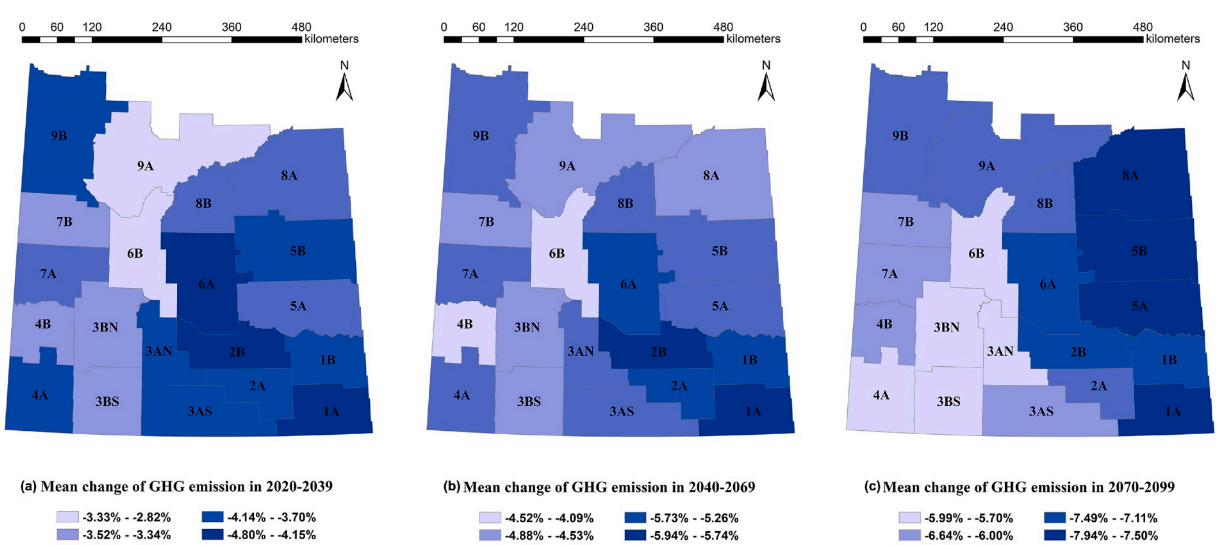

Fig. 6. Mean change in the GHG emission from beef cattle production due to climate change (a) in 2020–2039, (b) in 2040–2069 and (c) in 2070–2099.

other results regarding the impact of changing environment will need to be obtained using improved climate and process models. Future development of assessment methodology is also required to explore the mechanisms and interaction between many influencing factors.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Zhikun Chen: Writing - original draft, Data curation, Formal analysis, Conceptualization. **Chunjiang An:** Writing - review & editing, Formal analysis, Funding acquisition, Conceptualization. **Hanxiao Fang:** Conceptualization, Formal analysis, Data curation. **Yunlu Zhang:** Conceptualization, Formal analysis, Data curation. **Zhigang Zhou:** Conceptualization, Formal analysis, Data curation. **Yang Zhou:** Data curation, Formal analysis, Conceptualization. **Shan Zhao:** Data curation, Formal analysis, Conceptualization.

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