Management practices to improve the sustainability and profitability of cow-calf operations across Canada

By

Aaron James Knodel

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Department of Animal Science
University of Manitoba
Winnipeg, Manitoba
Canada, R3T 2N2

ABSTRACT

Increasing demand for food with higher environmental standards is shaping agricultural activities toward more sustainable food systems. The objective of this research was to estimate whole-farm greenhouse gas (GHG) emissions while concurrently examining the profitability of cow-calf operations with varying management practices across Canada. Twenty-five benchmark farms with similar environmental conditions and production practices were developed using data from 115 cow-calf operations. Greenhouse gas emissions including methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) were estimated using the Holos whole-farm model. Emission intensity was calculated as net GHG emissions (kg of CO_2 equivalent) divided by total liveweight (LW, kg) sold. Farm emission intensity ranged between 18.3 and 35.1 kg CO_2 equivalent/ kg LW. Both emissions and profitability varied widely across farms with those in the Western provinces reporting generally higher emission intensity, due to higher enteric CH_4 emissions. Farms that utilized tame grass and legume species reported lower enteric CH_4 emissions, while those that utilized extended grazing practices had lower manure CH_4 emissions. Growing annual grain crops for export was associated with higher net farm incomes. Modelling of future farm scenarios was conducted to assess impact of changes in on-farm management practices including grazing standing corn, adoption of rotational grazing, use of artificial insemination, creep feeding, shortened calving intervals, and improved watering systems on GHG emissions and economic outcomes. The impact of the changes in management practices was not consistent across all farms, resulting in a small (0.004%) increase to 4% reduction in GHG emissions while improving whole farm net cash income by 3 to 41 % and cow-calf enterprise profitability by 2 to 130%. Therefore, consideration of existing farm practices and the local environment is essential when considering changes in management to improve economic sustainability and reduce GHG emissions.

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I would also like to thank Mitacs Accelerate, the Canadian Cattle Association, the Beef Cattle Research Council, Canadian Roundtable for Sustainable Beef and the University of Manitoba for funding this project and sponsoring my studies.

I would also like to all the beef producers who participated in this study, as their engagement will help to serve the generations that follow them. Thank you to all Canadian farmers, as their tireless work feeds the world and too often goes unrecognized.

Finally, I would like to thank my parents for supporting and encouraging me throughout my academic career and always setting a good example for me throughout my life. Thank you to my wife Samantha for also inspiring and encouraging me through all the challenges I have faced. Thank you to my church family and all those who have prayed for me over the years and continue to support me, and to God who gave me the gifts to accomplish this work and blessed me with every day I have.

Contribution of Authors

A.J. Knodel: Conducted modeling, result interpretation, writing of thesis document and subsequent editing; K.H. Ominski, A.W. Alemu: Supervision, conceptualization, reviewing, and editing; B. Grant: Conceptualization, economic analysis and editing: E. Stephens and D. Brewin: Reviewing and editing; D. Fulawka: Review of model input and output data; Roland Krobel: Team lead for the Holos modeling group.

Dedication

I dedicate this work to my daughter Clara, who is the ultimate example of curiosity, she has already made me so proud. I hope this thesis can play some small part in creating a better world for her to live in.

LIST OF ABREVIATIONS

AAFC = Agriculture and Agri-Food Canada

AB = Alberta

ALUS = Alternative Land Use Services

AI = Artificial insemination

BC = British-Columbia

BMP = best management practices

BSE = bovine spongiform encephalopathy

CRSB = Canadian Roundtable for Sustainable Beef

CH_4 = Methane

CO_2 = Carbon dioxide

GDP = Gross domestic product

GHG = Greenhouse gas

GWP = Global warming potential

H_2 = Hydrogen

KPI = Key Performance Indicators

LW = Liveweight

MB = Manitoba

N_2O = Nitrous oxide

NO_2 = Nitrite

NH_3-N = Ammonia nitrogen

NO_3 = Nitrate

ON = Ontario

QC = Quebec

SARPAL = Species at Risk Partnership on Agricultural Lands

SK = Saskatchewan

SOP = Standard Operating Procedure

SLC = Soil Landscapes of Canada

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Foreword

This thesis is written in manuscript style following Canadian Journal of Animal Science outline, comprised of an abstract, introduction, materials and methods, results, discussion and conclusion. This thesis also contains a general introduction, literature review, general discussion and general conclusion, followed by literature cited. The manuscript has not been submitted for publication at the time of thesis completion.

1.0 General Introduction

Greenhouse gas (GHG) emissions associated with agricultural production have generated interest as consumers, private industry, commodity groups and governments have committed to reducing global emissions. According to the recent National Inventory Report (Environment and Climate Change Canada, 2024), Canadian beef production generates about 3.56% of the total national GHG emissions and 45% of agricultural emissions. Furthermore, on a global scale, the industry is the most emission-intensive production system when measured on a total emission basis compared to all other livestock animal species (FAO, 2015). The majority of beef production emissions in Canada are associated with the cow-calf sector (Beauchemin et al., 2010a), in which breeding stock are maintained on mid- to low-quality forages resulting in higher enteric methane (CH_4) as compared to the finishing sector where steers and heifers are fed high energy diets containing 85 to 90% concentrate (Sheppard et al., 2015).

Within the cow-calf sector, Canadian producers manage complex agro-ecosystems using diverse management practices and tools based on available resources, labor availability and a myriad of other factors. Several management practices have been demonstrated to reduce on-farm GHG emissions on cow-calf operations including increased use of legumes, and improved forage quality (Jonker et al., 2015, Beauchemin et al., 2009). However, many producers, even the most willing, are often reluctant to adopt mitigation strategies especially those that result in the potential for increased cost and reduced profit, with little or no financial incentive.

Given this diversity in production systems, it is challenging to identify management practices which lead to improved profitability as well as reduced on-farm emissions. Therefore, models that account for all the farm components and estimate whole-farm emissions have been used to evaluate the impact of management practices. Models developed in Canada (including the Holos whole-farm model, (AAFC 2024a) use regionally-specific data to estimate GHG emissions but currently lack an economic model component that can integrate farm emissions with cost of production data to provide a profitability analysis. To fill this gap, the objective of our research was to characterize management practices used on cow-calf farm across Canada using regional data from cow-calf producers, estimate GHG emissions generated by those farms, and the profitability of the farms, thereby determining potential management scenarios that can improve the economic and environmental sustainability of the cow-calf industry.

2.0 Literature Review

2.1 Overview of Canadian Beef Industry

2.1.1 Industry Characterization

The Canadian beef industry is complex as ecosystems and the management practices used are highly diverse with operating costs that can fluctuate significantly based on market prices of inputs. Nonetheless, the objective of the beef sector is to produce environmentally sustainable, high-quality meat to meet the growing demands of both domestic and international markets. The beef industry is divided into three sectors. These include: i) cow-calf, ii) backgrounding/stocker, and iii) finishing/feedlot production systems (Figure 1). Cow-calf production includes breeding stock (mature cows, breeding bulls, and replacement animals) that are maintained on-farm with weaned calves sold for backgrounding or finishing. Backgrounding is the period of growth between weaning and the finishing phase for slaughter during which cattle are provided with high forage-based diets for several months (from 6-12 months of age) until they have gained sufficient frame size (approximately 400-500 kg body weight) to enter the finishing stage. During the finishing phase, cattle are fed high-energy, grain-based diets to increase weight and add intramuscular fat for a high-value end product (Alemu et al. 2016). However, for grass-finished beef operations, the diet during finishing phase is comprised solely of high-quality forages.

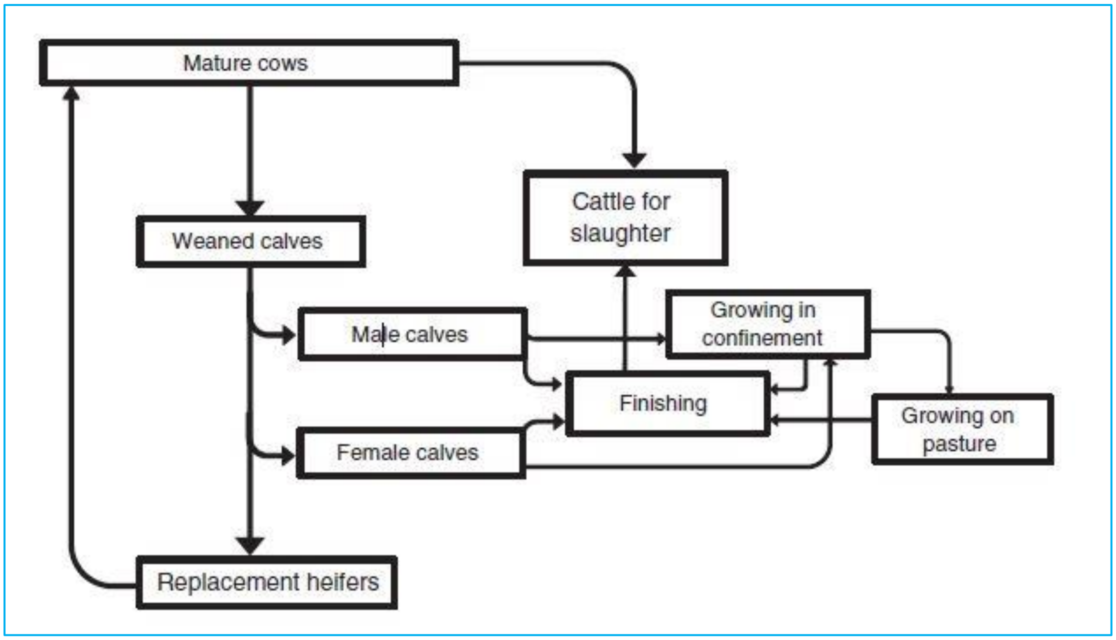

Figure 1. The beef cattle production cycle in Canada (adapted from Legesse et al. 2016)

The average number of beef cattle per farm in Canada has been steadily increasing over the past several decades and in 2022 was 115 head (Canfax 2022a). This follows the trend of other sectors of the agricultural industry which continue to consolidate, resulting in fewer but larger farms. However, the beef sector has a wide range of farm sizes with approximately 61% of producers managing less than 47 head while 16% have more than 122 head (Canadian Cattle Association 2020). The average herd size is also greatly influenced by location in Canada, as the Western provinces of Alberta and Saskatchewan tend to have larger herds than the Eastern and maritime provinces. Beef producers with smaller herds may rely on other sources of income including grain and oilseed operations as well as off-farm income (Heiberg and Syse 2020).

The beef cattle industry workforce is also diverse but is primarily comprised of owner operators that raise cattle with 60% of producers aged 45 or older, and 16% over 65 years of age (Canadian Agricultural Human Resources Council 2016). Almost 60% of beef farms are operated by male producers while 32% are jointly operated by male and female producers. The occurrence of female only operators is relatively low (Statistics Canada 2017a). It is important to note that the trend towards more females working in the industry has been steadily increasing over recent years.

The beef industry in Canada generates $21.8 billion in gross domestic product (GDP) and 71,000 jobs directly and 347,000 jobs in associated industries including transportation, meat packing and processing, feed processing, as well as equipment sales, maintenance and distribution (Kulshreshtha & Nagy 2021). Furthermore, there is a strong linkage between the beef industry and other agricultural sectors including crop/feed production and meat processing. In addition to their unique ability to convert high fiber feeds (unsuitable for human or monogastric consumption) it into high quality protein (meat, milk), the beef cattle industry also provides a market for grains that are damaged or spoiled, by-products from processing and distilling industries as well as cereal straw, among many others (Buckner et al. 2008). Furthermore, beef cattle can graze on marginal land that is not suitable for crop production which allows for better use and conservation of the land-base in Canada.

2.1.2 Regional differences in beef production systems in Canada

The majority of Canadian beef production takes place in the prairie provinces of Manitoba, Saskatchewan and Alberta which possess 9%, 21% and 42% of Canada's beef cattle, respectively (Statistics Canada 2017b). The Eastern provinces of Ontario and Quebec possess 13% and 9%, respectively, while British Colombia (5%) and the Atlantic provinces (2%) make up a relatively small portion of the Canadian beef herd.

The highly diverse landscape in Canada, with distinct differences in weather patterns, vegetation, topography, urbanization and other factors, has led to differences in management practices used to raise beef cattle. Management in the prairies tends to be more extensive with use of large grazing areas during the summer months and of extended grazing strategies (including swath, stockpiled and bale grazing) during the winter-feeding season (November to April). Alternatively, Eastern Canada is characterized by intensive grazing systems and traditional confined management systems in the winter months where animals are provided with stored forages/feeds (Sheppard et al. 2015). These differences in fall/winter management may be attributed to the relatively dry conditions and colder winters experienced in the Western prairies which lead to lower forage yields, but also the ability to leave forage bales uncovered as they are less susceptible to damage as compared to the Eastern provinces (Sheppard et al. 2015). Large feedlots and finished cattle are concentrated in Alberta along with the majority of the beef slaughter capacity (Canfax Research Services 2024). Using a cluster analysis approach based on 41 diagnostic variables (including herd size, production type, land use, feeding strategies, risk taking, and integration of other farm ventures) obtained from a nation-wide producer survey, Alemu et al. (2016) described 8 different clusters of beef farms in Canada, independent of their geographical location. These clusters were: i) small-scale, part-time cow–calf operations (37%); ii) cow-calf to finishing operations (7.7%); iii) large backgrounding and finishing operations (1.1%); iv) diversified cow-calf operations (11.3%); v) extensive cow-calf backgrounding operations (2.1%); vi) large cow-calf backgrounding operations (18.4%); vii) crop-beef mixed operations (22.2%); and viii) large finishing operations (0.2%). This diverse characterization demonstrates the complexity of Canadian beef production system.

2.1.3 Current industry challenges

The Canadian beef industry faces several significant challenges that impact the environmental sustainability and economic viability of the sector. Maintaining access to global markets in a competitive environment is vital to the Canadian agriculture sector including the beef industry because much of the beef produced in Canada is destined for export. Canada is among the top 11 beef producing and the top 10 beef exporting nations in the world, exporting 31% of the total beef and cattle produced in 2022 (Ghazalian 2024). The majority of beef and beef products are exported to the USA, Japan, and Mexico (Canfax Research Services 2024) with the majority of live cattle exports also going to the USA (AAFC 2024b). Factors including, disease outbreaks, competition from other nations, as well as trade barriers and tariffs plays a role in limiting Canadian beef exports to international markets. Although the bovine spongiform encephalopathy (BSE) outbreak occurred two decades ago, its impact was profound as it resulted in a significant loss in the Canadian export market (Moens 2006). As a result, many Canadian producers experienced negative profit margins and left the industry entirely (Mitura and Di Piétro 2004). Canada remains vulnerable to disease outbreaks such as foot and mouth disease as the potential for border closure poses a significant threat to the export market. In addition, other common bovine diseases (bovine respiratory disease, bovine viral diarrhea, avian influenza) continue to pose challenges to the economic viability of the beef industry.

Trade barriers have also limited market access. For example, Canada's export to the European Union (EU) is limited to beef raised without growth-enhancing technologies including implants (Canadian Cattle Association 2020). Implanting is a common practice to improve feed efficiency, and average daily gain while reducing feed inputs for finishing cattle (López-Campos et al. 2012). In addition, implants have been shown to reduce GHG and ammonia emissions, as well as improve land and water use (Aboagye et al., 2022). Beef exports may also be affected by geo-political trade disputes that can result in tariffs or border closure associated with BSE, as well as increased costs that were associated with the implementation of the country of origin labeling policy.

Labour shortage is another critical issue for the beef industry, as producers are challenged to find qualified employees to keep operations running at full capacity. In 2019, 49% of Canadian beef producers were unable to fill positions on their farm, costing the industry an estimated $334 million annually in lost production (Canadian Agricultural Human Resource Council 2019). Labor shortages are expected to grow as the average age of producers continues to increase sand rural depopulation continues, leaving fewer people to fill the labor gap. The beef industry often has less access to imported labour compared to other sectors of agriculture, because it requires year-round employment rather than seasonal labor thereby narrowing the number of potential workers (Canadian Agricultural Human Resource Council 2019). Labour is often in short supply in the processing sector as well, which was exacerbated by the COVID-19 pandemic (Rude 2020). The meat packing and processing industry by necessity requires many employees working closely together, and therefore, the risk of virus transmission poses a threat, making it difficult to recruit and maintain healthy workers necessary to operate at capacity (Donaldson 2020).

Conversion of perennial grassland to high value annual crops including grains and oilseeds (Statistics Canada 2016), as well as urbanization have created further challenges for the cattle industry as raising cattle requires an extensive land-base for grazing and feed production. Land prices in Canada have been steadily increasing for most of the 20th century, and in recent years, has been accelerated (Statistics Canada 2019a), making purchase of land increasingly difficult for new entrants to the industry. Over the past 20 years, the price of farmland in Canada has quadrupled, from $2,130 per hectare in 2001 to $9,753 in 2021 (NFU 2024).

Given that beef production is reliant on a sufficient quantity of high-quality forages, extreme weather (flooding, drought) and pest infestation associated with climate change have resulted in reduced forage and grain yields, leading to feed shortages and increased cost of production.

Finally, as the global population continues to grow, we must consider food systems that not only provide safe and healthy food but are also environmentally sustainable, including prudent use of resources (land, water and mined fertilizer nutrients) with limited environmental impacts (GHG and ammonia emissions). Therefore, it is imperative to identify management practices, programs and policies that simultaneously enhance both the economic and environmental sustainability of cow-calf operations in Canada.

2.1.4 Economic contribution of the Canadian cattle industry

The Canadian economy has historically relied on agriculture as one of its major industries since Confederation in the 19th century (Russell 2012). While much has changed during this time, the agriculture and agri-food industry remain a significant contributor to the national economy. It also plays a critical role in Canada's rural economy as it is a main source of income for 60,000 farms (Canadian Cattle Association, 2020) and is also an important secondary source of income for thousands of other farms.

2.1.5 Market structure of the cattle industry

The beef industry is a commodity market, and unlike supply-managed industries such as dairy or poultry, producers do not receive a fixed price for cattle as prices are dictated by market demand, with most calves sold in local auction marts (Fulton 2005; Canfax Research Services 2016). Therefore, producer economic viability is highly dependent on beef prices which are notoriously variable. Some producers minimize risk by using with forward contracts with finishing and processing companies that can allow for short term cash flow stability (Boyabatli et al. 2011). However, contracts are generally only available to producers with sizeable herds as larger volumes are less costly to procure for feedlots and processors. The buying market of live cattle for slaughter in Canada is highly concentrated among a few large companies, with Cargill and JBS have a combined market share over 95% (NFU 2020).

Lower prices may be one of the reasons that the average total income per family for beef producers in 2019 ($123,672.00) was lower than the average for grain and oilseed farmer households ($183,130.00) as well as the average for all farm types ($163,098.00; Statistics Canada 2022). One of the challenges faced by cow-calf producers is the inability to adjust to price changes, as it takes several years for an established herd to produce more calves (Hamilton and Kastens 2000). Additionally, cow-calf producers are faced with increased economic risk, as their operations are dependent on environmental factors outside their control, such as precipitation and weather, and risk mitigation through insurance for livestock or forages are not widely adopted.

2.2 Cow-calf Production Economics

2.2.1. Cost of Production

Costs associated with beef cattle production include purchase of the animal, feed, machinery, labour, land and other inputs. Feed costs comprise 42% and 22% of the cost of production associated with cow-calf and feedlot enterprises, respectively (Manitoba Agriculture 2024a; Manitoba Agriculture 2024b). For the cow-calf sector, much of this cost is associated with confined feeding over the winter period, which requires machinery and fuel costs to harvest, preserve (either drying or ensiling), and deliver forages that comprise the majority of the diet for beef cows (Sheppard et al. 2015). These activities require significant labour over the course of a winter and can increase maintenance and depreciation costs of equipment due to periods of extreme cold (Kan et al. 2017). As a consequence, many producers in Western Canada have adopted feeding and management strategies that minimize cost of production including extended grazing strategies, such as bale grazing, swath grazing, standing corn grazing and stockpile grazing (described in detail in section 2.2.2 below). In addition, many producers use low-cost by-products from grain and oilseed processing, and more recently, surplus food that does not meet the visual or nutrient quality standards for human consumption, to lower the cost of production.

Other costs include land ownership and rental, cost of insurance, fertilizer, storage buildings, and transportation (Rotz and Shinners 2007). Breeding costs, including purchase and maintenance of breeding stock such as bulls and replacement heifers (Manitoba Agriculture 2024a) also make up a large share of the total cost of production. Costs associated with artificial insemination (AI) include purchase of semen, pharmaceuticals, as well as labour input for synchronization and breeding. Other breeding costs include ultrasound to confirm pregnancy, as well as birthing assistance. While breeding inefficiency is not a direct cost, it represents a loss in potential revenue as it relates to the number of calves produced. A higher calving rate improves the potential for the operation to maintain profitability. Lower calving rates can be caused by several factors including breeding management, herd illness, environmental stress, inadequate feed quality or quantity and low body condition score (Lamb et al. 2014). Genetic improvement can have a significant influence on reproductive success, as well as calf performance through crossbreeding and selection, resulting in females that have high rates of calving and produce calves with high rates of gain. Producers can therefore improve their efficiency and reduce cost by improving the genetic potential of the breeding herd (Herd et al. 2003). In addition, implementing an aggressive culling program can insure minimal open cow rates (Dhuyvetter et al. 2007), which can reduce the cost of production. Other costs associated with beef production including auction mart fees, herd or crop insurance, utilities, manure removal, and feed testing (Manitoba Agriculture 2024a).

2.2.2 Extended Grazing Strategies to Reduce Feed Costs

Extended grazing strategies utilized by cow-calf producers to reduce the cost of production include bale grazing, stockpile forage grazing, swath grazing and grazing annual forages including standing corn (McGeough et al. 2017). Bale grazing involves placing bales in a consistent pattern in a field or pasture which cattle can "graze" on through the winter (Bachler 2019). To limit waste, cows are given access to several days of feed, controlled through the use of temporary electric fencing (Donohoe 2018). This strategy is low risk due to low cost of investment and no significant risk of loss of forage quality. However, it also results in lower savings, as producers must still grow, cut and bale forages and move them to the winter-feeding area, which makes up a large part of the feeding costs (McGeough et al. 2017). This strategy does, however, reduce the cost of labour through the winter, as well as eliminate tractor use during extreme cold. In addition, cattle also spread their own manure and therefore eliminate yardage costs. Furthermore, cows can access bales despite heavy snow or freezing rain.

Another feeding strategy that can save significant cost and is frequently used by Canadian beef industry is stockpile forage grazing (Sheppard et al. 2015), as it allows for a seamless extension of the low-cost summer grazing season. It involves allowing a section of pasture to go unharvested from mid-summer onward with subsequent grazing in the fall (McGeough et al. 2017). This system is very effective at reducing costs as it requires limited equipment or labour. However, there are limitations with this strategy including potential loss of forage yield to wildlife and insects, and forage quality due to advanced plant maturity. The forage plants may also be inaccessible if it is covered with significant snow depth or crusted hard snow. To minimize this risk, most producers will allow the cattle to graze stockpiled forage in the late fall and early winter when snowfall is not usually significant (Hitz and Russell 1998). Furthermore, producers must consider the species of forage in their pasture mix when planning for stockpile grazing, as many species will lose significant quality in the fall and may be unpalatable during winter or early spring grazing.

Swath grazing includes seeding annual cereals (*e.g.,* barley, oats) in the late spring or early summer, swathing at the "dough stage" and drying in the field until grazed in the winter (Rosser et al. 2013). Compared to conventional confined feeding of cows, swath grazing of triticale, corn and barley reduced feed and yardage costs by 67%, 47% and 37%, respectively (Baron et al. 2014). In addition to its economic benefits, Alemu et al. (2016) reported that swath grazing of either triticale or corn had a significant environmental benefit via reduced GHG emissions and increased energy use efficiency of beef farms. Similar to stockpiled forage grazing, swath grazing has limitations in that it can be affected by fall and winter weather, with deep or hard snow making the feed inaccessible to cattle, as well as warm and wet fall weather potentially producing mold in the swathed forage, leading to reduced palatability and quality (Alberta Agriculture 2004).

Winter grazing of standing corn is also used by many producers to reduce labour and equipment costs associated with confined feeding. Development of varieties that require fewer growing degree days to reach maturation have led to increased adoption of corn grazing. As with the other extended grazing strategies, temporary electric fencing is used to allocate feed every 2 to 3 days to reduce waste by ensuring that the cows will consume the entire corn plant and not selectively graze the cobs (Lardner et al. 2012), which may lead to acidosis or grain overload. Corn is also somewhat more resistant to issues of heavy or hard snow pack due to its height, with the thick plant stand also providing shelter from winter wind. Corn is generally low in protein (Hoorman et al. 2002), so supplementing of a high protein feed such as good quality alfalfa hay or high-protein by-products may be required, especially if cows graze corn when approaching the end of gestation when protein demand is increased due to advancing fetal growth (Klein et al. 2021).

Producers may also reduce feeding costs by using locally-produced feedstuffs including grain processing by-products. Most grains destined for human consumption are first processed before entering the food chain, producing by-products that are often high in fiber content, and although not suitable for human consumption, can be included in beef cow diets as ruminants have a unique capability to digest feeds with a wide range of fiber levels (Erickson et al. 2005). Since these by-products have few other uses, producers can obtain them at a low cost.

2.2.3 Sources of Revenue in Cow-calf Operations

The income received on Canadian cow-calf farms and ranches is primarily from the sale of weaned calves and culled animals. However, many producers may incorporate other livestock or crops to diversify their farm income. Alemu et al. (2016) created 8 cow-calf farm typologies using Canadian survey data; 37% were categorized as small-scale, part-time with extra revenue generated from other sources including off-farm income. In addition, 27% were categorized as mixed operation (crop-beef) with diversified operations including cereal and oilseed crop enterprises. For most Canadian producers, the sale of calves and the associated revenue occurs only once per year, therefore garnering the highest possible price for the calves sold is critically import to the financial viability of the operation. Weight and value of calves at the time of sale is affected by genetics, environment, nutrition age, as well as demand. In Canada, most calves are born in March with weaning occurring between October 15 and November 15 (Larson 2017), however, the optimum calving, weaning and sale date is unique to each operation.

A common strategy to add value to calves is via pre-conditioning, which includes weaning calves and starting on a background or feeder ration, as well as vaccinating, dehorning and castrating depending on the program (Pritchard and Mendez 1990). Pre-conditioning is intended to promote uniformity and reduce stress and shrink (weight loss) when transitioning from one farm to another, potentially increasing the value of the calves for feedlots (Avent et al. 2004).

Cow-calf producers may also choose to add value to their calves by backgrounding longer (Pope et al. 2011) which allows producers to market heavier calves at a time of year that may have more favorable prices without significant investment in facilities, particularly if feeding forage-based diets. This option is especially attractive if the producer has harvested excess winter feed, or if feed prices are very low and cattle prices are rising.

As indicated above, another revenue source for cow-calf producers is the sale of cull animals including cows, heifers and bulls. Producers often sell cull cows that are not reliably producing calves along with weaned calves in the fall (after pregnancy checking), although cull cow prices are typically at their lowest during this time (Peel and Doye 2017). Revenue from cull cow sales can potentially be increased by keeping cows longer until prices increase, while at the same time gaining additional weight and potentially improving returns. However, the profitability of this strategy also relies heavily on the price of winter feed and sale price of cull animals in the late winter or spring.

Cow-calf operations are often part of a mixed farming operation that includes a cash crop enterprise and therefore revenue generated from the cattle enterprise may not always be the primary income source (Alemu et al. 2016). Utilizing cattle on a mixed operation provides distinct advantages, particularly with farmland that has very wet, stony or unfertile portions that are not suitable for crop production. Grazing cattle can utilize these portions of land to graze forages and provide a revenue source for otherwise unproductive land.

2.2.4 Economies of Scale

Cow-calf production in Canada is characterized by a range of sizes of farms, with average herd sizes in the Eastern provinces (77 head) lower than Western farms (163 head; Statistics Canada 2018a, Sheppard et al. 2015). Net farm income per unit (weaned calf or cull cow) can be impacted by the size of the farm operation due to economies of scale whereby production efficiencies based on the size of the operation allow for adoption of techniques or investment in equipment (Savetpanuvong et al. 2011). Scale efficiency is relevant in cow-calf production as investments in infrastructure can significantly reduce required labor or increase volume of production. The size of an operation dictates the degree of mechanization as some farm equipment requires a large capital investment which may not be feasible for smaller operations as the same investment needs to be spread across a smaller herd size. However, the investment may be possible for a larger operation resulting in a decreased cost of production (or increased revenue) on a per cow basis (Samarajeewa et al. 2012). For example, the investment in larger harvest equipment may allow a producer to harvest more forage, using less fuel and labour, thereby reducing cost per cow, provided the herd is sufficiently large herd to make use of the full value of the investment.

Size of an operation can also play a role in marketing opportunities as buyers for the finishing market typically prefer to purchase large groups of uniform cattle for ease of feeding. Large scale operations can group calves by sex, weight and frame size, thereby capturing a price premium compared to smaller groups of less uniform calves. Producers selling large groups of calves can also eliminate the cost of auction market fees and reduce transport and animal handling costs by selling direct to a buyer (Danielce et al. 2020).

2.2.5 Bio-Economic and Bio-Physical Modelling

Modelling has been used extensively to analyze farming systems at many scales including single fields to whole farms, with the potential for selective optimization based on the priorities and parameters set out by the user (Weersink et al. 2002). Bio-economic models can be used to incorporate farm-level biological and management-based parameters to estimate economic viability. Bio-physical models consider farm management and biological constraints but also examine the impact of agriculture on the physical environment and the interactions of the two. This type of modelling can range in scope, as the physical environment can be examined from very small scale of soil and atmospheric changes, up to broad eco-system impacts. Therefore, model selection is important as geographical region, scope and context of data may only be compatible with only certain models (Weersink et al. 2002). Modelling is also used to estimate the environmental impact, including GHG emissions of crop and livestock production systems and will be discussed in more detail below.

2.2.6 Benchmarking of agricultural systems

Benchmarking of agricultural production in a standardized fashion allows for a clear comparison of global agriculture by country or region, and further, the scope of the data collected makes it conducive to the development of future farm scenarios which can compare current and future profitability. In implementing this, Agri-Benchmark (Agri Benchmark 2020), a global non-profit organization, is focused on collecting farm economic data in a standardized way to provide accurate descriptions and improve the economic sustainability via coordination with government and agricultural agencies in participating countries, including Canada. The organization has developed Standard Operating Procedures (SOPs) for step-by-step methods in establishing typical farm information and quantifying data for different production systems including beef, sheep, pig, poultry, cash crop, horticulture and fish.

The data collection methods used by Agri-Benchmark follows a unique "typical farm" approach, in which a non-existent virtual farm that contains the most representative aspects of a farm in a given region is created (Deblitz 2010). This approach has many advantages to the use of average farm data as it allows for a more accurate description of the agriculture in the region, comparable to using the median of a data set rather than the mean. The advantage of a typical farm type data set is that it combines the strengths of individual case study and survey data collection techniques. The typical farm approach acts as a hybrid by maintaining some of the representativeness and confidentiality of a survey approach with the quality and depth afforded by individual farm data. The level of representativeness in the typical farm approach is dictated by selection of participants, ensuring that different types of farms are included in the collection to capture all variables associated with production (Deblitz 2010).

2.3 Environmental Sustainability of Canadian beef industry

2.3.1 Environmental Impacts of Canadian Beef Production

In addition to economic sustainability, producers are challenged by commodity groups, government and consumers to adopt management practices that are also environmentally sustainable. As threats of climate change become more prevalent, GHG emissions have become an increasingly important issue in agriculture, especially in beef cattle production. Agriculture contributed 7.9% of Canadian GHG emissions in 2022 with beef production responsible for 2.4% of the total agricultural emissions (Environment and Climate Change Canada 2024; CRSB 2024a). There is an increasing pressure not only from governments through legislation to reduce GHG emissions from the beef cattle sector, but also from consumers who want to purchase more eco-friendly products (Campbell et al. 2015). Therefore, beef industry groups, including the Canadian Roundtable for Sustainable Beef (CRSB), have targeted emission intensity reductions of 33% by 2030. However, the sector's ability to meet these ambitious, yet laudable goals will only occur if economic as well as environmental sustainability are considered concurrently.

The main GHG associated with beef production include methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2; IPCC 2019). Enteric CH_4 has been estimated to account for an average of 61% of total cow-calf farm emissions, which includes all livestock-sourced emissions as well as those from crops grown directly for the livestock enterprise and manure during storage or field application (Legesse et al. 2016). Therefore, strategies to reduce enteric CH_4 emissions has been the focal point of emission reduction efforts (Tseten et al. 2022), which also led the federal government to develop an offset protocol to reduce enteric CH_4 emissions from beef cattle (Environment and Climate Change Canada 2023). In addition to the higher quantity produced, CH_4 emissions is targeted in beef production because it has 27 times the global warming potential per unit as compared to CO_2 (Pogue et al. 2023). While CH_4 carries a higher emission intensity it does so over a much shorter period (about 12 years) compared to other emission types (University of California, Davis 2023).

Due to the nature of the ruminant animal digestion process, CH_4 production is much greater in the beef and dairy industry relative to other livestock groups including poultry and swine. In ruminant animals, such as beef and dairy cattle, enteric CH_4 is produced during digestion of feedstuffs in the rumen via rumen microorganisms, as part of the normal digestive physiology (Hirstov et al. 2014). Ruminants consume a large portion of fibrous material as part of their diet, and are reliant on microorganisms such as bacteria, protozoa and fungi to breakdown complex molecules such as cellulose into smaller molecules useable by the animal as energy (volatile fatty acids). Methanogens in the rumen produce CH_4 which is released into the atmosphere via belching (Thompson and Rowntree 2020). Methane emissions from cattle also represent a loss in feed efficiency, ranging from 6-12% of the energy consumed (Freetly and Brown-Brandl 2013). In addition to enteric CH_4, a small proportion is also produced from stored manure.

Nitrous oxide is also a significant source of GHG emissions from the beef industry. Nitrous oxide gas is produced from manure and soil, when ammonia nitrogen (NH_3-N) from manure is broken down into nitrite (NO_2^-) by ammonia-oxidizing bacteria and further to nitrate (NO_3^-) by nitrite-oxidizing bacteria (Chandran et al. 2011; Xu et al. 2022). Beef cattle are relatively inefficient in utilizing feed nitrogen, with only 20% used for growth (NASEM 2016). Relatively high nitrogen excretion may, in part, be attributed to rapid rumen degradation of feed protein, resulting in increased production and absorption of NH_3 which is subsequently transformed to urea in the liver and excreted through urine. Furthermore, feeding excess protein above nutrient requirements results in increased nitrogen excretion (both in feces and urine).

Carbon dioxide makes up a relatively small portion (2-3%) of GHG emissions associated with on-farm beef production (Legesse et al. 2016). The majority of CO_2 emissions are sourced from fossil fuel consumption for harvesting, storing and transporting feed as well as heating and electricity for farm buildings.

2.3.2 Reducing the Environmental Impacts of Beef Production

The GHG emissions associated with several management strategies have been evaluated to minimize the environmental impact of beef production. Management practices shown to reduce emissions include: genetic improvement, feed and feeding management, manure storage and handling, and efficiency of production (Legesse et al. 2016). In an effort to minimize its environmental impacts and improve sustainability, the beef cattle industry has set goals to reduce GHG emission intensity by 33% by 2030, as indicated above, as well as to increase carbon sequestration, improve animal health and welfare as well increase biodiversity (Canada's National Beef Strategy 2020).

2.3.2.1 Feed and Feeding Management

Feeding management has been identified as a strategy to improve economic as well as environmental sustainability. As enteric CH_4 is the largest contributor of farm GHG emissions in beef cattle, feeding management plays a significant role in minimizing emissions of enteric CH_4

(Montes et al. 2013; Tseten et al. 2022). Generally, higher proportions of CH_4 are produced when cattle consume lower quality (higher neutral detergent fiber (NDF)) roughages and fibrous feed compared to high concentrate feedstuffs. However, this approach is not always practical in cow-calf operations which rely on pasture, forage and by-products. Therefore, increasing the quality of forages by adding legumes into hay and pasture, cutting hay at earlier maturity to reduce the NDF, and proper feed storage are options to reduce emissions in cow-calf operations (Beauchemin et al. 2011). In addition, strategies including rotational grazing can improve the quality of pastures (Jacobo et al. 2006; Badgery et al. 2017), thereby not only improving efficiency, and thus profitability, but also reducing enteric CH_4 emissions on a per cow basis by improving digestibility with higher quality feed.

The use of feed additives including fat, enzymes, seaweed, nitrate, plant secondary metabolites and the recently approved 3-nitrooxypropanol etc. have also been proposed as strategies to minimize enteric CH_4 emissions from beef cattle production systems (Beauchemin et al. 2020). However, addition of these supplements which are required in small quantities is challenging in cow-calf operations where extensive forage- and pasture-based feeding strategies are used.

2.3.2.2 Manure Management

Manure is the second major contributor to the total on-farm GHG emissions in beef operations via production of N_2O and CH_4 (Beauchemin et al. 2010; Legesse et al. 2016). Beef cows are either kept on pasture, where manure is not stored or handled, or in a partially-bedded area for winter feeding. In the latter, manure accumulates and is spread onto fields after the winter-feeding season or stored for some time before spreading. Quantity of emissions from manure are influenced by the type of storage (Pattey et al. 2005), type and amount of bedding materials used (Mathot et al. 2012) and method of manure application (Phan et al. 2012). Solid storage (stockpile, deep bedding) is the most common manure management strategy used by Canadian beef producers, while composting is also practiced to a lesser extent (Beaulieu 2004). Composting of beef manure tends to generate higher total GHG emissions as compared to static/stockpiled storage (Bai et al. 2020; Chen et al. 2020).

2.3.2.3 Carbon Sequestration

Carbon sequestration is a process by which CO_2 from the atmosphere is removed and stored long-term as soil organic carbon (Lal et al. 2015). The rate at which carbon is sequestered and stored is variable across crop types, soil type, growing conditions and weather. Perennial forage crops, which have extensive root systems, can store significant carbon, while annual crops are less effective (Ferchaud et al. 2016). Therefore, the extensive rangeland and pasture land used by Canadian beef production stores significant amounts of carbon (Liang et al. 2020). These perennial crops have little value without ruminant grazers which emphasizes the importance of cattle production in carbon sequestration (Liang et al. 2020). Further, grazing and harvest management strategies can play a role in the amount of carbon sequestered, as grazing strategies that allow for regrowth can allow for higher biomass yields and sink more carbon (Stanley et al. 2018). Finally, the carbon consumed by cattle as feed is also excreted and returned to the soil, either directly or through mechanical spreading. As it decomposes, much of the carbon in the manure is stabilized as organic soil carbon (Soussana et al. 2004).

Grazing areas may contain wetlands which provide a natural water source for cattle. These areas are more likely to be retained as natural habitat compared to areas used for grain production since drainage work is costly. Although wetlands can also be associated with CH_4 emissions, they are generally viewed as beneficial as they serve as a net sink of carbon (Badiou et al. 2011).

2.3.2.4 Biodiversity and Ecosystem Services

In addition to wetlands, grazing areas also contain forested areas – all of which provide natural habitat for wild animals and insects. Many species of endangered and non-endangered mammals, nesting birds, insects and plants make their homes in grasslands occupied by beef cows (Filazzola et al. 2020). One example is the burrowing owl (*Athene cunicularia hypugaea*), which is native to the Canadian prairies The population of these owls, who burrow into the ground rather than nesting in trees, have been dramatically affected by the increase in tillage of grasslands for annual crop production. In a holistic assessment based on 742 peer-reviewed publications, Pogue et al. (2018) reported the positive impacts of beef production on ecosystem services in the Canadian prairie.

2.3.3 Whole Farm Greenhouse Gas Modelling

As indicated above, mathematical whole-farm models can be used to assess GHG emissions from complex farm systems. The use of farm models is necessary to integrate the cropping and livestock components of beef cattle production systems and evaluate the impacts of changes in management practice on GHG emissions. Several whole-farm models have been used to examine GHG missions including IPCC Tier 2, HOLOS (AAFC 2024a), Unified Livestock Industry and Crop Emission Estimating System (ULICEES; Verge et al. 2012) and the Integrated Farm System Model (USDA 2023).

The HOLOS whole-farm model, which was developed by Agriculture and Agri-Food Canada (AAFC) to reflect Canadian production systems (AAFC 2024a). The HOLOS model uses input variables including soil type and texture, tillage and cropping practices, and land and equipment use. It also uses variables related to animal production, such as herd size and type, diet including nutrient profiles of feedstuffs and manure management. The model also estimates the net carbon activity on farm including carbon storage through perennial crops and trees. Using this input data, HOLOS estimates CO_2, CH_4 and N_2O emissions from all farm processes. It was designed to help producers and researchers to estimate GHG emissions from different sources within the farm and evaluate the impacts of changes in management on total farm emissions (AAFC 2024a). At present, the HOLOS model does not have an economic component, nor can it assess other sustainability metrics including biodiversity. However, the model has a built-in component for the use of agricultural shelterbelts (Kröbel et al., 2020).

2.4 Improving Economic and Environmental Sustainability of Canadian Beef Production

According to the CRSB National Beef Sustainability Economic Assessment (CRSB 2016) only 27.1% of cattle ranching and farming businesses were profitable in 2020, compared to 53% of all businesses in the agriculture, forestry, fishing and hunting sectors in the same year. Furthermore, increased and more volatile input markets and increased land prices have resulted in greater financial risk for cattle producers across the beef sector. Climate change, including increased risk of drought and flooding, have further threatened feed supplies. These challenges are heightened due to inequities in business risk management tools like full cost Livestock Price Insurance when compared to subsidized Crop Insurance. In addition, the lack of labour availability has created increased workload levels with potential negative repercussions, particularly for cow-calf producers who are most vulnerable, given the lack of resources. Consequently, economic barriers limit the ability and/or willingness to take on the risk to adopt and implement new technologies and management practices on-farm, including those that will reduce the environmental footprint of the sector. This is especially true if there is a lack of supporting evidence that implementation or adoption of best management practices (BMPs) with positive environmental outcomes will also yield increases in profitability. Therefore, it is imperative to identify management practices, programs and policies that simultaneously enhance both the economic and environmental sustainability of cow-calf operations in Canada.

2.4.1 Incentives for Producers

Although limited, there are incentive programs in Canada which aim to increase the economic viability of adopting management practices which improve environmental sustainability. The Alternative Land Use Services program (ALUS 2020) is available in 6 provinces to offset losses that may be associated with changes in management practices. For example, ALUS funds projects that protect riparian zones, improve water quality, increase biodiversity, and provide habitat for pollinators (ALUS 2020). Similarly, the Species At Risk Partnerships on Agricultural Lands (SARPAL) program focused on protecting habitat for several at-risk species in Canada (SARPAL 2020). These programs have achieved significant advancements in conservation and contribute to enhancing the number of hectares of protected land which provide ecological services.

As part of the measures taken to minimize the environmental impacts of the agricultural sector, the government of Canada announced the Agricultural Climate Solution (ACS) Program which incorporates two initiatives: the On-farm Climate Action Fund and Living Laboratories Program (AAFC 2022b). The goal of these initiatives is to help producers identify BMP’s that will minimize GHG emissions, increasing soil carbon storage and improving biodiversity.

2.5 Summary

The beef industry plays an essential role by contributing to the local and national economies and also to global food security. To achieve the commendable goals set out by the cattle industry to reduce GHG emission intensity by 33% by 2030, there is a growing and urgent need to better understand management practices which lead to improved profitability as well as environmental sustainability through a reduction in GHG emissions. Although there is a growing body of knowledge regarding strategies to reduce GHG emissions from beef cattle production systems, there is limited data that examines the economic benefit of adopting these management practices.

3. Research Hypothesis and Objectives

Hypothesis:

1. Cow-calf operations across Canada implement a wide variety of on-farm management practices including breeding, feeding, grazing, crop production, and manure handling. This spectrum of management practices combined with variable environmental conditions across Canada will result in differences in emission intensity and profitability of cow-calf operations across the country.
2. Changes to management practices to improve production efficiency including rotational grazing system, improving water quality on pasture, shortening calving intervals, creep feeding calves, utilizing artificial insemination (AI), and grazing standing corn, will reduce emission intensity and improve farm profitability. Therefore, its anticipated that income and emissions intensity will be significantly and positively correlated.

Objectives:

The main goal of this study was to investigate the diversity of management practices used in Canadian cow-calf production systems and further to explore the impact of the adoption of best management practices or "future farm scenarios" on emissions intensity and profitability.

The specific objectives were:

1. To analyze and estimate whole-farm GHG emissions from 25 benchmark farms with varying management practices located across Canada using the Holos model.
2. To examine the impact of adopting changes in management practices (future farm scenarios) on profitability and GHG emissions of several benchmark farms.
3. To simultaneously analyze measures of profitability and estimated emissions for benchmark farms and future farm scenario to identify practices which reduce emissions and increase profitability.

4. Manuscript

Management Practices to Improve Sustainability and Profitability of Cow-calf Operations Across Canada

A.J. Knodel[1], K.H. Ominski[1], B. Grant[4], D. Fulawka[1] R. Kröbel[3]. E. Stephens[3], D. Brewin[1] and A.W. Alemu[2]

[1] Department of Animal Science, University of Manitoba, Winnipeg, Manitoba, Canada, R3T 2N2

[2] Agriculture and Agri-Food Canada, Swift Current Research and Development Center, Box 1030, Swift Current, SK, Canada, S9H 3X2

[3] Agriculture and Agri-Food Canada, Lethbridge Research and Development Center, 5403 1 Ave S, Lethbridge, AB, Canada, T1J 4B1

[4]Canfax, 180, 6815 8th Street NE. Calgary, Alberta, Canada, T2E 7H7

4.1 Abstract

The goal of this study was to use benchmark farms which represented a typical farm in a given region to identify different types of cow-calf operations in Canada, estimate GHG emissions generated by each farm and estimate cost of production and farm profitability of those farms. Virtual benchmark farms were developed using data collected from 115 producers across Canada to capture a wide range of farm types in different regions of the country. Each benchmark farm was developed using detailed data collected from 3-6 producers to ensure each benchmark farm would be representative of each farm type in a given region. Once the benchmark farms were established, greenhouse gas (GHG) emissions were estimated using the whole-farm model, Holos (Version 4). The model calculated emissions from all on-farm processes associated with the cow-calf enterprise in the form of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). While the dataset for each farm pertaining to production process was robust, some model assumptions were made based on literature values for required inputs that were not collected as part of the benchmark development process. Emission intensity was calculated as net GHG emissions (kg of CO_2 equivalent, eq) divided by total liveweight (LW, kg) sold out from the enterprise. Net farm GHG emissions intensity varied widely across the 25 benchmark farms, ranging between 18.3 and 35.1 kg CO_2eq/kg LW. Farms that reported lower net emissions generally utilized higher quality forages and less fertilizer, had large areas of productive pasture and forage crops, and produced calves efficiently through high calving rates, high rates of gain and high stocking density. Farms in Western Canada tended to have higher enteric CH_4 emissions and relatively lower soil N_2O and energy use sourced CO_2 emission whereas farms in Eastern Canada generally reported higher rates of emissions from imported feeds. Similarly, costs of production and rates of profitability were highly diverse, especially when examining profitability where several farms reported negative income while others generated significant income even in the long-term. Generally, benchmark farms in Western Canada reported higher whole-farm net income, however this was often due to the sale of grain and oilseed crops, while Eastern farms included several smaller operations that reported significant annual losses. Modelling and analysis of several future farm scenarios via specific practice changes were made to several benchmark farms in order to determine if these

changes would reduce emission intensity and improve farm profitability. The practice changes included: implementing rotational grazing systems, improving water quality on pasture, shortening calving intervals, creep feeding calves, utilizing artificial insemination (AI) and grazing standing corn. These scenarios resulted in a range of improvements for both farm profitability and reduction of emissions. Scenarios that focused primarily on improving production efficiency such as shortened calving interval, water improvement and using AI yielded smaller but more consistent reductions in GHG emissions and improved profitability. Scenarios such as extended grazing and added legume species yielded more significant benefits under some conditions but were less consistent in others and therefore involved more risk. The results confirmed that increasing efficiency is a crucial component of both farm profitability and reducing GHG emissions. It also revealed that not all practices produce similar results across Canada, and consideration of existing farm practices and the local environment is essential in modelling future practice changes.

4.2 Introduction

Increased global demand for food products that are produced sustainability, has led to an increased focus on production systems, particularly in relation to GHG emissions. Animal agriculture, particularly the beef cattle industry, has come under pressure from consumers, industry leaders and government to reduce GHG emissions generated during production without compromising food safety and animal welfare. As the demand for animal-sourced foods is expected to increase (Lee et al. 2020), the Canadian cattle industry has the opportunity to meet this increased demand but must do so while meeting the environmental expectations of consumers and remaining economically viable.

Previous research based on cow-calf survey data (Alemu et al. 2017), has indicated that the majority of GHG emissions from beef production systems are in the form of CH_4 from enteric fermentation and manure storage (69% of total farm emissions) and N_2O from manure and soil (24% of total farm emissions). Furthermore, within the beef industry, it has been demonstrated that cow-calf operations generate approximately 80% of emissions with only 20% emitted from the finishing sector (Beauchemin et al. 2010b, Legesse et al. 2016). Further, it has been suggested that raising beef cattle is one of the most emission-intensive forms of meat/protein production commonly practiced in Canada as compared to pork, small ruminants and poultry (FAO 2015). This suggests that there is opportunity for the cattle industry, particularly the cow-calf sector, to reduce GHG emissions. Indeed, Canadian cattle producers have reduced GHG emissions intensity by 14% per kilogram of beef produced in 2011 compared to 1981 (Legesse et al. 2016). However, continued adoption of existing and novel GHG-mitigation strategies is imperative if producers are to meet the ambitious emissions reduction targets set out by the Canadian Roundtable for Sustainable Beef (33% by the year 2030; CSRB 2016).

Adoption of management strategies that improve environmental sustainability must also be economically viable. On average, beef producers have the lowest net income as compared to producers in any other Canadian agricultural sector (Statistics Canada 2014). According to the CRSB National Beef Sustainability Economic Assessment (CRSB 2024b) only 27.1% of cattle ranching and farming businesses were profitable in 2020, compared to 53% of all businesses in the agriculture, forestry, fishing and hunting sectors in the same year. Therefore, many producers require off-farm income to support their enterprise. Alemu et al. (2016) reported that 37% and 22% of Canadian cow-calf producers surveyed described themselves as small-scale, part-time operations with off-farm income and mixed (crop-beef) operations with income from crop sales, respectively. The economic landscape of cow-calf operations makes it difficult for producers to adopt practice changes that reduce emissions, if these practices decrease profitability of their operation.

Several Canadian studies (Beauchemin et al. 2010, Legesse et al. 2016; Alemu et al. 2017, Beauchemin et al. 2020,) have examined the impact of management practices on GHG emission intensity. Relatively few of such studies have included an accompanying economic analysis. Possberg & Kulshreshtha (2018) began to explore this gap in literature. However, they did not include different conditions across Canada and did not address implementation of practice changes. Our project explored the GHG emissions and farm profitability for 25 benchmark cow-calf operations across Canada based on current management practices, as well as adoption of alternative management strategies in an effort to understand management strategies that can improve profitability and reduce emission intensity.

4.3 Materials and Methods

4.3.1 Data Collection and Management

4.3.1.1 Producer Recruitment, Collection of Data and Creation of Benchmark Farms

In 2020, Canfax Research Services launched the Canadian Cow-calf Cost of Production Network (https://www.canfax.ca/resources/cost-of-production.html; Canfax 2022) which included 115 producers from across Canada who were recruited in coordination with provincial extension specialists, as well as a series of advertisements and blog posts. Producers interested in participating in the program completed an initial screening survey to determine their suitability for the program, as well as to characterize their beef herd based on size (number of animals) and management practices including winter feeding management, calving date, weaning date and farm location, as well other farm enterprises such as backgrounding and growing cash crops. This information was then used by Canfax staff and provincial specialists, to place producers of similar typologies in focus groups consisting of 3-6 participants. A total of 26 focus groups (typologies) across Canada were created (Figure 2). Canfax Research Services collected extensive data on individual management strategies and financial details including the categories referenced in Table 1, the data collected was from production in the year 2020, all assumptions on costs and prices were based on the market status in 2020. The data was collected in focus group meetings conducted virtually due to the public health orders which imposed group size restrictions associated with the outbreak of COVID-19 Canada at the time. The focus-group setting allowed for simultaneous collection from multiple producers at the same time, providing an opportunity for participating producers to initiate discussions on the data being collected, resulting in more detailed responses. Following the collection of data from each producer within the focus group, staff at Canfax Research Services compiled the individual farm data and took mean values of the dataset with some adjustments and removal of outliers, when appropriate, to create a representative benchmark farm for each focus group. The goal of developing the benchmark farms was to assemble a group of producers from the same region who used similar management strategies on their farms thereby generating a sample pool of comparable data points. For simplicity, provincial borders were used as the boundary to create benchmark farms. One exception was for ON, which was divided into two eco-regions (East and West) as the two regions of the province are significantly different and warranted distinction. Farms SK-1a and SK-1b were created based on the same focus group which was made up of producers that shared very similar herd characteristics but used very different management practices in feed production. The data from these producers were then used to create two benchmark farms that reflected both types of management. Producers were also asked to indicate potential management practice changes or "future farm scenarios" that could be adopted, given their regional conditions. Finally, producers, provincial extension personnel, and ruminant nutritionists were consulted to ensure that the benchmark farms were reflective of the actual farms including the relevant geographic constraints. For example, animal nutritionists were consulted to ensure that quantity and quality of feeds/diets met animal requirements based on physiological status and performance.

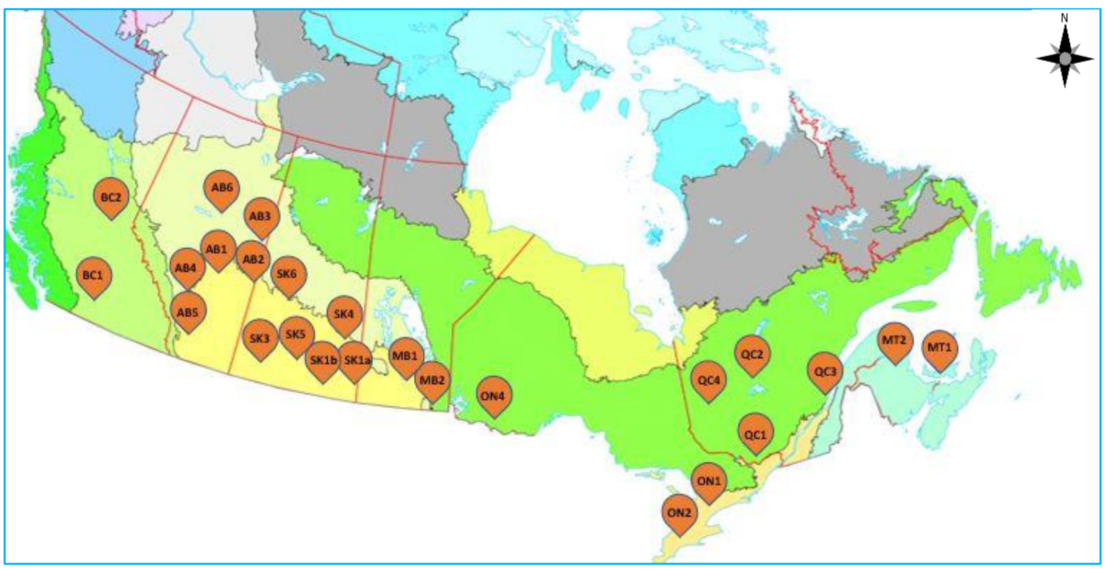

Figure 2. Distribution of benchmark farm locations across Canada indicated by the province(s) in which they were located (Maritime (MT); British Colombia (BC; Alberta (AB); Saskatchewan (SK); Manitoba (MB); Ontario ((ON) and Quebec (QC), as well as the farm number (1-6).

Table 1. Data collection included farm and herd characteristics, economic inputs/outputs and management data related to greenhouse gas emissions.

Farm and Herd Characteristics	Economic Information	Emissions-related Data
Housing, land area (pasture, cropping), number of animals (cows, bulls and heifers)	Costs of feed production/purchase	Feed types and detailed feed quality data, imported and on-farm produced feed information
Calving and weaning dates	Revenue from sold calves, backgrounders, cows and bulls	Housing and grazing management data
Replacement and calving rates	Fixed costs, rent, marketing and management costs	Manure storage, handling and application, fertilizer use

4.3.2 System Boundary and Functional Unit

When modelling a bio-physical system there must be a defined system boundary to establish the components that are included or excluded from the system. In the context of modeling farms, there are significant processes that occur upstream and downstream from a given farm in the food production chain. The distinction between which processes are assigned to the farm, and which are separate are often ambiguous and therefore a specific boundary must be established.

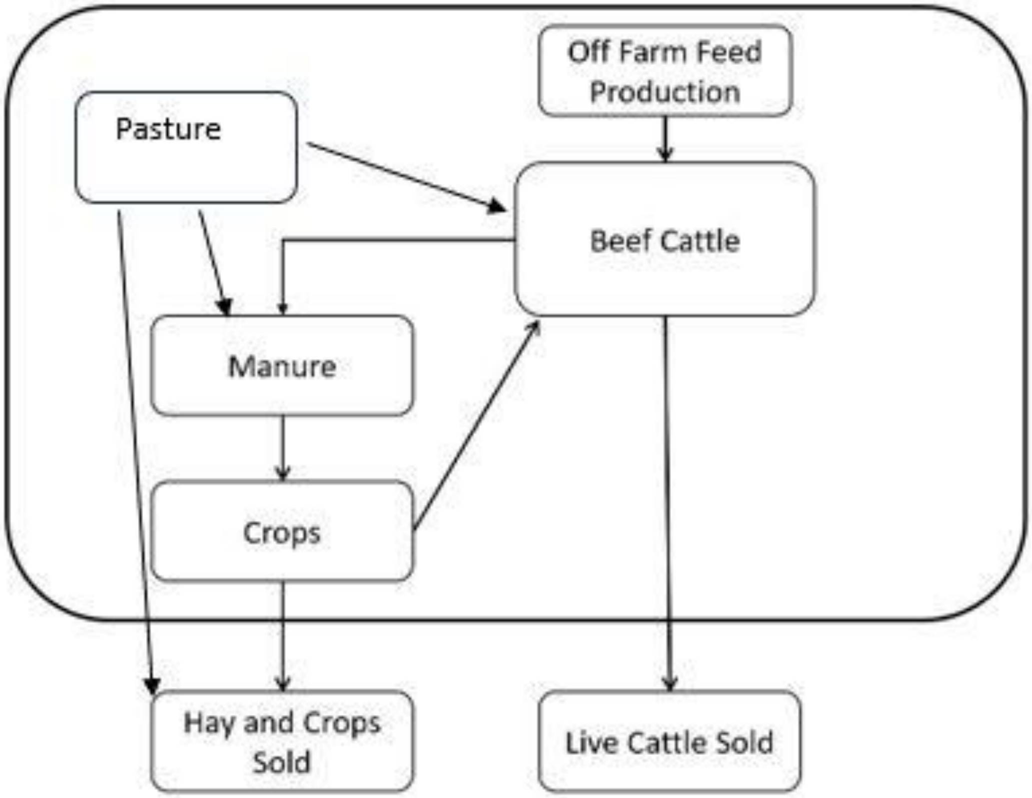

Figure 3. Components included in the systems boundary used to estimated greenhouse gas emissions from the benchmark farms.

The system boundary considered included all on-farm processes associated with livestock, manure management, as well as feed and crop production. When benchmark farms used feed products that were produced or processed off-farm and transported into the farm, emission factors from published literature were used to estimate the GHG emissions associated with the production and transportation of those products. Transportation-related emissions were calculated assuming the use of a semi-trailer and a distance of 100 km. This approach ensured that all inputs were accounted for, with no bias associated with source of feed (purchased vs produced on farm). Similarly, emissions from grain and forages that were produced and exported off-farm and not used in the cow-calf or backgrounding enterprises were excluded from analysis, as these emissions are unrelated to the beef operation. Down-stream emissions associated with live calves, cows and bulls after leaving the farm-gate were not included. Specifically, transportation or other processing emissions were not included in the analysis.

In a whole-farm or life cycle analysis studies, defining a functional unit is important. A functional unit defines the units of measure in the output of a modelling exercise, and how it relates to the inputs of a system. Common examples of food-related functional units associated with GHG production include carbon dioxide equivalents (CO_2eq) per kg of beef, per 100 calories of food, or per ha of land. Farm output was measured in total kilograms liveweight sold at the farm gate, which included all weaned calves, backgrounded calves, culled cows and bulls as described in other Canadian studies (Beauchemin et al., 2010, 2011; Alemu et al., 2017).

The main GHGs associated with beef cattle production and included in the analysis were CH_4, N_2O, and CO_2 (Beauchemin et al. 2010b). These gases have different global warming potentials (GWP) and therefore results were expressed CO_2e where 1 kg of N_2O is equal to 273 kg of CO_2, and 1 kg of CH_4 is equal to 27 kg of CO_2, on a time horizon of 100 years (Pogue et al., 2023). By using a standardized unit of measure, net emissions from different sources can be summed for a given farm and compared to other farms. Farm emission intensity was calculated based on net emissions produced and farm output (kgCO_2e/kg LW sold). By expressing results in the form of emissions intensity rather than total emissions, the mathematical bias towards smaller herd sizes which inevitably have lower total emissions was removed, and farms of differing herd sizes can be compared based on their efficiency rather than scale.

4.3.3 Whole-farm Modelling and GHG Estimation

Several whole-farm models e.g., Holos (Pogue et al. 2023), Cool Farm Tool (Cool Farm Alliance 2022), Integrated Farm System Model (Rotz et al. 2020) have been developed and used to estimate GHG emissions from the beef cattle industry. Whole-farm models are commonly used to estimate total farm emissions, as farms are often made up of distinct enterprises that have significant interaction and overlap. The whole farm approach allows for detailed examination for each enterprise and so that emissions can be assessed separately, but the interactions between enterprises are also captured. This is particularly important when modelling cow-calf farms, as there are often interactions between enterprises which can make contributions to emissions and carbon sequestration. For example, for farms that practice extended grazing techniques such as corn or swath grazing, models can capture the effect of cattle being housed on these fields of annual crops including the nutrients deposited and harvested by grazing activity.

For this project, the recently released version of the Holos model (Version 4; https://agriculture.canada.ca/en/agricultural-production/holos) was used to integrate the different components within the benchmark farms to estimate total farm GHG emissions.

4.3.4 The Holos Whole-farm Model

The recently released updated version (version 4) of the Holos whole-farm model (Agriculture Canada 2022a, Pogue et al., 2023), developed by Agriculture and Agri-Food Canada, was used to simulate GHG emissions for the benchmark farms created in the study. Recent updates to the model include improvement on the special scale of the model (using Soil Landscapes of Canada (SLC; Agriculture Canada 2011)) instead of eco-district), feed and land management, updated emission factors, soil N_2O emission calculation, manure management and related emissions, soil carbon sequestration, as well as soil water and shelterbelt use. Holos is an empirical model designed specifically for physical conditions and farm practices in Canadian agriculture, with the capacity to capture differences between management practices and farms. The model uses an IPCC Tier 2 approach, incorporating emission factors (Y_m) relevant to the Canadian landscape to estimate emissions from animal, crop and forage components (Pogue et al. 2023). The model utilizes polygons pre-set to environmental conditions specific to different regions based on SLC (Agriculture Canada 2011) mapping and integrates 30-year temperature and precipitation data for each polygon, using monthly averages for animal emission calculations, and daily averages to calculate soil temperature, and moisture. Holos has been used in several recent publications to estimate emission intensity and the impact of practice changes on Canadian beef and dairy farms (Legesse et al. 2016; Alemu et al. 2017) and is also used as an educational tool in academic programs. The model was used to estimate three main GHGs including CH_4, N_2O and CO_2.

4.3.4.1 Methane (CH_4) Emissions

Methane emissions, including enteric and manure CH_4, are widely considered to be the most significant source of emissions on cow-calf operations (Beauchemin et al. 2010b).

The model includes total feed intake, average daily gain, level of energy and diet digestibility for all classes of cattle. Enteric CH_4 is estimated using the IPCC Tier 2 Y_m conversion factor approach that considers the energy intake of the animal and a default conversion factor (Pogue et al. 2023). A separate equation is used in the model to estimate enteric emissions from beef calves. Furthermore, an alternative approach based on the application of simple linear equations from literature was used in the model to estimate enteric CH_4 (Pogue et al. 2023). The Holos model incorporates detailed feed information from the revised Nutrient Requirement of Beef Cattle (NASEM 2016) as a default feed database. This database includes values for feed ingredients including common grains, forages, concentrates, and supplements which provide the model user with alternatives when detailed feed analysis results are not available for a specific feed. Furthermore, the model also includes default diets for different groups of animals, enabling the user to choose diets similar to the operation being modelled. Alternatively, the user can formulate diets either based on the default feed ingredients or actual feed information entered. For our study, rations for different feeding periods as reported by the focus groups and included in the benchmark farms were entered in the form of a diet percentage for each ingredient. A complete nutrient profile of each ration based on the data entered for each ingredient and its relative proportion was calculated within Holos. In cases where no default values were available for feeds in the Holos model, nutritive values from alternative sources including Cowbytes diet formulation software (Alberta Agriculture 2012), published literature and reports were used. Nutrient requirements were calculated by Holos, considering monthly average temperatures, cattle class, body weight, physiological status, rate of gain, and housing type.

Methane emissions from manure are primarily related to environmental conditions and type of manure handling and storage. Manure CH_4 is calculated in the Holos model based on the production of volatile solids from manure produced during storage or handling practices provided by the benchmark farms. Volatile solids are emitted from the organic fraction of manure which can be further broken down into gases such as CH_4. As CH_4 is produced by bacteria under anaerobic conditions, emissions are dependent on how much time manure is stored in anaerobic conditions. Manure management systems considered in the model include solid storage, deep bedding, and composting (active, passive). Solid storage was defined as manure and bedding that was removed from housing and stored in a static pile until spreading. Deep bedding was defined as a bedding pack where bedding material was added throughout the feeding period and manure was removed once at the end of the period. Farm-specific manure management practices as reported by the focus-groups were used for the simulated benchmark farms.

4.3.4.2 Nitrous Oxide (N_2O) Emissions

Nitrous oxide emissions were calculated in the Holos model from multiple sources including direct and indirect emissions from manure storage and soils (hay, pasture and crop fields). Nitrous oxide emissions from soil were calculated based on rates of nitrification, denitrification, leaching, runoff and volatilization. These biological and physical processes are dependent on many environmental factors, such as soil properties and texture, moisture levels, temperature, drainage and evapotranspiration rates. For all the simulated benchmark farms in our study, location-specific corresponding model default data for climate and soil variables were used. Nitrous oxide emissions are also dependent on the total nitrogen in soils and residues, therefore rates of nitrogen application and plant species can greatly affect total N_2O emissions. The model estimated the nitrogen available to generate emissions from applied synthetic fertilizer and manure, nitrogen from manure deposited during grazing, and nitrogen from crop residues, including nitrogen fixed by legume crops. Nitrous oxide emissions were calculated from manure storage of all classes of cattle, rates of emissions dependent on form of storage and handling, as well as concentration of nitrogen in the manure. Nitrogen concentration in manure is directly correlated to the nitrogen fraction in the diet which is mainly contributed by the level of dietary protein, daily intake and animal use efficiency.

4.3.4.3 Carbon Dioxide (CO_2) Emissions

The Holos model estimated CO_2 emissions from energy use based on total energy usage for different farm activities including cropping, feeding and electricity. Energy emissions from cropping were estimated for field machinery usage for planting, fertilizer and pesticide applications, harvesting forage and crops as well as hauling and applying stored manure to fields. Emissions from electricity usage was calculated using average emissions produced per kilo-watthour (kWh) in each province. The model assumes electricity usage is only applied when cattle are managed in a barn or enclosed housing system (Pogue et al. 2023). Emissions from energy to produce commercial fertilizers and pesticides were calculated by the model based on number of applications and application rate, crop requirements and soil properties. Furthermore, CO_2 emissions were also calculated from soil management-related activities primarily based on the level of tillage and residue incorporation in annual crops and included the length of stand before reseeding to perennial crops.

4.3.4.4 Soil Carbon Sequestration

Holos uses the Introductory Carbon Balance Model (Kröbel et al. 2016a) to calculate soil carbon levels, as well as the associated related emissions and sequestrations. This approach separates soil carbon materials into two categories with separate calculations to estimate the carbon inputs into the "young" carbon pool derived from plant and manure sources, and the rate of decay and transfer into an "old" carbon pool, which has a slower rate of decomposition. Decomposition is also influenced by environmental factors such as soil temperature and moisture, as well as soil disturbance (primarily through tillage), which are also included in the algorithm. The level of carbon and nutrient stored in the crop residues are provided for all common crops and forages grown in Canada, and residues are separated by component (roots, straw, and grain). Default values for an estimated percentage of residue left in or on the soil are available, however custom residue rates can be added for scenarios when residue is removed (*e.g.,* baling of straw).

4.3.5 Model Assumptions

Due to the nature of modelling whole farm GHG emissions, it is impractical to collect data for every variable on a given farm. Therefore, evidence-based assumptions were made for missing data from the simulated benchmark farms. Default model assumptions were used when data points were missing, and literature values were used when the model was not designed to accommodate in the specific scenario under consideration.

4.3.5.1 Environmental Data Assumptions

The Holos model utilizes an interactive geographical map that features hundreds of polygons which represent areas agricultural regions in Canada. Each polygon is a data package which contains soil and weather data associated with the production area as provided by the Soil Landscapes of Canada (SLC; Agriculture Canada 2011). The model requires selection of a polygon which allows Holos to populate all default weather and soil data for that geographical region. As described above, each benchmark farm is hypothetical and has no physical location because each dataset is made up of data from the 3-6 farms that made up the focus group. As such, it was necessary to select a central geographical location for each benchmark farm which best represents all the contributing farms. To accomplish this, the GPS coordinates of each of the contributing farm's locations were obtained by referencing their postal code which was collected during data collection. To capture the differences in soil and climate variables between the contributing farms, each benchmark farm was simulated in the location of each of the contributing farms, and the model outputs were merged by taking a simple average of the output from each location. In some cases, the coordinates of a farm fell outside of the polygons available in Holos and the polygon closest to the benchmark coordinates was used. This method was used rather than taking an average of all the coordinates and choosing a single point, as there were significant distances between some farms, as well as lack of available polygons for large portions of several provinces, making it impossible to use the averaged point. Many of the Holos polygons have multiple input options for soil types depending on the soils in the area and the soil type that most closely matches the sand-to-clay ratio described in the collected data. Due to the lack of detail regarding soil type provided in the collected data set, default values were used for some benchmark farms.

4.3.5.2 Assumptions on Land Use and Cropping

When moisture content of crops and forage grown on farms was not available, default values available in Holos were used. It was assumed that no farms used irrigation on crops. Data regarding land use change was not collected and therefore it was assumed that none of the benchmark farms had recently broken grassland. Furthermore, data regarding the use of tillage on arable fields was not collected, and therefore the most common tillage practice in that province (intensive till, reduced till, or no till) as reported by Statistics Canada (Statistics Canada 2017c) was used. It was also assumed that producers did not change tillage practices from year to year. Data pertaining to the level of crop residue remaining after harvest was obtained from the published literature or using Holos default values to estimate nitrogen and carbon content of product, straw and roots, and proportion of straw and roots returned to the soil (except for when indicated that straw was baled and removed). It was assumed that residue was not returned to the soil for crops harvested for silage or hay, while all straw was returned to the soil when crops were harvested for grain unless all or a portion of it was baled. Crops that were grazed while standing (corn) assumed a utilization rate of 51% (Jose et al. 2020) and the remaining 49% of the leftover straw returned to soil in these fields. Nutritive values for grazing standing corn were not available in Holos or Cowbytes databases, so feed values used were retrieved from published data (Rasby et al. 2014a; Lakeland Agricultural Research Association 2017a). For annual crops that were used for swath grazing (e.g., barley, oat, triticale), a utilization rate of 72% (Baron et al. 2014b) was used assuming 28% of straw was returned to soil in these fields. Swath grazed crops were assumed to have the same nutritive values as if that same crop had been baled and stored (Baron et al. 2014b). As such, for nutritive value input, swath grazed barley would be entered into Holos as barley hay (as the model has no input option for swathed crops), and only the environmental conditions would be changed to accurately represent swath grazing. While applied nitrogen fertilizer rates were known from focus group data or supplemented by survey data for each crop, little detail regarding land applied manure was collected. Provincial average data regarding manure application was available without distinction of crop type from Statistics Canada (Statistics Canada 2019b), therefore it was assumed that producers applied manure according to provincial averages with it being equally applied to all fields of the same type regardless of crop species. Holos uses nitrogen and carbon content of above and below ground crop residue to estimate soil nitrogen levels. However, the default values available in the Holos database were used as no laboratory analyses were available. In cases where producers indicated use of intercrops, the residue values from each contributing crop were combined to provide an estimate of average residue nutrients in the field.

Since pasture yield data was not collected, it was back-calculated based on the hectares of pasture, number of animals grazing, length of grazing period and pasture utilization rate from (Legesse et al. 2018). Based on these yield calculations and input from producers during data collection, each farm was assumed to have pasture consisting of native grasses, tame grasses, or a 1:1 ratio of native and tame grasses. Model default values were used to estimate the nutrient profile for native hay and grass hay while 1:1 ratio pasture used nutritive values of each at a 1:1 ratio.

Fertilizer use data including method of application, season of application, and type of nitrogen fertilizer was not available for all farms. Further, all farms were assumed to follow the most common practice and average application rates as described by Fertilizer Canada, which provided data values specific to each crop (Fertilizer Canada 2020).

4.3.5.3 Manure Management Assumptions

For missing manure application data, it was assumed that manure was spread in the fall in the Western provinces (BC, AB, SK and MB) as described by Sheppard et al. (2015) whereas in the Eastern provinces (ON, QC and MT), manure was assumed to be spread in the spring. The date for spreading in spring was set as May 1st and the fall date as October 1st. When data regarding the specific fields to which manure was not available, it was assumed that it was spread on either all hay fields, crop fields, or both based on the most common practice in that province as reported by Statistics Canada (Statistics Canada 2019c). If a farm had no field crops, it was assumed all manure was spread onto hay fields, and if the farms had no hay or crop fields, it was assumed manure was spread onto pasture.

4.3.5.4 Assumptions Regarding Herd Characteristics

It was assumed that 50% of calves were male and 50% female for all farms (Foote 1977; Baublits et al. 2003), and all calves were managed under the same housing conditions as the cow herd until weaning. Furthermore, the Holos model default average values for milk yield (8 liter/cow/day) and nutrient profile (protein = 26.7%, energy = 5.68 Mcal/kg) were used. It was assumed that all mature cows and bulls had no change in body weight throughout the year. This is because during pregnancy season, mature cows gain weight that is lost during parturition with no net change in weight. It was assumed that all groups of animals received the same amount of bedding unless otherwise indicated by producers during data collection. No bedding was provided during extended grazing days unless reported by producers. No data regarding rations for bulls were collected, and therefore it was assumed that bulls received the same ration as cows unless indicated otherwise.

The type of outdoor winter housing for cattle varied widely among farms, however options within Holos included: barn housing, enclosed housing or on pasture. Barn housing was not common amongst benchmark farms, and was defined as having a permanent enclosed building where cattle would spend most of their time with access to an outdoor yard. Enclosed housing was defined as feeding in an outdoor yard where manure accumulated in the shelter/housing areas of the yard and feed was brought into this area on a regular basis with farm equipment. Pasture type included cattle fed on an arable field or pasture with significant space and no permanent structures or mechanical handling of manure.

Body weight of replacement heifers after weaning was not collected, however since heifers continue to grow throughout the production year, weight gain data was necessary to estimate average body weight as well as dry matter intake in the model. Therefore, it was assumed that heifers would attain the same mature weight as the cow herd, reaching 95% of mature cow weight at 2 years of age, and 100% of mature cow weight at 5 years of age (Kaps et al. 1999). The average daily gain was assumed to be static from weaning until two years, and then reduced from two years to five years, to ensure maturity was achieved by 5 years. Therefore, average daily gain during these periods was determined by dividing total weight gained (weaning to two years, and two years to five years) divided by the number of days in each time period.

4.3.5.5 Revenue assumptions

Costs and revenues for the economic analysis of this project were provided by producers during the focus-group sessions. This provided precise and region-specific values for each farm and captured variances in prices across Canada. The costs and revenues were based on data from the 2020 production year for benchmark farms and the future farm scenarios and did not account for potential increases (or decreases) in prices of cattle or costs of production.

Net income and net cash income were calculated using all sources of farm income, which included revenue from cropping enterprises. However, profitability measures (in units of $/cow wintered or $/lb weaned) included costs and revenues solely from the cow-calf enterprise.

Opportunity costs were calculated as part of the economic analysis and utilized in the long-term profitability figures. Opportunity costs were calculated as the potential income that could be earned from other uses of land, labour and capital utilized by the enterprises included in the benchmark farms. In future farms scenarios, the additional use of land, labour or capital required to implement the scenario were considered in the scenario long-term profitability analysis.

4.3.6 Post Modelling Adjustments

Model output is expressed as kilograms or tonnes of individual GHGs or as CO_2eq for each class of animal and field (annual, perennial), emission type and source. A spreadsheet with emission results was exported for each benchmark farm, and the average was obtained by taking the mathematical mean of each respective value using an automated script written in the R programming language. Emissions intensity (kg CO_2eq/kg LW) was calculated from total emissions (on-farm emissions plus emissions related to farm inputs, kg CO_2eq) divided by functional unit, total LW (kg) exported at the farm gate. Total liveweight exported at the farm gate was calculated as the average weight of each class of animal (weaned calves, backgrounders, culled cows and bulls) multiplied by the number of head sold.

4.3.7 Future Farms Scenarios

There were 60 initial future farm scenarios developed by the Canfax Research Services team, each consisting of a specific management change to a benchmark farm. Canfax Research Services developed a full economic analysis for each scenario to generate figures surrounding cost of implementation and expected return on investment for each scenario. By assessing relevance and practicality, 12 scenarios were selected to estimate net farm GHG emissions associated with the change in management associated with the future farm scenario. The scenarios selected for inclusion in this project were those that offered the greatest opportunity for emissions reduction and had the most significant economic benefit. The practices used in these scenarios were also identified by producers from focus group sessions to be realistic and generally beneficial to their operations. The practices used could also be potentially applied to a range of conditions across Canada and suitable for different sizes of operations, ensuring they are relevant to the current industry. In addition, some scenarios were modelled on several benchmark farms to capture differences in outcomes when the change in practice was adopted in different environments. These scenarios were modelled using identical input parameters as the benchmark farms except for those associated with the practice change. Therefore, differences in labor, cost and management changes that occurred as a result of the changes in each scenario were compared between benchmark farms.

4.3.7.1 Extended Grazing

Adoption of rotational grazing system during summer months was modelled on farms “BC-1, QC-1” and “AB-3” with the assumption that this would increase pasture productivity and extend the summer grazing season. The rate of productivity increase was dependent on regional factors for each farm and was determined in consultation with producers and provincial extension experts. It was assumed that there was no change in soil carbon sequestration or increase in forage quality following the use of rotational grazing, due to lack of definitive values available from literature (Byrnes et al. 2018). Due to fewer winter feeding days and thus less winter feed, surplus hay produced was exported. The hay field was then divided into two fields, one which was harvested for winter feed, and one for exported feed. The exported hay field emissions were discounted from the total farm emissions as they were no longer contributing to the cow-calf enterprise.

4.3.7.2 Calving Interval

An increase in calf weaning weight by shortening the calving interval and increasing the number of calves born in the first month of calving (shortening the calving season) was implemented on farms “AB-1” and “MB-1” The model inputs for these scenarios required only a change of average calving date and increase in weaning weights of calves. This scenario was modelled in two different stages, the first (scenario level 1) being a more modest narrowing of the calving season and condensing the calving season from 4 to 3 breeding cycles achieving a ratio of 37%, 33% and 30% of cows calving in the first, second and third cycles, respectively. The second level (scenario level 2) was a more aggressive change shortening to 3 cycles with 50%, 30% and 20% of cows calving in the first, second and third cycles, respectively. Since several years are required to make this practice change and each year resulted in improved economic benefits, this scenario was modelled in the first and the fifth year of implementation in an effort to capture the emission changes that would occur over time. It was assumed that prices for sold cattle were only changing based on an increase in average weight, there was no consideration for selling calves in a more narrow weight range to gain a premium price.

4.3.7.3 Improved Watering System

A scenario that examined the impact of improving water quality by digging a well and implementing a solar powered watering system on summer pasture was modelled on farm “AB-6”. This scenario did not require significant changes to the model inputs and consisted of an increase in average daily gain by 0.05 kg/day (Lardner et al. 2005).

4.3.7.4 Corn Grazing

A 30-day period of backgrounded calves grazing standing corn was modelled on farm “SK-1a”. It was assumed that there was no change in body weight or rate of gain of the calves relative to the benchmark farm since the scenario ration was comparable to the benchmark ration in nutritive value. Accordingly, an extra 7.4 hectares of land was required to grow the additional standing corn, and it was assumed that this additional corn was grown under identical cropping conditions as the standing corn grown on the benchmark farm. Following the corn grazing period, it was assumed that backgrounded calves returned to confined feeding with same conditions as the benchmark farm.

4.3.7.5 Creep Feeding of Calves

Creep feeding calves with a grain ration while still suckling milk was implemented on farm "SK-6" The ration consisted of 27% oats, 63% barley and 10% protein supplement (75.4% TDN, 11.4% CP) for 77 days while still receiving 8 kg of milk (dry matter) per day. It was assumed that calves would have an average increase in weaning weight of 13 kg (with 0.17 kg/day more gain) compared to the benchmark farm (Rasby & Niemeyer 2011). As barley made up the greatest proportion of the ration, it was assumed that two hectares of the barley crop that was exported from the benchmark farm was retained for creep feed

4.3.7.6 Artificial Insemination (AI)

The breeding program was changed to include 75% of cows bred through AI rather than natural service on farm "ON-4". To implement this scenario, it was assumed that the number of bulls in the herd would be reduced from 6 to 2, and that the bull culling rate would be reduced from 2 per year to 0.5 per year. It was also assumed that this scenario would increase conception rates by 2% (Lardner et al. 2015) which increased the number of total calves born. It was also assumed that the percentage of female calves sold increased by 1.3% compared to the benchmark farm due to increased rates of conception.

4.4 Results

4.4.1 Benchmark Farm Description

The 25 benchmark farms (2 in BC, 6 in AB, 5 in SK, 2 in MB, 4 in ON, 4 in QC, 2 in MT) were developed based on data collected from farms across Canada that captured the diversity in farm size, as well as the range of management practices and environmental factors that impact how farms operate.

Farm Size, Feeding and Grazing Management

As indicated in Table 2, there was considerable diversity in farm size and management practices among benchmark farms. The average herd size was 163 cows (ranging from 35 to 350), 14 replacement heifers (ranging from 0 to 68), 24 bred heifers (ranging from 3 to 67), and 78 backgrounders (ranging from 0 to 233). There was a trend towards larger herds in the prairie provinces (AB, SK, MB) as compared to BC and the Eastern provinces (Table 2). A wide range of management practices were observed between farms. For example, although all farms had a period of summer grazing with an average value of 163 days, large variation was observed among benchmark farms, ranging from 115 days for AB-1 to 215 days for BC-1 and SK-1b. Pasture type tended to be characterized by region, as the farms located in Western provinces utilized native or partially native pastures for summer grazing, while all farms in Eastern provinces grazed tame grass pastures. The length of the confined winter-feeding period ranged from 42 days for SK-1a to 240 days for QC-2, with an average of 155 days (Figure 4). Winter feed ingredients were somewhat variable, but most operations utilized primarily hay-based rations with 11 out of 12 farms in AB and SK utilizing cereal forages in the form of crop residues, silage, greenfeed or swath grazing. Furthermore, 88% of the benchmark farms produced more than half of their stored feed for the winter months while 52% produced all the stored feed required for the winter months (Table 2). However, QC-2, QC-4 and SK-1b purchased 75%, 50% and 100% of their winter feed, respectively from off-farm sources. Some benchmark farms purchased smaller portions (1% to 39%) of off-farm feed to supplement homegrown feed. Although not all farms practiced extended grazing, swath grazing of cereals, grazing standing corn, grazing cereal residue and bale grazing on pasture, these management practices were reported as common practice with the number of days ranging from 20 (AB-4) to 180 days (SK-1a, Table 3). Two farms implemented two different extended grazing practices within a season; SK-1a used swath (112 days) and corn (68 days) grazing while SK-4 used corn (60 days) and bale (60 days) grazing.

Table 2. Farm attributes and management variables of the 25 benchmark farms included in the study

Farm ID	Days grazing summer pasture	Days of extended grazing	Days of confined feeding	% of winter feed purchased	Primary winter feed ingredients	Primary type of pasture	Herd Size			
							Cows	Replacement heifers (< 12 mo)	Bred heifers (12-24 mo)	Backgrounders
BC-1	215	0	150	1%	Hay	Native	64	4	8	0
BC-2	155	0	210	2%	Hay, Screenings	Native	90	4	10	0
AB-1	115	60	190	0%	Swath grazing, Hay, Silage	Native	212	10	25	153
AB-2	139	80	146	0%	Swath grazing, Hay, Straw, Grain	Native	280	11	25	214
AB-3	131	54	180	0%	Swath grazing, Hay, Silage, Straw	Native	172	7	18	92
AB-4	154	20	191	0%	Swath grazing, Hay, Straw, Greenfeed	Native	54	2	5	0
AB-5	130	51	184	0%	Swath grazing, Hay, Straw, Grain, Greenfeed	50/50	220	7	18	167
AB-6	146	35	184	0%	Swath grazing, Hay, Straw, Grain	Native	152	8	14	0
SK-1a	143	180	42	0%	Swath grazing, Corn grazing, Hay	50/50	350	62	64	152
SK-1b	215	0	150	100%	Hay	50/50	350	27	65	233
SK-3	185	30	150	9%	Crop residue, Hay, Grain	Native	245	19	33	0
SK-4	200	120	45	3%	Corn grazing, Hay, Greenfeed	50/50	120	5	11	0
SK-5	165	60	140	39%	Crop residue, Silage, Straw,	Native	135	68	67	0

					Screenings, Camelina meal					
SK-6	179	0	186	0%	Silage, Hay, Grain	50/50	135	7	20	0
MB-1	165	110	90	10%	Corn grazing, Hay, Straw	Native	320	23	41	230
MB-2	185	0	180	7%	Silage, Hay, Grain	50/50	224	15	26	178
ON-1	180	0	175	6%	Silage, Hay, Screenings	Tame	50	3	5	42
ON-2	185	0	180	15%	Hay, DDGS	Tame	160	20	25	0
ON-4	132	178	55	0%	Silage, Hay	Tame	100	12	20	0
QC-1	165	0	200	0%	Hay	Tame	150	10	24	114
QC-2	125	0	240	75%	Hay	Tame	275	21	47	204
QC-3	165	0	200	0%	Hay	Tame	60	0	6	55
QC-4	165	0	200	50%	Hay	Tame	60	4	9	46
MT-1	185	180	0	0%	Hay	Tame	55	4	12	65
MT-2	145	0	220	0%	Hay	Tame	35	1	3	0
Mean	**163**	**46**	**155**	**12%**	**N/A**	**N/A**	**163**	**14**	**24**	**78**

The average length of winter-feeding period (confined + extended grazing) was 202 days (± 27 SD; Figure 4). Overall, AB farms had the longest average winter-feeding period (229 days) compared to the other provinces, however they also tended to use extended grazing practices, particularly swath grazing of cereal crops, more often than farms in other provinces (Table 3). None of the benchmark farms in BC and QC, nor used any extended grazing practices and therefore relied entirely on confined feeding during winter months. Similarly, all farms in ON and MT used confined feeding during winter months except for ON-4 and MT-1 which used bale grazing as part of their winter-feeding strategy. In addition, SK-1b and SK-6 also relied solely on confined feeding. Furthermore, cereal crops including corn grazing were not used in any benchmark farms in the Eastern and maritime provinces (Table 3). One farm in Manitoba (MB-1) grazed standing corn for 110 days and provided supplemental feed on pasture to extend the grazing season. Alternatively, no extended grazing strategies were used in MB-2 indicating the diversity in beef cattle management within a given province. Farms in SK were the most diverse in the use of extended grazing practices, with farms using bale grazing, corn grazing, swath grazing and grazing cereal crop residues to reduce the number of confined feeding days during the winter period.

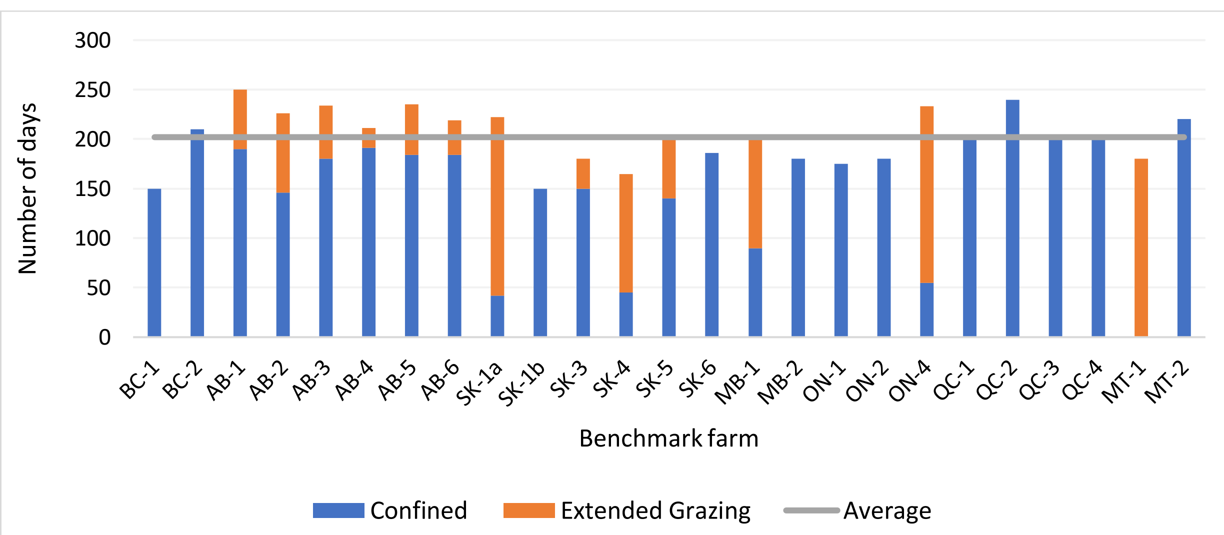

Figure 4. Number of days of winter-feeding (confined and extended grazing) for the 25 benchmark farms

Table 3. Number of days extended grazing practices were utilized on the benchmark farms (n = 13).

Farm ID	Days of swath grazing	Days of corn grazing	Days of grazing cereal residue	Days of bale grazing
AB-1	60	0	0	0
AB-2	80	0	0	0
AB-3	54	0	0	0
AB-4	20	0	0	0
AB-5	51	0	0	0
AB-6	35	0	0	0
SK-1a	112	68	0	0
SK-3	0	0	30	0
SK-4	0	60	0	60
SK-5	0	0	60	0
MB-1	0	110	0	0
ON-4	0	0	0	178
MT-1	0	0	0	180

Total liveweight exported from the farm, varied considerably across benchmark farms from 10,462 kg (for MT-2) to 128,155 kg (for SK-1b) with a mean value of 50,217 kg (± 32,671 Table 4). Liveweight exported from the farm was highly dependent on herd size, culling/ replacement rate and weight of calves when sold as farms that had longer backgrounding periods were able to sell heavier calves resulting in a higher total liveweight. Weaned and backgrounded calves comprised approximately 75% of the total live weight sold from the benchmark farms (ranged between 56% and 86%). Cull cows and bulls were second to calves in liveweight sales, with an average contribution of 25%.

Table 4. Average weaning weight (kg) and liveweight sold (kg) from weaned calves, cull cows and bulls, and total liveweight exported (kg) from the 25 benchmark farms included in the study.

Farm ID	Average weaning weight of calves (kg)	Liveweight sold - weaned calves (kg)	Liveweight sold - cull cows + bulls (kg)	Total weight sold (kg)
BC-1	269	11,638	4,748	16,386
BC-2	264	19,367	6,124	25,491
AB-1	271	49,059	17,705	66,764
AB-2	251	73,652	14,420	88,072
AB-3	241	36,756	11,026	47,782
AB-4	284	11,994	3,414	15,408
AB-5	246	48,489	8,167	56,656
AB-6	242	29,955	8,121	38,076
SK-1a	211	72,177	35,292	107,469
SK-1b	220	91,699	36,456	128,155
SK-3	253	46,447	19,315	65,762
SK-4	271	27,559	6,617	34,176
SK-5	277	25,944	13,330	39274
SK-6	321	30,685	13,057	43,742
MB-1	240	81,042	22,406	103,448
MB-2	220	52,634	11,197	63,831
ON-1	271	11,939	4,011	15,950
ON-2	252	27,820	14,425	42,245
ON-4	233	14,641	11,562	26,203
QC-1	274	40,870	13,563	54,433
QC-2	244	72,212	24,042	96,254
QC-3	289	16,282	4,589	20,871
QC-4	264	16,601	5,601	22,202
MT-1	247	19,480	7,407	26,887
MT-2	271	7,902	2,560	10,462
Average	**257**	**37,474**	**12,766**	**50,240**
Median	**253**	**29,955**	**11,197**	**42,245**
Min	**211**	**7,902**	**2,560**	**10,462**
Max	**321**	**91,699**	**36,456**	**128,155**
SD	**24.35**	**24,549**	**9,068**	**32,675**

4.4.2 Benchmark Farm and GHG Emissions

The estimated emission intensity for each benchmark farm is given by source and emission type in Table 5. Emission sources include CH_4 (from enteric fermentation and stored manure), direct and indirect N_2O (from stored manure and soil), CO_2 (related to energy use, and imported feed ingredients). Emission results are presented in the form of kg CO_2eq/kg LW (LW) sold at the farm-gate to account for the large differences in herd size between farms. Relative to farms in the Eastern provinces (ON, QC, MT), Western provinces (BC, AB, SK, MB) generally had relatively higher average enteric CH_4 emission intensity (16.9 *vs* 15.1 kg CO_2 eq/kg LW sold) and lower manure N_2O emissions (direct and indirect: 0.5 *vs* 1.0 kg CO_2 eq/kg LW) However, the opposite was true for soil N_2O emissions with higher intensity for Western than Eastern provinces; 4.7 *vs* 3.4 kg CO_2eq/kg LW sold. Average emissions intensity related to purchased and imported feed ingredients were higher in Eastern provinces (0.1 vs 1.0 kg CO_2 eq/kg LW sold) as very few farms in Western provinces purchased additional feed. Conversely, manure CH_4 and energy source emissions intensity fluctuated from farm-to-farm and did not show any specific trends based on farm geography but were more dependent on specific farm practices and environmental conditions.

Total GHG emissions for the benchmark farms ranged between 208,766 and 2,724,113 kg CO2 eq with an average value of 1,210,575 kg CO2 eq. Average farm emission intensity varied between 18.3 kg CO2 eq/kg LW sold (for QC-3) and 35.1 kg CO_2 eq/kg LW sold (SK-6) with an average emission intensity of 24.7 (± 4.7) kg CO_2 eq/kg LW sold (Table 5). The largest proportion of emissions for all benchmark farms was from enteric CH_4, which, on average, accounted for 59% of the total farm emissions. Manure CH_4 made up a smaller portion of total farm emissions (6%). Furthermore, the lowest emissions were associated with on-farm energy use (5%) and imported feed ingredients (2%). However, emissions varied widely across benchmark farms, particularly N_2O which had the largest standard deviation (2.35, Table 5). Nitrous oxide emissions (direct and indirect) were the second largest contributor to total farm emissions intensity (19%), with soil and stored manure contributing approximately 17% and 3%, respectively.

Table 5. Detailed emissions intensity (kg CO_2eq/kg LW sold) breakdown by source and emission type for the 25 benchmark farms

Farm	Enteric CH_4	Manure CH_4	Direct N_2O			Indirect N_2O			Total N_2O	Energy CO_2	Imported feed CO_2	**Total**
			Manure N_2O	Soil N_2O	**Total**	Manure N_2O	Soil N_2O	**Total**				
BC-1	17.33	0.22	0.00	1.35	1.35	0.00	2.29	2.29	3.64	0.49	0.30	21.98
BC-2	17.78	0.22	0.00	1.63	1.63	0.00	2.46	2.46	4.09	0.55	0.00	22.64
AB-1	14.92	3.17	0.85	3.18	4.03	0.35	2.86	3.21	7.24	1.20	0.00	26.53
AB-2	16.15	4.14	0.79	2.37	3.17	0.15	2.67	2.82	5.99	0.83	0.00	27.11
AB-3	17.39	5.45	1.08	4.64	5.72	0.21	3.60	3.81	9.52	2.20	0.00	34.56
AB-4	16.83	3.95	0.89	2.84	3.73	0.41	2.46	2.87	6.60	1.12	0.00	28.50
AB-5	17.32	4.36	0.79	1.48	2.27	0.14	2.16	2.30	4.57	0.64	0.00	26.89
AB-6	18.46	3.28	0.61	4.25	4.86	0.11	4.54	4.65	9.51	0.87	0.00	32.12
SK-1a	17.11	0.20	0.00	1.64	1.64	0.00	1.12	1.12	2.76	1.50	0.00	21.57
SK-1b	17.19	0.21	0.00	1.49	1.49	0.00	1.62	1.62	3.11	1.20	-0.44	21.27
SK-3	17.78	0.22	0.00	1.62	1.62	0.00	1.51	1.51	3.13	4.64	0.00	25.77
SK-4	15.59	0.19	0.00	2.03	2.03	0.00	1.79	1.79	3.82	1.84	-0.02	21.42
SK-5	19.59	0.33	0.02	1.38	1.40	0.00	1.10	1.10	2.50	1.21	0.99	24.62
SK-6	16.12	2.22	0.55	6.58	7.13	0.13	4.38	4.51	11.64	5.13	0.00	35.11
MB-1	15.34	0.30	0.57	0.73	1.31	0.12	0.80	0.92	2.23	0.41	0.01	18.29
MB-2	15.91	4.02	0.69	1.54	2.23	0.12	1.70	1.82	4.05	2.19	0.50	26.67
ON-1	13.94	3.49	0.78	3.26	4.04	0.42	1.22	1.64	5.68	0.84	0.98	24.93
ON-2	16.20	3.75	1.08	3.14	4.22	0.55	1.46	2.01	6.23	0.47	3.44	30.09
ON-4	18.52	1.59	0.31	1.84	2.15	0.18	2.03	2.21	4.36	1.25	0.00	25.72
QC-1	13.93	0.42	1.05	1.67	2.72	0.28	1.40	1.68	4.40	0.47	0.41	19.63
QC-2	14.30	0.48	1.32	1.19	2.51	0.35	1.71	2.06	4.57	0.51	0.92	20.78
QC-3	12.22	0.41	1.02	1.12	2.14	0.25	0.87	1.12	3.26	0.09	2.30	18.28
QC-4	14.73	0.48	0.96	1.35	2.30	0.23	1.21	1.45	3.75	0.19	1.01	20.16
MT-1	16.09	0.19	0.01	2.52	2.52	0.00	1.29	1.29	3.81	1.60	0.15	21.84
MT-2	16.16	0.18	0.00	1.76	1.76	0.00	1.14	1.14	2.90	0.69	0.02	19.95
Mean	**16.28**	**1.74**	**0.53**	**2.26**	**2.80**	**0.16**	**1.98**	**2.14**	**4.93**	**1.29**	**0.42**	**24.66**
Median	**16.16**	**0.48**	**0.61**	**1.67**	**2.27**	**0.13**	**1.70**	**1.82**	**4.09**	**0.87**	**0.00**	**24.62**
Min	**12.22**	**0.18**	**0.00**	**0.73**	**1.31**	**0.00**	**0.80**	**0.92**	**2.23**	**0.09**	**-0.44**	**18.28**

Max	**19.59**	**5.45**	**1.32**	**6.58**	**7.13**	**0.55**	**4.54**	**4.65**	**11.64**	**5.13**	**3.44**	**35.11**
SD	**1.65**	**1.76**	**0.44**	**1.30**	**1.46**	**0.16**	**0.99**	**1.00**	**2.35**	**1.20**	**0.83**	**4.66**

4.4.3 Benchmark Farm Economic Results

To capture the nuances of cost of production and total farm income on cow-calf operations in Canada, farm profitability was calculated by several different metrics, as indicated in Table 6. Net income and net cash income varied widely among benchmark farms ($-55,989 to $207,657 and $-17,263 to $252,331, respectively) with net cash income being higher for all farms as it excludes the cost of depreciation. When looking at net cash income, the effect of depreciation cost had a more significant impact on some farms than others. For example, several farms (AB-1, AB-2, AB-3, AB-6) had higher depreciation costs due to a larger amount of depreciable assets such as machinery and infrastructure; whereas other farms, including MB-2 and BC-2, had lower depreciation costs, due to minimal capital inputs and reduced depreciable assets on the farm. Profitability was calculated as the cost per cow kept through the winter and profit per pound of calf weaned (Table 6). These measures of profitability were reported under three criteria: short-, medium- and long-term profit. Short-term profit considered only cash costs of production, medium-term included cash costs and cost of depreciation, and long-term profit included cash costs, cost of depreciation and opportunity costs. As expected, long-term profit was lower than medium- and short-term profit while medium-term profit was lower than short-term profit. Benchmark farms BC-1, SK-3, SK-4, SK-5, ON-4, MT-1 and MT-2 reported the lowest short-, medium- and long-term profits. Conversely, AB-5, SK-1a, QC-1 and QC-2 reported the highest short- medium- and long-term profitability.

Table 6. Farm income and profitability for the 25 benchmark farms in Canada reported as farm income and short-, medium- and long-term profit per unit. Values in red font denote negative values.

Farm	Net income[1]	Net cash income[1]	$/Cow wintered[2]			$/lb calf weaned[2]		
			Short-term profit	Medium-term profit	Long- term profit	Short-term profit	Medium-term profit	Long- term profit
BC-1	$ -3,805.00	$ 17,835.00	$ 143.00	$ -190.00	$ -677.00	$ 0.36	$ -0.48	$ -1.72
BC-2	$ 20,682.00	$ 37,238.00	$ 374.00	$ 177.00	$ -363.00	$ 0.79	$ 0.37	$ -0.77
AB-1	$178,185.00	$252,331.00	$ 313.00	$ 216.00	$ 83.00	$ 0.72	$ 0.50	$ 0.19
AB-2	$104,805.00	$177,602.00	$ 388.00	$ 287.00	$ 94.00	$ 0.91	$ 0.68	$ 0.22
AB-3	$110,151.00	$188,994.00	$ 339.00	$ 212.00	$ -14.00	$ 0.88	$ 0.55	$ -0.04
AB-4	$ 14,150.00	$ 59,895.00	$ 371.00	$ 19.00	$ -314.00	$ 0.76	$ 0.04	$ -0.64
AB-5	$ 53,390.00	$110,414.00	$ 584.00	$ 481.00	$ 269.00	$ 1.41	$ 1.16	$ 0.65
AB-6	$ 31,418.00	$123,287.00	$ 320.00	$ 41.00	$ -140.00	$ 0.74	$ 0.10	$ -0.32
SK-1a	$ 58,654.00	$ 93,915.00	$ 353.00	$ 288.00	$ -14.00	$ 1.71	$ 1.40	$ -0.07
SK-1b	$ 33,474.00	$ 46,803.00	$ 215.00	$ 197.00	$ 89.00	$ 0.67	$ 0.61	$ 0.28
SK-3	$ -9,134.00	$ 18,143.00	$ 67.00	$ -31.00	$ -761.00	$ 0.16	$ -0.07	$ -1.82
SK-4	$ -10,591.00	$ 18,857.00	$ 157.00	$ -89.00	$ -805.00	$ 0.31	$ -0.17	$ -1.59
SK-5	$ -26,041.00	$ -465.00	$ -42.00	$ -226.00	$ -738.00	$ -0.10	$ -0.53	$ -1.74
SK-6	$207,657.00	$230,594.00	$ 183.00	$ 149.00	$ -118.00	$ 0.36	$ 0.30	$ -0.24
MB-1	$ 4,357.00	$ 44,345.00	$ 253.00	$ 191.00	$ -133.00	$ 0.63	$ 0.48	$ -0.33
MB-2	$ 20,451.00	$ 26,101.00	$ 280.00	$ 268.00	$ 57.00	$ 0.72	$ 0.69	$ 0.15
ON-1	$ 95,484.00	$112,707.00	$ 354.00	$ 286.00	$ -91.00	$ 0.72	$ 0.58	$ -0.18
ON-2	$ 37,534.00	$ 54,472.00	$ 285.00	$ 196.00	$ -70.00	$ 0.74	$ 0.51	$ -0.18
ON-4	$ 9,454.00	$ 50,829.00	$ -138.00	$ -311.00	$ -767.00	$ -0.43	$ -0.96	$ -2.38
QC-1	$ 25,210.00	$ 84,712.00	$ 692.00	$ 499.00	$ 83.00	$ 1.52	$ 1.10	$ 0.18
QC-2	$ 37,001.00	$ 90,945.00	$ 490.00	$ 390.00	$ 62.00	$ 1.22	$ 0.97	$ 0.15
QC-3	$ -17,181.00	$ -1,556.00	$ 194.00	$ 60.00	$ -302.00	$ 0.33	$ 0.10	$ -0.52
QC-4	$ 10,054.00	$ 27,254.00	$ 446.00	$ 308.00	$ -168.00	$ 0.99	$ 0.69	$ -0.37
MT-1	$ -55,989.00	$ -15,196.00	$ -73.00	$ -232.00	$ -547.00	$ -0.17	$ -0.55	$ -1.30
MT-2	$ -30,548.00	$ -17,263.00	$ -384.00	$ -699.00	$ -1,261.00	$ -0.77	$ -1.40	$ -2.53

[1]Net income = total income – total cost; net cash income = total income – total cost – depreciation cost

[2]Short-term profit = total income - cash costs of production; medium-term profit = total income - cash costs - cost of depreciation; and long-term profit = total income - cash costs - cost of depreciation - opportunity costs.

Herd size played role in determining economic outcomes, as indicated in Table 7. The correlation between herd size and profitability was not statistically significant ($P > 0.05$) when measured by net income, net cash income or short-term profit ($/cow wintered: Table 7). However, by analyzing different metrics of profitability including medium- and long-term profit ($/cow), farms with larger herds tend to have significantly higher profitability ($R^2 = 0.24$, $P = 0.013$ and $R^2 = 0.29$, $P = 0.006$, respectively).

Table 7. Measures of correlation between herd size and farm income and cow-calf enterprise profitability across the 25 benchmark farms

Item	Net income[1]	Net cash income[1]	$/Cow wintered		
			Short-term profit[2]	Medium-term profit[2]	Long-term profit[2]
Coefficient of correlation	0.26	0.30	0.32	0.49	0.53
R^2	0.07	0.09	0.10	0.24	0.29
P-value	0.201	0.146	0.119	0.013	0.006

[1]Net income = total income – total cost; net cash income = total income – total cost – depreciation cost
[2]Short-term profit = total income - cash costs of production; medium-term profit = total income - cash costs - cost of depreciation; and long-term profit = total income - cash costs - cost of depreciation - opportunity costs.

There was a statistically significant positive correlation ($P < 0.05$) between farm profitability (net income and net cash income) and emission intensity (Table 8). When comparing beef enterprise profitability there was no significant correlation ($P \geq 0.05$) between emission intensity and profitability in the short-, medium- or long-term ($/cow wintered). Benchmark farms SK-5, ON-4, MT-1 and MT-2 reported negative short-term profit (Figure 5). Although, SK-5 and ON-4 had emissions intensities above the group mean, MT-1 and MT-2 were 1% and 12% below the group mean. The remaining farms had positive short-term profit; 5 of which were below the mean while the remaining 15 were above.

Table 8. Measures of correlation between total farm emissions intensity (kg CO_2 eq/kg LW) and farm income and cow-calf enterprise profitability across the 25 benchmark farms.

	Net income[1]	Net cash income[1]	$/Cow wintered		
			Short-term profit[2]	Medium-term profit[2]	Long-term profit[2]
Coefficient of correlation	0.606	0.634	0.090	0.108	0.244
R^2	0.367	0.401	0.008	0.012	0.060
P-Value	0.001	0.001	0.669	0.607	0.239

[1]Net income = total income – total cost; net cash income = total income – total cost – depreciation cost

[2]Short-term profit = total income - cash costs of production; medium-term profit = total income - cash costs - cost of depreciation; and long-term profit = total income - cash costs - cost of depreciation - opportunity costs.

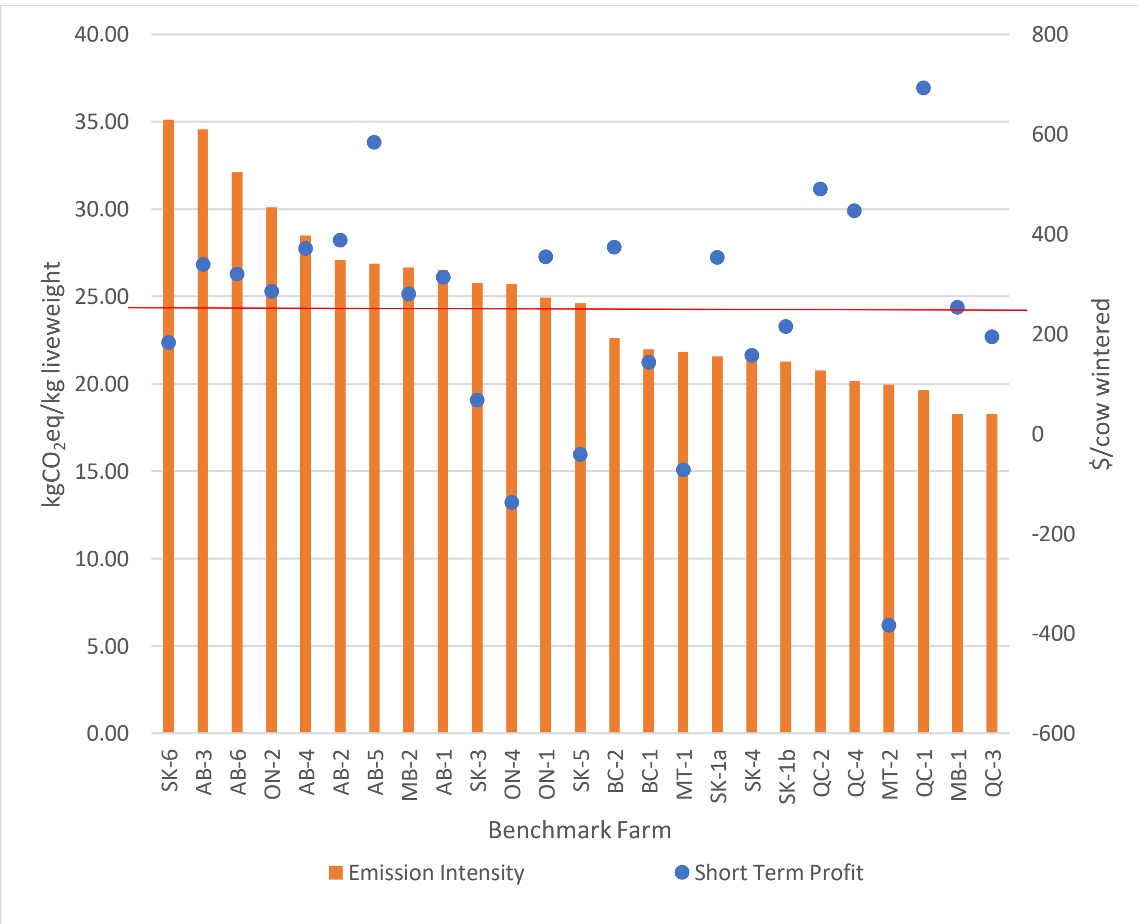

Figure 5. Short-term profit ($/cow wintered) and farm emissions intensity (kg CO_2 eq/kg LW) for the 25 benchmark farms in Canada. Average emission intensity (24.66 kg CO_2 eq/kg LW) is denoted by the red line.

4.4.4 Future Farm Scenarios

Simulating the adoption of extended grazing management resulted in an improvement in all income and profitability metrics (Table 9). However, the change in emissions intensity was not consistent for all scenario farms. For example, extending the grazing season by 20-d for BC-1 (extend) resulted in an increase in net income $3,909 and $4,352, respectively, as compared to BC-1 (benchmark). In addition, an $27.53, $20.76, and $56.56 increase in short-, medium-, and long-term profit metrics, respectively, was also realized in the cow-calf enterprise for BC-1 (extend) relative to BC-1 (benchmark). However, with the 20-d extended grazing period, farm emission intensity (kg CO_2eq/kg LW sold) increased slightly (0.41%) for BC-1 (extend) relative to the benchmark farm. When AB-3 adopted extended grazing for additional 11 days (AB-3 extend), all measures of profitability were increased including net farm income and net cash income by 11% and 7%, respectively. Further, short-, medium-, and long-term cow-calf enterprise profits were improved by 24%, 38% and 721%, respectively. There was a decrease in total farm emission intensity (0.99%) as compared to the benchmark farm. Similarly, QC-1 (extend) realized an 8% and a 3% increase in net farm income and net cash income, and a 32%, 39% and 60% increased in short-, medium-term, and long-term cow-calf enterprise profits, respectively, compared to the benchmark farm. The observed decrease in total emission intensity was the largest for QC-1-Extend (3.5%), compared to the benchmark farm, although grazing season was extended by a shorter duration (15d) than BC-1 (20d).

Table 9. Farm income, short-, medium- and long-term profitability and emission intensity associated with the adoption of extended grazing by selected benchmark farms

Farm	Net income[1]	Net cash income[1]	$/Cow wintered			Emission intensity ($kgCO_2eq$/ kg LW)	Days on pasture
			Short-term profit[2]	Medium-term profit[2]	Long-term profit[2]		
BC-1-Benchmark	-$3,805.00	$17,835.00	$143.00	-$190.00	-$677.00	21.98	215
BC-1-Extend	$104.19	$22,187.04	$170.53	-$169.24	-$620.44	22.07	235
BC-1 Change	$3,909.19	$4,352.04	$27.53	$20.76	$56.56	0.09	20
AB-3-Benchmark	$110,150.00	$188,994.00	$339.00	$212.00	-$14.00	34.56	131
AB-3-Extend	$122,806.85	$202,089.09	$420.61	$292.68	$91.51	34.22	142
AB-3 Change	$12,656.85	$13,094.09	$81.61	$79.68	$106.51	-0.34	11
QC-1-Benchmark	$25,210.00	$84,712.00	$692.00	$499.00	$83.00	19.63	165
QC-1-Extend	$27,133.76	$87,073.28	$714.25	$518.48	$132.98	18.93	180
QC-1 Change	$1,923.76	$2,361.28	$22.25	$19.48	$49.98	-0.69	15

[1]Net income = total income – total cost; net cash income = total income – total cost – depreciation cost
[2]Short term profit = total income - cash costs of production; medium-term profit = total income - cash costs - cost of depreciation; and long-term profit = total income - cash costs - cost of depreciation - opportunity costs.

Increasing weaning weights and producing more uniform calves by shortening the calving cycle had both environmental and economic implications for the cow-calf sector (Table 10). A change in the calving distribution with more calves born in the first cycle for AB-1 with an increase in weaning weight at level 1, resulted in a 13% and 9% increase in farm net income and net cash income, and a 13%, 20% and 43% increased in short-, medium-term, and long-term cow-calf enterprise profits, respectively, compared to the benchmark farm (Table 10). As the calving distribution of AB-1 in the first cycle decreased further, the increased weaning weight (level 2), led to a 15% and 11% increase in farm income and net cash income and a 18%, 26% and 58% increased in short-, medium- and long-term cow-calf enterprise profits, respectively, compared to the benchmark farm. Increased weaning weight at level 1 and 2 resulted in a reduction of farm emissions intensity by 2% and 3%, relative to the benchmark farm (Table 10).

Changing the calving distribution and increasing the weaning weight yielded similar results at both levels for the MB-1 farm (Table 10). Net income and net cash income were increased by 377% and 437% and 36% and 41% at level 1 and 2, respectively. Short- and medium-term profit were 12% and 16% higher at level 1, and 15% and 20% higher at level 2 compared to the benchmark farm, respectively. Furthermore, the loss in the long-term profit was significant; 87%

for implementation of scenario level 1 and 81% for scenario level 2. The impact of the practice change on farm emissions was minimal with less than 1% reduction in emission intensity for both levels. Emission intensity from all sources (CH_4, N_2O and CO_2) in these scenarios were slightly reduced and liveweight output was slightly increased.

Table 10. Farm income, short-, medium-, and long-term profitability and emission intensity associated with a decrease in the calving cycle and increase in weaning weights using two scenarios[1]

Farm[1]	Net income[2]	Net cash income[2]	$/Cow wintered[3]			Emission Intensity ($kgCO_2$ eq/kg LW)	Steer weaning weight (kg)	Heifer weaning weight (kg)
			Short-term profit	Medium-term profit	Long-term profit			
AB-1-Benchmark	$178,185.00	$252,331.00	$313.00	$216.00	$83.00	26.53	266	276
AB-1-Weaning weight level 1	$201,545.37	$275,685.39	$355.55	$258.27	$118.65	25.95	273	283
AB-1 Weaning weight level 1 change	$23,360.37	$23,354.39	$42.55	$42.27	$35.65	-0.58	7	7
AB-1-Weaning weight level 2	$205,132.13	$279,271.90	$368.73	$271.20	$131.08	25.84	278	288
AB-1 Weaning weight level 2 change	$26,947.13	$26,940.90	$55.73	$55.20	$48.08	-0.69	12	12
MB-1-Benchmark	$4,357.00	$44,345.00	$253.00	$191.00	-$133.00	18.29	230	249
MB-1-Weaning weight level 1	$20,803.89	$60,411.06	$282.55	$220.94	-$248.38	18.20	234	252
MB-1-Weaning weight level 1 change	$16,446.89	$16,066.06	$29.55	$29.94	-$115.38	-0.09	4	3
MB-1-Weaning weight level 2	$23,396.91	$62,702.33	$290.39	$228.77	-$240.97	18.13	236	254
MB-1-Weaning weight level 2 change	$19,039.91	$18,357.33	$37.39	$37.77	-$107.97	-0.16	6	5

[1]Calving interval: the assumption was shortening the calving season to increase weaning weight and producing calves with uniform weight. Two scenarios were examined:
Weaning weight level 1: Shorten calving distribution from four cycles to three cycles; AB-1 distribution to change from: 31%, 28%, 25%, 17% to 37%, 33%, 30% for each respective cycle over 5 years, while MB-1 changed from 59%, 25%, 11%, 5% to 62%, 27%, 12% over 5 years.
Weaning weight level 2: Shorten calving distribution from four cycles to three cycles; AB-1 distribution to change from: 31%, 28%, 25%, 17% to 50%, 30%, 20% for each respective cycle over 5 years, while MB-1 changed from 59%, 25%, 11%, 5% to 70%, 20%, 10% over 5 years
(Boyer et al. 2020)
[2] Net income = total income – total cost; net cash income = total income – total cost – depreciation cost
[3] Short term profit = total income - cash costs of production; medium-term profit = total income - cash costs - cost of depreciation; and long-term profit = total income - cash costs - cost of depreciation - opportunity costs.

An improvement in the watering system scenario was modelled for benchmark farm AB-6 which consisted of adding a solar-powered water pump and well for cattle on pasture to improve water quality. Net farm income and net cash income were increased by 41% and 12%, respectively while short-, medium- and long-term profits increased by 20%, 130% and 48%, respectively, relative to the benchmark farm. Total exported liveweight was increased by 1,107 kg. The observed improved efficiency contributed to the overall reduction in emission intensity by 4% for the future farm as compared to the benchmark farm.

Table 11. Farm income, short-, medium- and long-term profitability and emission intensity associated with improvements in the water system

Farm	Net income[1]	Net cash income[1]	$/Cow wintered			Emission Intensity ($kgCO_2$ eq/kg LW)	Exported Liveweight (kg)
			Short-term profit[2]	Medium-term profit[2]	Long-term profit[2]		
AB-6-Benchmark	$31,418.00	$123,287.00	$320.00	$41.00	-$140.00	32.12	38,076
AB-6-Water	$44,401.43	$137,467.63	$384.24	$94.43	-$73.06	30.79	39,183
AB-6 Difference	$12,983.43	$14,180.63	$64.24	$53.43	$66.94	-1.33	1,107

[1] Net income = total income – total cost; net cash income = total income – total cost – depreciation cost
[2] Short term profit = total income - cash costs of production; medium-term profit = total income - cash costs - cost of depreciation; and long-term profit = total income - cash costs - cost of depreciation - opportunity costs.

As part of the future farm scenarios, the impact of corn-grazing for backgrounded steers on benchmark farm SK-1a was also examined (Table 13). Although total exported liveweight did not change, the practice change resulted in a 27% increase in net income and 17% increase in net cash income. Profits also increased in the cow-calf enterprise with a 7%, 9% and 48% increase in the short-, medium-, and long-term profitability metrics. Therefore, the practice resulted in an increased profit across all units of measure while reducing farm emission intensity by 1.3%. The observed decrease in emission intensity was due to a slight decrease in enteric CH_4 however manure source CH_4 was unchanged. Crop emissions decreased while direct and indirect N_2O while energy emissions remained static.

Table 12. Farm income, profitability and emission intensity for standing corn grazing scenario and corresponding benchmark farm reported by farm income, cost of production, and profit per unit over short-, medium- and long-term profit analysis.

Farm	Net income[1]	Net cash income[1]	$/Cow wintered			Emission intensity ($kgCO_2$ eq/kg LW)	Exported liveweight (kg)
			Short- term profit[2]	Medium-term profit[2]	Long-term profit[2]		
SK-1a-Benchmark	$58,654.00	$93,915.00	$353.00	$288.00	-$14.00	21.57	107,469
SK-1a-Corn graze	$74,833.19	$110,087.11	$377.73	$313.14	$9.14	21.30	107,469
SK-1a Difference	$16,179.19	$16,172.11	$24.73	$25.14	$23.14	-0.27	0

[1] Net income = total income – total cost; net cash income = total income – total cost – depreciation cost
[2] Short-term profit = total income - cash costs of production; medium-term profit = total income - cash costs - cost of depreciation; and long-term profit = total income - cash costs - cost of depreciation - opportunity costs.

The economic and environmental implications associated with the adoption of creep on the SK-6 benchmark farm is reported in Table 13. Both net income and net cash income were increased by 10% while the cow-calf enterprise had a 2% profit increase for the short-, medium- and long-term profits. Emission intensity was overall by 4% in this scenario, primarily due to a reduction in enteric CH_4 and soil source N_2O.

Table 13. Farm income, profitability and emission intensity for creep feeding scenario and corresponding benchmark farm reported by farm income, cost of production, and profit per unit over short-, medium- and long-term profit analysis.

Farm	Net income[1]	Net cash income[1]	$/Cow wintered			Emission intensity ($kgCO_2$ eq/kg LW)	Exported liveweight (kg)
			Short-term profit[2]	Medium-term profit[2]	Long-term profit[2]		
SK-6-Benchmark	$207,657.00	$230,594.00	$183.00	$149.00	-$118.00	35.11	43,072
SK-6-Creepfeed	$227,548.70	$253,117.35	$186.66	$152.37	-$115.63	33.69	44,977
SK-6 Difference	$19,891.70	$22,523.35	$3.66	$3.37	$2.37	-1.42	1,905

[1] Net income = total income – total cost; net cash income = total income – total cost – depreciation cost
[2] Short-term profit = total income - cash costs of production; medium-term profit = total income - cash costs - cost of depreciation; and long-term profit = total income - cash costs - cost of depreciation - opportunity costs.

The AI future farm scenario modelled for ON-4 resulted in an increase in the overall profitability and reduction in farm emission intensity (Table 14). Net income was more than doubled at 130% increase and net cash income was increased by 24%. The cow-calf enterprise realized significant increases in profitability as well, with increases in short- (49%), medium- (22%) and long-term profitability (11%). However, the enterprise still reported negative income for all the three measures. Emission intensity was reduced by 1.08 kg CO_2eq/kg LW (4.2%) resulting from a slight reduction in net farm emissions as the reduction is primarily related to increased output.

Table 14. Farm income, profitability and emission intensity for artificial insemination (AI) scenario and corresponding benchmark farm reported by farm income, cost of production, and profit per unit over short-, medium- and long-term profit analysis.

Farm	Net income[1]	Net cash income[1]	$/Cow wintered			Emission intensity ($kgCO_2$ eq/kg LW)	Exported liveweight (kg)
			Short-term profit[2]	Medium-term profit[2]	Long-term profit[2]		
ON-4-Benchmark	$9,454.00	$50,829.00	-$138.00	-$311.00	-$767.00	25.72	26,203
ON-4-AI	$21,786.70	$63,158.15	-$70.11	-$243.66	-$682.49	24.64	26,410
ON-4 Difference	$12,332.70	$12,329.15	$67.89	$67.34	$84.51	-1.08	207

[1] Net income = total income – total cost; net cash income = total income – total cost – depreciation cost
[2] Short-term profit = total income - cash costs of production; medium-term profit = total income - cash costs - cost of depreciation; and long-term profit = total income - cash costs - cost of depreciation - opportunity costs.

4.5 Discussion

4.5.1 Farm characterization

The 25 benchmark farms (representing 115 farms) used in our study characterize the diverse nature of the cow-calf operations across Canada. This diversity was reflected not only in location across the country but also in herd size, management practices including feeding strategies, as well as additional enterprises on-farm. When comparing benchmark farms, several notable differences between farms in Eastern and Western provinces became apparent. Western farms tended to contain larger herd sizes (average 197 cows) compared to Eastern farms (average 101 cows). In agreement with our findings, Sheppard et al. (2015) also reported the dichotomy between the size of beef herd in Eastern (77 cows) and Western (163 cows) Canada.

In the current study, farms in the West were also much more likely to also grow annual crops for export, especially in the prairie region, compared to those in the East. Furthermore, benchmark farms located in Western Canada primarily grazed native pastures while those in the East, utilized tame pastures. Overall, the ratio of native and tame pasture observed in the current study (52% native, 48% tame) across all benchmark farms was slightly higher than previously reported values (43% native, 57% tame; Legesse et al. 2016). In addition, Western farms utilized extended grazing practices (Tables 1 & 2; Figure 4) including swath, corn and crop residue grazing and tended to utilize more annual crops as feed sources, while farms in the Eastern region relied almost exclusively on perennial crops (hay) for winter feeding. The average number of winter-feeding days across Canada reported in this study (202 days) was slightly higher than the average winter-feeding period of 180 days (ranging between 150 and 210 days) reported in the cow-calf survey for Western Canada (Larson, 2018).

Total beef exported from farms (kgs) was dependent on several factors including culling rate, date of calving and weaning (with earlier calving and later weaning yielding heavier calves) as well as backgrounding post-weaning leading to an increase in total weight marketed (Table 4). The average weaning weight recorded in this study (258 kg) was comparable to the value (257 kg) reported by Sheppard et al. (2015).

4.5.2 Benchmark farm greenhouse gas emissions

Average GHG emissions of the benchmark farms was 1,210,575 kg CO2 eq while emission intensity was 24.7 ± 4.7 kg CO_2 eq /kg LW sold. The average intensity value observed in our study was higher than the 12.7 kg CO_2e/kg LW reported by Legesse et al. (2016) and 13.0 kg CO_2e/kg LW reported by Beauchemin et al. (2010a) and slightly outside the range (12.5 – 23.1 kg CO_2e/kg LW) reported by Basarab et al. (2012) using the IPCC Tier 2 approach. Furthermore, the average intensity observed in our study was also considerably higher than the national average value (10.4 kg CO_2e/kg LW) reported by Aboagye et al. (2024). However, the average emission intensity reported herein was comparable to the values reported by Alemu et al. (2017), using an earlier version of the Holos model (Version 3). These authors examined 295 cow-calf farms across Canada and reported a range in emission intensity from 16.3 - 37.8 kg CO_2eq/kg LW sold. The range in emission intensity observed in our study (18.3- to 35.1 kg CO_2eq/kg LW sold) followed a similar trend in that the emissions intensity of the majority of farms were close to the mean value but there were outliers resulting in a difference of 9.6 kg CO_2eq/kg LW sold. The disparity of results between this study and earlier publications might be attributed to the differences in the scope, methodologies and model algorithms. For example, in our study, only cow-calf and backgrounding enterprises were considered whereas other studies (Legesse et al. 2016, Aboagye et al. 2024) included production from the feedlot sector which has a lower emission intensity due to the highly digestible, grain-based diets compared to cow-calf sector which relies on lower quality, forage-based diets. Another example is in model algorithms, the recently released version of the Holos model (Version 4) which integrates recent research developments including updated emissions factors was used, whereas Beauchemin et al. (2010a), Legesse et al. (2016) and Alemu et al. (2017a), used an earlier version of the model. The other difference among studies in reporting farm emission intensity is the inclusion/exclusion of soil carbon sequestration values due to differences in assessment approaches and gaps in data availability. Previous studies reported emission intensity without (e.g., Beauchemin et al. 2010a, Legesse et al. 2016, Alemu et al. 2017) and with (e.g., Basarab et al. 2012, Alemu et al. 2017b) carbon sequestration estimates. For example, Alemu et al. (2017b) reported 12-25% reduction in emission intensity following inclusion of soil carbon sequestration estimates in the whole-farm emission analysis.

However, soil carbon sequestration was not included in the current study as only one year of farm data was collected from focus groups during data collection process. The current version of the model (version 4) is designed to estimate soil carbon changes based on changes over several years at a minimum, or ideally, decades. As such, the model requires an extended timescale to make these calculations to account for the high variability in possible soil conditions as well as the effects of outlier data on any given year and the impact on long term soil carbon equilibrium. In addition to soil carbon, including the benefits of grazing systems on soil health, biodiversity and conservation is crucial to accurately assess the net environmental impact of cow-calf production systems, which were beyond the objective of this study.

In addition to differences in the model used, there were also differences in model inputs used between our study and previous studies. The goal of our study was to estimate emission intensities for selected benchmark farms that were representative of practices in a given region using data that was aggregated selectively to reflect regional differences in production practices and climate. The intent was to capture a diverse group of typologies (using a typical farm approach) rather than using an average value across the country, as implemented by Alemu et al. (2017).

GHG emissions by source

As indicated, enteric CH_4 was the most significant source of emissions on all farms (on average contributing 66% of total farm emissions) and had moderate variation among emission sources (average SD = 1.65; Table 5). Approximately 91% of total farm CH_4 emissions (ranging between 76% and 96%) were contributed from enteric sources. This is comparable to enteric CH_4 emissions reported by Alemu et al. (2017a) which accounted for 69% and 94% of total farm and total farm CH_4 emissions, respectively.

The observed trend for Eastern farms to have lower intensity of enteric CH_4 emissions as compared to Western farms can primarily be attributed to higher feed quality during summer grazing and feeding of legume hay during the winter feeding as both factors are significant drivers of enteric CH_4 emissions (Jonker et al. 2015). Manure CH_4 emissions were generally less associated with farm geography (East vs West) but were more related to the number of confined winter-feeding days where manure was stored and subsequently spread onto fields. Farms that practiced extended grazing strategies for all or most of the winter period had very low manure CH_4 emissions, largely due to more aerobic manure conditions on pasture compared to other storage conditions. Therefore, farms that kept animals on fields or pastures for most or all of the winter-feeding period, including farms SK-1a, MT-1, and MT-2, had much lower manure CH_4 emissions.

As indicated, N_2O from soil and manure also played a significant role in total farm GHG emissions, accounting for, on average, 20% of total farm emissions (ranging between 12% and 33%) with only 29% from manure sources while the remainder were from soils and crops. Alemu et al. (2017a) reported that N_2O emissions from cow-calf operations contributed approximately 24% (ranging between 15 and 39%) of the total farm emissions, of which 77% (ranging between 40 and 99%) were from manure. The wide range of differences in source of N_2O emissions reflect differences in farm practices such as manure application rate, as well as environmental conditions including temperature and precipitation (Thomas et al. 2008). The significant contribution of soil N_2O emissions in our study may be attributed to the proportion of benchmark farms (36%) from Eastern Canada compared to those reported by Alemu et al. (2017a) where 80% of the farms included in the analysis were from the Western region. Eastern farms also tended to have higher rates of both direct and indirect N_2O emissions from soil, partially because of increased use of fertilizer on hay fields. However, it is important to note that application rates were variable between farms of all regions. Season of application (spring or fall) and rate of manure application were obtained from Statistics Canada (2019b) as this data was not available for the benchmark farms. For example, it was assumed that Eastern farms applied manure in spring while Western farms applied in fall (Statistics Canada 2019b) and therefore the effects of increased temperature and moisture led to an increase in N_2O emissions from manure (Sommer et al. 2004). It was also assumed that all stored manure would be applied once every year on farm. However, it is possible that manure on some farms was stored for several years leading to differences in time of application compared to literature values (Statistics Canada 2019b).

Energy CO_2 emissions, which made up a smaller portion of total farm emissions, were primarily dependent on the size of the cropping enterprise, cropping practices and equipment usage. For example, swath grazing annual crops had lower energy usage compared to farms with larger cropping systems which relied on baled and stored feeds during the winter-feeding period. Similarly, farms with significant quantities of stored manure that required spreading had an increased use of energy, resulting in higher CO_2 emissions than those that did not. Alemu et al. (2016) reported that swath grazing can be an effective winter feeding alternative to reduce GHG emissions and increase energy use efficiency of the Canadian beef cattle industry. The authors indicated that swath grazing annual forages can reduce farm activity-related GHG emissions by 46 to 56% compared to conventional drylot feeding strategies.

4.5.3 Benchmark farm economic analysis

The economic analysis of benchmark farms (Table 6) revealed significant variation in the profitability of cow-calf operations which were primarily attributed to differences in farm management practices. For example, mixed farms reported significantly higher net incomes compared to beef-only operations as, on average, 28% of farm income was from a cash crop enterprise, with one farm (SK-6) receiving up to 78% of total income from crop sources.. Farms that utilized extended grazing practices also showed higher profitability, particularly among Western farms which utilized a variety of cost-saving practices. For example, among the Western benchmark farms, both SK-1a and SK-1b were among the most profitable farms and had very comparable herd characteristics. However, feeding strategies were distinct, with SK-1a relying on swath grazing, corn grazing and bale grazing to reduce costs of winter feeding and maximize use of land base, while SK-1b used a unique strategy and purchased all winter feeds thereby reducing costs of equipment maintenance and depreciation.

Herd size was related to profitability (Table 7) although the correlation was only significant in a medium- and long-term profits. The larger AB and SK farms such as AB-1, AB-2, AB-3, SK-1a and SK-6 reported positive net cash income and net income in the short- and medium-terms, however, the long-term profitability was very low or negative for several farms in this group. This shift in long-term profitability indicates that while larger farms might have more efficient production, they bare a significant economic burden caused by depreciation costs on the fleet of equipment required to service a large operation. Herd size, however, was not a definitive indicator of profitability, as there were several larger farms in this study that reported very low net incomes such as MB-1, MB-2 and QC-2 (Table 6). These three farms, despite having very large herd sizes, reported a very low net income, which indicates that herd size is not the only variable playing a significant role in profitability outcomes. Other variables, such as the assumed beef and crop prices impacted returns as well as level of depreciation costs, may impact the relationship between farm size and profit.

Another factor impacting total farm profitability was growing cereal and oilseed crops which contributed significantly to the two farms, AB-1 and SK-6, with the highest income. Where land is suited to annual crop production, it is frequently more profitable on a per hectare basis to grow annual grains rather than pasture or hay crops depending on soil and environmental conditions (Rashford et al. 2011). Farms that identified the opportunity for land use change were allocated an opportunity cost to account for this, which contributed to a significant portion of the opportunity costs assessed for benchmark farms. It should be noted that while crops provided a significant increase in profitability, the cow-calf enterprise remains valuable as a source of income for land that is poorly suited for crop production and diversifies cost and revenue risk portfolio.

The correlation between net farm income and farm emissions intensity was relatively weak, but statistically significant ($P \leq 0.05$, Table 8), conversely, cow-calf enterprise profitability was not correlated to emissions intensity in the short- medium- or long-term. While the R^2 values are relatively low, and there are several variables unaccounted for in this simple correlation test, it suggests that cow-calf operations that have a higher net income are likely to have a higher emission intensity (Figure 5). The correlation at the beef enterprise level shows a slightly higher R^2 value, particularly for long-term profitability. Further analysis would be required to confirm a true correlation between emissions intensity and farm profitability associated with cash crops.

4.5.4 Future farm scenarios

The future farm scenarios modelled as part of this project were intended to capture the impact of “real world” practice changes made under different farm conditions and to estimate the impact on farms emission intensity and profitability. A similar approach has been implemented by Lancaster and Larson (2020) to evaluate the impacts of changes in management practices on farm emissions and profitability of cow-calf production systems in the U.S.A.

4.5.4.1 Extended grazing season

The extended grazing season scenario assumed the implementation of rotational grazing would allow producers to increase the number of days on pasture thereby reducing the cost of stored winter feed, as well as the amount of stored and handled manure, leading to a reduction in emissions (Alemu et al. 2016). The economic outcomes were consistently positive for each of the future farms under this scenario (Table 9), as the investment of capital was low and required only a slight increase in labour to maintain the system. Since winter feed is one of the biggest costs on cow-calf farms, fewer winter feeding days yielded a significant increase in profitability.

Winter feeding practice on the emissions intensity of each farm was not as consistent as profit, as BC-1 had a slight increase (0.4%) while AB-3 had slight decrease (1.0%) and QC-3 had a more substantial decrease (3.5%). These differences in response may attributed to the quality of pasture and of winter feed. For example, pasture was low quality (TDN = 56.1, CP = 8.6) for BC-1 (extend) resulting in higher enteric CH_4 emissions, whereas the winter ration for the benchmark farm was comparatively higher quality (TDN = 58.2, CP = 11.7). AB-1 and QC-3 experienced a decrease in emissions primarily due to increased average diet quality and modest reductions in manure emissions due to less stored manure.

Assumptions made while simulating this scenario impacted observed results. For example, one of the assumptions was that there was no change in pasture quality with an increase in days on pasture as compared to the benchmark farms. Although there is limited evidence (Billman et al. 2020) indicating that implementing a rotational grazing system could improve pasture quality, productivity and composition, the available data does not contain the level of detail required in the Holos model.

However, under conditions where the implemented grazing system improved quality of summer pasture or improved pasture productivity, it is anticipated that emissions would be further decreased. It should be noted that the success of this scenario is dependent on the ability to increase available forage for grazing. For example, environmental conditions including drought might reduce or eliminate increased forage yield realized with changes in grazing management.

4.5.4.2 Increased weaning weight

This future farm scenario involved increasing average weaning weight by shortening the calving season and increasing the number of calves born in the first calving cycle to achieve higher average weights. As indicated in the Materials and Methods, this scenario was modelled in two different stages, the first (scenario level 1) being a more modest narrowing of the calving season and condensing the calving season from 4 to 3 breeding cycles achieving a ratio of 37%, 33% and 30% of cows calving in the first, second and third cycles, respectively. The second level (scenario level 2) was a more aggressive change shortening to 3 cycles with 50%, 30% and 20% of cows calving in the first, second and third cycles, respectively. The results of this scenario were modelled over five years after implementation as it requires multiple breeding seasons for the practice change to yield its potential results. This modelled scenario resulted in a significant improvement in farm net income and net cash income for AB-1 and MB-1 (Table 10) for both the level 1 and 2 weaning weight increases. Although cow-calf profitability increased consistently for AB-1 for both levels, only short- and medium-term profit were increased for MB-1 with a decrease in long-term profitability. This decrease is primarily due to the opportunity cost of investment in this scenario when capital could have been used for other investments. Prices received for calves is dependent on the time of year sold as cattle markets tend to have seasonal fluctuations, additionally more uniform groups of calves tend to receive a price per LW, these factors can influence the effect on enterprise profitability and were included in economic modelling assumptions. Net farm emissions increased slightly due to the increased average number of days calves were on farm prior to weaning. However, emission intensity was still reduced due to increased liveweight sold as a result of the increase in weaning weights. Therefore, the reduction in emission intensity is a function of improved production efficiency. A recent study by Possberg and Kulshreshtha (2018) observed similar results when examining the effects of improved weaning weight on both the profitability of the enterprise as well as a reduction in emissions intensity.

4.5.4.3 Water system

The observed increase in both net farm income and in short-, medium- and long-term profitability resulting from improvements in the summer watering system can be attributed to an increase production efficiency through improved average daily weight gain. The effect of water quality and source on cattle performance is well documented (Willms et al., 2002; Lardner et al. 2005). Willms et al. (2002) conducted a long-term study in Canadian prairies and reported that calves and yearling heifers drinking clean water gained 9% and 23% more body weight, respectively, as compared to those that drank directly from a pond or from a trough filled with pond water. In this study, it was assumed that the calves would gain an additional 0.05 kg/day as reported by Lardner et al. (2005) when drinking clean water.

The main cost of implementation for the scenario was in the first year and required very little additional cost of maintenance. Net farm emissions increased slightly, which was offset by the increased productivity resulting from the increased rate of gain in calves thereby decreasing farm emission intensity by -1.33 kg CO_2eq/kg LW.

4.5.4.4 Corn grazing

The corn grazing scenario modelled on benchmark farm SK-1a resulted in a positive economic outcome by reducing the cost of production for backgrounder steers, even when it was assumed that the steers had at the same rate of gain as the benchmark farm. The gain in profitability in this scenario is entirely attributed to cost saving on winter feeding by utilizing corn grazing which is less capital intensive per cow per day. As such, all measures of profitability increased following implementation of this scenario (Table 12) due in part to the high yield of standing corn. Jose et al. (2017) compared the conventional drylot feeding of beef cows with swath grazing standing corn or barley and observed that grazing standing corn during early winter period reduced feeding cost by 25% without affecting animal performance. Additionally, with the implementation of this scenario, emission intensity was decreased by 1.3% over the benchmark farm. The quality of standing corn (TDN = 68.2%, Rasby et al. 2014b; Lakeland Agricultural Research Association 2017b) used for analysis was comparable to the benchmark winter ration (TDN = 65.3%) that included barley grain and alfalfa-grass hay and as such, there was a very slight decrease in enteric CH_4 emissions. Manure CH_4 and N_2O emissions were not affected by grazing corn, and crop emissions were slightly reduced. Outcomes of implementing this scenario could be variable depending on farm location, and benchmark practices. The greatest negative impact on emissions from this scenario is from use of synthetic nitrogen fertilizer. Therefore, the ability to grow standing corn while relying on manure would reduce total emissions while improving profitability.

4.5.4.5 Creep feeding

The creep feeding scenario implemented on benchmark farm SK-6 resulted in a 10% increase in both net income and net cash income a more modest 2% increase in in each of the cow-calf enterprise profitability metrics (Table 13). This farm already grew cereal crops for export and the main cost to implement the scenario was to retain some grain for homegrown creep feed that was fed to growing calves. Profitability outcomes could differ if grain was not grown on the farm and must be purchased. Furthermore, outcomes are also dependent on market price of grain. Emissions were reduced by 4.2%, as creep feeding increased weight gain due to the increased energy density of the diet, leading to a 1905 kg increase in exported liveweight.

This emissions modelling carried some uncertainty due to the assumptions made regarding calf intake during the creep feeding period. It was assumed that calves would primarily be consuming the creep feed ration while nursing milk from the dam. However, depending on pasture quality, and milk production from the cow herd, calves may have consumed larger amounts of pasture forage than was included in the model ration input. While these inputs could have significant variation, the enteric CH_4 produced by calves during this period would not be significant relative to the main breeding herd and would not likely make a significant change to the overall emission results. A similar modelling study which examined the inclusion of creep feeding at different levels (Toro-Mujica, 2021) also reported a significant increase in financial income as well as a reduction in net farm emissions. However, several factors differ between the two studies including type of model used, modelled production system, grazing management, and creep supplementation level.

4.5.4.6 Artificial insemination (AI)

The use of AI as a means to improving breeding efficiency was implemented on benchmark farm ON-4, which resulted in a significant increase in net income, net cash income and all three metrics associated with cow-calf enterprise profitability (Table 14). By reducing the number of bulls required for breeding there was a 4.2% reduction in emissions from the cow-calf enterprise due to decreased number of animals required for the same output. However, an increase in calving rate by 1% over the benchmark farm (Lardner et al. 2015) was assumed which further reduced emission intensity by increasing total output. However, this scenario also carries some uncertainty in the model inputs. While producers may be able to improve breeding efficiency through AI (Baruselli et al. 2018), success is dependent on competency in AI procedures, availability of facilities for breeding and requires diligent management to achieve increased reproduction efficiency. Improper management could result in a significant decrease in breeding efficiency which would result in negative impacts for both emissions and economic outcomes.

4.6 Conclusions

In this study, it was observed that GHG emissions from cow-calf operations can vary widely due to differences in management practices and environmental conditions (temperature and precipitation) on the benchmark farms. This observation was not surprising as several previous studies have also noted a range of emission intensities for cow-calf operations across Canada (Legesse et al. 2016; Alemu et al. 2017). When examining emissions sources on farm, net farm emissions were impacted by farm location as farms in Western provinces had higher enteric CH_4 emissions relative to farms in the East which had slightly higher N_2O, and energy use related emissions. While regional trends were apparent, variation in emissions intensity within a region were also observed. The benchmark farms in SK were a good example of the range of emissions as SK 1a, SK 1b, SK 3 and SK5 were similar in magnitude with 21.57, 21.27, 25.77, 21.42 and 24.62, kg CO2eq/kg LW sold, however, SK-6 had a higher emission intensity of 35.11 kg CO2eq/kg LW sold because that operation had significant emissions from crop production. In addition, adoption of the same management practice also led to differences in emissions intensity. For example, adoption of rotational grazing by BC-1 led to a 0.4% increase in emissions but a 1.0% and 3.5% decrease in AB-3 and QC-1, respectively. One of the factors affecting emission intensity were forage quality in cow diets, with more digestible diets including tame grasses and legumes generating significantly less enteric CH_4 emissions. Farms that had more days for cows on pasture or winter feeding in a field or pasture setting had lower rates of manure CH_4 emissions Furthermore, farms with lower rates of nitrogen fertilizer application resulted in lower N_2O emissions especially when the nitrogen fertilizer was applied to forage fields. Similarly, farms with more productive tame forage crops tended to have slightly higher N_2O emissions due to increased use of fertilizer.

Farms that harvested cash crops for export realized an increase in net farm income relative to farms with beef-only enterprises. Overall, farms that minimized depreciation costs on assets such as machinery and infrastructure reported increased profitability in the medium- and long-term analysis. The most profitable operations reported high production efficiency including calving rate, rate of body weight gain, yield per hectare, and pasture stocking density.

The implemented future farm scenarios highlighted those practice changes for producers could improve their farms profitability while reducing emission intensity. Improving production efficiency (generally measured by increased liveweight exported without increases to cost of production or net emissions), was the key driver for making a significant impact both on the economic return and environmental sustainability.

The magnitude of improvement in production efficiency and the cost of practice implementation largely dictated the economic outcome of the future farm scenarios modelled. Therefore, practices that achieved a higher gain in efficiency with a lower investment cost led to a greater positive impact on farm profitability. For those management practices that resulted in a reduction of emissions intensity, its impact was greater when it resulted in increased production efficiency. Further reduction in emission intensity can be achieved via practices that improve diet quality and reduce storage and handling of manure.

When examining the metrics of profitability and emissions reduction simultaneously it is clear that improving production efficiency with minimal increase to inputs achieves an improvement in both domains, although in some scenario examples such as extended grazing and calving interval scenarios the reductions in emissions were minimal while the benefits to profitability were relatively higher. This means that while scenarios that improve profitability often result in reduced emissions, outcomes differ across the country, depending on management practices used, as well as impact of climate.

5.0 General Discussion and Implications

Commitments to reduce GHG emissions

As the world population grows, reaching more than 9.8 billion by 2050 (United Nations 2024), the demand for food is increasing. In addition, the sustainability of agricultural practices has become a focal point amongst policy developers, retailers and processors, commodity groups and consumers alike. As the impacts of climate change become more apparent, strategies to produce more food with a lower environmental footprint will become increasingly important

Efforts to reduce farm emissions via adoption of on-farm BMPs including federal government programs such as Agricultural Climate Solutions (ACS, https://agriculture.canada.ca/en/environment/climate-solutions) involving the On-Farm Climate Action Fund (Agriculture Canada 2022b) and the Living Lab Initiative (Agriculture Canada 2021). The On-Farm Climate Action Fund provides support to producers making practice changes to reduce farm emissions while the Living Lab Initiative aims to evaluate innovations that can reduce agricultural emissions and help farmers meet their production and economic goals. Commodity groups have also taken action to reduce on-farm emissions. As such, the Canadian Roundtable for Sustainable Beef has set an ambitious goal to reduce farm emissions intensity by 33% by the year 2030 (Canadian Cattle Association 2020). Furthermore, the agri-food sector has also made commitments to reduce emissions. For example, Maple Leaf Foods is positioned to reduced and offset all scope 1 (direct emissions) and scope 2 (emissions from energy produced to be used by the company) emissions making them a net zero emission company with the vision to eventually include scope 3 (indirect upstream and downstream) emissions (Maple Leaf Foods 2022).

Heterogeneity of farm management practices and GHG emissions in Canada

Canadian beef production systems are complex where differences in on-farm management practices regions and climate vary considerably from region-to-region. Although CH_4 emissions consistently comprise the greatest portion of emissions in the cow-calf production systems (Beauchemin et al. 2010), many variables contribute to net farm emissions. Due to this variability in practices and conditions, implementing strategies for emissions mitigation should be developed based on the opportunities specific to each operation in order to reduce net farm emissions while maximizing profits. For example, extending the grazing season reduced emissions in AB and QC but not in BC. Quite simply, there is no silver bullet approach. However, many prairie beef farms would be best served by improving hay and pasture quality and digestibility as enteric CH_4 emissions make up the majority of emissions in Western Canada and were directly related to forage quality (Beauchemin et al. 2009). Whereas some Eastern farms with high forage quality and productivity might generate lower emissions by reducing manure CH_4 and soil sourced N_2O.

Although not part of this study, increasing soil carbon sequestration through perennial forage crops and pasture can play a significant role in reducing net farm emissions (Stanley et al. 2018). Sequestration was not included as the Holos model, as described above, requires multiple years of farm data which were not available for this study. Therefore, the impacts of carbon sequestration on farm emission intensity for the benchmark farms as well as future farm scenarios was not assessed which could have reduced emissions (Rayes-Palomo et al. 2022). Sequestration on permanent pastures may have somewhat limited potential in long term reductions as some studies have shown that soil carbon can become saturated in permanent grasslands and additional sequestration can be difficult to attain (Wang et al. 2014). A recent study (Possberg & Kulshreshtha 2018) that did include estimates using Holos (Version 3) showed considerable reductions in emissions, particularly after modelling of land use conversion. The results of Possberg & Kulshreshtha (2018) indicate that further exploration of emission reduction through means of sequestered carbon could identify other practices that are beneficial for reducing emission intensity and increasing profitability.

Conflict of priorities

The economic viability of many cow-calf operations relies on the use of pastureland with poor quality soil that are not suitable for grain crop production and therefore, have relatively lower land values. In addition, many cow-calf producers also rely on low-cost, low-quality feedstuffs including straw, chaff, greenfeed, hulls, screenings, byproducts etc. as a feed source throughout the winter months. The ability for cattle to convert poor quality feeds into high quality protein products (milk and meat) is of significant importance to the economic sustainability of the industry (Sheppard et al. 2015). However, the relationship between low forage quality and increased enteric CH_4 production is well-documented (Beauchemin et al. 2009; Della Rosa et al. 2022). This leads to a large portion of farms, particularly in the prairie provinces where most beef is produced in Canada, that utilize low to mid-quality feeds (especially during late season grazing and winter feeding), generating higher enteric CH_4 emissions compared to farms in Eastern Canada. Therefore, the industry's economic strength is also an environmental weakness, as the low-cost associated with these lower quality forages reduces the cost of production but increases farm emission intensity. Total ration quality can be improved through a range of practices, including supplementation with higher energy feed ingredients including industry by-products (e.g., bakery waste, grain screenings, brewer's grains etc.) at modest costs. However, it can be challenging to find a consistent supply and often only producers with the necessary infrastructure and sufficient demand (to keep up with a processor supply) can take advantage of these lower-cost feedstuffs. Practices such as improved forage quality through rotational grazing, rejuvenation or cutting forage at earlier maturity have been shown to increase quality but may require additional management and labour. Further, they may not be applicable on low productivity land where pasture stocking density is very low, and yields are more limited.

There are several ongoing initiatives by different companies such as DSM (https://www.dsm.com/anh/home.html) and Rumin8 (https://rumin8.com/) and Alltech (https://www.alltech.com/) to develop technologies that minimize enteric CH_4 from ruminant animals. However, the main challenge in cow-calf production systems is delivering these ingredients to cattle out on pasture grazing forage rather than from a trough or bunk. Furthermore, consistent intake of a supplement can also be difficult to achieve when offered on a free-choice basis. Rumen modifier technologies can sometimes be administered by inclusion in mineral or water sources but may not be effective in situations with natural water sources or extensive rangeland where mineral and water intake are not consistent on a daily basis.

Since the affordability of utilizing low quality forages that increase CH_4 production is hard to overlook, changes in manure and crop management may offer another opportunity for consistent emission reduction and improved profitability. For example, adoption of extended winter grazing strategies leads to fewer days in confinement, therefore nutrients from manure and any wasted feed serve to improve fertility without the cost and labour of spreading and handling manure or using synthetic fertilizer. Extending the grazing season can also decrease farm GHG emissions by reducing manure d emissions (CH_4, N_2O) and farm energy farm energy emissions associated with manure handling (Alemu et al. 2016).

This study demonstrated that extending the grazing season, reducing the calving interval, improving the watering system, grazing corn, creep feeding and using AI decreased emissions intensity while improving some profitability. However, the GHG reductions shown were modest and, in some cases, negligible. As such, in order to achieve more significant reductions scenarios, it is important to examine the potential benefit of concurrently adopting multiple mitigation strategies.

On-farm adoption of best management practices (BMPs)

Cow-calf production systems are complex agro-ecosystems involving the sciences of animal, microbes, soil and crop biology and their interactions. As a result, changes in one management practice may have a chain impact on several farm components contributing to GHG emissions. For example, extending the grazing season with corn grazing led to a 1.3% reduction in emission intensity via reduced CH_4 and N_2O emissions. Adoption of BMP's to reduce GHG emissions is further complicated by the lack of economic data to support adoption of those practices. Further, the profitability of cow-calf operations in this study was shown to vary widely among benchmark farms and effects on farm profitability are of critical importance to producers who are considering practice adoption. While several of the future farm scenarios in this study reported positive economic effects from practice changes, there is also a potential for no or negative return on investment for practice changes under certain real-world conditions. The economic risk associated with adoption of novel management strategies on cow-calf operations is heightened by the lack of risk mitigation through insurance policies in the industry. While forage and livestock insurance are generally available, they are not widely adopted in cow-calf production, therefore producers often carry the full burden of financial risks.

This variability in profitability of practice implementation as described in this study may lead to increased risk to producers which can be a major barrier to adoption. Given the variability of results, an understanding of biological processes involved in farm emissions and detailed cost of production data is essential to determine how a practice change might affect a cow-calf operation under a variety of conditions. This knowledge is paramount to empower governments and policy makers to build programs for a diverse range of cow-calf operations.

Many practice changes utilize reducing cost to drive improved profitability, since feed costs comprise a majority of cow-calf enterprise budgets many producers may experiment with reducing feed quality or quantity to achieve cost reduction. While this may reduce costs in the short-term, poor nutrition can have significant effects on reproductive success in the short and long-term, as recent research regarding has suggested that the in-utero nutrient deficiencies can lead to long-term reproductive impacts due to fetal programming.

In addition, management changes and their implication on farm economic and environmental sustainability needs to be communicated clearly. Canada has a long history in designing and implementing extension programs that play a role in filling the gap between agricultural researchers and producers (Keesing 1965). However, recently there has been a shift in some of the provinces to reduce government extension program (Schoepp, 2022). A study in Alberta (Rollins et al., 2017) emphasized the importance of extension programs in encouraging the adoption of environmental BMPs. This is particularly important in the cow-calf sector where many of the feed ingredients are grown on-farm and therefore they do not benefit from the nutrition expertise offered by feed companies as that of feedlot, dairy, poultry and swine producers do.

Gaps in knowledge

While several whole-farm studies have been conducted to estimate farm emissions and understand the processes that create them as well as identify management practices that reduce GHG emissions, there are several areas that data is limited including soil carbon sequestration, particularly under different grazing and environmental conditions (Robertson et al. 2016).

Similarly, there are several sources of cost of production data for cow-calf production from academic sources and extension services. However, there is a lack of data specific to operations utilizing different management practices and geographical regions in Canada. This gap in available data is particularly relevant to the cow-calf industry as differences in practices and environmental conditions can have significant impacts relative to other livestock species.

Additionally, confusion surrounding a clear definition of grazing systems particularly when referring to rotational grazing (Briske et al. 2008). The term has become somewhat of an umbrella term and encompasses a range of practices which differ in their impact on forage quality and make accurate farm emission assessments regarding the impact of forage quality on enteric CH_4 emissions.

One variable that is not included in most studies on cow-calf sustainability is biodiversity and ecosystem services. A recent study by Pogue et al. (2018) established a framework and reported the positive impacts of Canadian beef production on ecosystem service. Most of the available whole-farm models including Holos lack the means to quantify biodiversity and assess how adoption of adoption of BMPs affects biodiversity and ecosystem services. While biodiversity is difficult to quantify and measure, it is an important component to the sustainability of the industry, particularly as it pertains to public perception.

Finally, and perhaps most importantly, is the lack of economic data associated with mitigation strategies to reduce GHG emissions. To the author’s knowledge, publications examining economic and environmental sustainability of Canadian beef operations is extremely limited (Kulthreshtha and Possberg 2018).

The role of efficiency

Efficiency of production in cow-calf operations is a key element when considering improvements in profitability or reduction of emission intensity and has been a focal point for innovation in researchers and producers. Improvements in production efficiency in cow-calf operations have focused on breeding and reproductive efficiency (Legesse et al. 2016) and rates of growth and feed conversion (Basarab et al. 2013). Many of the future farm scenarios examined in this study resulted in a decrease in emissions due to improved production efficiency. For example, decreasing the calving interval, improving the watering system, creep feeding, and use of AI, increased the liveweight of calves exported from the farm and therefore decreased emissions intensity.

However, to meet the ambitious goals of reducing primary GHG emission intensity of cattle production in Canada by 33% by 2030 and sequester additional 3.4 million tonnes of carbon every year (Canadian Cattle Association 2020) it will be necessary for producers to embrace practice changes beyond incremental improvements in animal efficiency. As such, adoption of several reduction strategies simultaneously will be necessary to achieve significant reductions in emission intensity of the industry. This would also allow for additive reductions and even synergistic effects between practices that may result in reductions beyond what would be achieved on their own. It may also be necessary to implement strategies that would directly reduce enteric CH_4 production that includes investments to improve forage quality or dietary energy or developing strategies to utilize methane inhibiting feed additives such as Bovaer® (previously called 3-NOP, https://our-company.dsm-firmenich.com/en/our-company/bovaer.html / Bover) or Agolin® (https://www.alltech.com/agolin).

Further considerations

Several practices were examined in this study to achieve the specified objectives and explore the economic and environmental impacts associated with practice changes on cow-calf operations. However, there are many potential opportunities that were not explored that may offer the potential to reduce emissions while improving profitability. As already discussed, the inclusion of carbon sequestration was an important component not included in this study. Similarly, the use of additive methane inhibitors were not considered.

Another relevant variable that was not covered in this study was feed conversion efficiency (Basarab et al. 2011) due to the limitation of the Holos model to account for this variable. While total dry matter intake in the model is based on published research, it fails to account for cattle that have been bred for low residual feed intake resulting in lower CH_4 emissions (Basarab et al. 2011). As methanogenesis is an energy-intensive process and does not produce a useable product (generating CH_4 as end product), it has a direct relationship with efficiency of feed digestion and utilization minimizing the energy available for milk or meat production (Hansen et al., 2013).

It should also be notes that the economic analysis conducted herein was based on costs and revenues data in 2020; a year where cattle prices in Canada were at a low point relative to the previous decade. Similarly, differences in time of year that calves are sold could impact revenue. These factors should be considered when examining the profitability of the benchmark farms in this study as many of the farms that reported low or negative income here might have had much different results had this analysis been done in a year with average or high cattle prices.

6.0 General Conclusion

Study conclusions:

- Cow-calf operations in Canada utilize different management practices. It is evident that Some practices, such as swath and bale grazing, are common to specific regions as they are driven by environmental factors. While others are implemented across Canada including retaining calves for backgrounding and winter feeding on pasture.
- The most significant factors affecting farm emission intensity were forage quality, the number of days spent on pasture where manure is not stored or handled, and the amount of nitrogen applied on fields.
- The variability of results from future farm scenarios indicates that management practices may not be universally implemented with consistent results. Environmental conditions and available resources should be considered before implementing practice changes.
- Profitability of cow-calf operations fluctuates widely across Canada, with larger farms generally incurring a higher net income compared to smaller ones. Farms that grew grains and oilseeds for sale off farm also realized a significant increase in net farm income compared to those that only raised cattle.
- Profitability of the cow-calf enterprise was dependent on many factors, but minimizing depreciation costs and high efficiency of production was the most consistent indicator of profitable farms, including both animal and accompanied crop performance.
- Practice changes to reduce emissions and increase profitability include improved production efficiency, improved productivity and/or quality of hay fields and pasture and extending the number of days on pasture without decreasing forage quality.
- This study is novel in that it simultaneously examined the impact of the adoption of management practices on environmental and economic sustainability. This type of information, although limited in published literature in Canada, is essential for the development of effective programs and policies necessary to ensure the viability of cow-calf operations in Canada.

Further work:

- While this study examined of 25 benchmark farms representing a broad scope of the industry, there are several production types that were not considered, including certified organic production, operations that include finishing cattle on grass, or small-scale operations, among others. While some of these production types don't make up a significant portion of the total Canadian industry, there may be opportunities to examine practices that could improve profitability and/or reduce emissions.
- Future farm scenarios were modelled for a limited number of practices on a few benchmark farms. However, in order to extrapolate the results found in this study, future studies should include additional scenarios as differences in environmental, economic and production variables could have a significant effect on outcomes and may identify novel practices that reduce emissions while increasing profitability.

7.0 References

Aboagye, I. A., Valappil, G., Dutta, B., Imbeault-Tétreault, H., Ominski, K. H., Cordeiro, M. R. C., Kröbel, R., Pogue, S. J., & McAllister, T. A. 2024. An assessment of the environmental sustainability of beef production in Canada. Can. J. Anim. Sci. **104** : 221-240

Agri-Benchmark 2020. Who we are. [Online] Available: http://www.agribenchmark.org/agribenchmark/who-we-are.html [2020 Dec. 14].

AAFC (Agriculture and Agri-Food Canada) 2017. An Overview of the Canadian Agriculture and Agri-Food System. [Online] Available: https://agriculture.canada.ca/en/sector/overview [2024 Dec. 5]

AAFC (Agriculture and Agri-Food Canada) 2020. Holos software program - Agriculture and Agri-Food Canada (AAFC). [Online] Available: https://www.agr.gc.ca/eng/scientific-collaboration-and-research-in-agriculture/agricultural-research-results/holos-software-program/?id=1349181297838 [2020 Dec. 9].

AAFC (Agriculture and Agri-Food Canada) 2022. Agricultural Climate Solutions. [Online] Available: https://agriculture.canada.ca/en/agricultural-production-tools-and-data/agricultural-climate-solutions [2022 Dec 15].

AAFC (Agriculture and Agri-Food Canada) 2024a. Holos. [Online] Available : https://agriculture.canada.ca/en/agricultural-production/holos [2024 Dec 21]

AAFC (Agriculture and Agri-Food Canada) 2024b. Red meat exports by country - year to date cumulative. [Online] Available: https://agriculture.canada.ca/en/sector/animal-industry/red-meat-and-livestock-market-information/trade/red-meat-exports-country [2024 Dec 30]

Agriculture Canada 2011. Soil Landscapes of Canada (SLC). [Online] Available: https://sis.agr.gc.ca/cansis/nsdb/slc/index.html [2022 Jun. 14].

Agriculture Canada 2020. Agricultural Greenhouse Gas Indicator - Agriculture and Agri-Food Canada (AAFC).). [Online] Available: https://agriculture.canada.ca/en/agricultural-production/agricultural-greenhouse-gas-indicator [2024 Dec. 5]

Agriculture Canada 2021. Living Laboratories Initiative. [Online] Available: https://agriculture.canada.ca/en/agricultural-science-and-innovation/living-laboratories-initiative [2022 Oct. 25].

Agriculture Canada 2022a. Holos software program version 4. [Online] Available: https://agriculture.canada.ca/en/agricultural-science-and-innovation/agricultural-research-results/holos-software-program [2022 Jun. 14].

Agriculture Canada 2022b. Agricultural Climate Solutions – On-Farm Climate Action Fund - agriculture.canada.ca. [Online] Available: https://agriculture.canada.ca/en/agricultural-programs-and-services/agricultural-climate-solutions-farm-climate-action-fund-0 [2022 Sep. 17].

Alberta Agriculture 2004. Swath Grazing in Western Canada: An Introduction.. Agri-Facts [Online] Available: https://open.alberta.ca/dataset/3035893 [2024 Dec. 5]

Alberta Agriculture 2014. Understanding supply factors for agricultural products. [Online] Available: https://www.alberta.ca/understanding-supply-factors-for-agricultural-factors [2024 Dec. 5]

Alberta Agriculture 2012. CowBytes 5.3.

Alemu, A.W., Amiro, B.D., Bittman, S., MacDonald, D., and Ominski, K.H. 2016. A typological characterization of Canadian beef cattle farms based on a producer survey. Can. J. Anim. Sci. **96**: 187–202. doi:10.1139/cjas-2015-0060.

Alemu, A.W., Amiro, B.D., Bittman, S., MacDonald, D., and Ominski, K.H. 2017a. Greenhouse gas emission of Canadian cow-calf operations: A whole-farm assessment of 295 farms. Agric. Syst. **151**: 73–83. Elsevier B.V. doi:10.1016/j.agsy.2016.11.013.

Alemu, A.W., Janzen, H., Little, S., Hao, X., Thompson, D.J., Baron, V., Iwaasa, A., Beauchemin, K.A., Krobel, R. 2017b. Assessment of grazing management on farm greenhouse gas intensity of beef production systems in the Canadian Prairies using life cycle assessment. Agric. Syst. **158:** 1-13.

ALUS 2020. FAQs - ALUS Canada. [Online] Available: https://alus.ca/home/about-us/what-is-alus/faqs/ [2020 Dec. 11].

Asem-Hiablie, S., Battagliese, T., Stackhouse-Lawson, K.R. Rotz, A.C. 2019. A life cycle assessment of the environmental impacts of a beef system in the USA. Int. J. Life Cycle Assess. **24**, 441–455. https://doi.org/10.1007/s11367-018-1464-6

Avent, R.K., Ward, C.E., and Lalman, D.L. 2004. Market Valuation of Preconditioning Feeder Calves. J. Agric. Journal of Agricultural and Applied Economics Appl. Econ. Assoc**. 36**: 173–183. doi:10.1017/s1074070800021933.

Bachler, J.J. 2019. Winter feeding beef cattle: A review on bale grazing in the northern great plains. North Dakota State University, Fargo, North Dakota. https://hdl.handle.net/10365/30957

Badgery, W., Millar, G., Broadfoot, K., Martin, J., Pottie, A., Simmons, A., Cranney, P. 2017. Better management of intensive rotational grazing systems maintains pastures and improves animal performance. Crop Pasture Sci. **12:**1131-1140 https://doi.org/10.1071/CP16396

Badiou, P., McDougal, R., Pennock, D., and Clark, B. 2011. Greenhouse gas emissions and carbon sequestration potential in restored wetlands of the Canadian prairie pothole region. Wetl . Ecol. Manag. **19**: 237–256. Springer. doi:10.1007/s11273-011-9214-6.

Bai, M., Flesch, T., Trouvé, R., Coates, T., Butterly, C., Bhatta, B., Hill, J., and Chen, D. 2020. Gas emissions during cattle manure composting and stockpiling. J. Environ. Qual. **49**: 228–235. doi:10.1002/jeq2.20029.

Baron, V.S., Doce, R.R., Basarab, J., and Dick, C. 2014a. Swath grazing triticale and corn compared to barley and a traditional winter feeding method in central Alberta. Can. J. Plant. Sci. **94**: 1125–1137. doi:10.4141/CJPS2013-412.

Baruselli, P.S., Ferreira, R.M., Sá Filho, M.F., Bó, G.A. 2018. Review: Using artificial insemination v. natural service in beef herds. Animal **12**: 45–52. doi:10.1017/S175173111800054X.

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

Basarab, J.A., Beauchemin, K.A., Baron, V.S., Ominski, K.H., Guan, L.L., Miller, S.P., and Crowley, J.J. 2013. Reducing GHG emissions through genetic improvement for feed efficiency: effects on economically important traits and enteric methane production. Animal **7**: 303–315. Cambridge University Press. doi:10.1017/S1751731113000888.

Basarab, J.A., McCartney, D., Okine, E.K., Baron, V.S. 2007. Relationships between progeny residual feed intake and dam productivity traits. Can. J. Anim. Sci. **87:** 489-502

Baublits, R.T., Brown, A.H., Johnson, Z.B., Rosenkrans, C.F., Rorie, R.W., and Sandelin, B.A. 2003. Variation in the Percentage of Female Births over Time in Five Breeds of Registered Beef Cattle. Prof. Anim. Sci**. 19**: 204–210. Elsevier Inc. doi:10.15232/S1080-7446(15)31406-6.

Beauchemin, K.A., Henry Janzen, H., Little, S.M., McAllister, T.A., and McGinn, S.M. 2010. Life cycle assessment of greenhouse gas emissions from beef production in Western Canada: A case study. Agric. Syst. **103**: 371–379. doi:10.1016/j.agsy.2010.03.008.

Beauchemin, K.A., Janzen, H.H., Little, S.M., McAllister, T.A., and McGinn, S.M. 2011. Mitigation of greenhouse gas emissions from beef production in Western Canada - Evaluation using farm-based life cycle assessment. Anim. Feed. Sci. Technol. **166–167**: 663–677. doi:10.1016/j.anifeedsci.2011.04.047.

Beauchemin, K.A., McAllister, T.A., and McGinn, S.M. 2009. Dietary mitigation of enteric methane from cattle. CAB Rev.: Perspect. Agric. Vet. **4**: 1–18. doi:10.1079/PAVSNNR20094035.

Beauchemin, K.A., McGinn, S.M., and Petit, H. V. 2007. Methane abatement strategies for cattle: Lipid supplementation of diets. Can. J. Anim. Sci. **87**: 431–440. doi:10.4141/CJAS07011.

Beauchemin, K.A., Ungerfeld, E.M., Eckard, R.J., Wang, M. 2020. Review: Fifty Years of Research on Rumen Methanogenesis: Lessons Learned and Future Challenges for Mitigation. Animal **14:**2-16. doi: 10.1017/S1751731119003100.

Beaulieu, M. 2004. Manure management in Canada. Farm Environmental Management in Canada.. Statistics Canada – Agriculture Division. Ottawa [Online] Available: https://publications.gc.ca/Collection/Statcan/21-021-M/21-021-MIE2004001.pdf

Beef Cattle Research Council 2016. Environment & Climate Change. [Online] Available: https://www.cattle.ca/sustainability/environment-and-climate-change [2022 Nov. 1].

Beef Cattle Research Council 2017. Canadian Beef Research and Technology Transfer Strategy 2018 - 2023.. [Online] Available: http://www.beefresearch.ca/about/national-beef-research-strategy.cfm [2024 Dec. 5]

Beef Cattle Research Council 2020a. Improving technology transfer and knowledge dissemination in the Canadian beef industry. [Online] Available: https://www.beefresearch.ca/factsheet.cfm/improving-technology-transfer-and-knowledge-dissemination-in-the-canadian-beef-industry-154 [2020 Dec. 11].

Beef Cattle Research Council 2020b. Enhancing Technology Transfer in the Canadian Beef Industry. [Online] Available: https://www.beefresearch.ca/factsheet.cfm/enhancing-technology-transfer-in-the-canadian-beef-industry-278 [2020 Dec. 11].

Billman, E.D., Williamson, J.A., Soder, K.J., Andreen, D.M., and Skinner, R.H. 2020. Mob and rotational grazing influence pasture biomass, nutritive value, and species composition. Agron J **112**: 2866–2878. doi:10.1002/AGJ2.20215.

Boonstra, E.M. 2022. Growth-Enhancing Technologies: A Strategy to Reduce the Environmental Footprint of Canadian Beef Production. M.Sc. Thesis, University of Manitoba.

Boyabatlı, O., Kleindorfer, P.R., and Koontz, S.R. 2011. Management Science Integrating Long-Term and Short-Term Contracting in Beef Supply Chains. Manag. Sci. **57**. doi:10.1287/mnsc.1110.1362.

Boyar, C.N., Griffith, A.P., Pohler, K.G., 2020. Improving beef cattle profitability by changing calving season length. J. Agric. Appl. Econ. **3:** 19-30.

Briske, D. D., Derner, J. D., Brown, J. R., Fuhlendorf, S. D., Teague, W. R., Havstad, K. M., Gillen, R. L., Ash, A. J., Willms, W. D. (2008). Rotational grazing on rangelands: Reconciliation of perception and experimental evidence. Rangel. Ecol. Manag. **61:** 3–17 https://doi.org/10.2111/06-159R.1

Broucek, J. 2014. Production of Methane Emissions from Ruminant Husbandry: A Review. J Environ. Prot. **05**: 1482–1493. doi:10.4236/jep.2014.515141.

Brown, D.R. 2000. A Review of Bio-Economic Models Comments greatly appreciated. Paper prepared for the Cornell African Food Security and Natural Resource Management (CAFSNRM) Program. [Online] Available: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=02b7a49c0fe95f45910d55d6bb0daa7a4a8f45ad

Buckner, C.D., Bremer, V.R., Klopfenstein, T.J., Erickson, G.E., Mark, D.R. 2008. Cattle CODE: An Economic Model for Determining Byproduct Cattle. 2008 Nebraska Beef Cattle Report [Online] Available: https://digitalcommons.unl.edu/animalscinbcr/19/

Byrnes, R.C., Eastburn, D.J., Tate, K.W., Roche, L.M. 2018. A Global Meta-Analysis of Grazing Impacts on Soil Health Indicators. J. Environ. Qual. **47**: 758–765. doi:10.2134/JEQ2017.08.0313.

Campbell, B., Khachatryan, H., Behe, B., Dennis, J., and Hall, C. 2015. Consumer Perceptions of Eco-friendly and Sustainable Terms. Agric. Resour. Econ. Rev. **44**: 21–34.

Canada's National Beef Strategy. 2020. 2030 Goals [Online] Available: https://beefstrategy.com/2030-goals

Canadian Agricultural Human Resource Council 2019. How Labour Challenges Will Shape the Future of Agriculture. Labour Market Information [Online] Available: https://cahrc-ccrha.ca/sites/default/files/2021-11/National%20Report_Final%20-%20EN%202019%20reduced%20size.pdf

Canadian Agricultural Human Resources Council 2016. Beef Industry. Labour Market Information [Online] Available: https://cahrc-ccrha.ca/sites/default/files/2021-11/factsheet_Beef_E_web.pdf

Canadian Cattle Association 2020. Canadian Beef Industry Goals | Canadian Cattle Association. [Online] Available: https://www.cattle.ca/sustainability/canadian-beef-industry-goals [2022 Sep. 17].

Canadian Cattle Association 2023. Canadian Beef Economics. [Online] Available: https://www.cattle.ca/canadian-beef-economics#:~:text=As%20a%20whole%2C%20the%20Canadian,jobs%20elsewhere%20in%20the%20economy. [2024 Dec 21]

Canadian Cattle Association 2022.September 23. Canada's beef industry leads the way in environmental practices | Canadian Cattle Association. [Online] Available: https://www.cattle.ca/canadas-beef-industry-leads-the-way-in-environmental-practices [2022 Oct. 4].

Canadian Cattlemen's Association 2020a. Market Access. [Online] Available: https://www.cattle.ca/advocacy/lobbying-issues/market-access/ [2020 Oct. 29].

Canadian Cattlemen's Association 2020b. Environment » The Canadian Cattlemen's Association. [Online] Available: https://www.cattle.ca/cca-resources/environment/ [2021 Jan. 7].

Canadian Roundtable for Sustainable Beef. 2024a. Our Impact. Calgary AB. [Online] Available: https://crsb.ca/our-impact/

Canadian Roundtable for Sustainable Beef. 2024b. National Beef Sustainability Assessment and Strategy Summary Report. Calgary AB. [Online] Available: https://crsb.ca/wp-content/uploads/2024/01/1.-SUMMARY-REPORT_CRSB-National-Beef-Sustainability-Assessment-Strategy_EN.pdf

Canfax 2022a. Canfax Research Services. 2021 Census of Agriculture. [Online] Available: https://canfax.ca/uploads/2021_COA_Summary.pdf

Canfax 2022b. Canfax Research Services. [Online] Available: https://www.canfax.ca/Research.aspx [2022 Jun. 14].

CRSB 2016. Canadian Roundtable of Sustainable Beef. National Beef Sustainability Assessment: Economic Assessment. [Online] Available: https://crsb.ca/wp-content/uploads/2021/12/NBSA_EconomicAssessment.pdf

Canfax Research Services 2024. Statistical Briefer July 2024. [Online] Available: https://canfax.ca/resources/reports/statistical-briefer.html [2024 Dec. 5]

Canfax Research Services 2020. Industry Fast Facts. [Online] Available: http://www.beefinfo.org/Default.aspx?ID=16&ArticleID=31 [2021 Jan. 6].

Chadran, K., Stein, L.Y., Klotz, M.G., Van Loosdrecht, M.C. 2011. Nitrous oxide production by lithotrophic ammonia oxidizing bacteria and implications for engineered nitrogen-removal systems. Biochem. Soc. Trans. **39:** 1832-1837.

Chen, Z., An, C., Fang, H., Zhang, Y., Zhou, Z., Zhou, Y., and Zhao, S. 2020. Assessment of regional greenhouse gas emission from beef cattle production: A case study of Saskatchewan in Canada. J. Environ. Manage. **264**: 110443. doi:10.1016/j.jenvman.2020.110443.

Cool Farm Alliance. 2022. Use the Cool Farm Tool. [Online] Available: https://coolfarmtool.org/

Conant, R.T., Cerri, C.E.P., Osborne, B.B., and Paustian, K. 2017. Grassland management impacts on soil carbon stocks: a new synthesis. Ecol. Appl. **27**: 662–668. doi:10.1002/EAP.1473.

Cusack, D.F., Kazanski, C.E., Hedgpeth, A., Chow, K., Cordeiro, A.L., Karpman, J., Ryals, R. 2021. Reducing climate impacts of beef production: A synthesis of life cycle assessments across management systems and global regions. Glob. Change Biol. Bioenergy. Glob **27:** 1721-1736.

Danielce, M.M., Paris, W., de Souza Vismara, E., Severo, M.M., de Menezes, L.F.G. 2020. Inherent auction factors that affect the selling price of calves. Revista Brasileira de Zootecnia **49**: 1-11doi:10.37496/RBZ4920190099.

Deblitz, C. 2010. AARES 54th Annual Conference agri benchmark. Braunschweig, Germany. http://www.agribenchmark.org/fileadmin/Dateiablage/B-Beef-and-Sheep/Misc/CD-AARES-1002.pdf

Donaldson, A.I. 2020.July 11. Aerosols in meat plants as possible cause of Covid-19 spread. Vet. Rec. **187:** 34-35. doi:10.1136/vr.m2702.

Donohoe, G.R. 2018. Sustainable Overwintering Systems for Beef Cows on the Canadian Prairies: Challenges and Solutions. Ph.D. Thesis, University of Manitoba, Winnipeg, Manitoba.

Environment and Climate Change Canada. 2023. Draft Federal Offset Protocol: Reducing Enteric Methane Emissions from Beef Cattle**.** [Online] Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/protocols/draft-reducing-enteric-methane-emissions-beef-cattle.html [2024 Dec 21]

Environment and Climate Change Canada. 2024. National Inventory Report, 1990–2022: Greenhouse Gas Sources and Sinks in Canada. [Online] Available: canada.ca/ghg-inventory

Eladawi, O.I., Gouda, S.M., Elnaggar, E.M., and El Maghawry, S. 2020. Evaluation Study on the Effect of Saccharomyces cerevisiae 1026 and Lactobacillus casei on Some Ruminal and Biochemical Parameters in Fattening Calves. Zagazig. Vet. J. **48**: 153–164.. doi:10.21608/ZVJZ.2020.20416.1088.

Erickson, G.E., Klopfenstein, T.J., Pol, K. Vander, Bremer, V., and Loza, P. 2005. Feeding of wet corn milling byproducts to beef. Vet. Clin. Food. Anim. **23:** 223-245

Ferchaud, F., Vitte, G., Mary, B. Changes in soil carbon stocks under perennial and annual bioenergy crops. 2016. Glob. Change Biol. Bioenergy **8:** 290-306

Fertilizer Canada. 2020. Stratus Ag Research Fertilizer use Canada [Access provided by Fertilizer Canada; https://fertilizercanada.ca/]

Food and Agriculture Organization of the United Nations. 2015. Global livestock environmental assessment model (GLEAM). [Online] Available: https://www.fao.org/gleam/en/

Filazzola, A., Brown, C., Dettlaff, M.A., Batbaatar, A., Grenke, J., Bao, T., Peetoom Heida, I., and Cahill, J.F. 2020. The effects of livestock grazing on biodiversity are multi-trophic: a meta-analysis. Ecol. Lett. **23**: 1298–1309. doi:10.1111/ele.13527.

Foote, R.H. 1977. Sex ratios in dairy cattle under various conditions. Theriogenology **8**: 349–356. doi:10.1016/0093-691X(77)90186-8.

Freetly, H.C., Brown-Brandl, T.M. 2013. Enteric methane production from beef cattle that vary in feed efficiency123. J. Anim. Sci. **91**: 4826–4831. doi:10.2527/jas.2011-4781.

Fulton, M. 2005. Canadian Agri-Food Policy Institute (CAPI) L'Institut canadien des politiques agro-alimentaires (ICPA) Farmers as Price Takers: How Farm Returns are Established. Ottawa, Ontario. [Online] Available: https://capi-icpa.ca/wp-content/uploads/2005/05/Farmers-as-Price-Takers-How-Farm-Returns-are-Established-2005.pdf

García-Ruiz, A., Cole, J.B., VanRaden, P.M., Wiggans, G.R., Ruiz-López, F.J., Van Tassell, C.P. 2016. Changes in genetic selection differentials and generation intervals in US Holstein dairy cattle as a result of genomic selection. Proc. Natl. Acad. Sci. **113**: 3995–4004. doi:10.1073/PNAS.1519061113/SUPPL_FILE/PNAS.201519061SI.PDF.

Ghazalian, P.L. 2019. Canada's beef exports: Border effects and prospects for market access. Can. J. Agric. Econ. **67**: 53–74. doi:10.1111/cjag.12173.

Ghazalian, P.L. 2024. Enhancing Canada's Beef Exports and Competitiveness in the Global Market. University of Calgary - School of Public Policy **17 : 1-33** doi:dx.doi.org/10.55016/ojs/sppp.v17i1.78430

Gu, C., Iwassa, A.D., Zhao, M. 2019. Purple prairie clover seed viability and germinability after passing through the digestive tracts of yearling steers. Can. J. Plant Sci. **99:** 734-739

Government of Canada 2020. Greenhouse gas sources and sinks: executive summary 2020 [Online] Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/sources-sinks-executive-summary-2024.html [2024 Dec. 5]

Griffin, W., Stalker, L., Adams, D., Funston, R., and Klopfenstein, T. 2012. Calving date and wintering system effects on cow and calf performance I: A systems approach to beef production in the Nebraska Sandhills. Faculty Papers and Publications in Animal Science. Lincoln.

Hamilton, S.F., and Kastens, T.L. 2000. Does Market Timing Contribute to the Cattle Cycle? Am. J. Agric. Econ. **82**: 82–96. doi:10.1111/0002-9092.00008.

Hansen, H.H., Storm, I.M.L.D., and Sell, A.M. 2013. Effect of biochar on in vitro rumen methane production. Acta. Agric. Scand. **62**: 305–309. doi:10.1080/09064702.2013.789548.

Heiberg, E.J., and Syse, K.L. 2020. Farming autonomy: Canadian beef farmers reclaiming the grass through management-intensive grazing practices. Org. Agric**.** **10**: 471–486. doi:10.1007/s13165-020-00291-6.

Herd, R., Archer, J., and Arthur, P. 2003. Reducing the cost of beef production through genetic improvement in residual feed intake: Opportunity and challenges to application. J. Anim. Sci. **81**: 9–17. doi:10.2527/2003.8113_suppl_1E9x.

Hitz, A.C., and Russell, J.R. 1998. Potential of stockpiled perennial forages in winter grazing systems for pregnant beef cows. J. Anim Sci. **76**: 404. doi:10.2527/1998.762404x.

Hoorman, J., Little, C., and Mccutcheon, J. 2002. Using Corn for Livestock Grazing How Should I Grow Corn That Will Be Grazed? Ohio State University. Columbus, Ohio. [Online] Available: https://ohioline.osu.edu/factsheet/anr-11

Hristov, A.N, Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G. 2014. Mitigation of methane and nitrous oxide emissions from animal operations: 1 A review of enteric methane mitigation options. J. Anim. Sci. **11:** 5045-5069

Hu, Z., Li, S., Guo, Q., Niu, S., He, N., Li, L., and Yu, G. 2016. A synthesis of the effect of grazing exclusion on carbon dynamics in grasslands in China. Glob. Chang. Biol. **22**: 1385–1393. John Wiley & Sons, Ltd. doi:10.1111/GCB.13133.

IPCC 2019. Refinement to the 2006 IPCC Guidelines for Nation Greenhouse Gas Inventories. [Online] Available: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

Jacobo, E.J., Rodríguez, A.M., Bartoloni, N., and Deregibus, V.A. 2006. Rotational grazing effects on rangeland vegetation at a farm scale. Range. Ecol. Manag. **59**: 249–257. doi:10.2111/05-129R1.1.

Jolly-Breithaupt, M.L., Harris, M.E., Nuttelman, B.L., Burken, D.B., MacDonald, J.C., Luebbe, M.K., Iragavarapu, T.K., and Erickson, G.E. 2019. Effects of Syngenta Enogen feed corn containing an α-amylase trait on finishing cattle performance and carcass characteristics. Transl. Anim. Sci. **3**: 504–512. Oxford Academic. doi:10.1093/TAS/TXY121.

Jonker, A., Muetzel, S., Molano, G., Pacheco, D., Jonker, A., Muetzel, S., Molano, G., Pacheco, D. 2015. Effect of fresh pasture forage quality, feeding level and supplementation on methane emissions from growing beef cattle. Anim. Prod. Sci. **56**: 1714–1721. doi:10.1071/AN15022.

Jose, D., Damiran, D., Penner, G.B., and Mckinnon, J. 2017.Effect of winter grazing system on beef cow performance and system costs. Western Beef Development Centre doi:10.13140/RG.2.2.22348.36486.

Jose, D., Larson, K., McKinnon, J.J., Penner, G.B., Damiran, D., and Lardner, H.A. (Bart) 2020. Effects of winter-feeding system on beef cow performance, ruminal fermentation, and system costs. Appl. Anim. Sci. **36**: 731–744. Elsevier. doi:10.15232/AAS.2020-01983.

Kan, Z.C., Lou, D.M., Cao, Z.Z., Hu, Z.Y., Liu, S., and Yang, Z.H. 2017. Effects of altitude on combustion characteristic during cold start of heavy-duty diesel engine. Int. J. Automot. Technol. **18**: 209–217. doi:10.1007/s12239-017-0020-x.

Kaps, M., Herring, W.O., and Lamberson, W.R. 1999. Genetic and Environmental Parameters for Mature Weight in Angus Cattle J. Anim. Sci. **77**: 569–574.

Kebreab, E., Clark, K., Wagner-Riddle, C., and France, J. 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. Can. J. Anim. Sci. **86**: 135–158. doi:10.4141/a05-010.

Keesing, P.B. 1965. A study of provincial agricultural extension services in Canada: 1952-1961. University of British-Colombia. DOI: 10.14288/1.0104630

Kelly, J., and Campbell, D. 1994. Trade-off theory. Am. Econ. Rev. **84**: 422–426. doi:10.2307/2117871.

Kevin C. Dhuyvetter, Terry L. Kastens, Michael, W.O., and John F. Smith 2007. Western Dairy Management Conference. Page *in* Cow Culling Decisions: Costs or Economic Opportunity? Reno, Nevada.

Khatiwada, B., Acharya, S.N., Larney, F.J., Lupwayi, N.Z., Smith, E.G., Islam, M.A., and Thomas, J.E. 2020. Benefits of mixed grass–legume pastures and pasture rejuvenation using bloat-free legumes in Western Canada: A review. Can. J. Plant Sci. **100**: 463–476.

Kröbel, R., Bolinder, M.A., Janzen, H.H., Little, S.M., Vandenbygaart, A.J., and Kätterer, T. 2016. Canadian farm-level soil carbon change assessment by merging the greenhouse gas model Holos with the Introductory Carbon Balance Model (ICBM). Agric. Syst. **143**: 76–85. doi:10.1016/J.AGSY.2015.12.010.

Kröbel R, Moore J, Ni YZ, McPherson A, Poppy L, Soolanayakanahally RY, Amichev BY, Ward T, Laroque CP, Van Rees KCJ, and Akhter F. 2020. Demonstration and testing of the improved shelterbelt component in the Holos model. Front. Environ. Sci. **8:**149.

Kulshreshtha, S., and Nagy, C. 2021. Economic Impacts of Cattle Sector in Canada – A Regional Multiplier Analysis. Department of Agricultural and Resource Economics - University of Saskatchewan. [Online] Available: https://canfax.ca/uploads/Final_Multiplier_Report_with_Growth_Scenario_June_11_2021.pdf] [2024 Dec 21]

Kuorikoski, J., Lehtinen, A., and Marchionni, C. 2010. Economic Modelling as Robustness Analysis. Brit. J. Philos. Sci. **61:** doi:10.1093/bjps/axp049.

Lacy, C.R., and Knight, C.H. 2012. Profitable Cattle Marketing for the Cow-Calf Producer. University of Georgia Extension [Online] Available:

https://extension.uga.edu/publications/detail.html?number=B1078&title=profitable-cattle-marketing-for-the-cow-calf-producer

Lakeland Agricultural Research Association 2017. Winter Grazing Standing Corn in the Lakeland. Bonnyville, Alberta. [Online] Available: https://laraonline.ca/wp-content/uploads/2021/10/lara-factsheet-winter-grazing-corn-2017.pdf

Lal, R., Negassa, W., Lorenz, K. 2015. Carbon sequestration in soil. Curr. Opin. Environ. Sustain. **15:** 79-86. doi:10.1016/j.cosust.2015.09.002.

Lamb, G.C., Dahlen, C., Mercadante, V., and Bischoff, K. 2014. What Is the Impact of Infertility in Beef Cattle? University of Florida IFAS Extension. [Online] Available: https://edis.ifas.ufl.edu/publication/AN208

Lancaster, P.A., Larson, R.L. 2022. Evaluation of Strategies to Improve the Environmental and Economic Sustainability of Cow–Calf Production Systems. Animals. **12**: 385.

Lardner, B., Larson, K., and Damiran, D. 2015. Comparison of Fixed-Time Artificial Insemination Vs. Natural Service in Beef Cows: Reproductive efficiency and System. Western Beef Development Centre. [Online] Available: https://www.beefresearch.ca/fact-sheets/comparison-of-fixed-time-artificial-insemination-vs-natural-service-in-beef-cows-reproductive-efficiency-and-system-cost.pdf

Lardner, B., Larson , K., Bsa, L.P. 2012. Winter Grazing Beef Cows With Standing Corn. Western Beef Development Centre [Online] Available: http://westernbeef.org/pdfs/fact_sheets/2012/2012.03_WBDC_Winter_Grazing_Beef_Cows_with_Standing_Corn.pdf

Lardner, H.A., Kirychuk, B.D., Braul, L., Willms, W.D., Yarotski, J. 2005. The effect of water quality on cattle performance on pasture. Aust. J. Agric. Res. **56:** 97-104

Larson, K. 2018. Western Canadian Cow-Calf Survey. University of Saskatchewan. http://westernbeef.org/pdfs/wcccs/2017_WCCCS_Summary-FINAL.pdf

Legesse, G., Beauchemin, K.A., Ominski, K.H., McGeough, E.J., Kroebel, R., MacDonald, D., Little, S.M., and McAllister, T.A. 2016. Greenhouse gas emissions of Canadian beef production in 1981 as compared with 2011. Anim. Prod. Sci. **56**: 153–168. doi:10.1071/AN15386.

Legesse, G., Cordeiro, M.R.C., Ominski, K.H., Beauchemin, K.A., Kroebel, R., McGeough, E.J., Pogue, S., and McAllister, T.A. 2018. Water use intensity of Canadian beef production in 1981 as compared to 2011. Sci. Total Environ. **619–620**: 1030–1039. doi:10.1016/j.scitotenv.2017.11.194.

Legesse, G., Small, J.A., Scott, S.L., Kebreab, E., Crow, G.H., Block, H.C., Robins, C.D., Khakbazan, M., and McCaughey, W.P. 2012. Bioperformance evaluation of various summer pasture and winter feeding strategies for cow-calf production. Can. J. Anim. Sci. **92**: 89–102. doi:10.4141/cjas2011-082.

Liang, C., MacDonald, J.D., Desjardins, R.L., McConkey, B.G., Beauchemin, K.A., Flemming, C., Cerkowniak, D., and Blondel, A. 2020. Beef cattle production impacts soil organic carbon storage. Sci. Total Environ. **718**: 137273. doi:10.1016/j.scitotenv.2020.137273.

Lipsey, M.K., Doherty, K.E., Naugle, D.E., Fields, S., Evans, J.S., Davis, S.K., and Koper, N. 2015. One step ahead of the plow: Using cropland conversion risk to guide Sprague's Pipit conservation in the northern Great Plains. Biol. Conserv. **191**: 739–749. doi:10.1016/J.BIOCON.2015.08.030.

López-Campos, Ó., Basarab, J.A., Baron, V.S., Aalhus, J.L., and Juárez, M. 2012. Reduced age at slaughter in youthful beef cattle: Effects on carcass merit traits. Can. J. Anim. Sci. **92**: 449–463. doi:10.4141/CJAS2012-014.

Manitoba Agriculture 2024a. 2025 Cost of Production Beef Cow-Calf [Online] Available: https://www.gov.mb.ca/agriculture/farm-management/cost-production/pubs/cop-beef-feedlot-finishing.pdf [2024 Dec. 5]

Manitoba Agriculture 2024b. 2025 Cost of Production Beef Feedlot Finishing. [Online] Available: https://www.gov.mb.ca/agriculture/farm-management/cost-production/pubs/cop-beef-300-cow-calf.pdf [2024 Dec. 5]

Maple Leaf Foods 2022. Energy and Emissions - Maple Leaf Foods - Sustainability Report. [Online] Available: https://www.mapleleaffoods.com/sustainability-report/better-planet/energy-and-emissions/ [2022 Oct. 25].

Mathot, M., Decruyenaere, V., Stilmant, D., and Lambert, R. 2012. Effect of cattle diet and manure storage conditions on carbon dioxide, methane and nitrous oxide emissions from tie-stall barns and stored solid manure. Agric. Ecosyst. Environ. **148**: 134–144. doi:10.1016/j.agee.2011.11.012.

McCartney, D., Basarab, J.A., Okine, E.K., Baron, V.S., Depalme, A.J., Depalme, V.S., 2004. Alternative fall and winter feeding systems for spring calving beef cows. Can. J. Anim. Sci. **84**: 511–522.

McCaughey, W.P., and Chen, W. 1999. Benefits of including forage legumes in pastures and their management. Proceedings of the Western Canadian Forage and Grazing Conference, Saskatoon, SK, Canada.

McGeough, E.J., Cattani, D.J., Koscielny, Z., Hewitt, B., and Ominski, K.H. 2017. Annual and perennial forages for fall/winter grazing in Western Canada. Can. J. Plant Sci. **98**: 247–254. doi:10.1139/cjps-2017-0228.

Mitura, V., and Di Piétro, L. 2004. Canada's beef cattle sector and the impact of BSE on farm family income. Agriculture Division - Statistics Canada, Ottawa, Ontario.

Mortenson, M.C., Schuman, G.E., Ingram, L.J. 2004. Carbon Sequestration in Rangelands Interseeded with Yellow-Flowering Alfalfa (Medicago Sativa ssp. Falcata). Environ. Manag. **33:** 475-481

Montes, F., Meinen, R., Dell, C., Rotz, A., Hristov, A.N., Oh, J., Waghorn, G., Gerber, P.J., Henderson, B., Makkar, H.P.S., and Dijkstra, J. 2013. SPECIAL TOPICS-Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. J. Anim. Sci. **91**: 5070–5094. doi:10.2527/jas.2013-6584.

Moore, K.J., Lenssen, A.W., and Fales, S.L. 2020. Factors Affecting Forage Quality. Forages: 701–717. doi:10.1002/9781119436669.CH39.

National Academies of Sciences, Engineering, and Medicine. 2016. *Nutrient Requirements of Beef Cattle: Eighth Revised Edition*. Washington, DC: The National Academies Press. https://doi.org/10.17226/19014.

National Research Council 2016. Nutrient Requirements of Beef Cattle: Eighth Revised Edition. Nutrient Requirements of Beef Cattle, 8th Revised Edition. National Academies Press. doi:10.17226/19014.

NFU (National Farmers Union). 2020. Meat packing concentration makes Canada's food system vulnerable. [Online] Available: https://www.nfu.ca/policy/meat-packing-concentration-makes-canadas-food-system-vulnerable/ [2024 Dec 21]

NFU (National Farmers Union). 2024. Canadian Agriculture by the Numbers. [Online] Available: https://www.nfu.ca/wp-content/uploads/2024/03/Canadian-Ag-by-the-Numbers-2024.pdf (Oct 2, 2024)

Paine, L.K., Undersander, D., and Casler, M.D. 1999. Pasture Growth, Production, and Quality Under Rotational and Continuous Grazing Management. J. Prod. Agric. **12**: 569–577.:10.2134/JPA1999.0569.

Pattey, E., Trzcinski, M.K., and Desjardins, R.L. 2005. Quantifying the reduction of greenhouse gas emissions as a result of composting dairy and beef cattle manure. Nutr. Cycl. Agroecosyst. **72**: 173–187. doi:10.1007/s10705-005-1268-5.

Peel, D.S., and Doye, D. 2017. Cull Cow Grazing and Marketing Opportunities. Oklahoma State University Extension [Online] Available: https://extension.okstate.edu/fact-sheets/cull-cow-grazing-and-marketing-opportunities.html [2024 Dec. 5]

Phan, N.T., Kim, K.H., Parker, D., Jeon, E.C., Sa, J.H., and Cho, C.S. 2012. Effect of beef cattle manure application rate on CH 4 and CO 2 emissions. Atmos. Environ. **63**: 327–336. doi:10.1016/j.atmosenv.2012.09.028.

Phetteplace, H.W., Johnson, D.E., and Seidl, A.F. 2001. Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States. Nutr. Cycling Agroecosyst. **60:** 99–102. doi:10.1023/A:1012657230589.

Pogue, S.J., Alemu, A.W., Moreira dos Santos, M., McPherson, A., Kroebel, R. 2023. Holos Version 4.0 - Algorithm Documentation. Agriculture and Agri-Food Canada Technical Report (in preparation).

Pogue, S.J., Kröbel, R., Janzen, H.H., Beauchemin, K.A., Legesse, G., de Souza, D.M., Iravani, M., Selin, C., Byrne, J., and McAllister, T.A. 2018. Beef production and ecosystem services in Canada's prairie provinces: A review. Agric. Syst. **166**: 152–172. doi:10.1016/j.agsy.2018.06.011.

Pope, K.F., Schroeder, T.C., Langemeier, M.R., and Herbel, K.L. 2011. Cow-Calf Producer Risk Preference Impacts on Retained Ownership Strategies. J Appl. Agric. Econ. **43**: 497–513. doi:10.1017/s1074070800000031.

Possberg, M. and Kulshreshtha, S. 2018. Beef enterprise profitability and greenhouse gas emissions on Manitoba farms. EC Agriculture **4:** 29-38.

Pritchard, R.H., and Mendez, J.K. 1990. Effects of preconditioning on pre- and post-shipment performance of feeder calves. J. Anim. Sci. **68**: 28–34. doi:10.2527/1990.68128x.

Rao, S.C., Northup, B.K., Phillips, W.A., Mayeux, H.S. 2007. Interseeding Novel Cool-Season Annual Legumes to Improve Bermudagrass Paddocks. Crop. Sci. **47:** 168-173.

Rasby, R.A., Niemeyer, S.W. 2011 Creep feeding beef calves. University of Nebraska-Lincoln Extension [Online] Available: https://extensionpubs.unl.edu/publication/g2077/creep-feeding-beef-calves

Rasby, R., Drewnoski, M., and Stalker, A. 2014. Grazing Crop Residues with Beef Cattle. University of Nebraska-Lincoln Extension [Online] Available: https://extensionpubs.unl.edu/publication/ec278/2014/pdf/view/ec278-2014.pdf [2024 Dec. 5]

Rashford, B.S., Walker, J.A., and Bastian, C.T. 2011. Economics of Grassland Conversion to Cropland in the Prairie Pothole Region. Conserv. Biol. **25**: 276–284. doi:10.1111/J.1523-1739.2010.01618.X.

Reyes-Palomo, C., Aguilera, E., Llorente, M., Díaz-Gaona, C., Moreno, G., & Rodríguez-Estévez, V. 2022. Carbon sequestration offsets a large share of GHG emissions in dehesa cattle production. J. Clean. Prod. **358.** https://doi.org/10.1016/j.jclepro.2022.131918

Rinehart, L. 2006. Pasture, Rangeland and Grazing Management. [Online] Available: www.attra.ncat.org [2022 Oct. 25].

Robertson, F., Crawford, D., Partington, D., Oliver, I., Rees, D., Aumann, C., Armstrong, R., Perris, R., Davey, M., Moodie, M., Baldock, J., Robertson, F., Crawford, D., Partington, D., Oliver, I., Rees, D., Aumann, C., Armstrong, R., Perris, R., Davey, M., Moodie, M., and Baldock, J. 2016. Soil organic carbon in cropping and pasture systems of Victoria, Australia. Soil Res. **54**: 64–77. doi:10.1071/SR15008.

Rollins, C.L., Simpson, S.R., Boxall, P.C. 2017. Evaluating an agricultural extension program aimed at improving biodiversity in Alberta, Canada. Can. J. Agric. Econ. **66:**331-353

Della Rosa, M.M., Sandoval, E., Luo, D., Pacheco, D., and Jonker, A. 2022. Effect of feeding fresh forage plantain (Plantago lanceolata) or ryegrass-based pasture on methane emissions, total-tract digestibility, and rumen fermentation of nonlactating dairy cows. J. Dairy. Sci. **105**: 6628–6638. doi:10.3168/JDS.2021-21757.

Rosser, C.L., Górka, P., Beattie, A.D., Block, H.C., McKinnon, J.J., Lardner, H.A., and Penner, G.B. 2013. Effect of maturity at harvest on yield, chemical composition, and in situ degradability for annual cereals used for swath grazing. J. Anim. Sci. **91**: 3815–3826. doi:10.2527/jas.2012-5677.

Rotz, A.C. 2020. Integrated Farm System Model. [Online] Available: Integrated Farm System Model : USDA ARS [2022 Dec. 15].

Rotz, C.- Al, and Shinners, K. 2007. Hay Harvest and Storage. Pages 601–616 *in* R.F. Barnes, K.J. Moore, C.J. Nelson, and M. Collins, eds. The Science of Grassland Agriculture Sixth Edition. Blackwell Publishing, Ames, Iowa.

Rude, J. 2020. COVID-19 and the Canadian cattle/beef sector: Some preliminary analysis. Can. J. Agric. Econ. **68**: 207–213. doi:10.1111/cjag.12228.

Samarajeewa, S., Hailu, G., Jeffrey, S.R., and Bredahl, M. 2012. Analysis of production efficiency of beef cow/calf farms in Alberta. Appl. Econ. **44**: 313–322. doi:10.1080/00036846.2010.507173.

SARPAL 2020. SARPAL | OSCIA. [Online] Available: https://www.ontariosoilcrop.org/oscia-programs/sarpal/ [2020 Dec. 11].

Satyasai, K.J.S., and Balanarayana, M. 2018. Can mechanization in agriculture help achieving sustainable development goals? Agric. Econ. Res. Rev. **31**: 147. doi:10.5958/0974-0279.2018.00030.7.

Savetpanuvong, P., Tanlamai, U., and Lursinsap, C. 2011. Suxstaining innovation in information technology entrepreneurship with a sufficiency economy philosophy. Int. J. Innov. Sci. **3**: 69–81. doi:10.1260/1757-2223.3.2.69.

Schellenberg, M.P., Waddington, J., and King, J.R. 1994. Direct seeding of alfalfa into established Russian wildrye pasture in south-West Saskatchewan. Can. J. Plant Sci. **74**: 539–542. doi:10.4141/cjps94-096.

Schoepp, B. (2022). Loss of extension services left a hole in rural communities. *Alberta Farm Express*. [Online] Available : https://www.albertafarmexpress.ca/opinion/schoepp-loss-of-extension-services-left-a-hole-in-rural-communities/

Sheppard, S.C., Bittman, S., Donohoe, G., Flaten, D., Wittenberg, K.M., Small, J.A., Berthiaume, R., McAllister, T.A., Beauchemin, K.A., McKinnon, J., Amiro, B.D., Macdonald, D., Mattos, F., and Ominski, K.H. 2015. Pratiques d'élevage des bovins de boucherie dans les écorégions du Canada en 2011. Can. J. Anim. Sci. **95**: 305–321. doi:10.4141/CJAS-2014-158.

Silveira, G. Da, and Slack, N. 2001. Exploring the trade-off concept. Int. J. Oper. Prod. Manag. **21**: 949–964. doi:10.1108/01443570110393432.

Skinner, R.H., and Dell, C.J. 2016. Yield and Soil Carbon Sequestration in Grazed Pastures Sown with Two or Five Forage Species. Crop. Sci. **56**: 2035–2044. doi:10.2135/CROPSCI2015.11.0711.

Smith, S.R., Bouton, J.H., and Hoveland, C.S. 1989. Alfalfa Persistence and Regrowth Potential under Continuous Grazing. Agron. J. **81**: 960–965. doi:10.2134/AGRONJ1989.00021962008100060023X.

Sommer, S.G., Petersen, S.O., and Møller, H.B. 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutr. Cycling. Agroecosyst. **69**: 143–154. doi:10.1023/B:FRES.0000029678.25083.FA.

Soussana, J.-F., Soussana, J.-F., Loiseau, P., Vuichard, N., Ceschia, E., Balesdent, J., Chevallier, T., and Arrouays, D. 2004. Carbon cycling and sequestration opportunities in temperate grasslands. Soil. Use. Manag. **20**: 219–230. doi:10.1079/sum2003234.

Stanley, P.L., Rowntree, J.E., Beede, D.K., DeLonge, M.S., and Hamm, M.W. 2018. Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in MidWestern USA beef finishing systems. Agric. Syst. **162**: 249–258 doi:10.1016/j.agsy.2018.02.003.

Statistics Canada 2014. Average total income of farm operators by farm type. [Online] Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210007201 [2024 Dec. 5]

Statistics Canada 2016. Land Use. [Online] Available: https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210040601 [2020 Oct. 29].

Statistics Canada 2017a. Farm and Farm Operator Data. [Online] Available: https://www150.statcan.gc.ca/n1/pub/95-640-x/2016001/article/14811-eng.htm [2020 Oct. 21].

Statistics Canada 2017b. Alberta has the most beef cattle in Canada and the second largest total farm area. [Online] Available: https://www150.statcan.gc.ca/n1/pub/95-640-x/2016001/article/14808-eng.htm [2020 Oct. 27].

Statistics Canada 2017c. Tillage practices used to prepare land for seeding. [Online] Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210040801 [2021 Nov. 23].

Statistics Canada 2017d. Farm management survey. [Online] Available: https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvInstrumentList&Id=425075 [2023 Sep. 5].

Statistics Canada 2018a. Snapshot of Canadian Agriculture: Chapter 1. [Online] Available: https://www150.statcan.gc.ca/n1/pub/95-640-x/2011001/p1/p1-01-eng.htm [2020 Oct. 20].

Statistics Canada 2018b. Labour force characteristics by sex and detailed age group, annual, inactive. [Online] Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1410001801 [2020 Oct. 20].

Statistics Canada 2019a. Value per acre of farm land and buildings at July 1. [Online] Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210004701 [2020 Oct. 29].

Statistics Canada 2019b. Frequency of manure application on farms, by farm production type. [Online] Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210021001 [2021 Nov. 24].

Swinton, S.M., and Black, J.R. 2000. MODELING OF AGRICULTURAL SYSTEMS. Michigan State University. doi:10.22004/AG.ECON.11581.

Thomas, S.M., Beare, M.H., Francis, G.S., Barlow, H.E., and Hedderley, D.I. 2008. Effects of tillage, simulated cattle grazing and soil moisture on N2O emissions from a winter forage crop. Plant. Soil. **309**: 131–145. doi:10.1007/S11104-008-9586-4.

Thompson, L.R., and Rowntree, J.E. 2020. INVITED REVIEW: Methane sources, quantification, and mitigation in grazing beef systems. Appl. Anim. Sci. **36:** 556-573 doi:10.15232/aas.2019-01951.

Torell, R., Myrer, G., and Rimbley, N. 2016. Selling Cattle on the Slide. Western Beef Resource Committee. Max C. Fleischmann College of Agriculture. Cooperative Extension Service)(USA)

Toro-Mujica, P. 2021. Evaluation of feed strategies and changes of stocking rate to decrease the carbon footprint in a traditional cow-calf system: A simulation model. Front. Vet. Sci. **8:** 587168

Tseten, T., Sanjorjo, S.A., Kwon, M., Kim, S.W. 2022. Strategies to Mitigate Enteric Methane Emissions from Ruminant Animals. J Microbiol Biotechnol. **32:** 269-277. doi: 10.4014/jmb.2202.02019

Twine, E.E., Rude, J., and Unterschultz, J. 2016. Country of Origin Labeling and Structural Change in U.S. Imports of Canadian Cattle and Beef. Can. J. Agric. Econ. **64**: 545–563doi:10.1111/cjag.12096.

United Nations. 2013. World must sustainably produce 70 per cent more food by mid-century – UN report. [Online] Available: https://news.un.org/en/story/2013/12/456912 [Oct 30, 2023].

United Nations. 2024. World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100. [Online] Available: https://www.un.org/en/desa/world-population-projected-reach-98-billion-2050-and112-billion-2100 [Dec 3, 2024)

United States Department of Agriculture. Integrated Farm System Model. 2023. [Online] Available: https://www.ars.usda.gov/northEast-area/up-pa/pswmru/docs/integrated-farm-system-model/

University of California, Davis. 2023. Methane has been the Achilles heel of cattle emissions. It may be part of the climate solution [Internet][Available: https://clear.ucdavis.edu/news/methane-has-been-achilles-heel-cattle-emissions-it-may-be-part-climate-solution

Verge, X.P., Dyer, J.A., Worth, D.E., Smith, W.N., Desjardins, R.L., McConkey, B.G. 2012. A Greenhouse Gas and Soil Carbon Model for Estimating the Carbon Footprint of Livestock Production in Canada. Animals. **3:**437-454. https://doi.org/10.3390/ani2030437

Wang, X., VandenBygaart, A.J., and McConkey, B.G. 2014. Land Management History of Canadian Grasslands and the Impact on Soil Carbon Storage. Rangel. Ecol. Manag. **67:** 333-343

Weersink, A., Jeffrey, S., and Pannell, D. 2002. Farm-Level Modeling for Bigger Issues. Agric. Econ. Rev. **24**: 123–140. doi:10.1111/1058-7195.00009.

Wigley, T.M.L. 1998. The Kyoto Protocol: CO2, CH4 and climate implications. Geophys. Res. Lett. **25**: 2285–2288 doi:10.1029/98gl01855.

Willms, W.D., Kenzie, O.R., McAllister, T.A., Colwell, D., Veira, D., Wilmshurst, J.F., Entz, T., Olson, M.E. 2002. Effects of water quality on cattle performance. J. Range. Manage. **55:** 452-460

Xu, Z., Li, R., Wu, S., He, Q., Ling, Z., Liu, T., Wang, Q., Zhang, Z., Quan, F. 2022. Cattle manure compost humification process by inoculation ammonia-oxidizing bacteria. Bioresour. Technol. 344: 126314