Effects of age and time of first calving on greenhouse gas emissions from simulated beef farms grazing four stockpiled forage treatments in late fall/early winter

by

Megan Donnelly

A Thesis submitted to the Faculty of Graduate Studies of
The University of Manitoba
In partial fulfillment of the requirements to the degree of

MASTER OF SCIENCE

Department of Animal Science
University of Manitoba
Winnipeg

Abstract

The impacts of age (2 vs 3 yrs), time (March vs June) of first calving and stockpiled forage quality (TDN) for late fall/early winter grazing on whole-system greenhouse gas (GHG) emissions and net revenues from cow-calf production systems were examined in this study. Farm simulations were conducted using the Holos model to estimate whole-farm GHG emissions from 16 systems in Brandon, Manitoba, Canada. Each simulation began with 118 newborn, female calves and ended upon weaning of their 6th calf with GHG emissions measured annually over 8-10 yrs. The steady-state herd consisted of 75 mature cows and 22 heifers, or 85 mature cows and 12 heifers, 4 bulls and their progeny. Four stockpiled forages/forage mixtures were evaluated: i) standing corn (COR), ii) tall fescue/meadow bromegrass (TFM); iii) orchard grass/alfalfa (OGA), and iv) tall fescue/alfalfa/cicer milkvetch (TAC). An economic analysis was conducted to estimate annual net revenues from the steady-state herd. Enteric methane (CH_4) was the largest GHG emission source accounting for 57 to 65% of emissions across all systems. Cumulative GHG emissions (over the 8-10 yr period) were 5-14% lower with heifers calving at 2 vs 3 yrs of age, and 2-9% lower for March vs June calving within the 2-yr calving systems. Cumulative GHG emissions ranged from 4205-4765, 4329-4982, 4593-5460, and 4470-5029 Mg CO_2e for systems grazing COR, TFM, OGA, and TAC, respectively. Emissions were highest from OGA, the lowest-TDN treatment, in all systems. Greenhouse gas intensity estimates ranged from 15.6 to 21.0 kg CO_2e kg liveweight^{-1}. Estimated net revenues were 5-7% higher with heifers calving at 2 vs 3 yrs of age and 9-14% higher for June- vs March-calving systems. Using 2021 market prices, net revenues averaged -\$57,776, -\$59,685, -\$59,999, and -\$70,179 yr^{-1}, for OGA, TFM, TAC, and COR systems, respectively. This study suggests that (i) a reduction in the age at first calving (2 vs 3 yrs) should reduce GHG emissions and increase annual revenues; (ii) calving in March vs June should reduce GHG emissions but decrease annual revenues; and (iii) grazing stockpiled forages with higher TDN should reduce GHG emissions and annual revenues from cow-calf systems.

Acknowledgements

I would like to sincerely thank both of my advisors Dr. Kim Ominski and Dr. Emma McGeough for their continued guidance throughout my time at the U of M as a graduate student. Thank you for keeping me on track while also providing me with valuable opportunities to connect with members of outside organizations to help guide my project. This led to an opportunity for employment during my Master’s program that improved my knowledge of the Holos model and provided me with insight into the workings of Manitoba Agriculture. I truly appreciate your constant support and positive encouragement as I was nearing completion of this thesis. Thank you for being readily available whenever I had questions or needed guidance--I wouldn’t have been able to get through this program without you both.

Thank you to my committee members Dr. Karin Wittenberg, Dr. Derek Brewin, and Dr. Doug Cattani for your valuable input and guidance throughout my project. I truly appreciate your questions and advice during committee meetings that would go on to shape my thesis project into what it is. I would like to send a sincere thank you to Ben Hamm; thank you for your willingness to help with my understanding of the cost of production spreadsheets and for being readily available to answer my many questions regarding background calculations, inputs, and assumptions. Thank you for your patience as I navigated the many assumptions of my own project that did not perfectly line up with those of the spreadsheets, I couldn’t have completed my economic analysis without your help.

To my Club 149 pals, Sidonie, Paul, Brandon, and Rhea, I’m so happy to have met you all. Your presence made our office environment so much fun even during the occasional visit from a cockroach. I already miss laughing a little too loud with you all.

Finally, I would also like to acknowledge the Lord Selkirk Association of Rupert's Land Agriculture Scholarship and the Cyril L. Anderson-Feed-Rite (Masterfeeds) Grad Fellowship in Animal Nutrition for their financial support.

Dedication

This thesis is dedicated to Grandma Donnelly who encouraged and supported me unconditionally throughout my many years of schooling.

List of abbreviations

Abbreviation	Definition
ADF	Acid detergent fiber
ADG	Average daily gain
AUM	Animal unit month
BCRC	Beef Cattle Research Council
BMP	Best management practice(s)
BW	Body weight
C	Carbon
CanSIS	Canadian Soil Information System
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COP	Cost of production
COR	Standing corn forage treatment
CP	Crude protein
CRSB	Canadian Round Table for Sustainable Beef
cwt	Hundredweight
d	Day
DAFOSYM	Dairy Forage System Model
DE	Digestible energy
DL	Drylot
DM	Dry matter
DMI	Dry matter intake
DMY	Dry matter yield
EF	Emission factor
GEI	Gross energy intake
GHG	Greenhouse gas(es)

GRSB	Global Round Table for Sustainable Beef
H_2	Hydrogen
ha	Hectare
hr	Hour
IFSM	Integrated Farm Systems Model
IPCC	Intergovernmental Panel on Climate Change
IVDMD	In vitro dry matter digestibility
kg	Kilogram
km^2	Square kilometer
LCA	Lifecycle assessment
MAP	Monoammonium phosphate
MBFI	Manitoba Beef and Forage Initiatives
MCF	Methane conversion factor
MP	Metabolizable protein
Mg	Megagram
mo	Month
N	Nitrogen
NDF	Neutral detergent fiber
N_2O	Nitrous oxide
OGA	Orchard grass/alfalfa forage treatment
P	Phosphorus
RFI	Residual feed intake
SF_6	Sulphur hexafloride
t	Tonne
TAC	Tall fescue/alfalfa/cicer milkvetch forage treatment
TDN	Total digestible nutrients
TFM	Tall fescue/meadow bromegrass forage treatment
TMR	Total mixed ration

USDA	United States Department of Agriculture
VFA	Volatile fatty acid
VFI	Voluntary feed intake
WBDC	Western Beef Development Centre
WCCCS	Western Canadian Cow-Calf Survey
Y_m	Methane emission factor
Yr	Year
Yrs	Years

Table of contents

List of tables

List of figures

Foreword

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

1.0 Introduction

The projected rise in the human population to 9.8 billion in 2050 (UN 2017) paired with rising per capita income and food consumption is expected to increase the global demand for food production by 60% (FAO 2017). Increases in population, urbanization and income are expected to cause an increased demand for livestock-derived food, which is estimated to increase globally by 38% between 2020 and 2050 (Komarek et al. 2021). In developing countries, beef production is expected to increase 1.9% annually until 2050 (Alexandratos and Bruinsma 2012). Although Canada is well positioned to meet the growing global demand for beef and other animal-derived foods, there are several factors limiting the expansion of beef production including continued development of residential, commercial, and industrial areas resulting in permanent losses of agricultural land and pastureland conversion to cropland to produce feed for human consumption (Pogue et al. 2018), as well as economic viability (Manitoba Agriculture 2022a). Increased temperatures in Canada through global warming could help to expand land available for food production towards the north, however, increased drought frequency and intensity of storms may limit these benefits (Warren and Lemmen 2014). In addition to these factors, our ability to respond to the growing demand for animal-derived foods will be dictated by our capacity to do so in an environmentally sustainable fashion. Recently, governments and industry stakeholders have set goals to reduce the environmental footprint of our food systems. For example, the Canadian Round Table for Sustainable Beef has targeted emission reductions of 33% by 2030, sequestration of an additional 3.4 million tonnes (t) of carbon (C) per year, and maintenance and enhancement of the 13.8 million hectares (ha) of grassland used by beef producers (CRSB 2022a). To achieve these ambitious goals, the efficiency of production on the existing or perhaps smaller agricultural land base must be improved. Areas of focus to improve production efficiency include advances in animal and forage plant genetics, animal nutrition and pasture management including selection of forage species, as well as reproduction including age at first calving and time of the calving season. Improvements in production efficiency will increase the quantity of beef produced, improving farm profitability, and reducing GHG intensity of the cow-calf system (Stewart et al. 2009). Best management practices (BMP) that aim to reduce the GHG footprint of Canadian beef production should be implemented beginning at the farm level and should target the cow-calf sector as it contributes 78-80% of on-farm GHG emissions produced across all sectors of the beef production system (Beauchemin et al. 2010; Legesse et al. 2015). However, there is limited published data evaluating management practices targeting the cow-calf herd in western Canada and their impacts on whole-farm GHG emissions (Stewart et al. 2009; Beauchemin et al. 2011) and the associated economic outcomes (Modongo and Kulshreshtha 2018; Possberg and Kulshreshtha 2018). Thus, the evaluation of GHG mitigation strategies that target age at first calving, time of the calving season and forage nutritive value within the cow-calf system can help provide the necessary information for producers to improve production efficiencies to reduce their environmental footprint and improve economic outcomes.

2.0 Literature review

2.1 Winter feeding of beef cattle

The Canadian beef industry plays an essential role in Canada's economy, with 9.6 million head on beef operations in 2021 (Statistics Canada 2022a), contributing on average $9.1 billion per year in cash farm sales from 2016-2020 (Canfax 2021a). The beef production cycle typically includes 3 specialized phases referred to as cow-calf, backgrounding, and finishing (Sheppard et al. 2015; Alemu et al. 2016). The cow-calf phase focuses on producing calves and is predominantly forage-based, with the backgrounding phase utilizing low concentrate, high-forage diets to achieve moderate growth, and allowing for muscle and bone maturation of calves following weaning (Zenobi et al. 2014). Lastly, the finishing phase focuses on the rapid fattening of backgrounded cattle offered high-grain diets in preparation for slaughter (Beauchemin et al. 2010; Sheppard et al. 2015). In western Canada, cow-calf producers have traditionally overwintered beef cows in a confined drylot feeding system with hay or silage offered as feed (Kelln et al. 2011; McGeough et al. 2018). However, many cow-calf producers in the Canadian prairies have adopted fall/winter grazing strategies as alternatives to confined winter feeding to reduce overwintering costs (Kelln et al. 2012; Biligetu et al. 2014; Sheppard et al. 2015). These strategies can provide ancillary benefits as manure is deposited directly onto the field, eliminating the need for manure removal, and improving soil fertility while at the same time reducing labor costs compared to traditional confinement feeding (Nelson and Burns 2006; Jungnitsch et al. 2011; Kelln et al. 2012). These strategies include bale grazing, swath grazing, stockpiled perennial and annual forage grazing, straw-chaff grazing, and grazing of standing corn (Kelln et al. 2012; Sheppard et al. 2015).

2.2 Rationale for extending the grazing season

Feed is a major input for beef production and is reported as the highest annual cost for cow-calf producers in the Prairies (Kelln et al. 2011; Zenobi et al. 2014; Damiran et al. 2016), with winter feed accounting for 45% of production costs in Manitoba (Manitoba Agriculture 2022a). Larson (2011) surveyed 22 cow-calf producers across Saskatchewan comparing the top 25% low-cost producers to those remaining. Low-cost producers had total production costs of \$512 cow^{-1}, \$147 cow^{-1} lower than the remaining producers, with winter feed and bedding costs accounting for 34-35% of these costs. These authors reported that the low-cost producers incorporated extended grazing strategies including bale grazing, straw/chaff grazing, and swath grazing, with minimal use of bale processors and silage feeding, thus demonstrating the cost savings achieved by feeding on pasture during the fall/winter period. Manitoba Agriculture estimated feeding costs of \$2.60 cow^{-1} d^{-1} during a confined winter feeding period of 195 days, utilizing an alfalfa-grass hay and barley grain-based ration, compared to \$1.18 cow^{-1} day^{-1} during a 35-d extended winter grazing period utilizing stockpiled forage (Manitoba Agriculture 2022a). In this same analysis, the use of crop residue, stockpiled forage grazing, swath grazing, and standing corn grazing over winter resulted in winter feed costs of \$0.89, \$1.18, \$1.46, and \$1.28 cow^{-1} d^{-1}, respectively. Extended grazing strategies reduce the need for purchased and/or stored feeds (Mata-Padrino et al. 2017), thus mitigating costs associated with mechanically harvesting hay, feed storage, labor, manure management, and fossil fuel use (Baron et al. 2014; Alemu et al. 2016; McGeough et al. 2018).

2.3 Prevalence of winter grazing strategies in Canada

A Canadian survey examined management practices on 1009 beef operations across a range of ecoregions and production strategies in 2011, with significant differences in the Prairies compared to the eastern provinces of Ontario and Quebec (Sheppard et al. 2015). Of the 1009 operations surveyed, 803 incorporated grazing strategies (at any time of year) and 58% of those incorporating grazing utilized winter grazing strategies that included grazing of rolled or processed forages (44%), bale grazing (42%), stockpiled forage grazing (29%), grazing of swathed cereal crops (25%), standing corn grazing (7.1%), and grazing of other feedstuffs (1.9%). Producers adopted these strategies for various reasons including reduced production costs for feed, fuel, and manure handling (80%), reduced labor/time spent feeding and harvesting (58%), improved cattle condition and health (42%), and agronomic benefits including improved soil fertility and increased forage yields (35%). The main reasons producers avoided winter grazing strategies included too much snow (50%), lack of winter watering system (40%), cold weather (30%), as well as a concern about wasted feed (29%). Of the 803 operations that included grazing strategies at any time of year, those in the east reported less winter grazing (35%) than the prairie provinces (65%), possibly due to higher levels of precipitation associated with loss of leaves, leaching of mineral, and resulting forage nutrient loss.

Similarly, the Western Canadian Cow-Calf Surveys (WCCCS I and WCCCS II), conducted by Western Beef Development Centre (WBDC) and the University of Saskatchewan in 2014 and 2017, examined winter grazing strategies of 411 and 261 cow-calf producers, respectively, from British Columbia, Alberta, Saskatchewan, and Manitoba (WBDC 2015; 2018). Use of winter-feeding strategies by producers decreased from 76% in 2014 to 62% in 2017, possibly due to concerns of wasted feed and animals losing body condition (Sheppard et al. 2015; WBDC 2018). From WCCCS I, extended grazing strategies included bale feeders

(67%), bale processors (machinery used to process and feed chopped hay; 46%), bale grazing (33%), grazing rolled forages (28%), stockpiled grass (18%), swath grazing (17%), crop residue (17%), standing corn (6%), and 17% reported other winter feeding methods including the use of silage, sorghum, grain, pellets, total mixed ration (TMR), and haylage. In 2017, the WCCCS II reported bale grazing as the most utilized winter feeding method (47%), followed by crop residue grazing (41%), stockpiled grazing (40%), swath grazing (28%), standing corn grazing (13%), bale processor (8%), and rolled forage (7%). Use of bale grazing, stockpiled grazing, swath grazing, crop residue grazing, and standing corn grazing strategies were higher in 2017 than 2014.

These extended winter grazing strategies, alone or in combination (with the use of more than one method in sequence over the winter feeding period; Alemu et al. 2016), can be used to improve the productivity of the overwintering system (McGeough et al. 2018), whilst ensuring animal nutrient requirements are met based on changing environmental conditions and physiological status of the herd.

2.4 Methods for late fall and early winter grazing

As bale, swath, and stockpiled grazing are among the most frequently used extended grazing strategies (WBDC 2018), they will be described in more detail below, with an emphasis on stockpiled forage grazing.

Bale grazing is one of the most utilized winter feeding strategies in western Canada (Sheppard et al. 2015; WBDC 2018). Hay bales are placed in a grid pattern on hayfields or pastures in the fall/winter (Jungnitsch et al. 2011; McGeough et al. 2018), with animal access to bales controlled using electric fence to regulate consumption and reduce waste (Kallenbach 2006; Kelln et al. 2012). Benefits of bale grazing include improvements to pasture yield, increased soil inorganic nitrogen (N), and improved capture and recycling of nutrients due to manure and urine deposition directly on the field (Jungnitsch et al. 2011; Kelln et al. 2012). However, these authors reported concerns with high concentrations of feed and manure located at each bale grazing site, resulting in decreased uniformity in nutrient distribution compared to a swath grazing or crop residue grazing system, thus amplifying the potential for nutrient leaching (Chen et al. 2017).

Swath grazing is a system for late fall/early winter grazing where cereals are cut at a target stage of maturity from heading until dough stage and placed in windrows on pasture for the animals to graze (Entz et al. 2002; Baron et al. 2004). Benefits of this grazing strategy compared to traditional drylot feeding include reduced labor requirements as harvesting and hauling of feed, feed delivery and manure removal are either reduced or eliminated (McCartney et al. 2004; Baron et al. 2014). Further, cost benefits are realized compared to drylot feeding and bale grazing systems as baling of forage is not necessary (Volesky et al. 2002). Limitations of this grazing strategy may include decreased weight gains due to increased cattle energy requirements for walking, foraging, and maintaining body temperature during winter compared to a drylot feeding system in which cattle are housed in sheltered pens (McCartney et al. 2004). Additionally, swaths will be covered by snow during the winter (Alemu et al. 2016), and accessibility under deep snow or ice may critically limit energy intake in cold weather when cow nutritional requirements increase (Aasen et al. 2004); however, these benefits and limitations apply to many winter grazing strategies, including bale and stockpiled forage grazing.

2.4.1 Stockpiled forage grazing

Stockpiled grazing systems are characterized by standing forage accumulated from spring regrowth or after an early-mid season grazing or harvest event (Entz et al. 2002; Baron et al. 2004; Biligetu et al. 2014; McGeough et al. 2018). In high-moisture areas of western Canada, it is possible to graze or mechanically harvest twice prior to stockpiling, while drier areas may only support one grazing or harvest (Peng 2017). Stockpiled pastures are typically strip-grazed, utilizing temporary fencing to allocate forage, leading to improved forage utilization when compared to continuous grazing methods (Poore et al. 2000). Accumulated forages are grazed in the fall, early winter, and sometimes in the spring, provided that forage is accessible under snow cover, as excessive levels may limit access (Willms et al. 1993; Riesterer et al. 2000; Poore and Drewnoski 2010). Snow can become trampled by cattle or under adverse weather conditions can become crusted, further limiting the animal's ability to graze, which is an important consideration for producers when adopting these grazing strategies (Riesterer et al. 2000; Meyer et al. 2009). The benefits of stockpiled forage grazing are similar to that of bale and swath grazing strategies; however, harvesting, hauling, and feed delivery costs are eliminated, and manure removal is not necessary as it is in a drylot feeding system. Winter feed cost savings of 45% have been reported for a stockpiled perennial grazing system at the WBDC in Saskatchewan when compared to traditional drylot feeding (Kulathunga et al. 2015).

2.4.1.1 Selection of forages for stockpiled grazing

Selection of perennial and annual forages for use in stockpiled systems should consider adaptation to climatic conditions, yield potential, retention of quality into the fall/winter, DM losses during winter, regrowth under fall climatic conditions, and resistance to weathering after growth ceases (Baron et al. 2004; Peng 2017). Standing stockpiled forages are typically mature at time of grazing, with decreased nutritive value compared to vegetative plants, but are often able to meet nutrient requirements of dry beef cows in early to mid-gestation who have lower nutrient requirements than those in late gestation or growing cattle (Poore and Drewnoski, 2010).

Due to a decline in nutritive value that has been observed with maturation of grass monocultures, mixtures of grasses and legumes are commonly used for stockpiled grazing in western Canada (Biligetu et al. 2014). Grazing systems based on grasses mixed with legumes provide soil N through N fixation, thus reducing fertilizer requirements (Nelson and Burns 2006). As a consequence, numerous studies have been conducted to compare grass-legume mixtures with perennial grass or legume monocultures. Hewitt et al. (2018) examined 8 perennial pure grass or legume crops and 15 grass-legume mixtures for use in stockpiled grazing systems in Manitoba. Overall, grass-legume mixtures had higher yields and greater nutritive values (TDN and CP) than pure stands of grasses or legumes. More specifically, the Courtenay tall fescue-Oxley II cicer milkvetch mixture and Courtney tall fescue paired with other legumes demonstrated the highest potential for stockpile grazing of beef cows when considering yield and nutritive value, given that the CP and TDN were higher relative to other treatments that included Killarney orchard grass, Success hybrid bromegrass, Fleet and Armada meadow bromegrass, and Algonquin and Yellowhead alfalfa, alone and in grass-legume combination. Several other studies have confirmed that the nutrient profile of tall fescue is well-suited for winter grazing of spring-calving beef cows in mid-gestation (Poore et al. 2000; Meyer et al. 2009) and it has become a popular choice for late fall/early winter grazing due to its timely regrowth under fall climatic conditions, resistance to weathering (DM loss), and its ability to maintain forage nutrient concentration compared to other cool-season forages (Riesterer et al. 2000; Baron et al. 2004; Poore and Drewnoski, 2010).

In a comparison of stockpiled perennial forages in Lacombe, AB, Canada, Baron et al. (2005) reported stable yields from meadow bromegrass over 3 yrs, averaging 4900 kg ha^{-1}, with higher yields compared to the 4 other grasses (smooth and meadow bromegrass, orchard grass, Kentucky bluegrass, and creeping red fescue), which ranged from 3327-3960 kg ha^{-1} on average with the stockpiled forage accumulation period beginning mid-July and harvest (grazing) in mid-October. However, the average CP concentration (DM basis) of meadow bromegrass (9.1%) was lower than all other grass species within that study, ranging from 9.7-12.3% on average over 3 yrs. Similarly, Biligetu et al. (2014) reported that CP concentrations for meadow bromegrass monocultures (5.0% DM) were significantly lower ($P < 0.05$) than 5 of 7 other grass monocultures (northern wheatgrass, western wheatgrass, Russian wildrye, big bluestem, and switchgrass) which had CP concentrations ranging from 6.4-7.8% DM. However, when meadow bromegrass was combined with alfalfa in a grass-legume mixture in the same study, average CP concentrations (8.0% DM) were significantly higher ($P < 0.05$) than the meadow bromegrass monoculture. In a study conducted by Kopp et al. (2003), meadow bromegrass mixed with alfalfa also had a higher CP concentration (14.2% DM; $P < 0.05$) compared to a meadow bromegrass monoculture (12.4% DM). Meadow brome and alfalfa species have also been shown to have yield advantages for stockpiled grazing compared to grass species. Baron et al. (2005) reported that smooth bromegrass, orchard grass, Kentucky bluegrass, and creeping red fescue, required an accumulation period beginning in early July to provide adequate yield (at least 2000 kg ha^{-1}) for stockpiled grazing, while meadow bromegrass and alfalfa species had adequate yield when the accumulation period began later, in mid-July. In terms of maintaining nutritive value over the late fall/early winter (across 4 accumulation periods), these authors reported that creeping red fescue was ideal for stockpiled forage grazing due to its low neutral detergent fiber (NDF) and increased water-soluble carbohydrate concentration which remained relatively unchanged from mid-July until mid-October. However, meadow bromegrass was considered the best adapted species across years and varying accumulation periods due to its consistently high forage yields, which averaged 6113, 4900, and 2243 kg ha^{-1} for accumulation periods that began on July 1st, July 15th, and August 1st, respectively. Additionally, Peng (2017) reported meadow bromegrass to have the highest potential for stockpiled grazing based on yield potential when grown together with alfalfa stands upon examination of 23 cool-season perennial grass and legume mixtures. Biligetu et al. (2014) reported higher DM yields (2449-2758 kg DM ha^{-1}; $P < 0.05$) from 3 grasses (northern wheatgrass, crested wheatgrass, and green needle grass) mixed with alfalfa, compared to a crested wheatgrass monoculture, the highest-yielding grass monoculture in their study. Although crested wheatgrass was the highest yielding grass monoculture (2143 kg DM ha^{-1}), early maturity resulted in lower ($P < 0.05$) average CP concentrations (5.3% DM) compared to 5 of 7 grass monocultures (Russian wildrye, western wheatgrass, big bluestem, switchgrass, and northern wheatgrass). Alfalfa mixed with other cool-season grasses including meadow bromegrass, Russian wildrye, western wheatgrass, northern wheatgrass, and green needle grass resulted in higher DM yields ($P < 0.05$) than the same grasses mixed with other legumes (cicer milkvetch and sainfoin).

Although grass-legume mixtures have been shown to have many benefits including increased yield compared to grass monocultures, alfalfa presents challenges when used in stockpiled forage mixtures due to leaf loss resulting in yield loss and decreased nutritive value following frost. Therefore, it is ideal to graze in September and October (Baron et al. 2004;

Baron et al. 2005). Compared to alfalfa, cicer milkvetch has been reported to better retain its leaves and nutritive value following frost and can be utilized for grazing in the late fall, however, its low yield may limit its value for stockpiling (Peng 2017), especially under drought conditions (Biligetu et al. 2014).

Standing corn grazing is a strategy used by approximately 6-7% of Canadian beef producers that practice extended grazing (Sheppard et al. 2015; WBDC 2015). Due to advances in plant genetics, hybrid corn varieties have been developed that require lower crop heat units for growth and therefore can be grown in western Canada where the growing season and climate is colder compared to eastern Canada (Lardner et al. 2012). Although snow cover may reduce availability of other annual forages, the tall stature and high stem-to-leaf ratio of standing, whole-plant corn make it more accessible for cattle to graze in the late fall/early winter (Willms et al. 1993). Hewitt et al. (2016) evaluated the yield and nutritive value of 7 annual crops for their use in stockpiled grazing systems for beef cows. Forage species included Fusion corn, Haymaker oats, Hazlet fall rye, Maverick barley, Aubade westerwold ryegrass, Golden German foxtail millet, and Mammoth soybean. Apart from one site-year with low forage DM yield (4365 kg DM ha^{-1}), corn had the highest DM yields ranging from 12,594-28,798 kg DM ha^{-1} across all site-years. Crude protein concentrations were highest (14-23% DM) for fall rye and soybean species for all site years, with corn having a significantly lower CP concentration (7-8% DM). Overall, corn demonstrated the highest potential for stockpiled forage grazing of the 7 annual forage species examined based on DM yield and TDN, but due to low CP concentration, protein supplementation may be required.

In a 3-yr stockpiled grazing study in Saskatchewan, Jose et al. (2017) compared 3 wintering systems: (i) whole plant, low heat unit hybrid standing corn grazing (CORN), (ii) whole plant swathed barley grazing (BAR), and drylot pen feeding barley greenfeed hay (DL) for 45-77 days between October and January. Whole-plant corn (10,648 kg ha^{-1}) had higher yields than BAR (7811 kg ha^{-1}) and had the highest TDN concentration (68%) compared to BAR and DL (61% and 54%, respectively). Crude protein concentration was highest for BAR (11.5%), followed by DL (10.3%), and CORN (10%). These authors concluded that both CORN and BAR were useful alternatives for winter feeding compared to the traditional DL system, however, advised that snow cover in the winter may limit accessibility to swaths and standing forage, and selection of plant-parts will occur when grazing whole plant corn, reducing forage utilization (50% compared to 68% and 84% for BAR and DL, respectively).

Further, Lardner et al. (2012) compared 5 varieties of corn grazed in the winter (November to February), confirming that all 5 varieties produced adequate yields and quality (TDN) to meet the nutritive requirements of dry beef cows over the grazing period. However, to avoid selective grazing of cobs, access to new areas of standing corn were controlled with portable electric fencing, thus, ensuring proper forage utilization. Dry matter yields (DMY) for the 5 corn species ranged from 9056 to 12,867 kg DM ha^{-1}, CP ranged from 6.4 to 8.1%, and TDN concentration of the whole corn plants ranged from 68.6 to 70.8%.

Finally, Dickson (2022) examined the use of Fusion corn for stockpiled grazing in the late fall/early winter (October to December) in Manitoba compared to 3 perennial forage mixtures including: (i) tall fescue/meadow bromegrass/alfalfa (TFM), (ii) orchard grass/alfalfa (OGA), and (iii) tall fescue/alfalfa/cicer milkvetch (TAC). Corn yielded 68%, 79%, and 57% higher (6342 kg DM ha^{-1}) than OGA, TAC, and TFM, respectively, and had the highest TDN (72% DM), but ranked lowest in CP (6.8% DM). Standing corn provided additional benefits for extended winter grazing in times of freezing rain and heavy snow fall (20 cm) as the upright nature of whole-plant corn allowed heifers to graze above the snow while the perennial treatments bent and broke at the top. Additionally, standing corn can provide protection from cold winter weather and wind, as shown by the heifers grazing corn in the same study spending less time at shelters/windbreaks compared to those grazing the 3 perennial forage treatments (Dickson 2022).

2.5 Improving production efficiency of the breeding herd

The CRSB has suggested that a reduction in the age at first calving would be a viable strategy to reduce GHG emission intensity from beef production by increasing the number of calves produced in the lifetime of the cow (CRSB 2020), with heifers calving at 2 yrs of age as the optimal reproductive target (Diskin and Kenny 2014). Beauchemin et al. (2011) examined 2 strategies for GHG emission mitigation from the 8-yr cow-calf LCA conducted by Beauchemin et al. (2010), that targeted improvements in production efficiency from the breeding stock (mature cows and bulls). The first strategy evaluated an increase in the longevity of the cows and bulls in the breeding herd by 1 yr to allow for an additional calving season, which resulted in a higher total calf liveweight (477,000 kg), over the 8-yr LCA, compared to the baseline (418,000 kg). The second strategy evaluated an increase in the number of calves produced per year through improvements in calf survival to weaning (from 85 to 90%), increasing total liveweight (443,000 kg) compared to the baseline (418,000 kg). The observed increases in total liveweight resulted in decreased GHG emission intensities from both scenarios. Increasing the longevity of the breeding herd by 1 yr decreased emission intensity by less than 1%; however, increasing the number of calves weaned lowered emission intensity by 4%. In both scenarios, total GHG emissions were increased from the baseline (5446 t CO_2e), totaling 6191 and 5561 t CO_2e for strategies targeting increased longevity of the breeding stock and increased number of calves weaned, respectively. However, in the latter scenario, the increase in total emissions was offset by the increase in liveweight produced, resulting in a GHG intensity (12.55 kg CO_2e kg beef^{-1}) lower than that of the baseline (13.04 kg CO_2e kg beef^{-1}) and the former strategy targeting increased longevity of the breeding herd (12.98 kg CO_2e kg beef^{-1}). These results demonstrated that improvements in production efficiency (in terms of number of calves produced) can reduce the GHG emission intensity of a beef cow-calf production system in western Canada, in agreement with the priorities of the CRSB to reduce GHG emission intensity via a reduction in age at first calving (CRSB 2020).

Typically, cow-calf producers in western Canada calve in the late winter or early spring (March) and wean calves in the fall (Sheppard et al. 2011; WBDC 2018); however, many have adopted late spring or summer (June) calving dates with the goal of reducing costs and improving calf survival, thus, improving production efficiency (Thompson et al. 2012). In a comparison of March- and June-calving systems in Nebraska, Clark et al. (1997) observed similar pregnancy rates (95%) for March- and June-calving cows. However, weaning weights were less for cows calving in June (198 kg) compared to March (214 kg). Therefore, in a cow-calf system with calves sold at weaning, the liveweight output from any given year would be less for June-calving systems, resulting in an increased GHG emission intensity (emissions per kg of liveweight). The effects of June-calving on whole-system GHG emissions in western Canada are not well-established; however, if selection of calving month can provide improvements to production efficiency, GHG emission intensity of the cow-calf system will be reduced (Beauchemin et al. 2011).

2.6 Production costs of the Canadian beef herd

The beef sector in Canada is subject to rapid changes in profitability as the price of cattle depends on availability and cost of feed, import and export constraints, and the trade of cattle in the global market (Sheppard et al. 2015). The 2020 Canadian Cow-Calf Cost of Production Network examined production and cost data from 25 cow-calf and 3 dairy-beef operations consisting of 115 producers across Canada from British Columbia to the Maritimes that represent a wide variety of production systems (Canfax 2021b). The average annual cost of production was \$1,123 cow^{-1} across all provinces, with the highest cost (\$1,922 cow^{-1}) from a Quebec farm, and the lowest (\$709 cow^{-1}) from a farm in Alberta (Canfax 2021b), compared to \$1,307 cow^{-1} estimated in Manitoba in 2020 (Manitoba Agriculture 2021). Results of the 2020 Canadian Cow-Calf Cost of Production Network reported that only 32% (8 out of 25) of farms were able to cover long-term cash, depreciation, and opportunity costs, and those that could cover these costs often had multiple enterprises generating multiple streams of revenue (Canfax 2021b). The largest cost to cow-calf producers was feed (41%), with the most cost-intensive feeding period during the winter. Most farms in Alberta, Saskatchewan and Manitoba incorporated extended grazing strategies such as swath or corn grazing, while farms in Quebec, Ontario and British Columbia did not. The lowest winter feeding costs were achieved by producers utilizing extensive feeding such as swath or standing corn grazing instead of drylot feeding, demonstrating the economic advantages of this practice in the late fall/early winter.

In a comparison of 3 wintering systems conducted by Jose et al. (2017), beef cows grazed either whole plant standing corn (CORN), whole plant swathed barley (BAR), or were fed barley greenfeed hay bales in a traditional drylot pen (DL). Total costs per cow per day were \$2.35,

\$2.54, and \$3.21 cow^{-1} day^{-1} for BAR, CORN, and DL, respectively. Feed costs were \$1.43 (BAR), \$1.61 (CORN), and \$1.74 (DL) cow^{-1} day^{-1}, accounting for 54-63% of total costs which included salt and mineral, bedding, labor, equipment, and yardage including depreciation and manure removal (Jose et al. 2017). Feed, equipment, and yardage costs were highest for the DL system and as a result, total system costs of CORN and BAR were 21 and 27% lower, respectively.

2.7 Effects of age and time of calving on system profitability

As previously described, an earlier age at first calving for beef heifers will increase the number of calves produced within the cow-calf system, thereby increasing revenues from marketed liveweight. This increase in cattle numbers allows for fixed costs to be shared over a larger number of animals (Larson 2011). In Saskatchewan, Larson (2011) examined the top 25% of producers with the lowest total costs per cow in comparison to the remaining participants in a survey involving 22 cow-calf producers. The average herd size for the low-cost producers was higher (534 cows) compared to the remaining producers (188 cows) and costs were \$147 cow^{-1} lower for the low-cost producers due to the larger herd size and ability for the producers to spread fixed costs across a larger herd. Herd size was a major contributing factor to the reduction in production costs, evident from the 40% reduction in yardage costs per cow observed for low-cost producers (Larson 2011). Further, in an economic analysis examining production costs and revenues of the GHG mitigation strategies incorporated by Beauchemin et al. (2011), Modongo and Kulshreshtha (2018) reported an increase in cattle revenues of \$38,869 when the weaning rate (number of calves weaned) was increased from 85 to 90%. Although land area required to produce feed was increased, leading to a 4.6% increase in feed costs, gains in beef revenues offset these increased expenses compared to the baseline. Not all scenarios from Beauchemin et al. (2011) that reduced GHG emission intensity were economically viable, and adoption of these strategies would require additional incentives to producers to incorporate. Monetary incentives could provide an additional stream of revenue to the production system.

Selection of calving month varies between production systems within western Canada. Most producers utilize calving in the late winter or early spring (March) to lengthen the growth period of calves prior to weaning in the fall (Thompson et al. 2012). However, to reduce production costs, many cow-calf producers have adopted June calving (Sheppard et al. 2011) to take advantage of benefits including decreased requirements for labor, more favorable weather conditions, and less harvested and processed feeds required for confinement diets during lactation as cattle are instead grazing pastures (Adams et al. 2001). Studies have suggested that June-calving systems could better match the high energy requirements of lactating cows with the nutrient content of immature growing pasture forages compared to a traditional March-calving system (Clark et al. 1997; Adams et al. 2001; Thompson et al. 2012; Khakbazan et al. 2015). In a cost examination of March and June calving in Nebraska, Adams et al. (2001) reported a reduction in hay requirements for June-calving systems (100 kg) compared to March-calving systems (2000 kg) over 4 years; however, the June-calving system required about 27 kg cow^{-1} more protein supplement annually. Labor was reduced by 61% for the June-calving system compared to March-calving. Weaning rate did not differ between calving months, but June calves had lower (23-32 kg) weaning weights than March calves. These authors concluded that the feed and labor savings associated with June-calving outweighed the reduction in weaning weight. Similarly, Stonehouse et al. (2003) observed no difference between the weaning rate of winter/spring (February-April) and summer (June-August) calving in Ontario. This differed from a western Canadian study by Durunna et al. (2014) who reported differences in weaning rates between March- (97-99%) and June-calving systems (94-95%). It was suggested by these authors that spring-born calves were more mature by fall and therefore more likely to survive heavy storms that occur during this period compared to summer calves.

Clark et al. (1997) examined the economic performance of a cow-calf operation calving in either March or June in Nebraska. Results of this study were similar to Adams et al. (2001) as hay for confinement diets was reduced for June-calving systems (14 kg cow^{-1} yr^{-1}) compared to March-calving systems (1442 kg cow^{-1} yr^{-1}) across 3 yrs, and protein supplementation was required for June cows. These authors reported benefits associated with June calving that included less dystocia, elimination of buildings and equipment for calving, reduced labor requirements associated with monitoring cows, and less instance of calf scours, though weaning weights for March calves were higher (214 kg) on average than June calves (198 kg). However, higher calf prices in January for June-born calves offset the decreased revenue associated with lighter calves in this system.

In a Canadian study, Sirski (2012) demonstrated that June calving was more profitable than March calving at 3 locations in western Canada (Brandon, MB, Lanigan, SK, and Swift Current, SK); however, revenue risk was higher due to the risk associated with selling calves in the January market. Therefore, while a producer may save on total costs with adoption of June calving, they may be exposed to higher market risk, demonstrating the importance of producers understanding their own costs and expenses incurred (Sirski 2012). Khakbazan et al. (2015) compared the revenues and risks associated with March- and June-calving cow-calf production systems based on system data from Sirski (2012) and Durunna et al. (2014). These authors emphasized the reduction in system costs for the June system compared to March which was primarily due to feed cost reductions in the confinement period of -\$0.04 to -\$0.82 hd^{-1} d^{-1} across the 3 locations. Although, the March system was slightly favored in terms of higher net revenue potential, the risk associated with this system was larger due to higher revenue variances. Higher calf prices were reported in the January market compared to October due to lower supply of calves.

2.8 Modeling whole-farm extended grazing systems

Whole-farm models allow for the integration of complex processes including crop production, crop harvest, feed storage, grazing, feeding, and manure handling, as well as economic outcomes to examine the long-term impacts of various management strategies on productivity, economic viability, and environmental impact (Rotz et al. 2005). The latter is important in beef cattle production systems which have been criticized for increased water, feed, and land use as well as production of GHG emissions (Legesse et al. 2015; 2018). These models can be used to compare GHG emission sources including methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) associated with changes in crop and livestock management in agricultural production systems. A whole-systems approach is critical as reductions in GHG emissions from one part of a farming system can often lead to an increase in emissions from another sector (Janzen et al. 2006). Enteric CH_4 associated with the microbial breakdown of feed in the digestive tract of ruminant animals is responsible for the majority of emissions from beef production (Beauchemin et al. 2010; Legesse et al. 2015). Nitrous oxide from agricultural soils, indirect N_2O associated with N leaching and volatilization, and CO_2 from fossil fuel use must also be considered to determine the full impact of changes in management on total GHG emissions.

2.8.1 The Intergovernmental Panel on Climate Change (IPCC) Empirical Model

Mathematical models used to calculate CH_4 emissions can be classified into 2 main groups: empirical (statistical) models developed from simple equations relating the inputs and outputs of a system (Thornely and France 2007), and dynamic mechanistic models (Alemu et al. 2011). The Intergovernmental Panel on Climate Change (IPCC) empirical model is commonly used in livestock GHG emission studies (Beauchemin et al. 2010; Alemu et al. 2011; Stewart et al. 2014).

The IPCC model has recommended equations for estimating enteric CH_4 emissions, with 3 tiers representing increasing levels of methodological complexity. According to IPCC (2006), Tier 1 is a basic method designed to use readily available statistics and default emission factors (EF) to estimate enteric CH_4 emissions. In Canada, provincial and national inventory values of enteric CH_4 are obtained using Tier 2 methodology, which is intermediate in its complexity, calculating CH_4 production from ruminants based on their gross energy intake (GEI) and the default CH_4 conversion factor (Y_m) as described by Alemu et al. (2011). Methane conversion factors represent the extent to which feed energy is converted to CH_4 (IPCC 2006). For example, good quality, average quality, and poor-quality forages would have Y_m factors of 0.065, 0.070, and 0.080, respectively (Little et al. 2008). The most accurate and demanding methodology in terms of complexity and data requirements is Tier 3, which requires detailed dietary and animal information to calculate CH_4 emissions.

Legesse et al. (2011) compared predictions of enteric CH_4 emissions between empirical (IPCC Tier 2 and ELLIS) and mechanistic (COWPOLL and MOLLY) models from cow-calf production systems in western Canada. Estimates of enteric CH_4 emissions varied by 26-35% between models, higher than the variation observed between production systems (3-5%). These authors reported limitations in the comparison of current models to predict enteric CH_4 due to differences in methodologies. For example, the IPCC Tier 2 model utilizes a fixed Y_m factor (0.065) for grazing beef cattle, while COWPOLL, MOLLY, and ELLIS Y_m factors differed between feedstuffs (alfalfa-grass and grass hay) within each model, and between multiparous and primiparous cows, ranging from 0.051-0.052, 0.063-0.067, and 0.077-0.080 for ELLIS, COWPOLL, and MOLLY, respectively. Additionally, estimation of dry matter intake (DMI) differed between models; COWPOLL, MOLLY, and ELLIS use specific daily DMI, however, the equation used does not include factors such as climate and feeding behavior of cattle that may influence actual DMI. When these estimates are compared to IPCC Tier 2, in which DMI is estimated from liveweight (kg), ADG (kg d^{-1}), and feeding system (confinement or grazing), milk production, pregnancy status, and diet digestibility, differences in outputs are apparent (Legesse et al. 2011). This variation between models, as well as their ability to examine a finite number of input variables, demonstrates challenges in their use to predict enteric CH_4 emissions from beef cow-calf systems compared to measured emissions.

2.8.2 The Holos Model: a tool to estimate and reduce GHG emissions from farms

Holos is a whole-farm empirical model developed by Agriculture and Agri-Food Canada to estimate whole system GHG emissions including enteric and manure CH_4, soil and manure derived N_2O, and CO_2 from farm energy/fuel use. (Little et al. 2008; Beauchemin et al. 2010). Soil C change emissions and sequestration from land use (tillage practice, fallow land, perennial crop areas and grasslands) are also considered (Little et al. 2008). Greenhouse gas emissions are estimated on a monthly time step for livestock operations and an annual time step for cropping systems, based on information available for individual farms (Little et al. 2008; Alemu et al. 2017). Users can examine GHG emissions associated with changes in farm practices including diet manipulation and pasture management including selection of forage species as well as tillage and manure management. Holos is based primarily on IPCC (2006) methodology, modified for Canadian conditions where possible. To account for the range of climates, land and soil types, and farm production practices, Holos provides an ecodistrict selection tool which is linked to default values for soil type and texture, precipitation, and potential evapotranspiration from the Canadian Soil Information System (CanSIS), National Ecological Framework (Little et al. 2008). One limitation of the Holos model is that it lacks a detailed economic component which may be found in other models such as the Integrated Farm Systems Model (IFSM; Rotz et al. 2005). In 2017, Holos incorporated a basic economic cost/benefit analysis as a sub-component to Holos 3.0. A new version of the Holos model (4.0) was released in March 2022 with updated Canadian emission factors and a C model.

2.8.2.1 Lifecycle assessments using the Holos model

Several Canadian studies have examined GHG emissions from Canadian beef production (cow-calf, backgrounding, and feedlot finishing) systems. Legesse et al. (2015) conducted a life-cycle assessment (LCA) to estimate emissions (cradle to farm gate), reporting GHG emission intensities of 15.6 kg CO_2e kg liveweight^{-1} and 12.7 kg CO_2e kg liveweight^{-1} for 1981 and 2011, respectively. The largest proportion of GHG emissions reported in this study was from enteric CH_4 production (73% of total emissions), with more than 78% arising from the cow-calf sector. This decline in GHG emission intensity of 18% over 30 years can be attributed to improved reproductive efficiencies, increased ADG and slaughter weight, increased crop yields, and reduced time to slaughter. Carbon dioxide equivalents (CO_2e) were used as the standardised metric for GHG emissions based on the global warming potentials (GWP) of CH_4, N_2O, and CO_2 (Legesse et al. 2015).

Beauchemin et al. (2010) conducted an 8-yr LCA using the Holos model to calculate whole-farm emissions representative of western Canadian cow-calf operation, including backgrounding and feedlot finishing as well as the cropland system required to supply feed and bedding for the cattle. The simulated farm was located in Vulcan, Alberta with climate, soil, and crop inputs as well as native pasture species representative of this region. Greenhouse gas sources included on-farm CH_4 emissions from cattle and manure, on-farm N_2O emissions from manure and soils, off-farm N_2O emissions from N leaching, run-off and volatilization, CO_2 emissions from energy/fuel used for cropping, feed processing, feeding, and application of fertilizer and herbicide. The LCA was initiated with 120 newborn heifer calves and 4 newborn bulls born in February or March. Weaning of calves occurred at 7 months and heifer calves were bred at 15 months, producing their first calf at 24 months of age. Culling of cows occurred after the weaning of their 7th calf. Total GHG emissions were calculated by summing the emissions from all feedlot cattle for one complete 8-yr cycle. These authors reported that 80% of total GHG emissions were attributed to the cow-calf system, while only 20% were attributed to the backgrounding and feedlot systems, both contributing roughly equally. This LCA estimated the GHG intensity of beef production in southern Alberta at 22 kg CO_2e (kg carcass^{-1}), with the largest contribution from enteric CH_4 (63%), followed by N_2O from soil and manure (27%), while CH_4 from manure and CO_2 energy emissions combined were 10%. Enteric CH_4 was predominantly from the cow-calf system (84%), with considerably lower emissions from the feedlot phase due to the brief duration of feeding and the use of grain-based finishing rations.

Using the same western Canadian farm simulation from Beauchemin et al. (2010), Beauchemin et al. (2011) discovered the greatest reductions in GHG emission intensities (17%) when a combination of mitigation strategies were applied to the cow herd specifically, compared to reductions of 8% when single strategies were applied. These mitigation strategies included the addition of oilseeds (canola seed) to the diet of breeding stock in the winter (8% reduction in emission intensity), incorporation of corn DDGS to the diet of breeding stock (6% reduction) and improving forage quality (increasing CP concentration from 12.0 to 14.0% DM) for breeding stock by harvesting hay at an earlier stage of maturity (5% reduction). Mitigation strategies applied to the feedlot system had a smaller impact on GHG emissions (2-4% reduction in GHG emission intensity) as only 20% of total emissions were from the feedlot phase within the baseline (Beauchemin et al. 2010). These authors also examined the GHG intensity of the system when native pasture was replaced with recently seeded pasture (1-8 years); resulting in a soil C gain that more than offset all GHG emissions. Further, strategies to improve livestock management such as increased longevity of breeding stock and improved calf survival (calf crop increased from 85 to 90% through changes in herd management) also lowered GHG emission intensities by <1% and 4%, respectively, and can be combined with other strategies for further emission reduction.

Stewart et al. (2009) selected 11 management practices to examine their effects on whole-farm GHG emissions from a simulated beef production system in western Canada using a model-based approach primarily based on IPCC (2006) equations as well as data from other Canadian studies. The baseline farm included a cow-calf, backgrounding, and feedlot finishing system with grass pasture and cropland that included alfalfa-grass hay (cow-calf and backgrounding) as well as barley grain for feedlot finishing. These authors compared a reduction in the application of synthetic N fertilizer by 50%, and by 100% to the baseline system; in both scenarios, total farm CO_2e decreased. However, emission intensity expressed as total emissions per unit of protein was increased by approximately two-fold compared to the baseline due to reductions in yield, proving that reductions in one area of the production system do not always result in improvements on a whole-system basis. Elimination or reduction in fertilization of forage by 50% resulted in the largest increases in emissions per t of protein produced on the MB and SK farms, respectively. Grass pasture (CP 12.5%) was replaced with alfalfa-grass pasture (CP 17.1%) for grazing which reduced total farm CO_2e, primarily enteric CH_4 due to the increased nutritive value of alfalfa compared to grass as a consequence of increased rate of digestion and energy utilization, while the increased protein content of the diet, along with N synthesis from alfalfa, increased the available non-ammonia N that reached the small intestine, improving overall digestive efficiency (Frame and Laidlaw 2005; Stewart et al. 2009). These authors also examined the impact of an additional 136 days of grazing fall/winter pasture; higher rates of synthetic N fertilizer were required due to the shortened confinement period reducing the amount of stored manure available for application on cropland that did not receive direct manure deposition, increasing N_2O and CO_2 (Stewart et al. 2009). However, enteric CH_4 emissions were increased due to higher GEI on pasture compared to in confinement, as well as a lower CH_4 conversion factor for manure deposited on pasture. Emissions per unit of protein output (t) exported from the farm were similar to that of the baseline. Reductions in total farm emissions were seen with the addition of fat to the diet of finishing cattle including a 20% reduction in enteric CH_4; however, decreased DMI (-14.3%) and ADG (-17.0%; Boadi et al. 2004) resulted in an increase in time spent in the feedlot, more feed consumed, and increased system emissions in other areas such as manure CH_4 and N_2O from additional manure output.

As previously stated, targeting the finishing system for potential emission reduction may not be as effective as targeting the cow-calf system as feedlot emissions typically contribute less to the whole system (Beauchemin et al. 2010). Results from these studies confirm that the greatest opportunities for emission mitigation lie within the cow-calf herd with emphasis on mature beef cows; thus, future research should examine strategies to reduce GHG emissions from this sector.

2.8.3 The Integrated Farm Systems Model (IFSM)

The IFSM is a research and education tool used to evaluate environmental and economic sustainability of agricultural production systems including crop (no animal), beef, and dairy operations (Rotz et al. 2013; 2015). Developed by the United States Department of Agriculture (USDA), the model was created through a major revision of the Dairy Forage System Model (DAFOSYM) when the development and incorporation of a beef herd component was added (Rotz et al. 2005). The IFSM has advantages over the Holos model as it contains a more developed economic component. Production costs, incomes, and economic return for each year are simulated with annual fixed costs for equipment and structures summed with predicted annual expenditures (labor, fuel, and other resources) to estimate the total cost of production. This value is then subtracted from the total income received for animal, milk, or excess feed sales to determine a net return to management (Rotz et al. 2013).

The IFSM has the ability to simulate crop production, feed intake, animal growth and performance, and the return of manure nutrients back to the land over an extended timeframe (Rotz et al. 2015; 2019). The model was primarily developed for regions of the United States, limiting applicability for Canadian regions, however, there has been some application of the IFSM model in Southern Canada (Ontario and Quebec) with weather and crop data from these regions utilized (Jégo et al 2015). Default crop, feed, animal, and manure management options are reflective of the major strategies used in the United States, thus, the Canadian model, Holos, may be better suited for estimation of GHG emissions produced from production systems in Canada.

2.9 Future research

Models such as Holos and IFSM, as well as other whole-farm models, are valuable research and teaching tools that explore the impacts of changes in management and technology on whole-farm GHG emissions. Many authors, (Little et al. 2008; Beauchemin et al. 2010; Stewart et al. 2014; Legesse et al. 2015; Rotz et al. 2005; 2019) have provided the baseline for future evaluation of the potential benefits of GHG mitigation strategies, but the continued development of these models, as well as analysis of scenarios which reflect current production practices is essential to examine the impact on whole-farm GHG emissions. Mitigation strategies that reduce GHG emissions in one area of the production system may result in increases in another, reinforcing the importance of using a whole-systems or LCA approach to evaluate the benefits of the proposed practices (Stewart et al. 2014; Little et al. 2017). However, selecting strategies based only on total emissions may be misleading when productivity and economic outcomes are not considered; for example, expressing productivity as GHG emissions per unit of protein produced (Stewart et al. 2009), per unit of calf weaned, or per unit of land area required. As the human population rises and demand for food continues to increase, improving production efficiencies in a sustainable manner will become increasingly important to protect the biodiversity, water sources, soils, and forage species contained within the grasslands grazed by cattle in Canada. Increased production of annual crops for human consumption will pose a challenge to the expansion of beef production systems which rely heavily on pasture and perennial forages to feed cattle (Statistics Canada 2017c; Pogue et al. 2018). Therefore, future research should examine the impacts of changes in cow-calf management on the whole production system, including all GHG sources as well as productivity of the system (GHG intensity) while considering the economic viability of implementing these changes in management. Additionally, further development of model components to estimate C storage and effects on system biodiversity will allow for a broader understanding of the whole-system implications of beef produced in Canada.

2.9.1 Gaps in knowledge

Management strategies for improvement of environmental and production/economic efficiencies within Canadian cow-calf systems have been explored separately, however, limited knowledge exists that addresses optimal practices considering both the environmental footprint (GHG emissions produced) and economic viability (net revenue) of the production system. This knowledge gap should be addressed and therefore forms the basis of the hypotheses for this thesis.

3.0 Research hypothesis and objectives

3.1 Hypothesis

1. Effect of age at calving on greenhouse gas emissions

Greenhouse gas intensity is a measure of emissions expressed per functional unit of output such as kg of liveweight, carcass weight, or number of calves weaned from a production system. A standard metric of carbon dioxide equivalents (CO_2e) is used to express GHG emissions based on the GWP of CH_4, N_2O, and CO_2 (Legesse et al. 2015). Increased production efficiency, including decreased age at first calving and increased number of calves weaned in the lifetime of a cow (Beauchemin et al. 2011), will result in lower emission intensities (CRSB 2020). By improving calf survival to weaning (from 85% to 90% through changes in herd management) to improve total liveweight produced, Beauchemin et al. (2011) demonstrated a GHG emission intensity reduction of 4% in a single year. Even if weaning rate is static, beef herds with heifers bred to give birth to their first calf at 2 yrs of age will have a higher number of calves over the lifetime of the cow compared to those calving for the first time at 3 yrs of age. Therefore, it is hypothesized that within simulated beef cattle production systems under western Canadian conditions utilizing stockpiled grazing, heifers giving birth to their first calf at 2 yrs of age will have lower GHG emission intensities (Mg CO_2e per kilogram of liveweight output) compared to those calving at 3 yrs of age.

2. Effect of time of calving on greenhouse gas emissions

Cow-calf producers in western Canada typically calve between January and March (WBDC 2018), however some producers have adopted June-calving to reduce production costs (Sheppard et al. 2015) and avoid adverse spring weather during calving. Peak lactation, when cow energy requirements are highest, occurs 8-9 weeks post-calving (NRC 2016), occurring in early May for March calving systems. Approximately one third of cow-calf operations in Canada (36%) begin grazing cow-calf pairs as early as May; however, by June this percentage is increased to 96% (Sheppard et al. 2015). Therefore, peak lactation in most March-calving systems will occur while cows are still in confinement offered preserved feed. This feed typically includes high-quality hay and grain (Manitoba Agriculture undated a) with rations formulated to meet requirements for lactation. The higher nutritive value (TDN) and inclusion of grain in the diet will result in less enteric CH_4 produced compared to June-calving systems grazing pasture in early August during peak lactation. This reduction in CH_4 can be explained by the lower Y_m factor associated with good- versus average-quality forages (Little et al. 2008). Inclusion of cereal grains in forage-based diets has been well established to reduce enteric CH_4 emissions from beef cattle systems (Boadi et al. 2004). Thus, is hypothesized that reductions in GHG emissions and resulting emission intensities (Mg CO_2e per kilogram of liveweight output) will be reduced when heifers calve in March compared to June.

3. Effect of forage quality on greenhouse gas emissions

Diets of higher nutritive value in terms of total digestible nutrients (TDN) or the inclusion of high-starch feeds such as corn have been shown to reduce enteric CH_4 production by favoring production of propionic acid as the predominant fermentation pathway in the rumen (Johnson and Johnson 1995). Propionic acid production utilizes available H_2, thus lowering H_2 available for methanogenesis (Beauchemin et al. 2008). In addition, feed with higher digestibility and lower fiber content will have an increased passage rate (Moss et al. 2000), reducing the residence time of feed in the rumen and thereby reducing CH_4 production. Therefore, it is hypothesized that pregnant beef heifers grazing stockpiled forage species with higher TDN/starch content will have lower greenhouse gas (GHG) emissions than lower TDN, starch-free forages with a higher fiber content.

4. Effect of age at calving on profitability

Total liveweight produced and sold in a single year from a cow-calf herd is highly dependent on the weaning rate (number of calves weaned). When first calving is delayed from 2 yrs until 3 yrs of age, costs are incurred without income from a marketable calf, therefore total annual liveweight from the cow-calf system is reduced. It is hypothesized that heifers calving for the first time at 2 yrs of age will be more profitable, in terms of total costs per kg of liveweight produced, than the same system with heifers calving for the first time at 3 yrs of age.

5. Effect of time of calving on profitability

Adoption of calving into late spring/early summer has the potential to reduce production costs by utilizing pasture forage that is able to meet cow nutrient requirements and provide a more favorable climate for newborn calves (Thompson et al. 2012), which will reduce calf death loss (Adams et al. 2001). Clark et al. (1997) observed less dystocia (calving difficulty) with June-calving cows compared to March-calving cows though pregnancy rates were similar. In addition to the benefits associated with calf survival, June calving has the potential to reduce labor required for harvest and delivery of feed (Sheppard et al. 2011) and reduce the need for additional buildings and shelters for calving (Adams et al. 2001). June calving has been shown to be more profitable than March calving at 3 locations in western Canada due to their ability to take advantage of an increased number of low-cost bale grazing days for June calving and a reduction in confined feeding compared to the March system (Sirski 2012). It is therefore hypothesized that cow-calf production systems calving in June will be more profitable than those calving in March.

3.2 Research objectives

The objectives of this study were to use the Holos research model and the Manitoba Agriculture (2021) Cow-calf Cost of Production Guidelines to estimate the total GHG emissions, productivity (total liveweight exported from the farm), and profitability of cow-calf production systems utilizing the following management systems:

1. Heifers calving at 2 years compared to 3 years of age
2. Heifers calving on March 1st compared to June 1st at both ages
3. Heifers grazing 1 of 4 stockpiled forage treatments in the late fall/early winter
    i) Standing corn (COR)
    ii) Tall fescue/meadow bromegrass (TFM)
    iii) Orchard grass/alfalfa (OGA)
    iv) Tall fescue/alfalfa/cicer milkvetch (TAC)

4.0 Manuscript

Effects of age and time of first calving on greenhouse gas emissions from simulated beef farms grazing four stockpiled forage treatments in late fall/early winter

M. Donnelly[1], E.J. McGeough[1], K. Wittenberg[1], D. Brewin[2], D. Cattani[3] B. Hamm[4]

and K. Ominski[1]

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

[2]Department of Agribusiness & Agricultural Economics, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2

[3]Department of Plant Science, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2

[4]Manitoba Agriculture, Vita, Manitoba, Canada R0A 2K0

Contribution of authors: K.O., E.J.M., and K.W. contributed to the conception and design of the study. M.D. conducted the modeling work. D.B. and B.H. contributed advice related to the economic analysis. M.D. drafted the manuscript and prepared all tables and figures. All authors reviewed the manuscript critically and M.D. applied all author revisions.

4.1 Abstract

The impacts of age (2 vs 3 yrs), time (March vs June) of first calving and stockpiled forage quality (TDN) for late fall/early winter grazing on whole-system greenhouse gas (GHG) emissions and net revenues from cow-calf production systems were examined in this study. Farm simulations were conducted using the Holos model to estimate whole-farm GHG emissions from 16 systems in Brandon, Manitoba, Canada. Each simulation began with 118 newborn, female calves and ended upon weaning of their 6th calf with GHG emissions measured annually over 8-10 yrs. The steady-state herd consisted of 75 mature cows and 22 heifers, or 85 mature cows and 12 heifers, 4 bulls and their progeny. Four stockpiled forages/forage mixtures were evaluated: i) standing corn (COR), ii) tall fescue/meadow bromegrass (TFM); iii) orchard grass/alfalfa (OGA), and iv) tall fescue/alfalfa/cicer milkvetch (TAC). An economic analysis was conducted to estimate annual net revenues from the steady-state herd. Enteric methane (CH_4) was the largest GHG emission source accounting for 57 to 65% of emissions across all systems. Cumulative GHG emissions (over the 8-10 yr period) were 5-14% lower with heifers calving at 2 vs 3 yrs of age, and 2-9% lower for March vs June calving within the 2-yr calving systems. Cumulative GHG emissions ranged from 4205-4765, 4329-4982, 4593-5460, and 4470-5029 Mg CO_2e for systems grazing COR, TFM, OGA, and TAC, respectively. Emissions were highest from OGA, the lowest-TDN treatment, in all systems. Greenhouse gas intensity estimates ranged from 15.6 to 21.0 kg CO_2e kg liveweight^{-1}. Estimated net revenues were 5-7% higher with heifers calving at 2 vs 3 yrs of age and 9-14% higher for June- vs March-calving systems. Using 2021 market prices, net revenues averaged -\$57,776, -\$59,685, -\$59,999, and -\$70,179 yr^{-1}, for OGA, TFM, TAC, and COR systems, respectively. This study suggests that (i) a reduction in the age at first calving (2 vs 3 yrs) should reduce GHG emissions and increase annual revenues; (ii)

calving in March vs June should reduce GHG emissions but decrease annual revenues; and (iii) grazing stockpiled forages with higher TDN should reduce GHG emissions and annual revenues from cow-calf systems.

4.2 Introduction

In Canada, the agriculture sector is responsible for an estimated 8.2% of greenhouse gas (GHG) emissions (55 Mt CO_2e) with approximately 43% of these emissions arising from enteric methane (CH_4), of which 35% are from beef cattle (Environment Canada 2022a). Within western Canadian beef production, from cow-calf through to feedlot finishing, approximately 80% of enteric CH_4 emissions are from the cow herd alone (Beauchemin et al. 2010; Legesse et al. 2015). As such, mitigation strategies that target this sector have the potential for the largest reductions. From 1981 to 2011 in Canada, CH_4 emissions per unit of beef produced have declined by 14% (Legesse et al. 2015), through improved animal performance and production efficiencies (Beauchemin et al. 2020). However, global GHG reductions are currently off track to achieve the goal set out by the United Nations of net-zero emissions by 2050 (UN 2022), which suggests that further improvements are necessary.

Mitigation of GHG emissions from the cow-calf sector requires an examination of all sources of enteric and manure CH_4, manure and soil N_2O, and energy CO_2 (Alemu et al. 2016). A whole-systems approach is necessary to adequately assess potential GHG mitigation practices as a decrease in emissions from one area of production may result in an increase in another (Stewart et al. 2009). Empirical models including the Holos research model (Little et al. 2008) have been developed to estimate GHG emissions and evaluate the effects of management changes on GHG emissions prior to making changes within the live herd (Beauchemin et al. 2011).

Potential strategies for GHG emission mitigation in cow-calf production systems include improved diet nutritive value (Stewart et al. 2009), as well as improved reproductive efficiency (Beauchemin et al. 2011); however, potential management changes that are successful in one production system may not have the same positive effects within other systems. For cattle managed in non-confined systems, diet quality can be improved via management of grasslands, increased productivity of pasture species (including selection of complimentary, regionally appropriate forage species), and strategic use of supplements (FAO 2017), resulting in decreased GHG emissions (Stewart et al. 2009). Previous research has demonstrated that increasing the weaning rate (number of calves weaned) within a cow-calf system will result in a lower GHG intensity (Beauchemin et al. 2011). Additionally, delaying calving from spring (February-March) to summer (June) will reduce costs associated with harvested feed and calving infrastructure and reduce labor required (Adams et al. 2001; Khakbazan et al. 2015), potentially reducing energy CO_2 produced from burning of fossil fuels. However, the effect of summer calving on whole-system GHG emissions from western Canadian cow-calf systems is not well established. The aim of this study was to explore the effects of age at first calving, time (month) of calving, and stockpiled grazing of annual and perennial forage species in the late fall/early winter on total GHG emissions and profitability from a simulated beef cow-calf production system in western Canada.

4.3 Materials and methods

4.3.1 Description of the simulated cow-calf production system

Modeled systems were representative of a beef cow-calf operation located near Brandon, MB, Canada with 97 reproductive females including 75 mature cows (3-8 years of age) and 22 heifers that were categorized as (i) bred heifers (15-24 or 27-36 months of age), (ii) growing heifers (not bred; 15-27 months of age), or (iii) replacement heifers (8-15 months of age), as well as 4 mature bulls and their progeny which consisted of male and female calves. The size of the operation was reflective of the average number of beef cows and heifers on cow-calf operations in Manitoba in 2016 (Statistics Canada 2017a). This year was selected as production data (liveweight, ADG, and DMI) from bred heifers grazing stockpiled forage treatments which differed in nutritive value was used to create the current LCA (Dickson 2022).

The LCA began with the birth of 118 female calves in the first year, which were followed through 8 or 9 production cycles for 2- and 3-yr calving systems, respectively (Figure 1). The number of production cycles was dependent on the time required for the original group of female calves in each system to grow and produce 6 calves (with a single calf produced per cow per year). Also included at the start of the LCA were 139 mature beef cows for a period of 8 months (from calving until weaning in Yr 1) to account for the emissions produced during the nursing period from the cows that gave birth to the 118 female calves (85% weaning rate; WBDC 2018). For all modeled systems, the cycle ended upon weaning of the 6th calf crop to account for the typical reproductive lifespan of beef cows in western Canada. Bulls were brought into the herd at mature liveweight (900 kg), 7 mo prior to the time of first breeding in each system (November 1 for March-calving systems and February 1 for June-calving systems) and remained in the LCA until its completion. A bull replacement rate of 25% was included for the purposes of the economic analysis; however, the number of bulls and associated inputs (diet formulations and housing) were identical between modeled systems, thus GHG emissions would not differ if bulls were replaced. The steady-state herd was defined as the point in time when the herd contained 97 reproductive females (mature cows, bred heifers, growing heifers and replacement heifers), including 75 or 85 beef cows at or close to mature weight which occurred in Yr 5 or 6 for the 2- and 3-yr calving systems, respectively. Female calves not destined for herd replacement were not considered as reproductive females within the herd. The length of time required for cows to reach mature weight differed between calving systems and was dependent on the stockpiled forage treatment grazed in the late fall/early winter, with March-calving cows reaching maturity between 31-39 mo and June-calving cows reaching maturity between 34-41 mo.

4.3.2 Comparison of the timing and age at first calving

To examine differences in cow-calf reproductive management, including age at first calving and time of calving on animal performance and GHG intensities, 4 modeled systems were examined: i) Heifers born on March 1st calving for the first time at 2-yrs of age (MC2); ii) Heifers born on March 1st calving for the first time at 3-yrs of age (MC3); iii) Heifers born on June 1st calving for the first time at 2-yrs of age (JC2); and iv) Heifers born on June 1st calving for the first time at 3-yrs of age (JC3). Heifers were first bred at either 15 (Mathison 1993; Beauchemin et al. 2010) or 27 mo of age and produced a single calf at either 24 or 36 mo of age, respectively, with an average calving date of the 1st of March or June. Weaning rate, defined as the number of calves weaned per female exposed, was 85% on average for all reproductive females which included death losses of 3.1% within the first 24 hrs after birth, 2.2% on pasture after 24 hours, and a 1.3% abortion rate (Beauchemin et al. 2010; WBDC 2018). A gender ratio of 1:1 was assumed for male and female calves. Years with an uneven ratio of male and female calves were assumed to have one additional female calf, and weaning weights were assumed to be the same for both genders.

Calves that were not destined for herd replacement were assumed to be sold upon weaning (WBDC 2018) and contributed to the liveweight output of the production system along with culled mature cows and culled bred heifers. Liveweights for newborn calves, mature cows, and bulls were 40, 600, and 900 kg, respectively (Little et al. 2008; Beauchemin et al. 2010; Sheppard et al. 2011). Typically, beef calves in western Canada would be weaned, on average, at 7 mo of age (Beauchemin et al. 2010; Legesse et al. 2015). However, as the average calving dates within the current study occurred on the first day of each month (March 1 and June 1), and weaning occurred on the last day of the month (October 31 and January 31), calves were 8 months of age at weaning at the end of October (MC2, MC3) or January (JC2, JC3) with an average weaning weight of 223 kg used for this study. Under commercial conditions, the calving period would span 60-80 d (WBDC 2018) resulting in calves of different ages (6-8 mo) at the time of weaning. The weaning weight in the current study was slightly lower but comparable to Durunna et al. (2014) who reported weaning weights for spring and summer calves in western Canada of 265 and 237 kg, respectively, with an average of 251 kg. Sheppard et al. (2011) reported average weaning weights of 245 kg in eastern Canada, calving between March and May, comparable to the heifers in this simulated operation calving in either March or June. Culling and herd replacement occurred at weaning each year, with a replacement rate of 18% for bred heifers (WBDC 2018) and 12% for mature cows (Legesse et al. 2015; Manitoba Agriculture 2022a).

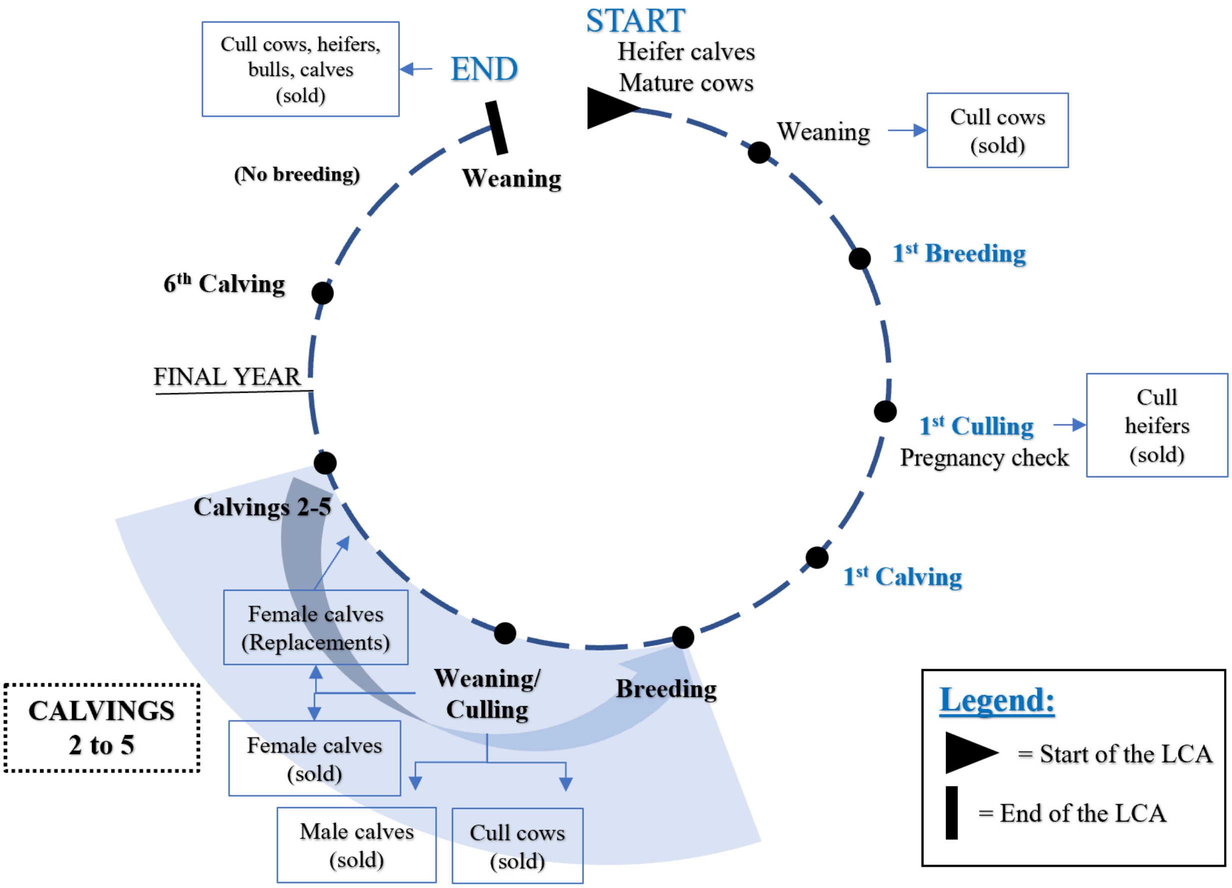

Figure 1. The cow-calf production system following heifer calves from birth (start) through 6 lifetime calvings (end).

4.3.3 Feeding strategies and diet composition in each phase of the production cycle

Feeding strategies, including diet composition and duration time for each class of cattle are reported in Table 1. All cattle were assumed to be fed in confinement from January 1 to May 31, grazing alfalfa-grass pasture from June 1 to September 30 and grazing 1 of 4 stockpiled forage treatments from October 1 to December 31 with some exceptions. All heifers at 15 mo of age (bred or growing heifers) as well as bulls at all ages were fed an alfalfa-grass hay and barley grain formulated ration (AARD 2011) in confinement from October 1 to December 31, as stockpiled grazing performance data for DMI and liveweight gain was not available for 15-mo-old heifers nor bulls grazing the stockpiled forages/forage mixtures from Dickson (2022). This approach ensured that stockpiled forages were grazed by bred heifers or bred cows across all calving systems.

Diets of nursing calves consisted of milk from 0-3 mo of age after which calves were assumed to begin grazing available tame pasture (March-calving systems) or stockpiled forages (June-calving systems) from 4 to 7 mo of age (without supplementation), consuming an average of 4.0 kg DM forage and 0.84 kg milk per day for both steer and heifer calves (Legesse et al. 2015; Table 1). Diets for all other classes of cattle were formulated to meet NRC requirements (NRC 2016) using Cowbytes ration balancing software (AARD 2011). Mature cow rations in confinement consisted of grass hay, barley grain, and barley straw, with the addition of salt, mineral, and vitamins A, D, and E in a mixed ration with no additional feed additives (Table 2). Heifers and cows that had not yet reached mature weight utilized these same feed components apart from grass hay which was replaced by an alfalfa-grass mixed hay (Table 2). Bull confinement rations consisted of grass hay, barley grain and barley straw supplemented with 20% crude protein molasses-based block containing salt, mineral, and vitamins A and E.

Table 1. Cattle class, age, liveweight, and feeding strategies for March- (MC) and June-calving (JC) systems with heifers first calving at 2- or 3-years of age.

Class of cattle	Age (mo)		Liveweight (kg)		Duration in each feeding strategy (d)			
	Start	End	Start	End	Nursing + grazing[a]	Confinement	Pasture	Stockpiled grazing
Calves								
MC	0	8	40	223	245	-	-	-
JC	0	8	40	223	245	-	-	-
Replacement heifers								
MC2	8	15	223	377	-	212	0	0
MC3	8	15	223	335	-	212	0	0
JC2	8	15	223	337	-	120	92	0
JC3	8	15	223	325	-	120	92	0
Growing heifers								
MC2	-	-	-	-	-	-	-	-
MC3	15	27	335	538	-	243	122	0
JC2	-	-	-	-	-	-	-	-
JC3	15	27	325	497	-	243	122[b]	0
Bred heifers								
MC2	15	24	377	508	-	59	122	92
MC3	27	36	538	600	-	59	122	92
JC2	15	24	337	521	-	151	30	92
JC3	27	36	497	600	-	151	30	92
Mature cows	32-44[c]	32-103[d]	600	600	-	151	122	92

[a] Male and female calves are nursing for the first 92 d of life, then begin to consume available forage (4.0 kg DM d^{-1}) in addition to milk (0.84 kg d^{-1}) at 4 mo of age (Legesse et al. 2015).

[b] Total days on pasture (122) consisted of 2 separate grazing periods of 30 and 92 d.

[c] Mature cow age range reflects the time at which mature weight (600 ± 23 kg) is reached within each system which differed between stockpiled grazing strategies given the varying nutritive value of the forages.

[d] Mature cow ages varied at end of the LCA due to herd replacement. Mature cows that existed in the herd since the start of the LCA ranged in age from 91 to 103 mo for 2- and 3-yr calving systems, respectively.

4.3.4 Cropping systems and forage management

All feeds were assumed to be grown on farm, with average annual and perennial forage and crop yields obtained from Manitoba production data as described in Table 2. As indicated, alfalfa-grass hay, grass hay, barley, and summer pasture yields included multi-year average data. Late fall/early winter stockpiled forage yield and nutrient concentration (TDN and CP) data was obtained from a preceding grazing trial conducted by Dickson (2022) with the same annual and perennial forage treatments described in the current study: i) Fusion grazing corn (*Zea* mays; COR), ii) Courteney tall fescue (*Schedonorus arundinaceus*)/Fleet meadow bromegrass (*Bromopsis* biebersteinii; TFM), iii) Killarney orchard grass (*Dactylis glomerata*)/Algonquin alfalfa (*Medicago* sativa; OGA), and iv) Courtney tall fescue/Algonquin alfalfa/Oxley II cicer milkvetch (*Astragalus* cicer; TAC). First-cut perennial yield data was not available from the grazing site from Dickson (2022); therefore, forage DM yields for the same forage species were obtained from Peng (2017) and used within the current economic analysis to estimate the COP for the stockpiled perennial forage treatments. Forage DM yields from Peng (2017) were collected from the Agriculture and Agri-Food Research Center farm located in Saskatoon, SK, Canada (52°07′ lat, 106°38′ long) in June 2016. Dry matter intake values as % of liveweight for heifers in the 3 perennial stockpiling grazing treatments were set as 1.32, 1.40, and 1.21% for TFM, OGA, and TAC, respectively, as reported by Dickson (2022). Dry matter intake was not measured for heifers grazing COR, and as such the DMI was set to 1.9% of BW (Anderson 2020) for the modeling exercise. The production of barley grain for feed did not produce sufficient residual straw to meet bedding requirements of 1.0 T cow^{-1} yr^{-1} (Manitoba Agriculture 2021; 2022a). Therefore, the straw required for bedding was assumed to be a purchased input.

Synthetic N in the form of urea (46-0-0) and phosphorus (P) in the form of monoammonium phosphate (MAP; 11-52-0) were applied to annual and perennial crops as described in Table 3 (Dickson 2022). Since MAP fertilizer contains 11% N, the rate of urea application was reduced accordingly and is reflected in the N fertilizer rate. Nitrogen fertilizer was not applied to mixed legume-grass stands.

Table 2. Yield and nutritive value (TDN, % DM and CP, % DM) of feedstuffs included in confinement rations and grazed during summer or late fall/early winter.

Crop	Moisture Content (%)	TDN (%DM)	CP (%DM)	Yield (kg DM ha^{-1})
Barley grain	14	83.0	12.5	3007[a]
Alfalfa-grass hay	13	60.0	14.0	3605[b]
Grass hay	10	58.0	10.7	3476[c]
Alfalfa-grass pasture	72	59.0	14.2	3880[d]
Stockpiled forage[e]				
COR	35	72.0	6.8	6342
TFM	55	53.9	7.3	4485
OGA	51	44.8	8.5	4294
TAC	57	54.9	10.3	3890

[a] 10-yr average (2008-17) as-fed barley crop yield (MASC 2019) adjusted to DM yield based on 14% moisture content (AARD 2011)

[b] 10-yr average yield for tame hay (Statistics Canada 2017b)

[c] 4-yr average yield for fertilized meadow bromegrass pasture (Kopp et al. 2003) with 12% harvest losses included (Rotz and Muck 1994)

[d] 4-yr average yield for fertilized alfalfa-meadow bromegrass pasture (Kopp et al. 2003)

[e] Stockpiled forage (COR – standing corn; TFM – tall fescue/meadow bromegrass; OGA – orchard grass/alfalfa; TAC – tall fescue/alfalfa/cicer milkvetch). Yields, TDN, CP, and moisture content data from a grazing trial conducted in Brandon, Manitoba, obtained from Dickson (2022)

Table 3. Fertilizer inputs for annual and perennial forage crops used in the lifecycle assessment.

Crop	N Fertilizer rate (kg N ha^{-1})	P Fertilizer rate (kg P_2O_5 ha^{-1})	Source
Annuals			
Stockpiled COR[a]	57	1	(Dickson 2022)
Barley grain	80	30	(Stewart 2008)
Perennials			
Hay (alfalfa-grass)	0	40	(Kopp et al. 2003)
Hay (grass)	120	40	(Kopp et al. 2003)
Alfalfa-grass summer pasture	0	40	(Kopp et al. 2003)
Stockpiled TFM[a]	74	42	(Dickson 2022)
Stockpiled OGA[a]	50	42	(Dickson 2022)
Stockpiled TAC[a]	50	42	(Dickson 2022)

[a] Actual fertilizer inputs for annual and perennial stockpiled forages/forage mixtures from a grazing trial conducted in Brandon, Manitoba, Canada (COR – standing corn; TFM – tall fescue/meadow bromegrass; OGA – orchard grass/alfalfa; TAC – tall fescue/alfalfa/cicer milkvetch).

Harvest losses of 12% (Rotz and Muck 1994) were applied to the grass hay DMY as the DMY from Kopp et al. (2003) was for standing forage measured via hand-clipping (Table 3), while harvest losses for barley and alfalfa-grass hay were included in the reported harvested yields. Forage utilization values represent the volume of forage consumed, with the remainder allocated as feed waste. Forage utilization values for stockpiled forages were 59% and 80% for stockpiled standing corn and perennial forage mixtures, respectively (Hutton et al. 2004; Anderson 2020), 80% for hay and 50% for summer pasture (Rotz and Muck 1994; Legesse et al. 2018). Land area required to produce feed for all classes of cattle was based on total DMI estimated using Cowbytes ration formulation software (AARD 2011), and from Dickson (2022) in which DMI of bred heifers grazing stockpiled forages in the late fall/early winter was estimated using the n-alkane technique (Dove and Mayes 2005).

4.3.5 Manure management

Manure was either deposited directly on pasture during summer and late fall/early winter grazing or accumulated in deep-bedded pens during confinement. Manure from confinement was removed after cows moved to pasture and stockpiled until applied to cropland (Stewart et al. 2009; Beauchemin et al. 2010).

4.3.6 Estimation of GHG emissions

Greenhouse gas emissions were estimated using Holos Research version 3.0, a whole-farm model based on IPCC Tier 2 methodology (IPCC 2006) and modified for Canadian conditions (Little et al. 2008; Alemu et al. 2017). Greenhouse gas emissions from enteric fermentation, manure management, cropping systems, and energy use on-farm were estimated based on farm management practices on a 1-yr timestep. Temperature and percentage of annual breakdown of soil N_2O were entered as monthly inputs and precipitation, potential evapotranspiration, and crop information (synthetic fertilizer rates, area of crop, crop yield, and moisture content) were entered for the growing season (May-October). Animal information including number of animals, number of days on farm, liveweights, type and duration of housing, manure management, custom diet information (TDN and CP), and Y_m factor were entered monthly. Diets were formulated for each stage of production (2- to 5-mo period) with average ambient temperature adjusted accordingly.

4.3.6.1 Climate and soil characteristics

To capture location dependent factors, Holos contains an ecodistrict map for users to select a farm location which is linked to default values for soil type, soil texture, and land topography data, as well as coefficients for emission equations (Little et al. 2008). The farm in the current study was located within ecodistrict 758 in the Subhumid Prairies ecozone on coarse black/grey chernozem soil type (AAFC 2019). This location was selected for its proximity to the Manitoba Beef and Forage Initiatives' (MBFI) Johnson Farm, in Brandon, Manitoba, Canada (49.875931" N, -99.905592" W) where the grazing trial which was the basis of this study was conducted (Dickson 2022). Intensive tillage practices were assumed within all cropping systems until Yr 3 of the simulation when tillage management was changed to no-till representative of the tillage history at the MBFI research station (Dickson 2022). Average temperatures and growing season precipitation data for Brandon, MB, Canada were obtained from 2014-2022 (Environment Canada 2022b; Time and Date 2022; WWO 2022).

4.3.6.2 Greenhouse gas emission sources

Greenhouse gas emission sources estimated within Holos included enteric CH_4, manure CH_4, direct N_2O, indirect N_2O, and energy CO_2. More specifically, enteric CH_4 is produced as a by-product of microbial fermentation in the rumen, manure CH_4 is produced through on-farm storage and decomposition of manure (Kebreab et al. 2006), direct N_2O emissions are produced on-farm from agricultural soils and stored manure, indirect N_2O emissions are produced from N leaching off-farm that is converted to N_2O in the surrounding environment (Janzen et al. 2008), and energy CO_2 emissions are produced through the burning of fossil fuels in tractors and other machinery on farm, as well as through the decomposition of C stored within the soil (Little et al. 2008; Janzen et al. 2008). All emission sources were expressed as Mg CO_2 equivalents (Mg CO_2e). Default GWPs were assigned to the 3 main GHGs: $CO_2 = 1$, $CH_4 = 28$, and $N_2O = 265$ (Myhre et al. 2013), and Y_m values were assigned as listed in Table A4-9 of the Holos manual (Little et al. 2008). Carbon that may have been sequestered from changes in land use (tillage practice, incorporation of fallow land), perennial cropland and grasslands was not included in the GHG emission estimates in the current study.

4.3.7 Economic analysis

A cost of production (COP) analysis was conducted using the beef cow-calf COP budget from Manitoba Agriculture (2021) for each modeled system using the steady-state herd. The budget used 2021 market prices for calves, bulls, cull cows, and cull heifers sold, and assigned a fixed cost at fair market value ($1,800) to replacement heifers to account for costs incurred to raise them from birth until approximately 2 yrs of age (expert opinion: Benjamin Hamm, Farm

Management Specialist for Manitoba Agriculture). Costs associated with the 11 bred heifers in each of the 3-yr calving systems (feed, straw, veterinary medicine, heifer selling costs and commissions, manure removal, pastureland and extended grazing costs) were analyzed separately and added to the cow-calf COP budget. Assumptions for herd replacement, calf crop, weaning weights, and number of bulls used in the modeled system were also adopted in the COP analysis.

The total annual cost of production consisted of (i) fixed costs (value of improved pastureland, machinery and equipment, buildings and facilities (including depreciation), water systems, fencing, and other facility costs), (ii) operating costs (veterinary medicine and supplies, bedding, fuel and maintenance of machinery, utilities, marketing and transportation for sold or culled animals, and manure removal), and (iii) owner labor and living costs, which were all adopted from Manitoba Agriculture (2021). Buildings and equipment were valued at new cost and manure removal was assumed to be conducted by a commercial contractor.

Within each system, feed costs for mature cows (\$ cow^{-1} d^{-1}) during confinement included cost of hay, barley grain and straw, 1:1 mineral, and blue salt, but did not include additional diet additives present in some diets such as magnesium oxide and any additional vitamins (ADE and selenium; AARD 2011), as these feed ingredient options were not offered in the budget (Manitoba Agriculture 2021), and their inclusion was minimal.

Summer pastureland within the modeled systems was assumed to be owned and categorized as improved (tame) pasture, with a stocking density of 1 cow ha^{-1} to account for 50% forage utilization by cattle during grazing. Input costs for stockpiled corn (seed, fertilizer, herbicide, tillage, land taxes, and labor) were obtained from Manitoba Agriculture (2021). Stockpiled perennial forage costs were estimated using the Standing Hay Cost Calculator from

Manitoba Agriculture (2022b) based on the standing yield and moisture contents of TFM, OGA, and TAC (Dickson 2022), and included operating (establishment, fertilizer, herbicide, crop insurance, land taxes, and interest on operating) and fixed costs (land investment) for standing hay production. The estimated perennial forage costs were \$0.022 kg^{-1} for OGA and \$0.026 kg^{-1} for TFM and TAC. These forage costs were entered into the cow-calf COP budget for each of the 3 perennial treatments along with their respective forage yield, moisture content, and planned grazing days to estimate the total cost of each stockpiled grazing period.

The beef cow-calf COP budget estimated the total annual costs as well as the daily costs (\$ cow^{-1} day^{-1}) associated with summer grazing (122 d), stockpiled grazing (92 d), and confinement feed (151 d), for each of the 16 systems. Gross revenues (the sum of all money generated annually) were estimated from animals marketed within each year (cull cows, cull heifers, and calves not kept for herd replacement), which were sold at 2021 market prices (Manitoba Agriculture 2021; Equation 1). Net revenues were reflective of the estimated gross revenue minus total production costs (Equation 2).

Equation 1: Gross revenue (\$ yr^{-1}) = (# of animals marketed yr^{-1}) * (liveweight (lbs) /100) * market price (\$ cwt^{-1})

Equation 2: Net revenue (\$ yr^{-1}) = gross revenue (\$ yr^{-1}) – total cost of production (\$ yr^{-1})

4.4 Results

4.4.1 Whole-system cumulative GHG emissions

Cumulative GHG emissions from all sources are depicted in Figure 2. Of the 4 calving systems, MC2 produced the lowest total GHG emissions (4205-4593 Mg CO_2e), while the MC3 system produced the highest (4765-5029 Mg CO_2e), irrespective of stockpiled forage treatment. The only exception was for the OGA treatment in which total emissions (5460 Mg CO_2e) were higher for JC3 compared to MC3 (5311 Mg CO_2e). March calving systems with heifers calving for the first time at 2 yrs of age (MC2) had 12-16% lower total emissions than MC3. Similarly, June calving systems produced 5-8% lower total emissions when first calving occurred at 2 compared to 3 yrs of age. Of the 4 stockpiled grazing treatments, OGA had in the highest total emissions (4593-5460 Mg CO_2e), and was 9-15% higher than COR, the treatment with the lowest total emissions (4205-4765 Mg CO_2e). The other 2 perennial mixtures, TFM and TAC, had similar GHG emissions ranging from 4329-4982 and 4470-5029 Mg CO_2e, respectively.

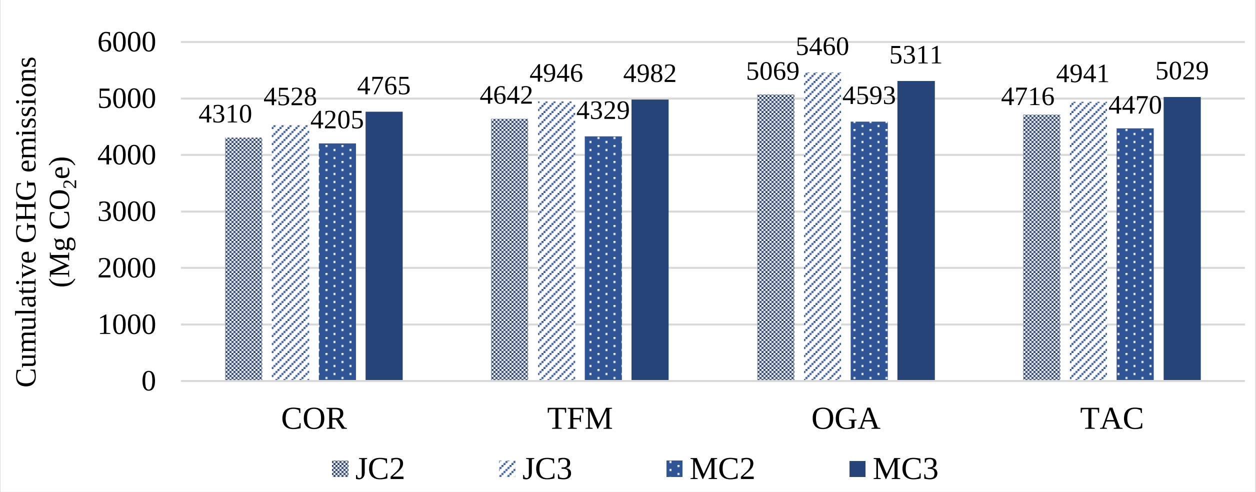

Figure 2. Cumulative greenhouse gas emissions (Mg CO_2e) from 16 modeled cow-calf systems for the full production cycle comparing age (2 vs 3 yrs) and time (March – MC; June – JC) at first calving when grazing 1 of 4 forage treatments (COR - standing corn; TFM - tall fescue/meadow bromegrass; OGA - orchard grass/alfalfa; TAC - tall fescue/alfalfa/cicer milkvetch) in the late fall/early winter.

Annual GHG emissions (Mg CO_2e) for each of the 4 calving systems are depicted in Figure 3. The length of time required for reproductive females to reach 6 lifetime calvings varied from 8-10 calendar yrs and was dependent upon the age at first calving and time of calving with Yr 1 beginning on the 1st of March or June. Total emissions from Yr 2 in each system were identical between stockpiled forage treatments as stockpiled grazing did not occur in Yr 2 by the group of growing or bred heifers aged 16-18 (JC2 and JC3) or 19-21 mo (MC2 and MC3). However, Yr 2 emissions differed between the 4 calving systems (419, 420, 448, and 468 Mg CO_2e for JC3, MC3, MC2, and JC2 systems, respectively). Annual GHG emissions for the June-calving systems followed a similar pattern in that emissions from Yrs 1-4 were lower than Yrs 5-8 (JC2) or 5-9 (JC3) and decreased in the final year of production. However, total emissions from MC2 were higher in Yr 1 than in Yrs 2-4. Further, total emissions from Yr 1 of MC2 were 26-64% higher than emissions from Yr 1 of JC2. Similarly, total emissions from Yr 1 of MC3 were 13-49% higher than JC3. Emissions from both MC2 and MC3 declined from Yr 1 to Yr 2 and then followed the same general trend as the June-calving systems, increasing until they reached a peak in Yr 6. The JC2 and JC3 systems report emissions in Yr 9 and Yr 10, respectively, since weaning occurs at the end of January.

Total emissions for each year of production, were generally highest for systems incorporating OGA compared to the other forage treatments, followed by either TFM or TAC, and were lowest for COR with few exceptions. Exceptions included Yr 2 emissions, as described above, as well as Yr 4 emissions for MC2, for which TAC had the highest emissions (578 Mg CO_2e) followed by COR (537 Mg CO_2e), OGA (511 Mg CO_2e), and TFM (471 Mg CO_2e). In addition, in Yr 4 of the MC3 system, OGA ranked highest (582 Mg CO_2e) followed by TAC (560 Mg CO_2e), COR (556 Mg CO_2e), and TFM (530 Mg CO_2e).

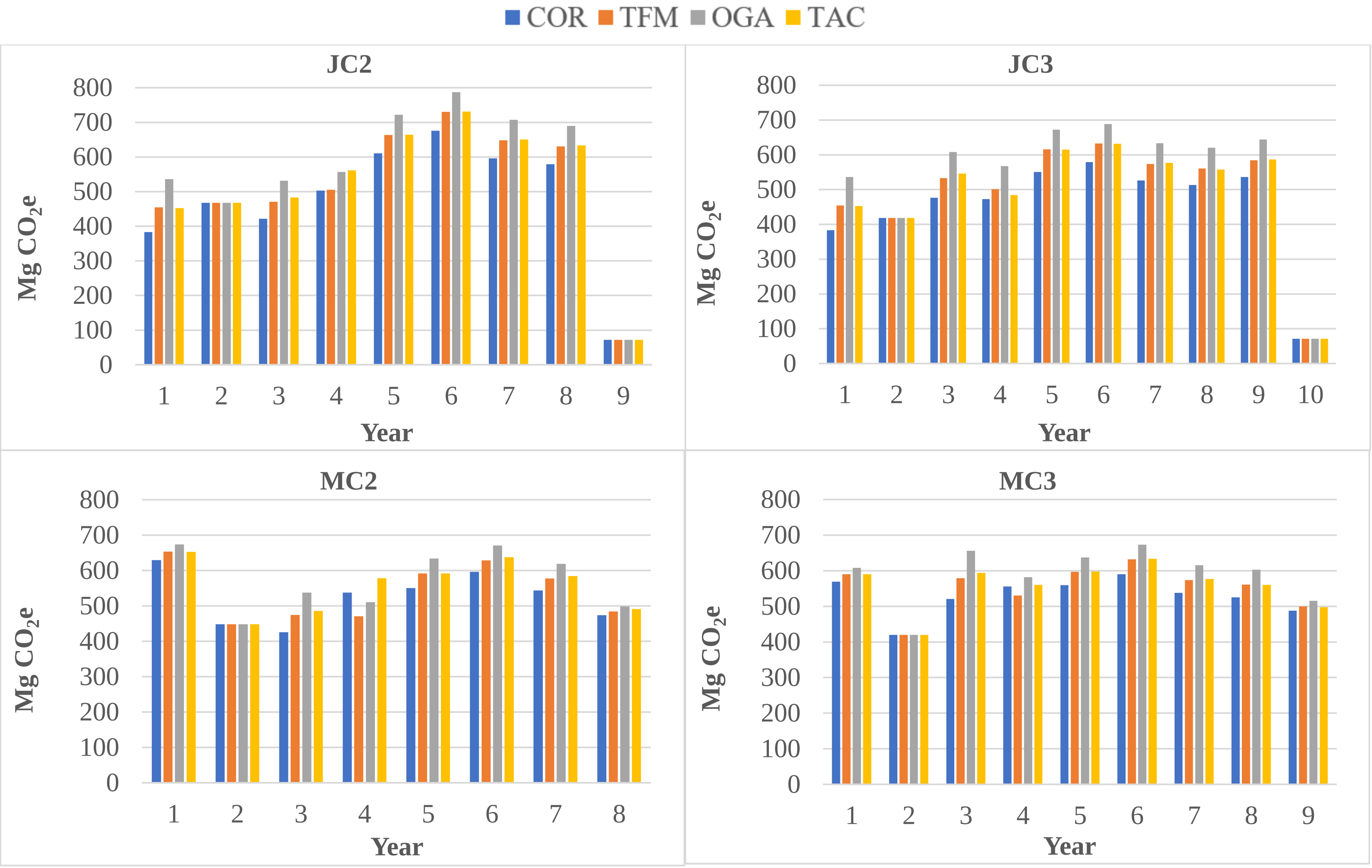

Figure 3. Annual greenhouse gas emissions (Mg CO$_2$e) for all modeled years for 16 systems comparing age (2 vs 3 yrs) and time (March – MC; June – JC) at first calving when grazing 1 of 4 forage treatments (COR - standing corn; TFM - tall fescue/meadow bromegrass; OGA - orchard grass/alfalfa; TAC - tall fescue/alfalfa/cicer milkvetch) in the late fall/early winter.

4.4.2 Contributions of individual GHG sources to total emissions

The largest contributing source of GHG emissions for all modeled systems was enteric CH_4, accounting for 57-65% of total emissions produced, followed by direct N_2O (17-19%), manure CH_4 (9-11%), energy CO_2 (5-9%), and indirect N_2O (4-5%; Table 4). Enteric CH_4 in the system with the lowest total GHG emissions (MC2 COR) contributed 6% less to the total emissions than the system with the highest total GHG emissions (JC3 grazing OGA). The contribution of enteric CH_4 to total emissions for JC3 was, on average, 5-7% higher than JC2; however, in both March-calving systems, the proportion of enteric CH_4 emissions was the same between 2- and 3-yr calving. Systems utilizing OGA for stockpiled grazing had the highest enteric CH_4 contributions (61-65%) compared to the other 3 stockpiled forages, except for the JC3 system grazing TFM or TAC. Systems utilizing COR had the lowest enteric CH_4 contributions (56-60%) but had a higher proportion of emissions from energy CO_2 (7-9%) compared to OGA systems (5-7%).

Table 4. Percent contribution to total greenhouse gas (GHG) emissions by source for 16 beef production systems comparing age (2 vs 3 yrs) and time (March – MC; June – JC) of first calving and grazing 1 of 4 stockpiled forage treatments in the late fall/early winter.

	Contribution to total emissions (%)															
	MC								JC							
Stockpiled forage[a]	COR		TFM		OGA		TAC		COR		TFM		OGA		TAC	
Age at calving (yrs)	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3
Emission source																
Enteric CH_4	59	59	61	61	62	62	60	60	57	60	59	62	61	65	59	62
Manure CH_4	11	11	10	10	10	10	10	10	10	10	10	9	9	9	9	9
Direct N_2O	18	18	18	18	18	18	19	19	19	18	19	17	18	17	19	18
Indirect N_2O	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	5
Energy CO_2	7	7	6	6	5	5	6	6	9	7	8	6	7	5	8	6

[a] Stockpiled forage treatments included 1 annual (COR – standing corn) and 3 perennial (TFM – tall fescue/meadow bromegrass; OGA – orchardgrass/alfalfa; TAC – tall fescue/meadow bromegrass/alfalfa) forage species for stockpiled late fall/early winter grazing.

4.4.3 Relationship between enteric CH_4 and nutritive value (TDN) of the grazed stockpiled forages

Figure 4 demonstrates the relationship between the nutritive value (in terms of TDN as a percentage of DM) of the stockpiled treatments and the resulting cumulative enteric CH_4 emissions (cumulatively across all system years). The treatment with the lowest TDN value (OGA; 45% DM basis) had the highest enteric CH_4 emissions (2843-3292 Mg CO_2e); 8-14%, 7-15%, and 15-31% higher than TFM, TAC, and COR, respectively. Conversely, COR had the highest TDN (72% DM), and the lowest enteric CH_4 emissions (2437-2808 Mg CO_2e) compared to the 3 perennial treatments. The TFM and TAC treatments had similar TDN (54 and 55% DM) and similar enteric CH_4 emissions (2621-3014 and 2665-3058 Mg CO_2e, respectively).

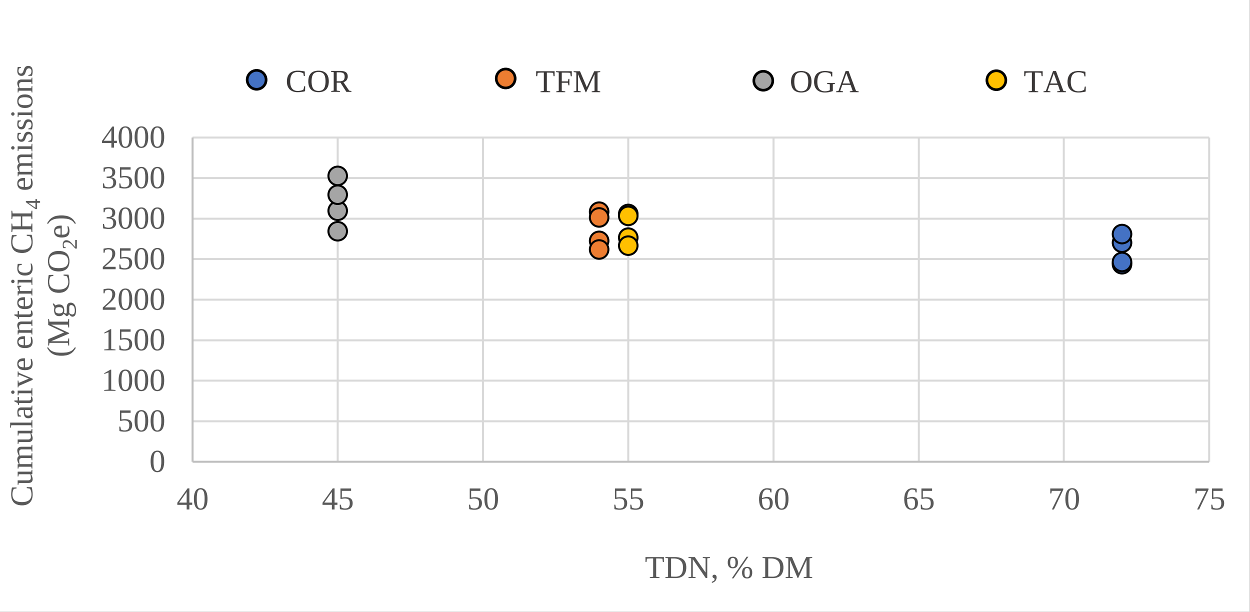

Figure 4. Relationship between cumulative enteric CH_4 emissions (Mg CO_2e) across all system years and TDN (%DM) for 4 stockpiled forage treatments (COR - standing corn, TFM - tall fescue/meadow bromegrass, OGA - orchard grass/alfalfa, TAC - tall fescue/alfalfa/cicer milkvetch) from 16 systems comparing age (2 vs 3 yrs) and time (March – MC; June – JC) at first calving.

4.4.4 Liveweight output from modeled systems

Cumulative liveweight produced (kg) included all cattle sold (including culls) from all years of the production cycle (Figure 5). The March-calving systems showed only slight differences (≤1.4%) in liveweight produced between MC2 and MC3. March-calving systems utilizing TAC for stockpiled grazing resulted in the highest liveweight output for both the 2- and 3-yr calving systems, which was marginally higher (0.1-0.2%) than both COR and OGA. Liveweight produced from both JC2 and JC3 was highest for systems incorporating COR for stockpiled grazing, followed by TAC, TFM, and OGA, respectively. The JC3 system grazing COR produced 0.2, 0.7, and 1.0% more liveweight than the same system grazing TAC, TFM and OGA, respectively, while JC2 systems grazing COR produced 0.2, 0.5, and 0.7% more liveweight than TAC, TFM, and OGA, respectively. Though there were differences in cumulative liveweight produced, the range from lowest to highest output (259,558 to 269,785 kg) was only 3.9% between all systems, thus indicating marginal differences overall when considering all system years. Annual output values in kg of liveweight are reported in Table 1.A of the Appendix.

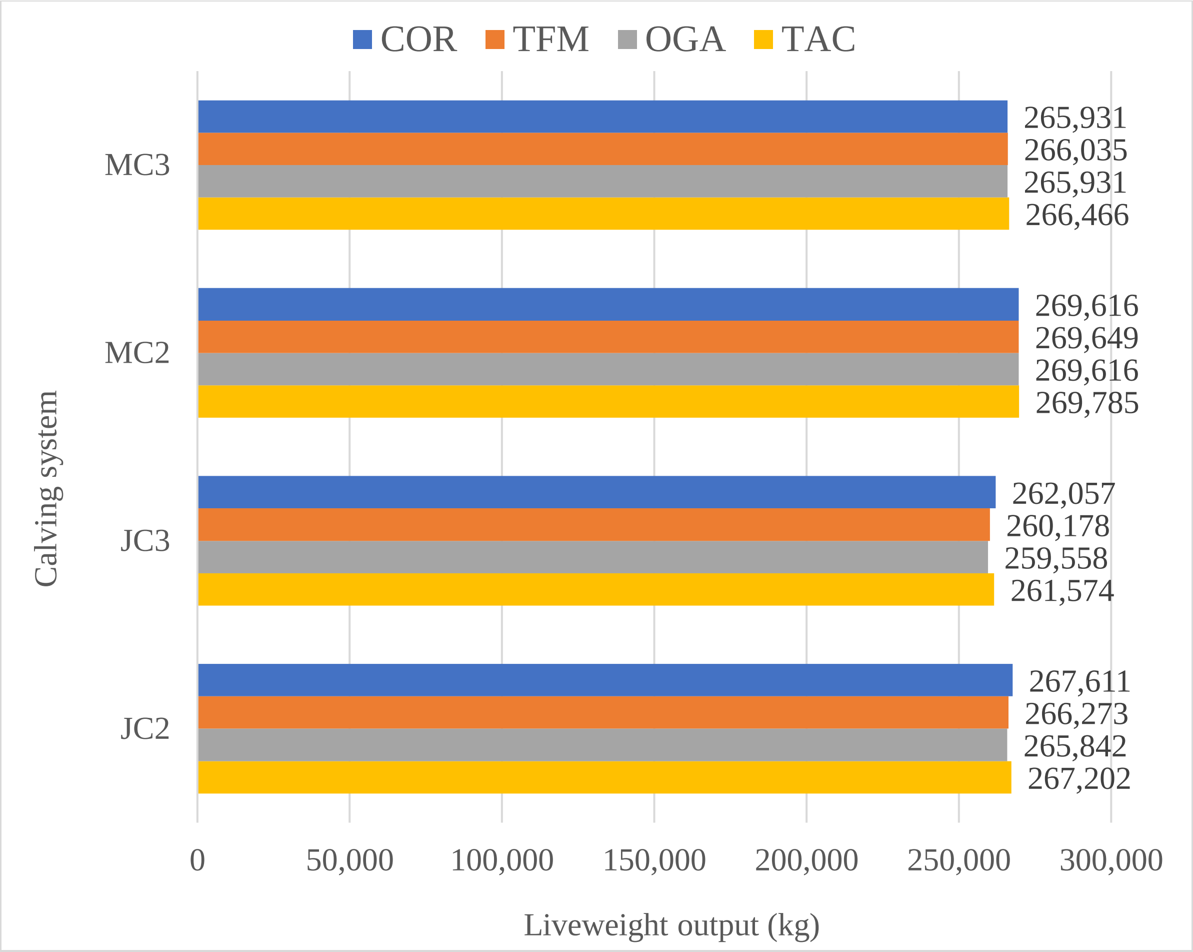

Figure 5. Cumulative liveweight produced (kg) from 16 modeled systems across 8 (MC2; JC2) or 9 (MC3; JC3) production cycles comparing age (2 vs 3 yrs) and time (March – MC; June – JC) at first calving when grazing 1 of 4 forage treatments (COR - standing corn; TFM - tall fescue/meadow bromegrass; OGA - orchard grass/alfalfa; TAC - tall fescue/alfalfa/cicer milkvetch) in the late fall/early winter.

4.4.5 Greenhouse gas emission intensities

The estimated cumulative GHG emission intensities for each modeled system ranged from 15.6 to 21.0 kg CO_2e kg liveweight^{-1} (Figure 6), with the numerically highest intensity resulting from JC3 grazing OGA during the stockpiled grazing period (October to December). In all March- and June-calving systems, those that utilized OGA for stockpiled grazing had the highest emission intensities followed by TAC, TFM, and COR. More specifically, systems using OGA had GHG emission intensities that were 2-11% higher than TAC, 6-11% higher than TFM, and 9-21% higher than COR. Systems that incorporated COR for stockpiled grazing had the lowest GHG emission intensities for both age and time at first calving comparisons, with the lowest intensity (15.6 kg CO_2e kg liveweight^{-1}) observed when COR was grazed in the MC2 system. The range in GHG intensities between the 4 stockpiled forage treatments was less for MC2 and JC2 (1.4-3.0 kg CO_2e kg liveweight^{-1}) than MC3 and JC3 (2.1-3.7 kg CO_2e kg liveweight^{-1}). Both March-calving systems had a smaller range in GHG intensities between stockpiled forage treatments (1.0-1.4 kg CO_2e liveweight^{-1}) compared to those calving in June (3.0-3.7 kg CO_2e kg liveweight^{-1}). In general, GHG emission intensities of each stockpiled treatment had a similar pattern when comparing the 4 calving strategies (March- and June-calving at both 2- and 3-years of age); MC2 had the lowest emission intensity followed by JC2, MC3, and JC3. The only exception was for COR grazed in the MC3 system, which had a higher intensity (17.9 kg CO_2e kg liveweight^{-1}) than JC3 (17.3 kg CO_2e kg liveweight^{-1}). Within each stockpiled forage treatment, the lowest difference in GHG intensities between the 4 calving systems was observed for TAC and COR (2.3 kg CO_2e kg liveweight^{-1}) followed by TFM (2.9 kg per CO_2e kg liveweight^{-1}), and OGA (4.0 kg per CO_2e kg liveweight^{-1}). The MC2 and MC3 systems had the lowest difference (2.1 kg per CO_2e kg liveweight^{-1}) in GHG emission intensity regardless of the stockpiled forage treatment. The JC2 and JC3 systems had larger variation in GHG emission intensity, with a range of 3.1 to 3.7 kg per CO_2e kg liveweight^{-1}, respectively.

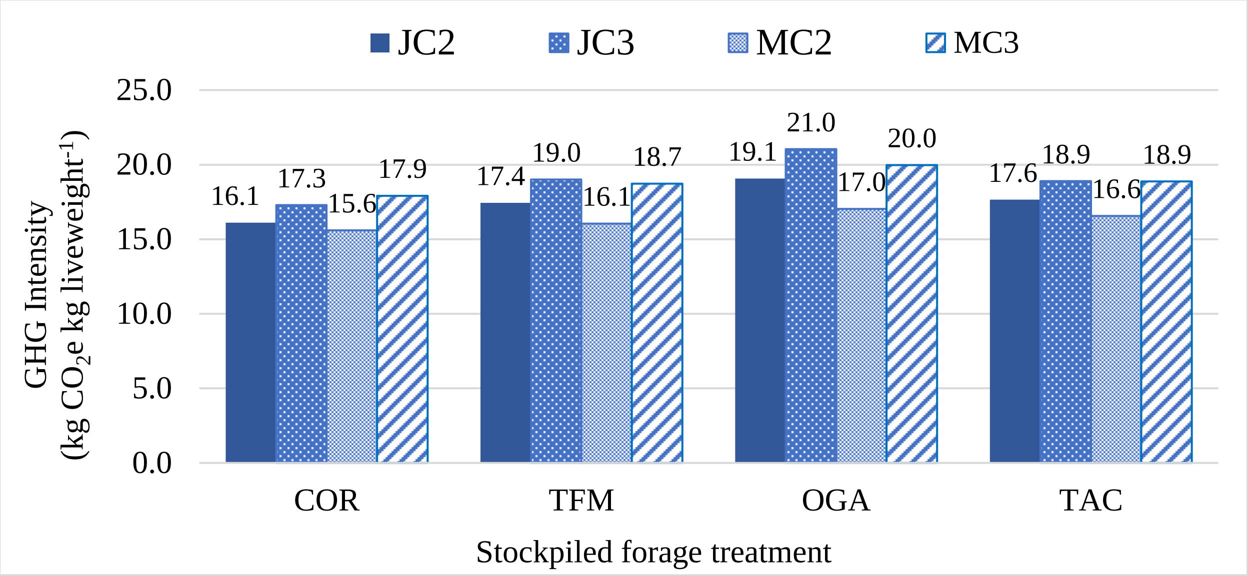

Figure 6. Cumulative greenhouse gas emission intensities (kg CO_2e kg liveweight^{-1}) from all system years of 16 modeled systems comparing age (2 vs 3 yrs) and time (March – MC; June – JC) at first calving when grazing 1 of 4 forage treatments (COR - standing corn; TFM - tall fescue/meadow bromegrass; OGA - orchard grass/alfalfa; TAC - tall fescue/alfalfa/cicer milkvetch) in the late fall/early winter.

Cumulative GHG emissions per kg of calf sold for each of the 4 stockpiled forage treatments had the same ranking as the GHG emissions per kg of liveweight sold in Figure 6 (data not shown). However, GHG emissions per kg of calf sold were 3.1-3.4 times higher across all 16 production systems compared to GHG emissions per kg liveweight. The MC3 and JC3 systems produced fewer total calves (79,447 kg liveweight sold) than the MC2 and JC2 systems (85,250 kg liveweight sold). Thus, the 3-yr calving systems had higher intensities per kg of calf sold compared to those calving one year earlier (14.9-16.2% higher for JC3 compared to JC2, and 20.6-24.9% higher for MC3 compared to MC2). Similarly, cumulative GHG emissions per ha of land base required (data not shown) showed the same ranking between the 4 stockpiled forage treatments as Figure 6. However, the lower land area requirements of JC2 resulted in lower GHG intensity (2.5-3.0 Mg CO_2e ha^{-1}) compared to MC2 (2.8-3.2 Mg CO_2e ha^{-1}).

4.4.6 Land base requirements

The land base required to produce feed for confinement diets (hay and barley grain), summer pasture grazing, and stockpiled forage grazing within each of the 16 production systems ranged from 1434 to 1723 ha (Figure 7). In each of the 4 calving systems, those utilizing COR for stockpiled grazing required the smallest total land base over the production cycle (1434-1689 ha) except for JC2 in which TFM had the lowest requirement. Conversely, the largest land base (1486-1723 ha) required across all systems was TAC which was 2.0-3.6% higher than COR. Land base required for TFM and OGA was only 0.1-2.0% and 0.2-3.0% lower than COR, respectively. The largest difference in land base required between the 4 stockpiled grazing treatments was observed in the MC2 system (3.6%) between COR (1434 ha) and TAC (1486 ha).

Land area required was categorized into annuals (barley grain) and perennials for confined feeding (alfalfa-grass and grass hay), summer pasture (alfalfa-grass) and stockpiled annual and perennial forages (COR, TFM, OGA, or TAC) for late fall/early winter grazing as summarized in Figure 8. Summer pasture accounted for the largest proportion of land required in both MC2 and MC3, representing 47-50% of the total hectares, as well as in the JC3 system (45-46%). Summer pasture in the JC2 system was less, accounting for 37-39% of total land area. In this system, land required to produce perennial forages for confinement diets made up a larger portion of the total (39-40%) compared to the 2 March-calving systems (30-35%), and the JC3 system (27-28%). Area for annual crops (6-8%) and stockpiled grazing (10-21%) contributed the least to the total land area.

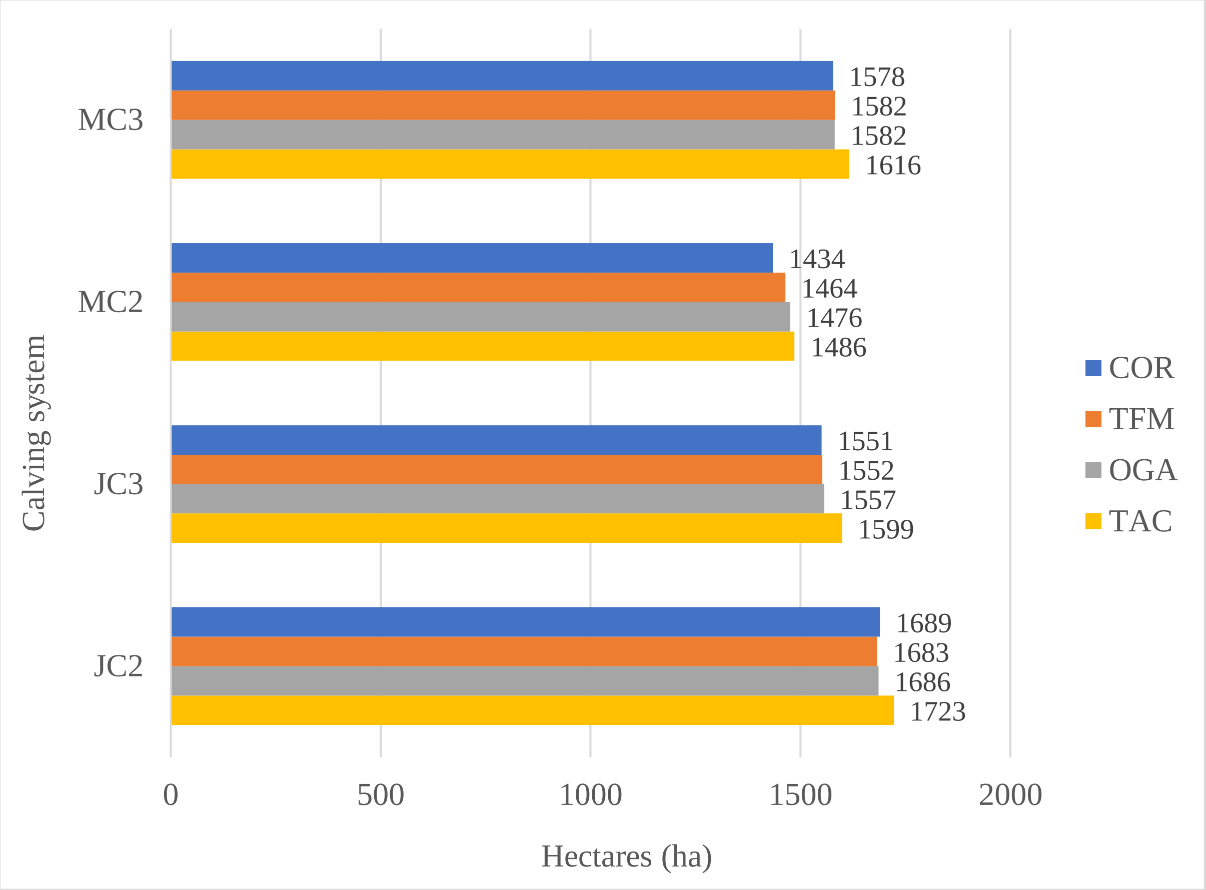

Figure 7. Total land area (ha) required across all years for 16 modeled systems comparing age (2 vs 3 yrs) and time (March – MC; June – JC) at first calving when grazing 1 of 4 forage treatments (COR - standing corn; TFM - tall fescue/meadow bromegrass; OGA - orchard grass/alfalfa; TAC - tall fescue/alfalfa/cicer milkvetch) in the late fall/early winter.

Figure 8. Land area (ha) required for feed production for 16 modeled systems comparing age (2 vs 3 yrs) and time (March – MC; June – JC) at first calving when grazing 1 of 4 forage treatments (COR - standing corn; TFM - tall fescue/meadow bromegrass; OGA - orchard grass/alfalfa; TAC - tall fescue/alfalfa/cicer milkvetch) in the late fall/early winter.

4.4.7 Economic analysis

4.4.7.1 Annual production costs from the steady-state cow-calf herd

Estimated annual cost of production (COP) at steady-state were relatively similar between 2- and 3-yr calving systems, with costs just 1% higher for JC2 versus JC3 and 2% higher for MC2 versus MC3 (Table 5; Figure 9). However, larger cost differences were observed between March- and June-calving systems; with those calving in March having 5.3-6.0% and 5.9-6.7% higher annual costs than June for both 3-yr and 2-yr calving systems, respectively. Comparison of systems by stockpiled forage treatment indicated that the highest production costs were incurred from systems incorporating COR followed by TAC, TFM, and OGA, for all age and time of calving comparisons. The COR systems costs were, on average, 9.5% higher than OGA, 7.9% higher than TFM, and 7.6% higher than TAC. Of all 16 systems, JC3 grazing OGA had the lowest total COP (\$127,404 year^{-1}), 15.1% lower than MC2 grazing COR which had the highest COP (\$150,082 year^{-1}).

4.4.7.2 Operating costs

Feed costs for the steady-state year were highest for 3-yr calving systems compared to those calving at 2-yrs of age; 0.9-2.7% and 3.4-6.1% higher for March- and June-calving systems, respectively (Table 5). Time of calving had a larger effect on annual feed costs, with those incurred in the March-calving systems being 14.1-19.3% and 16.9-23.9% higher than the June-calving systems for those calving at 2- and 3-yrs, respectively. Total feed costs included the cost of the stockpiled grazing period; however, when removed, feed costs would differ by no more than \$555 year^{-1} for the herd in any given system. Feed costs for stockpiled forages were lowest for OGA, followed by TFM, TAC, and COR. Systems incorporating OGA resulted in average cost reductions of 64%, 24%, and 21% compared to COR, TAC, and TFM, respectively.

Marginal differences in “other" operating cost totals for 2- and 3-yr calving systems were observed with 2-yr systems having 0.23-0.79% and 1.1-1.7% higher costs than the 3-yr system for March- and June-calving systems, respectively. Time of calving affected operating cost totals to a larger extent as the MC3 system had 7.9-9.5% higher operating costs than JC3, and MC2 had 8.9-10.7% higher operating costs than JC2. The total cost for owner labor and living was 7.8% higher for the 2-yr calving systems compared to 3-yr calving systems. Fixed costs for livestock, buildings, machinery, and pastureland were the same for all systems, apart from slight differences in the fixed costs for livestock, with a maximum difference of \$156 year^{-1} based on finance rates and cow value.

Table 5. Total system operating costs (\$ year^{-1}), operating interest, and fixed costs from the steady-state herd calving for the first time at 2- or 3-yrs of age, in March (MC) or June (JC) and utilizing 1 of 4 stockpiled forage treatments for late fall/early winter grazing.

	Operating Cost: Feed[a]	Operating Cost: Other[b]	Total Operating Costs + Interest[c]	Fixed Costs[d]	Total Cost of Production[e]
MC2					
COR	$ 57,515	$ 42,135	$ 102,141	$ 30,941	$ 150,082
TFM	$ 46,975	$ 42,126	$ 91,328	$ 30,941	$ 139,270
OGA	$ 45,187	$ 42,135	$ 89,505	$ 30,941	$ 137,446
TAC	$ 47,486	$ 42,101	$ 91,827	$ 30,941	$ 139,768
MC3					
COR	$ 58,040	$ 39,900	$ 100,389	$ 31,097	$ 147,248
TFM	$ 48,222	$ 39,900	$ 90,324	$ 31,097	$ 137,184
OGA	$ 46,175	$ 39,900	$ 88,227	$ 31,097	$ 135,086
TAC	$ 48,366	$ 39,900	$ 90,472	$ 31,097	$ 137,332
JC2					
COR	$ 49,204	$ 42,270	$ 93,761	$ 30,941	$ 141,702
TFM	$ 38,335	$ 42,389	$ 82,742	$ 30,941	$ 130,683
OGA	$ 36,466	$ 42,431	$ 80,869	$ 30,941	$ 128,810
TAC	$ 38,956	$ 42,312	$ 83,300	$ 30,941	$ 131,241
JC3					
COR	$ 50,859	$ 39,900	$ 93,028	$ 31,097	$ 139,887
TFM	$ 40,622	$ 39,919	$ 82,554	$ 31,084	$ 129,400
OGA	$ 38,706	$ 39,904	$ 80,575	$ 31,067	$ 127,404
TAC	$ 41,057	$ 39,900	$ 82,981	$ 31,097	$ 129,840

[a] Cost of barley grain, forages, salt and mineral, and stockpiled grazing forages (COR – standing corn, TFM – tall fescue/meadow bromegrass, OGA – orchard grass/alfalfa, and TAC – tall fescue/alfalfa/cicer milkvetch)

[b] Cost of straw, veterinary medicine, breeding, fuel and maintenance, utilities, manure removal, insurance, herd replacement, pasture rental and operating, and miscellaneous office expenses.

[c] Feed and other operating costs combined with interest (5%) charged on half of operating subtotals (Manitoba Agriculture 2022a).

[d] Fixed costs for livestock, buildings, machinery and equipment, and pastureland and fencing.

[e] Sum of all operating (including interest) and fixed costs as well as cost of labor and living ($17,000 for 2-yr calving systems and $15,763 for 3-yr calving systems).

4.4.7.3 Cost contributions by category

Figure 9 indicates the average annual cost contribution across all 16 cow-calf systems from each category examined in the COP analysis for the steady state year. Annual cost contributions varied between systems for feed (28-39%), other operating costs (27-33%), fixed costs for livestock (2-3%), buildings (3%), machinery and equipment (11-13%), and pastureland and fencing (4-5%), and 11-13% of annual costs were attributed to the owners cost of labor and living. On average, the largest contributor to annual COP in the steady state herd year was feed (34%), with the highest feed cost contributions from COR systems (35-39%) compared to TAC (30-35%), TFM (29-35%), and OGA (28-34%).

Within the cow-calf COP budget (Manitoba Agriculture 2021), costs associated with summer pasture were divided between pasture operating costs and fixed costs for pastureland and fencing, and not categorized under feed costs. This categorization was due to the multitude of other summer grazing options available within the COP budget (rented pasture, community pasture, and grazing of Crown lands). However, costs associated with summer pasture were included in the following analysis of annual feed costs.

A more detailed description of average annual feed costs (\$ yr^{-1}) across the 16 cow-calf systems for each feed category (alfalfa-grass and grass hay, barley grain, and salt/mineral for confinement feeding, summer pasture, and stockpiled forages) is demonstrated in Figure 10. The largest cost contributor (%; Table 6) was alfalfa-grass and grass hay for confined feeding (40%), accounting for \$22,410 (JC2 OGA) to \$26,040 yr^{-1} (MC3 COR). Summer pasture forages accounted for 24% of the average annual COP, ranging from \$14,179 (3-yr calving systems) to \$15,193 yr^{-1} (2-yr calving systems). Stockpiled forages accounted for 18% of the average annual COP, with the highest costs from COR (\$19,047 yr^{-1}) followed by TAC (\$8,957 yr^{-1}), TFM

(\$8,577 yr^{-1}), and OGA (\$6,767 yr^{-1}). Barley grain accounted for 13% of the average annual COP, ranging from \$4,627 (JC2 OGA) to \$11,617 yr^{-1} (MC3 TFM). Lastly, salt and mineral accounted for 4% of the average annual COP, ranging from \$2,299 (MC3 systems) to \$2,721 yr^{-1} (JC2 COR). When evaluating the calving system (as a percentage of annual feed costs; Table 6), the 2- and 3-yr calving systems differed by 0-3%, with 3-yr systems demonstrating slightly higher contributions from hay (0-1%) and barley grain (1-3%), and slightly lower contributions from summer pasture (1-2%). June-calving systems grazing the 3 stockpiled perennial treatments showed a slightly higher contribution (1%) to annual feed costs from hay used for confined feeding and a 2-4% higher contribution from forages used for stockpiled grazing compared to March-calving systems, and as a result, contribution from barley grain for confinement diets was 6-8% lower for June-calving systems. The cost of hay used for confined feeding as a proportion of annual feed costs was less for systems utilizing COR for stockpiled grazing (35 and 36% for March- and June-calving systems, respectively), compared to the 3 perennial treatments which ranged from 41-44% of annual feed costs. The lower cost contribution from hay for confined feeding in COR systems was accompanied by a higher cost contribution from stockpiled forages, accounting for 26-30% of annual feed costs, compared to the perennial systems (11-16%).

Annual feed costs (\$ yr^{-1}) for all 16 systems are reported in Figure 11 for confinement diet components (alfalfa-grass and grass hay, barley grain, and salt/mineral), summer pasture, and stockpiled forages used for late fall/early winter grazing. Hay costs were 0.27-1.9% higher for MC3 compared to MC2 and 1.9-3.4% higher for JC3 compared to JC2. Larger cost differences were observed for barley grain between the 2- and 3-yr calving systems; MC3 had 1.5-10.6% higher barley grain costs than MC2, and JC3 had 29.9-34.3% higher costs compared to JC2. Summer pasture costs were 7.2% less for both 3-yr calving systems compared to those calving at 2-yrs. Annual costs for stockpiled forages were nearly the same for COR systems at both ages of first calving (differing by 0.02%). For the 3 stockpiled perennial treatments, annual stockpiled forage costs were 1.1, 1.4, and 2.3% higher for TAC, OGA, and TFM, respectively, for JC3 and MC3 compared to JC2 and MC2. Annual hay costs between March- and June-calving systems were 11.0-12.3% lower for JC2 compared to MC2 and 9.3-11.0% lower for JC3 compared to MC3. Costs for barley grain were 55.3-55.8% lower for JC2 compared to MC2 and 42.8-47.1% lower for JC3 compared to MC3. However, summer pasture and stockpiled forage costs did not differ between March- and June-calving systems. Annual stockpiled forage costs were lowest for OGA, which were, on average, 21.1, 24.5, and 64.5% lower compared to TFM, TAC, and COR, respectively.

The highest contributors to the "other" operating costs category were pasture operating (20%), which included fertilizer, herbicide, land development, fence maintenance, and taxes associated with summer pasture, and herd replacement (17%), which was reflective of the difference in cost between replacement heifers and the market value of the culled cow (Figure 12). Breeding costs (feed, bedding, veterinary medicine, pasture, and replacement costs for bulls), as well as fuel, maintenance, and repairs for machinery and buildings, each made up an additional 13% of other operating costs.

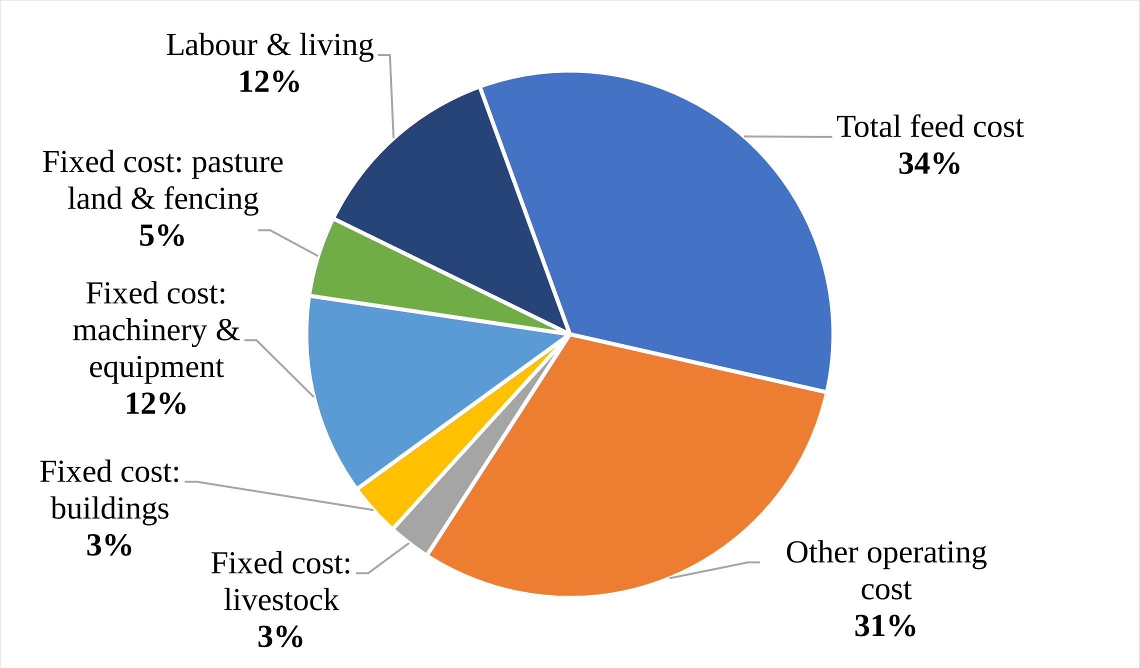

Figure 9. Average annual cost contribution of fixed and operating costs using 2021 market prices for 16 cow-calf production systems.

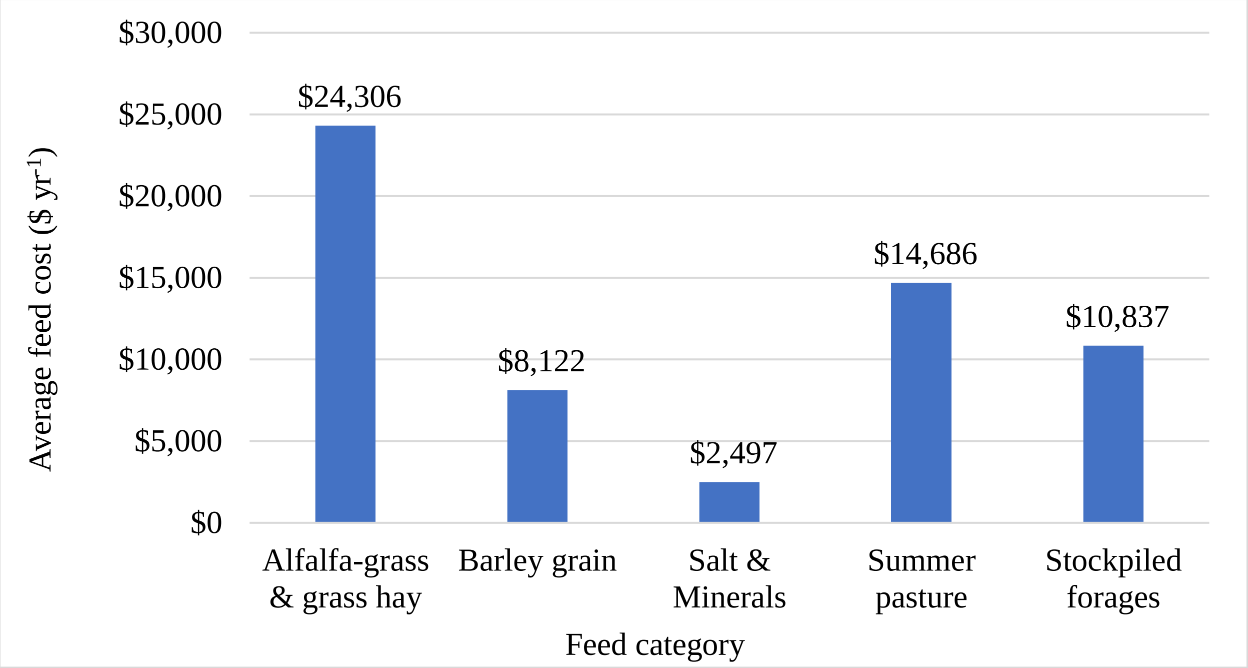

Figure 10. Average annual feed cost contribution ($ year^{-1}) for 16 cow-calf production systems using 2021 market prices.

Table 6. Feed costs as a proportion of annual feed costs for 16 modeled cow-calf systems comparing age (2 vs 3 yrs) and time (March—MC vs June—JC) of first calving and grazing 1 of 4 stockpiled forage treatments for late fall/early winter.

	Proportion of annual feed costs (%)															
Age at calving	2 yrs								3 yrs							
Time of calving	March				June				March				June			
Stockpiled forage[a]	COR	TFM	OGA	TAC	COR	TFM	OGA	TAC	COR	TFM	OGA	TAC	COR	TFM	OGA	TAC
Feed category																
Hay	35	41	42	41	35	42	43	42	36	41	43	41	36	42	44	42
Barley	14	17	17	17	7	9	9	9	15	19	19	18	9	11	12	11
Salt & mineral	3	4	4	4	4	5	5	5	3	4	4	4	4	5	5	5
Summer pasture	21	24	25	24	24	28	29	28	20	23	24	23	22	26	27	26
Stockpiled forages	26	14	11	14	30	16	13	16	26	14	11	14	29	16	13	16

[a] Stockpiled forage treatments included 1 annual (COR – standing corn) and 3 perennial (TFM – tall fescue/meadow bromegrass; OGA – orchard grass/alfalfa; TAC – tall fescue/meadow bromegrass/alfalfa) forage species for stockpiled late fall/early winter grazing.

Figure 11. Average annual feed cost contribution (\$ year^{-1}) from alfalfa-grass and grass hay, barley grain, and salt/mineral for confinement feed, summer pasture, and 1 of 4 stockpiled forage treatments (COR - standing corn; TFM - tall fescue/meadow bromegrass; OGA - orchard grass/alfalfa; TAC - tall fescue/alfalfa/cicer milkvetch) grazed in the late fall/early winter within 16 cow-calf systems comparing age (2 vs 3 yrs) and time (March – MC; June – JC) of first calving.

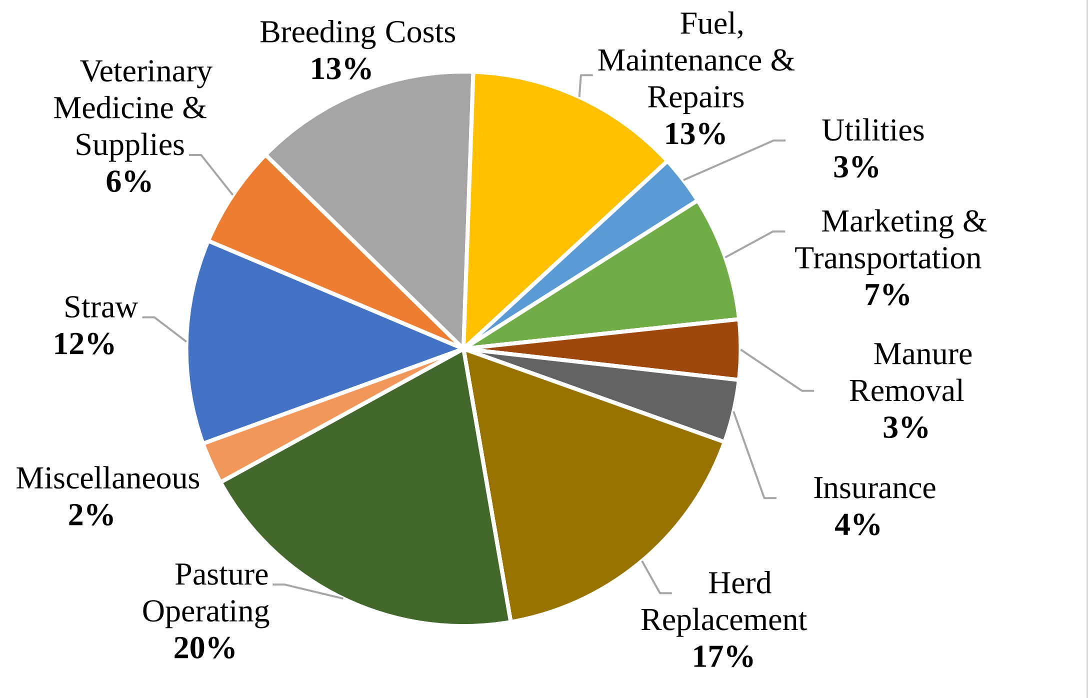

Figure 12. Average annual contribution of "Total Other Operating Costs" using 2021 market prices for 16 cow-calf production systems.

4.4.7.4 Annual production costs as a proportion of liveweight output

Liveweight output from a single steady-state year, which included culled cows, culled heifers, and calves marketed (not including female calves kept for herd replacement), was highest from the MC2 system (20,296 kg yr^{-1}), followed by JC2 (20,218 kg yr^{-1}), MC3 (18,607-18,635 kg yr^{-1}), and JC3 (18,287-18,418 kg yr^{-1}; Figure 13). Annual production costs per kg of liveweight produced in the steady-state year (Figure 14) ranged from $6.37 (JC2 grazing OGA) to $7.91 (MC3 grazing COR). Calving at 2 yrs resulted in 6.5-6.9 and 7.8-8.6% lower costs ($ kg liveweight^{-1}) than calving at 3 yrs for March- and June-calving systems, respectively. Additionally, costs were 3.9-4.2 and 5.1-6.2% lower for systems calving in June versus March, for the 3- and 2-yr calving systems, respectively. Finally, costs were lowest in stockpiled grazing systems incorporating OGA, which was 8.2-9.1% lower than COR, 1.3-1.5% lower than TFM, and 1.3-1.8% lower than TAC. Costs on average, for all calving systems, differed by only 0.3% between TFM and TAC, with highest costs incurred when grazing COR ($7.01-$7.91 kg liveweight^{-1}).

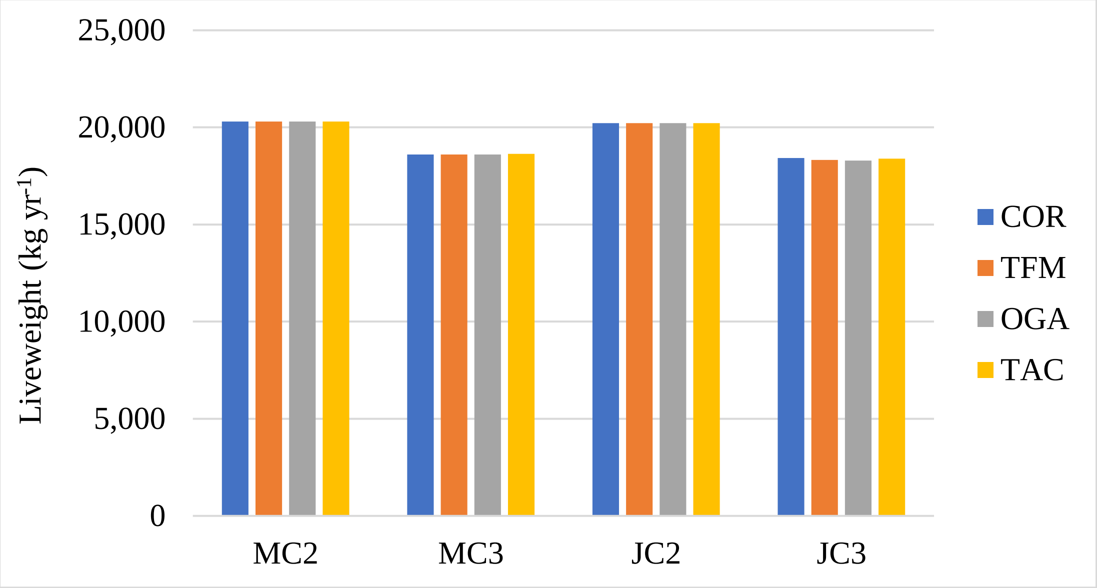

Figure 13. Annual liveweight produced (kg yr^{-1}) during steady-state from 16 cow-calf systems comparing age (2 vs 3 yrs) and time (March – MC; June – JC) of first calving when grazing 1 of 4 forage treatments (COR - standing corn; TFM - tall fescue/meadow bromegrass; OGA - orchard grass/alfalfa; TAC - tall fescue/alfalfa/cicer milkvetch) in the late fall/early winter.

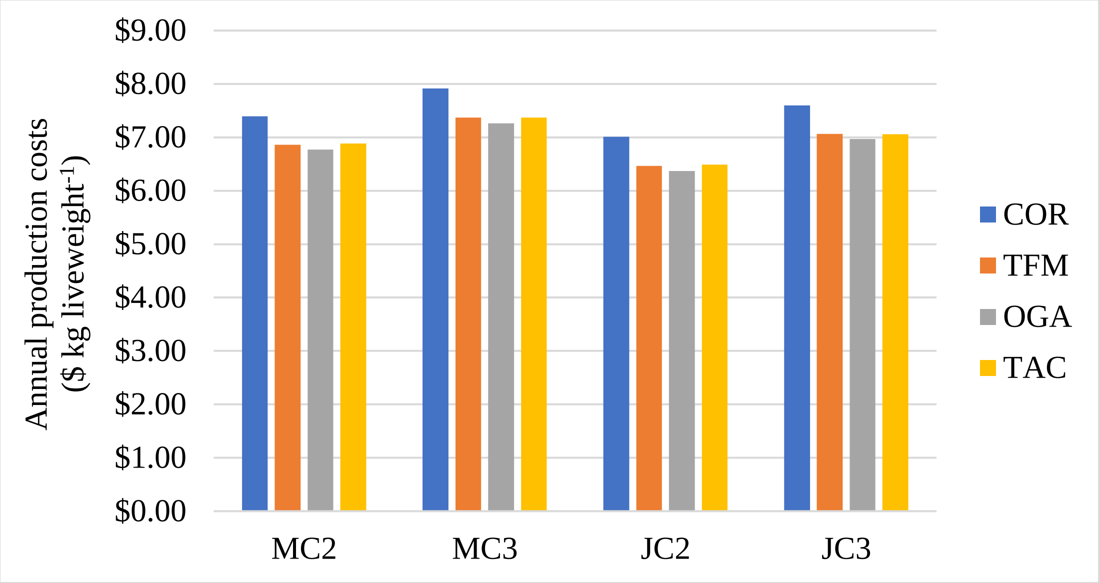

Figure 14. Annual system costs per kilogram of liveweight during steady-state from 16 cow-calf systems comparing age (2 vs 3 yrs) and time (March – MC; June – JC) of first calving when grazing 1 of 4 forage treatments (COR - standing corn; TFM - tall fescue/meadow bromegrass; OGA - orchard grass/alfalfa; TAC - tall fescue/alfalfa/cicer milkvetch) in the late fall/early winter.

4.4.7.5 Feed costs for breeding females

Daily feeding cost per cow by age and time of calving, as well as stockpiled grazing strategy included summer grazing ($1.47 cow^{-1} d^{-1}), stockpiled grazing ($0.86-2.44 cow^{-1} d^{-1}), and confinement feeding ($2.17-3.04 cow^{-1} d^{-1}; Table 7). Feeding costs for bulls (data not shown) both on summer pasture and in confinement (winter feeding) remained the same across all 16 systems, therefore were not included in the comparison of feeding costs. Costs for summer pasture grazing, which included pastureland, fencing and pasture operating costs (land development, fertilizer, herbicide, fence maintenance, and taxes), were the same for each of the 16 modeled systems These costs were $0.33-0.61 cow^{-1} d^{-1} higher than the cost of the 3 stockpiled perennial treatments used for stockpiled grazing in the late fall/early winter, while the cost of grazing stockpiled COR exceeded summer pasture by $0.95-0.97 cow^{-1} d^{-1}. Pre-calving winter feed costs were \$0.70-1.11 cow^{-1} d^{-1} higher than summer pasture grazing costs, and post-calving winter feed costs (March-calving systems only) were \$0.44-0.87 cow^{-1} d^{-1} higher than pre-calving winter diets. Pre- and post-calving winter feed costs were similar between the 4 stockpiled grazing treatments for all calving systems, differing by no more than \$0.03 cow^{-1} d^{-1}. Stockpiled grazing costs for systems utilizing OGA (\$0.86-0.87 cow^{-1} d^{-1}) were 20% lower than TFM, 24% lower than TAC, and 64% lower than COR.

Feed costs for bred heifers calving at 3-yrs (within MC3 and JC3) are listed in Table 8. The cost of summer pasture grazing was \$1.17 heifer^{-1} d^{-1} and did not differ based on month of calving or stockpiled forage grazed. Stockpiled grazing costs were lowest for OGA (\$0.82 heifer^{-1} d^{-1}) for both March- and June-calving systems, which were \$0.31, \$0.34, and \$1.53 heifer^{-1} d^{-1} lower than TFM, TAC, and COR, respectively. Confinement (winter) feeding costs were lower, on average, for JC3 (\$3.01-3.15 heifer^{-1} d^{-1}) compared to MC3 (\$3.12-3.45 heifer^{-1} d^{-1}).

Table 7. Annual feeding costs ($ cow^{-1} d^{-1}) for mature beef cows on a cow-calf operation in Manitoba in 2021 comparing age (2 vs 3 yrs) and time (March—MC vs June—JC) of first calving and grazing 1 of 4 forage treatments in the late fall/early winter.

System	Summer grazing (122 d)	Stockpiled grazing[a] (92 d)	Winter feed pre-calving[b] (59-122 d)	Winter feed post-calving[c] (92 d)
MC2				
COR	$1.47	$2.44	$2.57	$3.03
TFM	$1.47	$1.08	$2.57	$3.04
OGA	$1.47	$0.86	$2.57	$3.03
TAC	$1.47	$1.14	$2.58	$3.04
MC3				
COR	$1.47	$2.42	$2.56	$3.02
TFM	$1.47	$1.09	$2.56	$3.02
OGA	$1.47	$0.87	$2.56	$3.02
TAC	$1.47	$1.14	$2.56	$3.02
JC2				
COR	$1.47	$2.44	$2.20	-
TFM	$1.47	$1.08	$2.18	-
OGA	$1.47	$0.86	$2.17	-
TAC	$1.47	$1.14	$2.20	-
JC3				
COR	$1.47	$2.42	$2.22	-
TFM	$1.47	$1.09	$2.22	-
OGA	$1.47	$0.87	$2.22	-
TAC	$1.47	$1.14	$2.22	-

[a] Cattle grazed 1 of 4 stockpiled forages/forage mixtures in the late fall/early winter (COR – standing corn; TFM – tall fescue/meadow bromegrass; OGA – orchard grass/alfalfa; TAC – tall fescue/meadow bromegrass/alfalfa)

[b] Confinement feeding: 59 d for March calving and 122 d for June calving systems

[c] Confinement feeding: March calving only

Table 8. Annual feeding costs ($ heifer^{-1} d^{-1}) for bred heifers approaching 3 years-of-age on a cow-calf operation in Manitoba in 2021 comparing time (March—MC vs June—JC) of first calving and grazing 1 of 4 forage treatments in the late fall/early winter.

System	Summer grazing (122 d)	Stockpiled grazing[a] (92 d)	Winter feeding[b] (151 d)
MC3			
COR	$1.17	$2.35	$3.12
TFM	$1.17	$1.13	$3.45
OGA	$1.17	$0.82	$3.34
TAC	$1.17	$1.16	$3.34
JC3			
COR	$1.17	$2.35	$3.01
TFM	$1.17	$1.13	$3.09
OGA	$1.17	$0.82	$3.06
TAC	$1.17	$1.16	$3.15

[a] Cattle grazed 1 of 4 stockpiled forages/forage mixtures in the late fall/early winter (COR – standing corn; TFM – tall fescue/meadow bromegrass; OGA – orchard grass/alfalfa; TAC – tall fescue/meadow bromegrass/alfalfa).
[b] Confinement feeding

4.4.7.6 Gross revenue from cow-calf production systems

Gross revenue was reflective of the sum of all income generated within a single, steady-state year from marketed cattle sold at 2021 market prices (Table 9). In accordance with Manitoba Agriculture (2021), cull cows were sold at a market price of $83.00 cwt^{-1} and resulted in gross revenues ranging from $9,875.34 year^{-1} for MC3 and JC3, to $10,972.60 year^{-1} for MC2. Within each of the 4 calving systems, gross revenues from cull cows were not affected by stockpiled grazing treatments, except for JC2 in which earnings ranged from $10,763.44 to $10,892.92, with COR having the highest revenue followed TAC, TFM, and OGA. The gross revenue from cull cows within JC2 was (\$79.70-209.20 yr^{-1}) less than MC2, while JC3 and MC3 systems were the same. This difference was due to the presence of 1 cull cow in the JC2 system that was not yet at mature weight at the time of culling (January 31). Therefore, liveweights differed slightly between systems based on the ADG of each stockpiled forage treatment grazed.

Cull heifers were marketed at a price of \$150.00 cwt^{-1}, resulting in earnings ranging \$2,895.00 year^{-1} for JC2 (across all stockpiled grazing strategies) to \$4,293.00 for MC3 utilizing TAC for stockpiled grazing. Gross revenue was the same across stockpile forage treatments for MC2 and JC2 but varied within the 3-yr systems at both times of calving depending on the stockpiled forage treatment grazed, more specifically, ranked from highest to lowest for MC3 was TAC, TFM, and COR/OGA. However, the largest difference was only 0.13% between stockpiled treatments (TAC and COR/OGA). Differences in gross revenue between stockpiled grazing systems were present for JC3 as well; COR had the highest gross revenue followed by TAC, TFM, and then OGA. However, the largest difference was only 0.62%, between COR (\$70,701.69 year^{-1}) and OGA (\$70,266.69 year^{-1}).

Calves were marketed at a price of \$217.50 cwt^{-1}, an average of the male and female calf market prices from Manitoba Agriculture (2021), resulting in earnings of \$57,250.35 for both MC3 and JC3, and \$64,206.00 for both 2-yr calving systems, with calves contributing the highest dollar amount to the total annual gross revenue within all systems. Figure 15 demonstrates the contribution to annual gross revenue from each category of animals sold including cull cows, cull heifers, and calves.

Table 9. Annual gross revenues ($ year^{-1}) of the 16 cow-calf production systems comparing age (2 vs 3 yrs) and time (March—MC; June—JC) of first calving and grazing 1 of 4 forage treatments in the late fall/early winter.

System	Cull cows[a]	Cull heifers[b]	Calves[c]	Total
MC2				
COR	$ 10,972.60	$ 3,006.00	$ 64,206.00	$ 78,184.60
TFM	$ 10,972.60	$ 3,006.00	$ 64,206.00	$ 78,184.60
OGA	$ 10,972.60	$ 3,006.00	$ 64,206.00	$ 78,184.60
TAC	$ 10,972.60	$ 3,006.00	$ 64,206.00	$ 78,184.60
MC3				
COR	$ 9,875.34	$ 4,200.00	$ 57,250.35	$ 71,325.69
TFM	$ 9,875.34	$ 4,218.00	$ 57,250.35	$ 71,343.69
OGA	$ 9,875.34	$ 4,200.00	$ 57,250.35	$ 71,325.69
TAC	$ 9,875.34	$ 4,293.00	$ 57,250.35	$ 71,418.69
JC2				
COR	$ 10,892.92	$ 2,895.00	$ 64,206.00	$ 77,993.92
TFM	$ 10,794.98	$ 2,895.00	$ 64,206.00	$ 77,895.98
OGA	$ 10,763.44	$ 2,895.00	$ 64,206.00	$ 77,864.44
TAC	$ 10,863.04	$ 2,895.00	$ 64,206.00	$ 77,964.04
JC3				
COR	$ 9,875.34	$ 3,576.00	$ 57,250.35	$ 70,701.69
TFM	$ 9,875.34	$ 3,249.00	$ 57,250.35	$ 70,374.69
OGA	$ 9,875.34	$ 3,141.00	$ 57,250.35	$ 70,266.69
TAC	$ 9,875.34	$ 3,492.00	$ 57,250.35	$ 70,617.69

Cattle grazed 1 of 4 stockpiled forages/forage mixtures in the late fall/early winter (COR – standing corn; TFM – tall fescue/meadow bromegrass; OGA – orchard grass/alfalfa; TAC – tall fescue/meadow bromegrass/alfalfa).

[a] Number of cull cows sold annually was either 9 (MC3, JC3) or 10 (MC2, JC2).

[b] Number of cull heifers sold annually was 2 for all systems.

[c] Number of calves sold annually was either 54 (MC3, JC3) or 60 (MC2, JC2).

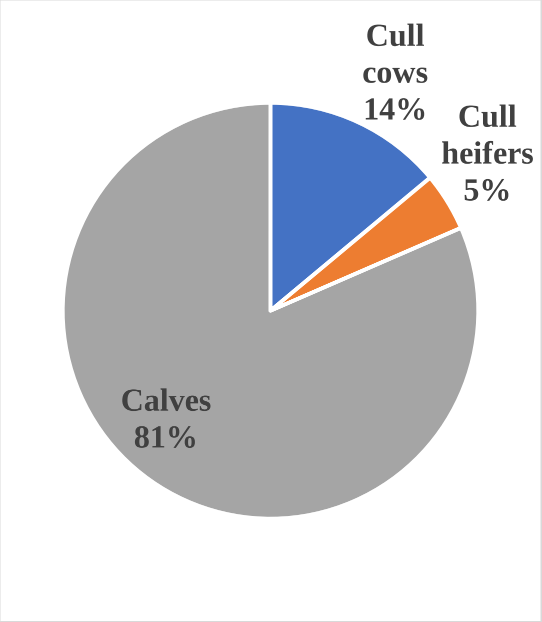

Figure 15. Average proportion of annual gross revenue generated by each cattle category (cull cows, cull heifers, and calves) from 16 cow-calf systems.

4.4.7.7 Net revenue from cow-calf production systems

Net revenues for each of the 16 modeled systems in a single steady-state year were negative, with losses ranging -\$50,946 to -\$75,922 year^{-1} (Figure 16). Net revenues were 5.3-7.2% higher (less negative) for MC2 versus MC3, and 7.9-10.8% higher for JC2 versus JC3. Further, net revenues were 8.9-10.4% higher (less negative) for JC3 versus MC3 and 11.4-14.0% higher for JC2 versus MC2. Systems incorporating OGA had the lowest losses in net revenue, making OGA the most cost-efficient of the stockpiled forage treatments with net revenues 19.1-25.0% higher than COR, 3.4-4.6% higher than TAC, and 3.1-3.6% higher than TFM.

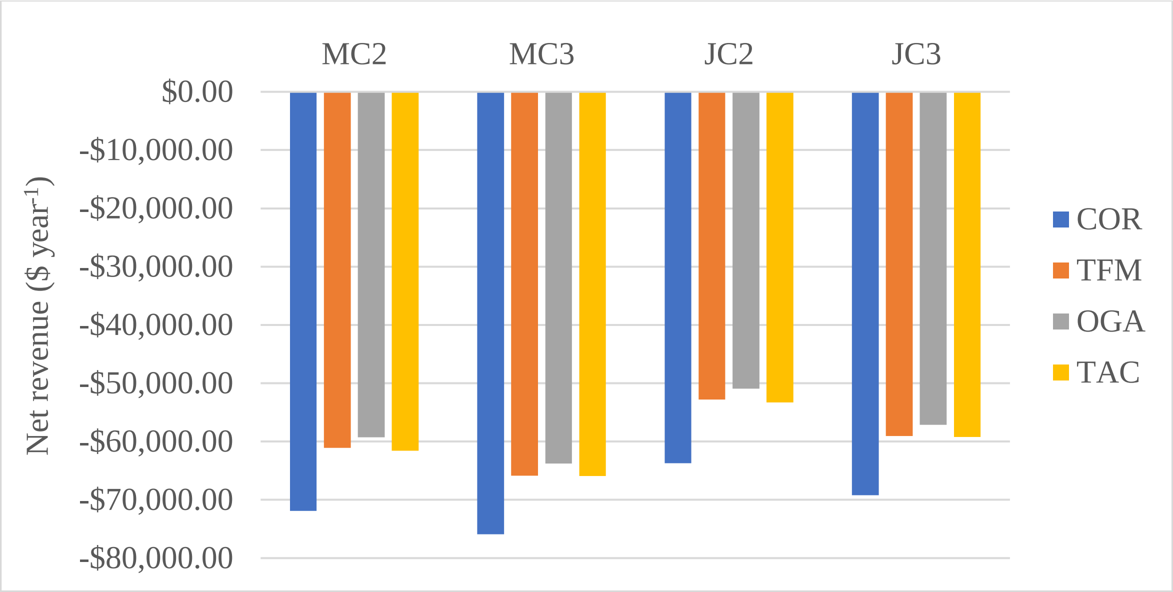

Figure 16. Annual net revenues from 16 cow-calf systems comparing age (2 vs 3 yrs) and time (March – MC; June – JC) of first calving when grazing 1 of 4 forage treatments (COR - standing corn; TFM - tall fescue/meadow bromegrass; OGA - orchard grass/alfalfa; TAC - tall fescue/alfalfa/cicer milkvetch) in the late fall/early winter.

4.5 Discussion

4.5.1 Whole-system GHG emissions by source

4.5.1.1 Enteric CH_4

Enteric CH_4 accounted for the largest proportion of cumulative GHG emissions, accounting for 57-65% of emissions produced across the 16 modeled systems, followed by direct N_2O (17-19%), manure CH_4 (9-11%), energy CO_2 (5-9%), and indirect N_2O (4-5%). This was similar to the enteric CH_4 contribution (63%) reported by Beauchemin et al. (2010) in another western Canadian 8-yr beef LCA conducted using the Holos model. In an additional western Canadian study examining GHG emissions for calf-fed and yearling-fed systems, enteric CH_4

emissions also contributed the largest portion (53-54%) of total GHG emissions (Basarab et al. 2012). Similarly, Alemu et al. (2017) estimated that 67-68% of total emissions associated with various grazing management systems in western Canada were from enteric CH_4. As forages (hay in confinement, summer pasture, and stockpiled grazed in the late fall/early winter) made up 92-94% of the annual feeding in the current study based on land area allocated to feed production, enteric CH_4 being the dominant GHG was not unexpected. Due to its large contribution to total GHG emissions, strategies to reduce enteric CH_4 emissions have been studied extensively in western Canada and it remains an important area to target, particularly for the cow-calf sector.

Differences in enteric CH_4 production between the 2- and 3-yr calving systems were attributed to differences in cattle numbers, liveweights, and diet nutritive value. The JC3 and MC3 systems in Yr 2 produced similar emissions (419 and 420 Mg CO_2e, respectively), that were primarily from enteric CH_4. These systems were similar as both 3-yr calving systems had lower heifer ADG from weaning until first breeding, with MC3 liveweights higher than JC3 by no more than 68 kg, which resulted in a slightly higher volume of enteric CH_4 produced based on heifer DMI. In addition, the JC3 system contained the 139 mature from the beginning of the LCA (and their associated enteric CH_4 emissions) for one month (January 1st to 31st) of Yr 2, increasing the volume of enteric CH_4 produced in Yr 2 from JC3. The systems with heifers calving at 2 yrs produced a calf crop one year prior to those calving at 3 yrs and therefore had a larger number of calves produced within the system. Within the steady-state period, MC2 and JC2 produced 72 calves (60 calves marketed and 12 kept for herd replacements) while MC3 and JC3 produced 64 (53 calves marketed and 11 kept for herd replacement), a difference of 8 calves for each calf crop. However, calves contributed only 3-4% of the total enteric CH_4 emissions when compared to the rest of the herd. Conversely, mature cows were responsible for the majority of enteric CH_4 emissions from the cow-calf herd since they were the largest category of animals in the herd, had the highest average liveweights, and consumed feed of lower nutritive value (low TDN and high NDF) compared to bred, growing, and replacement heifers. Within Holos, animal liveweight has a direct effect on the volume of enteric CH_4 produced from the modeled system as heavier cattle have a higher DMI and thus increased production of enteric CH_4 compared to those with lighter liveweight at the same level of production (Grainger et al. 2007; Beauchemin et al. 2008). Although increasing DMI is expected to increase gross production of enteric CH_4, the amount of CH_4 emitted as a percentage of GEI would be reduced, demonstrating improvements in terms of production efficiency (Beauchemin and McGinn 2006).

When GHG emissions were examined for each calendar year, differences were apparent in Yr 1 of the LCA between the March- and June-calving systems. Total emissions (primarily from enteric CH_4) were 26-64% higher in Yr 1 for MC2 compared to JC2, due to the additional emissions produced from March 1 to May 31 in the March-calving systems. This demonstrates the importance of selecting an appropriate time frame when comparing annual GHG emissions from systems incorporating different management strategies such as month of calving.

Estimated differences in cumulative enteric CH_4 emissions (2437-3292 Mg CO_2e) across all system years may be attributed to differences in the nutritive value of the stockpiled forages, as an increase in TDN concentration was accompanied by a decrease in modeled enteric CH_4 emissions. Systems utilizing COR had the lowest cumulative GHG emissions of the 4 forages used for stockpiled grazing as this treatment had the highest TDN (72% DM) and lowest NDF concentration (45% DM) when sampled prior to grazing. Forages of higher TDN or those with a higher starch content such as COR have been well-established to have a negative impact on CH_4 production (Christophersen et al. 2014), as they favor production of propionate, which, in its formation, utilizes available H_2, making it less available for methanogens (Johnson and Johnson 1995; Russell et al. 1998; Moss et al. 2000). Furthermore, high-starch diets lower rumen pH to which methanogenic bacteria are more sensitive (Beauchemin et al. 2008). Forages with lower NDF concentrations such as COR will have increased digestibility and increased passage rate of digesta (Jung and Allen 1995), potentially reducing enteric CH_4 production (Boadi et al. 2004). Conversely, OGA had the lowest TDN (45% DM) and highest NDF concentration (67% DM) and resulted in the highest estimated system enteric CH_4 emissions when utilized for stockpiled grazing. The higher fiber content of OGA favors the formation of acetate within the rumen, generating H_2 as an energy source for methanogenic bacteria to use and produce CH_4 (Beauchemin et al. 2008). Forages with high NDF concentrations contain high levels of structural carbohydrates (hemicellulose, cellulose, and lignin), indicative of poor forage digestibility, and when consumed by cattle, may result in decreased ruminal rate of passage and increased volume of enteric CH_4 production compared to forages with lower NDF concentrations (Okine et al. 1989).

Thompson et al. (2021) examined a 50:50 orchard grass:alfalfa mixture, similar to the OGA treatment in the current study, and observed lower DMI and slower rumen passage rates when compared to a botanically diverse, cool-season species mixture that included alfalfa, orchard grass, red and white clover, birdsfoot trefoil, chicory, meadow fescue, and timothy, with a different species dominating the mixture each year of the 3-yr study (chicory, red clover, or orchard grass). Decreased passage rate resulted in a longer residence time in the rumen and an increase in enteric CH_4 produced per unit of intake, without affecting liveweight gain. Authors attributed the differences in enteric CH_4 production to the inclusion of forage chicory (19.4 and 51.7% in the first 2 years of study), a highly digestible, low-fiber species which has been shown to produce less enteric CH_4 than both alfalfa and perennial ryegrass/white clover mixtures in sheep (Waghorn et al. 2002).

Dickson (2022) reported that cattle grazing low-TDN forages such as OGA could benefit from supplementation during late fall/early winter grazing to meet maintenance requirements and reduce losses in liveweight under cold weather conditions. Reducing losses in liveweight during the stockpiled grazing period may become increasingly important as producers move to increase the length of time cattle spend on pasture to reduce winter feeding costs.

4.5.1.2 Bred heifer liveweight losses during the stockpiled grazing period

As indicated, liveweight inputs have a direct impact on CH_4 emissions. Bred heifer liveweights following their first stockpiled grazing period (October 1 to December 31) differed between systems due to differences in ADG reported by Dickson (2022). Systems grazing OGA had the highest liveweight losses (-0.59 to -2.74 kg d^{-1}) relative to the other treatments (-0.06 to -2.45 kg d^{-1}), due to low TDN of the stockpiled forage. Forage TDN concentrations on a DM basis from Dickson (2022) were as follows: OGA 45%, TFM 54%, TAC 55%, and COR 72%; and of these, all but OGA were able to meet pregnant replacement heifer energy requirements of 51-60% TDN (NRC 2016). Stockpiled corn exceeded the recommended TDN concentration due to its high starch content (McCartney et al. 2009); however, it's CP concentration was low (6.8%), but comparable to the CP concentrations reported by Lardner et al. (2012) for whole-plant corn grazed in the late fall (6.4-8.1% DM). Stockpiled COR in the current study did not meet the recommended CP concentration for pregnant replacement heifers of 7.2% at 1 to 3 months of pregnancy (March-calving systems), or 7.3% at 4 to 6 months of pregnancy (June-calving systems; NRC 2000). Crude protein values were cited from NRC (2000) and not NRC (2016) because the updated beef cattle protein requirements from the latter have adopted metabolizable protein (MP) as the means of expressing protein requirements rather than CP. Van Soest (1982) has suggested that 7% is the minimum dietary CP concentration for effective microbial fermentation. The 3 perennial forage treatments were able to meet CP requirements for both stages of pregnancy. These results suggest that CP supplementation is necessary for pregnant heifers grazing COR in the late fall/early winter, which would be an important consideration for producers when selecting the type of forage for stockpiled grazing as additional costs are incurred for purchase and delivery of a protein supplement. However, selection of forage species for stockpiled grazing must also consider environmental conditions such as snow and ice cover, ambient temperature, windchill, and available shelter (McGeough et al. 2018), factors that will increase cattle nutrient requirements during periods of extreme cold (NRC 2016). Corn may be advantageous compared to stockpiled perennial forages due to its tall plant structure that allows cattle to graze above snow cover and its ability to provide wind protection, reducing the time cattle spend at windbreaks (Dickson 2022). Further, future research should examine the effects of liveweight losses following the late fall/early winter grazing period (Dickson 2022) on the heifers and their progeny, including calf birth weight and future calving success.

Losses in liveweight in the late fall/early winter reported by Dickson (2022) could also be attributed to low forage DMI. It is recommended that dry beef cows have a DMI that is 1.8-2.5% of liveweight, and in extreme cold conditions (-30°C), this target can increase up to 2.7-2.8% of liveweight (NRC 2016; Manitoba Agriculture undated b). However, due to the slower rate of passage associated with high fiber forages such as OGA, it may not be possible to increase DMI. The forage intake values as % of liveweight used in the model for heifers in the 3 perennial stockpiling grazing treatments were set as 1.32, 1.40, and 1.21% for TFM, OGA, and TAC, respectively, as reported by Dickson (2022), and 1.9% of liveweight for COR (Anderson 2020). This suggests that the DMI as % BW of the stockpiled perennial forages may have been reduced by factors such as cold weather and wind causing cattle to spend more time at shelters/windbreaks, or the lower nutritive quality (TDN) of the stockpiled forages grazed. Forage DMI was not measured for COR in the grazing study by Dickson (2022) and therefore DMI as a % of liveweight between the annual and perennial treatments could not be compared.

4.5.1.3 Percent contribution of enteric CH_4 to total GHG emissions

In terms of the impact of calving systems, the contribution (%) of enteric CH_4 to cumulative GHG emissions was 3-4% higher for JC3 systems compared to JC2, while no differences were observed between MC3 and MC2 systems. This may have been attributed to the slower growth rates from weaning until first breeding within the 3-yr calving systems, utilizing diets of lower nutritive value (TDN and CP) to achieve lower ADG than the 2-yr calving systems, which would increase enteric CH_4 produced during this period (Boadi et al. 2004; Stewart et al. 2009). However, the same result would have been expected between the MC3 and MC2 systems. The percent contribution (and cumulative emissions; Mg CO_2e) from enteric CH_4 were higher for JC3 compared to JC2 due to the additional year of production required for each cow to produce 6 calves. However, steady state annual emissions (Mg CO_2e) were higher for JC2 compared to JC3, indicating potential environmental benefits of JC3 at steady state.

Differences in the percent contribution of enteric CH_4 to cumulative system GHG emissions between March- and June-calving systems (1-3%) were associated with the length of time required for cattle to reach maturity (31-39 and 34-41 mo for March and June systems, respectively), as well as differences in DMI of stockpiled forages grazed by mature cows in late fall/early winter. Specifically, cows within the June- and March-calving systems were in their 5th and 8th month of lactation, respectively, when the stockpiled grazing period began. Dry matter intake values (AARD 2011) for June cows were, on average, 1 kg d^{-1} higher than March cows, reflective of the increased energy requirements of the month of lactation (NRC 2016). Thus, the land area and associated synthetic N fertilizer inputs were higher for June-systems, which increased the proportion of emissions contributed by energy CO_2 by up to 2% for June- compared to March-calving systems.

4.5.1.4 Differences between modeled and measured estimates of enteric CH_4

The modeled enteric CH_4 emissions in the current study as well as the enteric CH_4 emissions measured using the sulfur hexafluoride (SF_6) tracer gas technique from Dickson (2022) both differed numerically between the 4 stockpiled forage treatments. Dickson (2022) observed numerically lower CH_4 produced from heifers grazing COR (165.6 ± 21.5 L d^{-1}) compared to TFM (235.4 ± 26.3 L d^{-1}), OGA (211.3 ± 21.4 L d^{-1}), and TAC (227.1 ± 18.6 L d^{-1}). However, no significant differences in enteric CH_4 emissions between the stockpiled forage treatments were observed in the field trial.

Variation exists among measured and modeled estimates of enteric CH_4 as demonstrated by Alemu et al. (2011). These authors compared enteric CH_4 estimates from 4 models (IPCC

Tier 2, Ellis, COWPOLL, and MOLLY) to measured values from a variety of Canadian research studies, in which most utilized the SF_6 tracer gas technique to measure CH_4. Large variations (7.4-63.2%) between enteric CH_4 estimates were observed among models when estimating Y_m, demonstrating the uncertainties associated with modeled estimates of enteric CH_4 production, and the dependence of model results on model selection. However, these authors suggested that the integration of multiple models, such as the use of mechanistic models (COWPOLL and MOLLY) to estimate regional Y_m values which can then be used as inputs for IPCC models, could help to minimize uncertainty and provide a more robust approach to the estimation of enteric CH_4 (Alemu et al. 2011).

4.5.1.5 Manure CH_4

Methane emissions from manure in the current study accounted for 9-11% of total emissions (Mg CO_2e), higher than the 5% (2% from the cow-calf herd and 3% from feedlot manure) reported by Beauchemin et al. (2010). Most of the yearly manure CH_4 emissions were produced from January to May (8-14 Mg CO_2e mo^{-1}) when cattle were housed in confinement. Emissions were considerably lower from June to September (1 Mg CO_2e mo^{-1}) when cattle were on pasture and from October to December (2-3 Mg CO_2e $month^{-1}$) when cattle were stockpiled grazing [data not shown]. This is because the CH_4 conversion factor (MCF), the percentage of feed energy converted to methane (IPCC 2006), is larger for deep bedding systems in confinement (0.017), and lower on pasture where manure is deposited directly onto the ground (0.010). If the number of extended grazing days was increased further (reducing the time spent in confinement), it would be expected that annual manure CH_4 emissions would be reduced.

4.5.1.6 Direct and indirect N_2O

Direct N_2O emissions, which accounted for 17-19% of total emissions, were attributed to both livestock and cropping inputs and differed based on climatic variables such as temperature and precipitation, as well as synthetic N fertilizer inputs for annual and perennial crops. In the steady-state herd, livestock direct N_2O emissions from manure contributed, on average, 70% more to total emissions than crop direct N_2O from agricultural soils. Most livestock direct N_2O emissions occurred between June and September for all systems as cattle were on pasture at that time. Production of direct N_2O is dependent on the emission factor (EF_{direct}) associated with the manure handling system which was higher for cattle depositing manure directly on pasture (0.02 kg N_2O-N (kg N)$^{-1}$) compared to the EF_{direct} of deep bedding during the confinement period (0.01 kg N_2O-N (kg N)$^{-1}$). Although synthetic N fertilizer application rates for crops grown to produce confinement feed (barley grain, alfalfa-grass, and grass hay) did not change between systems, differences in total N fertilizer applied were observed due to small differences in land area required for each crop, which were calculated based on cattle DMI requirements (AARD 2011). Although the highest rate of synthetic N fertilizer application was for TFM (74 kg N ha^{-1}), compared to the other stockpiled forage treatments, including OGA (50 kg N^{-1}), the latter had the highest average direct N_2O emissions per year. This may be attributed to the losses in liveweight which occurred over winter in the OGA system and therefore, greater amounts of feed were required following the stockpiled grazing period to achieve higher ADGs to reach mature weight. Within the modeled system, growing season (May to October) precipitation was lowest in Yr 2 (276 mm) and therefore resulted in low crop direct N_2O emissions, which, for the MC2 (COR) system was 17 Mg CO_2e (data not shown). Although the Yr 2 herd cannot be compared directly to other years, if growing-season precipitation was increased, for example, to that of Yr 6 (564 mm), crop direct N_2O would have increased more than twice that of Yr 2 (48 Mg CO_2e) from the same system.

Indirect N_2O also contributed to total system GHG emissions through N leaching and runoff from agricultural soils (Alemu 2016), which was calculated using a default EF for volatilization and leaching from IPCC (2006). Only small differences in indirect N_2O were observed between systems, ranging 22-27 Mg CO_2e across all 16 modeled systems. Estimated indirect emissions from manure and soils in our study are comparable to Alemu (2016), who reported a 4.5% contribution to total emissions. Of the 4 stockpiled grazing systems, OGA resulted in the highest average indirect N_2O emissions, however, the magnitude of difference was small (1 Mg CO_2e in each system). Most indirect N_2O emissions occurred in April when snow melt typically occurs, decreasing slightly throughout the growing season (May to October), with the lowest emissions occurring in the winter months. This increase in spring soil N_2O emissions was expected as wet soil conditions from snow melt often stimulates N_2O production (Rochette et al. 2008), emphasizing the importance of examining N_2O emissions in spring as well as during snow-free periods to avoid an underestimation of emissions. Indirect N_2O emissions are higher in the summer than the winter months as cattle are depositing urine and dung directly onto pastureland, contributing N to agricultural soils, along with synthetic N fertilizer, that may contribute to N leaching and runoff into riparian zones, streams, and rivers where drainage water eventually flows (IPCC 2006).

4.5.1.7 Energy CO_2

Energy CO_2 produced from the burning of fossil fuels in tractors and other machinery on farm contributed 5-9% of total GHG emissions. Energy CO_2 estimates for beef production systems in western Canada, reported by Beauchemin et al. (2010) and Alemu (2016), were similar, at 5% and 6% of total GHG emissions, respectively. Energy CO_2 emissions were dependent on the land area used for crop production in each system as well as the amount of fertilizer applied to crop or hay land. The JC2 system had the highest land area requirements primarily due to the need to produce grass hay for mature cows during the confinement period. This differed from the MC2 system since March-calving cows were lactating in confinement, consuming a higher-energy diet primarily consisting of alfalfa-grass hay and barley grain. Land area for grass hay production had the highest rate of synthetic N fertilizer (120 kg N ha^{-1}) of all forages and crops, which increased the volume of energy CO_2 produced in the JC2 system compared to MC2 and the resulting percent contribution to total emissions (9%). Additionally, replacement heifers (8-15 mo of age) within the JC2 and JC3 systems grazed summer pasture for 3 mo prior to first breeding, while the MC2 and MC3 systems were fed in confinement. The low forage utilization factor of summer pasture grazing (50%) compared to that of confinement forages (hay; 80%) increased the land area required to produce forage for heifers on pasture, which led to an increase in energy CO_2 emissions from fuel used for seeding and fertilizer application. Lastly, the JC2 system had higher ADGs compared to JC3 which were necessary to reach the goal of 61% mature liveweight by first breeding (Fox et al. 1988), thus DMI and resulting land area requirements were increased.

4.5.2 Greenhouse gas emission intensities

Greenhouse gas intensity estimates from beef production can be expressed as total GHG (CO_2e) per unit of liveweight or carcass weight produced and vary widely between locations and studies (Beauchemin et al. 2009). In the current study, GHG emission intensities ranged from 15.6 to 21.0 kg CO_2e kg liveweight^{-1}. Vergé et al. (2008) previously reported a lower emission intensity of 10.4 kg CO_2e kg liveweight^{-1} based on an industry-wide estimate of Canadian beef production from the 2001 census year including cow-calf, backgrounding, and feedlot systems. The inclusion of the feedlot phase and its use of high energy, grain-based feed rations is expected to lower the overall GHG intensity estimate compared to forage-based feeding strategies used in cow-calf production (Johnson and Johnson, 1995; Beauchemin et al. 2010). In an Alberta-based study including cow-calf, backgrounding, and feedlot phases, Beauchemin et al. (2010) reported a GHG intensity estimate of 13.04 kg CO_2e kg liveweight^{-1}. The Y_m values used within that study, similar to the current study, were based on IPCC (2006) Tier 2 methodology, whereas Vergé et al. (2008) used only a single Y_m factor (Y_m = 0.06). Alemu et al. (2017) examined the LCA from Beauchemin et al. (2010), with the addition of 92 days of swath-grazed triticale in the late fall/early winter and the replacement of native pasture (wheatgrass and needle and thread community) with re-established rough fescue prairie from a long-term (> 60 yr) grazing study, to compare light (1.2 AUM ha^{-1}) and heavy (2.4 AUM ha^{-1}) continuous grazing by cow-calf pairs from May to October. The authors reported GHG emission intensities that ranged from 14.5-16.0 kg CO_2e kg liveweight^{-1}. Legesse et al. (2015) examined GHG production of Canadian, industry-wide, beef produced in 1981 and 2011 and reported emission intensities of 14.0 kg CO_2e kg liveweight^{-1} and 12.0 kg CO_2e kg liveweight^{-1}, respectively.

Cumulative GHG emission intensities (estimated from all system years) of systems calving at 3 yrs were higher than those calving at 2 yrs, regardless of the time of calving, as the total liveweight output was less. Although weaning weights were the same across all systems, heifers calving at 2 yrs of age had higher ADG values from weaning until first breeding than heifers in the 3-yr calving systems, grew slower, and were older by the time they reached the production target of 61% liveweight by time of breeding (Fox et al. 1988). As a result, culled heifers (and cull cows close to maturity) had higher liveweights at culling in the 2-yr calving systems compared to the 3-yr calving systems, increasing the total liveweight output of the system. Further, total GHG emissions were higher for MC3 compared to MC2, and JC3 compared to JC2, largely due to the length of time required for each system to achieve 6 calves within their lifetime. Heifers calving at 2 yrs of age (MC2 and JC2), achieved 6 lifetime calvings 1 year prior to those calving at 3 yrs of age, resulting in an additional year of emissions with no output in the form of calves sold.

Time of calving and choice of stockpiled forage did not affect cumulative GHG emission intensities to the same extent as early age at first calving. Overall, GHG emission intensities were not significantly impacted by differences in cumulative liveweight produced from modeled systems as there were only slight differences observed. Therefore, differences in cumulative GHG emission intensity would be reflective of the differences in GHG emissions (Mg CO_2e) previously described. However, if the GHG emission intensity of a single year at steady state was examined, the effects of differences in annual liveweight output may have a greater effect on GHG emission intensity as GHG emissions and liveweight output would not be spread across multiple yrs of the LCA in which the herd is still becoming established (prior to the steady state).

4.5.3 Land base

Total land areas ranged from 1434-1723 ha across the 16 modeled systems, with the lowest land area requirement from the MC2 system utilizing COR for stockpiled late fall/early winter grazing. Differences in land area required were attributed to differences in cattle DMI, forage yields, and forage utilization (waste) values at each stage of feeding. The JC2 system had the highest land requirements due to the later calving date and larger number of days on pasture for replacement heifers compared to the March-calving systems, resulting in slower growth (lower ADG) from weaning until first breeding, and increased DMI and land area required to achieve 61% of mature liveweight at time of first breeding (Fox et al. 1988). Increased number of days on summer pasture for replacement heifers would increase the land base required to a greater extent for summer pasture compared to confinement feeding and stockpiled grazing, as summer pasture had the lowest forage utilization value (50%) compared to hay (80%; Rotz and Muck 1994; Legesse et al. 2018), stockpiled perennials (80%; Hutton et al. 2004), and stockpiled standing corn (59%; Anderson 2020). Systems utilizing COR had slightly lower land requirements in all calving systems except for JC2. For MC2 and JC3, reductions in total land area were seen due to reductions in the area required for hay production, while the MC3 system had reductions in land area for barley grain and stockpiled forage production which resulted in a slightly lower land area. However, the extent of the overall differences in land area (ha) required between the 4 stockpiled forage treatments was minimal (0.1-3.6%).

4.5.4 Economic analysis

4.5.4.1 Annual total cost of production

Estimated annual production costs at steady-state were 1-2% higher for systems calving at 2 yrs compared to 3 yrs primarily due to differences in labor and living costs ($17,000 and $15,763 yr^{-1} for 2- and 3-yr systems, respectively). The difference in labor costs would be indicative of the large number of cows and heifers calving in the 2-yr system (75 cows and 10 heifers) compared to the 3-yr system (66 cows and 9 heifers) and the labor required at time of calving ($25.00 hr^{-1} at 8 hrs cow^{-1} yr^{-1}; Manitoba Agriculture 2021). It is important to note that the economic analysis did not consider the reduction in labor that would be expected for June systems calving on pasture compared to March systems calving in confinement, due to the reduced environmental stress of summer calving that has been shown to decrease labor costs and increase calf survival (Funston et al. 2016).

The estimated cost of forages for stockpiled grazing was $94.00-191.00 yr^{-1} higher for 3-yr calving systems compared to 2-yr calving systems, apart from COR, which was $3.00 yr^{-1} higher for the 2-yr systems. The observed differences were attributed to differences in the number of cows/heifers grazing stockpiled forages and the land area estimated within the COP budget to produce the stockpiled forage to feed the herd. The 2-yr calving systems had 75 mature cows and 10 cows approaching mature weight that were grazing stockpiled forages, with 12 replacement heifers that were not, and instead were fed in confinement. The 3-yr systems had 75 mature cows and 11 heifers grazing stockpiled forages, while 11 replacement heifers were fed in confinement. It is important to note that the COP budget provides an estimation of land area requirements for stockpiled forage grazing using an average value for forage DMI, which is then used to calculate the cost of the stockpiled grazing period. Therefore, cost estimations were not indicative of the differences in DMI between stockpiled forage treatments observed from Dickson (2022), nor the exact land base that was calculated within the LCA. The 3-yr calving systems had higher land requirements compared to those calving at 2-yrs, thus, the annual cost of stockpiled forage grazing was increased.

Other operating costs (fuel, utilities, marketing/transport, manure removal, insurance, herd replacement, pasture operating, straw (bedding), veterinary medicine, breeding and other miscellaneous costs) differed slightly between the 2- and 3-yr calving systems including a small reduction in bedding costs for the 3-yr systems (\$4,699 yr^{-1}) compared to the 2-yr systems (\$5,100 yr^{-1}), which would reflect the lower bedding requirements for systems producing less calves each year (MC3 and JC3).

June-calving systems had lower annual costs compared to those calving in March due to lower feed costs for forages and barley used in confinement rations. This agrees with Carriker et al. (2001) who reported cost savings for weaned calves born in June compared to March due to a reduction in harvested forages and expenses associated with feeding and calving labor. Feed costs for each stockpiled grazing treatment did not differ when time of calving differed because the number of mature cows and heifers were the same between MC2 and JC2, as well as MC3 and JC3. Use of the cow-calf COP budget (Manitoba Agriculture 2021) to estimate the cost of stockpiled grazing systems has limitations because it can only accommodate stockpiled grazing of a single group of mature cows. For the purposes of this economic analysis, feed costs for bred heifers grazing stockpiled forages were estimated separately using the cow-calf COP spreadsheet adjusted for bred heifer liveweights and added to annual system costs.

Of the 4 forage treatments examined during the stockpiled grazing period, OGA resulted in the lowest total production costs. Its low standing forage cost of \$0.022 kg^{-1} made it the most cost-efficient perennial forage treatment compared to \$0.026 kg^{-1} for TFM and TAC. Standing forage costs for the stockpiled perennial treatments were estimated using a full-season yield

(Manitoba Agriculture 2022b), consisting of an early harvest or grazing in June (with forage DM yields adopted from Peng 2017), and the late fall/early winter stockpiled forage DM yields from Dickson (2022). The OGA treatment had the highest full-season forage yield (9694 kg DM ha^{-1}) compared to TFM and TAC (8923 and 9290 kg DM ha^{-1}, respectively), resulting in the lowest estimated standing forage cost of the stockpiled perennial mixtures. Although OGA resulted in the lowest production costs, bred heifer liveweight losses were the highest when grazing OGA due to its low TDN (Dickson 2022). Stockpiled OGA might appear to offer benefits based on input costs alone, however, these would be outweighed by the poor productivity (liveweight loss) and potential negative impacts on reproductive efficiency (Kasimanickam et al. 2021), whilst increasing the environmental footprint of the system due to high GHG emissions compared to the other stockpiled systems. Alternatively, COR systems had the highest total production costs due to its high input costs and low yields (Dickson 2022), resulting in an average cost of \$2.43 cow^{-1} d^{-1} for mature cows throughout the 92-d grazing period. To explain, grazing costs for COR systems were higher than would be expected as the standing corn yield (7.0 tons DM ha^{-1}; Dickson 2022) was low compared to the provincial average of 13.0 tons DM ha^{-1} (Manitoba Agriculture 2021), resulting in larger land requirements and associated input costs to graze the same number of animals. Corn yields for stockpiled grazing have been reported in several other studies, ranging from 6.2 to 9.1 tons DM ha^{-1} (Lardner et al. 2017), 11.7 tons DM ha^{-1} (Jose et al. 2017), and 12.0-15.5 tons DM ha^{-1} with an average yield of 13.5 tons DM ha^{-1} (Baron et al. 2014). Although average whole-plant corn yields from these studies were primarily lower than the estimate used in the COP analysis (Manitoba Agriculture 2021), they are greater than the corn yield reported by Dickson (2022) and, if used in this economic analysis, would have resulted in lower land area requirements and costs associated with standing corn grazing.

4.5.4.2 Feed and other operating costs

Given that the fair market value of feedstuffs did not differ between systems, annual feed costs in the steady state were higher for the 3-yr calving systems compared to those calving at 2-yrs (0.9-6.1%) due to differences in nutritional and therefore feed requirements for maintenance, growth, and lactation (AARD 2011). This result was unexpected because heifers within the 2-yr calving system were bred at 15 mo of age and managed to reach 61% of mature liveweight at breeding (Fox et al. 1988) through consumption of a higher energy diet with higher DMI. This was compared to heifers in the 3-yr calving system which were slower-growing as they had an additional year of growth prior to breeding at 24 mo of age, which would be expected to increase feed costs. Further, there were more mature cows calving in the 2-yr system compared to the 3-yr system, increasing feed requirements during lactation as well as costs of the 2-yr system. However, a larger amount of grass hay was fed in the 2-yr calving system, which had a lower cost (\$145 t^{-1}) compared to alfalfa-grass hay (\$154 t^{-1}) that was used more in the 3-yr system in the diet of bred heifers, contributing to the higher annual feed costs of the 3-yr systems. Annual "other" operating costs from the 2-yr calving system including veterinary medicine, breeding costs (bulls), fuel and machinery, utilities, manure removal, insurance, marketing/transport of sold animals, herd replacement, and pasture operating costs were, on average, 0.2-1.7% higher than the 3-yr calving systems. These costs were similar as both herds had the same number of reproductive females (97) and differed only in the proportion of mature cows. The primary difference between the 2 calving systems was associated with the number of calves produced and resulting annual revenue from liveweight sold in each system, which will be discussed subsequently.

Annual feed costs were 14.1-23.9% higher for March-calving systems compared to those calving in June primarily due to costs associated with hay and barley grain for confinement diets. As peak lactation occurs 8-9 weeks post-calving (NRC 2016), March-calving cows have their highest energy requirements occurring during their period of confinement. Conversely, June-calving cows are grazing summer pasture during this period of increased energy requirements for lactation. It has been well-established that pasture grazing is more cost-effective than feeding in confinement (Jose et al. 2017; Manitoba Agriculture 2021; 2022a). Other operating costs for MC2 were \$135-296 yr^{-1} higher than JC2 and \$0-19 yr^{-1} higher for JC3 compared to MC3, due to small differences in herd replacement costs. As previously described, herd replacement costs were reflective of the cost difference between replacement heifers and the market value of the culled cow/heifer. Thus, slight variation in liveweight for cows and heifers between the 2 systems, as well as between stockpiled forage treatments, resulted in slight differences in the value of culled animals and resulting herd replacement costs. Annual feed costs of the 4 stockpiled grazing treatments were lowest for OGA (64, 24, and 21% lower than COR, TAC, and TFM, respectively, as previously discussed based on the contribution of feed costs to total annual production costs.

4.5.4.3 System costs per kg of liveweight produced

An examination of production costs per kg of liveweight produced allows for a comprehensive analysis of system productivity, examining both input costs and returns from marketable liveweight. When considering costs per kg of liveweight, the ranking of cow-calf systems did not change when compared to total production costs alone; systems incorporating OGA for stockpiled grazing were the most cost-efficient, and those incorporating COR were the least. For all calving systems, TFM and TAC had comparable production costs and liveweight produced having identical stockpiled forage input costs (\$ kg^{-1}) and comparable TDN concentrations. Given that liveweight output was highest when heifers calved at 2-yrs compared to 3-yrs, lower costs for MC2 and JC2 systems were realized compared to MC3 and JC3. The higher annual liveweight estimated from 2-yr calving systems was attributed to the larger number of calves sold annually (60 calves yr^{-1}) compared to the 3-yr calving systems (54 calves yr^{-1}), the number of cull cows sold (10 and 9 cull cows yr^{-1} for the 2- and 3-yr systems, respectively), and differences in the liveweight of culled heifers.

Increased liveweight produced within any beef production system will allow for GHG emissions to be spread across a greater output whether it is kg of total liveweight (calves, culls), calf weight, or number of calves weaned. Therefore, management decisions should target improvements in feed efficiency, reproductive success, and genetic selection for improved growth rates (Terry et al. 2020), which will require less feed while maintaining the same level of production (Elolimy et al. 2018). If the weaning rate (number of calves weaned per female exposed) was increased from 85% (Beauchemin et al. 2010; WBDC 2018) to 90%, it is reported that GHG emission intensity would decrease by 4% (Beauchemin et al. 2011). Other strategies that may increase production efficiency included increasing carcass weights through genetic selection of medium- and large-framed cattle, reducing age at slaughter, maintenance of heterosis, and increasing the quantity of concentrates in the diet (Terry et al. 2020). However, consideration of disadvantage with the latter strategy is critical to provide a holistic evaluation of proposed mitigation strategies. Additionally, this would negate the benefits of cattle utilizing a human inedible plant product and converting it to high quality protein and energy for human consumption.

4.5.4.4 Feed costs for breeding females

This analysis reported that the highest feed costs (\$ cow^{-1} d^{-1}) occurred within the confined feeding period, due to fuel and labor requirements for harvest and delivery that are not incurred with pasture grazing. The cost of summer grazing (\$1.47 cow^{-1} d^{-1}) was higher than the default COP estimates from Manitoba Agriculture (2021; 2022a) of \$0.91 and \$1.13 cow^{-1} d^{-1}, respectively. This may be due to the smaller number of mature cows (75-85) in the current study compared to the Manitoba Agriculture scenario (150) resulting in system costs spread over a smaller number of animals. Confined feeding costs ranged from \$2.17 to \$3.04 cow^{-1} d^{-1}, which were comparable to Manitoba Agriculture (2021) and (2022a) values of \$2.15 and \$2.60 cow^{-1} d^{-1}, respectively. Stockpiled grazing in the late fall/early winter has been shown to be more cost-efficient than confined feeding (Poore and Drewnoski 2010; Manitoba Agriculture 2021; 2022a), which was demonstrated in the current study with the 3 stockpiled perennial treatments (\$0.86-1.14 cow^{-1} d^{-1}), but not for COR (\$2.44 cow^{-1} d^{-1}). Baron et al. (2014) reported feeding costs of \$0.78, \$1.05, \$1.24, and \$1.98 cow^{-1} d^{-1}, for swath-grazed triticale, corn, and barley, compared to traditional confined feeding, respectively, and therefore concluded that corn can be an economically viable alternative to confined feeding. However, due to the low corn yield used within the current study which was grown in the grazing study of Dickson (2022), this was not the case. Improvements in agronomic practices to improve yields would be expected to facilitate these cost savings. For example, increasing the standing corn yield from 7.0 (Dickson 2022) to 13.0 tons DM ha^{-1} (Manitoba Agriculture 2021) would decrease the costs of the stockpiled grazing period from \$2.44 to \$1.30 cow^{-1} d^{-1}.

4.5.4.5 System revenues

Net revenues, representing total production costs minus gross revenue for a single year at steady state, were negative for all 16 production systems, ranging from -\$50,946 to -\$75,922 year^{-1}. Net losses were also reported in the default, 150-head cow-calf herd analysis from Manitoba Agriculture (2021) and (2022a) of -\$63,880 and -\$13,753 yr^{-1}, respectively. Market prices for calves in 2022 were higher (\$268.04 cwt^{-1}) than 2021 (\$212.83 cwt^{-1}), which contributed to the higher net revenue estimated in 2022. Throughout western Canada, calf prices have increased 29, 30, and 31% for Manitoba, Saskatchewan, and Alberta, respectively, between October 2020 and October 2022, ranging from \$165.50 to \$217.85 cwt^{-1} (Statistics Canada 2022b). Market prices used within the COP analysis of \$110.00 cwt^{-1} for cull cows and \$180.00 cwt^{-1} for cull heifers were the same in 2021 and 2022.

In a study examining June versus March calving in Nebraska, Carriker et al. (2001) reported higher market prices for June calves sold at weaning in January compared to March calves sold in October, with a price increase of approximately \$10 cwt^{-1} in 1998. Typically, January has higher seasonal calf prices compared to October, as demonstrated by Carriker et al. (2001), and more recently from the Alberta and Manitoba calf markets, which reported calf price increases from October to January of \$0.14-9.90 cwt^{-1} and \$1.55-12.38 cwt^{-1}, for Alberta and Manitoba, respectively, for all years between October 2017 and January 2022 (Statistics Canada 2022b), apart from a single time period where Manitoba calf prices decreased by \$2.39 cwt^{-1} between October 2018 and January 2019.

4.6 Conclusions

The Holos Research model, like all models, has limitations when estimating whole-farm GHG emissions from simulated farming system. Fluctuations in daily temperature and weather events as well as changes in forage nutritive value and cattle DMI are factors that cannot be easily addressed through modeling. However, use of the Holos model provided an opportunity to examine management strategies for improvement of both environmental and economic efficiencies with the following outcomes:

1. Effects of age at calving on greenhouse gas emissions

As expected, simulated beef cow-calf production systems with heifers producing their first calf at 2-yrs of age resulted in lower cumulative GHG emissions (Mg CO_2e) and emission intensities (kg CO_2e kg liveweight^{-1}) compared to those calving at 3-yrs of age. The simulated 2-yr calving systems (MC2 and JC2) resulted in a larger number of calves produced cumulatively across all system years and at steady state compared to the 3-yr calving systems (MC3 and JC3), leading to small increases in total liveweight output (kg) of no more than 4% between systems. Reductions in GHG intensities (kg CO_2e kg liveweight^{-1}) were driven primarily by reductions in total emission sources (Mg CO_2e) for the 2-yr systems. When GHG emission intensities were examined per kg of calf weaned, the magnitude of emissions per unit of output was 3.1-3.4 times as high across all production systems (GHG emissions per kg of calf weaned) compared to GHG emissions per kg of liveweight.

2. Effect of time of calving on greenhouse gas emissions

The hypothesis that reductions in GHG emissions and resulting GHG emission intensities would result from heifers calving in March compared to June was also supported based on these simulations. Cumulative system emissions were reduced by 12-16% for March-calving systems, primarily due to reductions in enteric and manure CH_4. Greenhouse gas emission intensities were 2-7% lower for March- compared to June-calving systems, apart from the MC3 and JC3 systems grazing TAC, which had the same emission intensity, or COR, of which MC3 was higher.

3. Effects of forage quality on greenhouse gas emissions

The hypothesis that systems with heifers grazing stockpiled forage species with higher nutritive value (TDN) would have lower cumulative GHG emissions and emission intensities was supported. This study suggests an inverse relationship between the nutritive value (TDN, % DM) of the stockpiled forage treatments and enteric CH_4 emissions (Mg CO_2e) in each production system, with enteric CH_4 as the highest contributing emission source, accounting for 57-65% of GHG emissions across all systems. Of the 4 forage treatments examined, COR had the highest estimated TDN concentration (72% DM) and produced the lowest enteric CH_4 emissions (2437-2808 Mg CO_2e), while OGA had the lowest TDN (45% DM) and produced the highest (2843-3292 Mg CO_2e).

4. Effect of age at calving on profitability

As hypothesized, beef cow-calf production systems at steady state were more profitable with heifers calving at 2-yrs of age compared to 3-yrs of age in terms of total production costs per kg of liveweight produced. The main revenue stream within the cow-calf production system was calves sold. The annual income from the sale of calves from the 2-yr calving system was higher than that of the 3-yr system due to the larger number of calves produced annually. Cost of feed was the largest expense, accounting for 34% of costs on average across all systems. Feed costs were slightly higher for 3-yr systems compared to 2-yr systems due to differences in nutritional needs and therefore feed requirements for maintenance, growth, and lactation.

5. Effect of time of calving on profitability

The final hypothesis, stating that cow-calf production systems calving in June would be more profitable than those calving in March, was also supported in these simulations. This result was primarily due to lower costs for confinement feed (grass hay, alfalfa-grass hay, and barley grain), but also due to reduced labor costs associated with June-calving. Operating costs excluding feed were similar between MC2 and JC2, as well as MC3 and JC3 systems. Although a single, average calf weaning weight was used, lower calf weaning weights for calves born in June have been demonstrated in other studies (Carriker et al. 2001), which would reduce total liveweight output from the June-calving system.

5.0 General discussion

5.1 National and global demands for sustainability

Many governments, commodity groups, and private sector organizations have set ambitious goals to reduce the environmental impacts of beef production in Canada including the mitigation of GHG emissions. The Canadian Round Table for Sustainable Beef as well as the Global Round Table for Sustainable Beef, for example, have set long-term strategic goals to reduce GHG emissions by 30% by 2030 (GRSB 2021). The Food and Agriculture Organization (FAO) has outlined 3 major livestock solutions for climate change that target productivity improvements to reduce GHG emission intensities, carbon sequestration through improved pasture management, and better livestock integration in a circular bioeconomy, minimizing waste materials and energy by re-circulating them within the beef production system (FAO

2017). Since 2009, the Government of Alberta has incorporated protocols that incentivise low-C beef production including selection of low residual feed intake (RFI) beef cattle and a protocol addressing digestion and manure handling that allows users to quantify GHG emission reductions from changes in feeding and technology in Alberta's feedlots (Alberta Government 2012; 2016). The latter protocol, developed by Trimble Corporation Canada, implemented practices that would increase feed efficiency of beef production and has generated over 50,000 t of C offsets in Alberta's feedlots between 2016 and 2020 (Haugen-Kozyra 2021; Alberta Carbon Registries 2019). The Government of Manitoba has also set out initiatives to develop sustainable protein sources including an investment of $2.85 million over 5 years into the Manitoba Beef and Forage Initiatives to conduct research supporting increased cattle grazing on the landscape, with projects targeting the improvement of marginal pastures through rotational grazing and detection of soil C changes due to grazing management (Manitoba Agriculture 2022c). Funding for projects like these and investment into long-term, strategic goals will continue to guide future research and management decisions for producers to work towards sustainable beef production.

One of the most significant challenges of the 21st century is to meet the above sustainability goals while providing an adequate global food supply, which is expected to increase by 61% (from 8.4 to almost 13.5 billion t per yr) in order to feed 9.7 billion people by the year 2050 (FAO 2017). Consumption of beef in developing countries is expected to increase 1.9% each year until 2050 (Alexandratos and Bruinsma 2012). Thus, export countries such as Canada have the potential to take advantage of this opportunity. However, this will require an adequate feed supply. This may be particularly challenging for ruminant production systems which rely heavily on the use of natural pasture and perennial forage land for feed as it is being replaced by annual crops for human and animal consumption (Statistics Canada 2017c; Pogue et al. 2018). More specifically, the reported land area for natural and tame pasture declined by 3 and 8%, respectively, while cropland increased by 7% between the 2011 and 2016 Census of Agriculture (Statistics Canada 2017c). Availability of perennial forage land is expected to decline further as simulation models predicted that 10,500 km^2 of additional cropland expansion could occur in Canada by 2030 (Zabel et al. 2019), which will result in further degradation of soils and release CO_2. To meet the above goals for sustainability while increasing food production for a growing global community, identification of management strategies which improve production efficiency and economic viability are critical.

5.2 Management strategies to reduce the GHG intensity of beef

Many strategies for GHG emission reduction from beef production have targeted backgrounding and feedlot systems (Boadi et al. 2004; Stewart et al. 2009; Beauchemin et al. 2011). However, the greatest potential for emission mitigation exists within the cow-calf sector, as enteric CH_4 contributes 78-80% (Beauchemin et al. 2010; Legesse et al. 2015) of total beef production system emissions (from cow-calf through to feedlot finishing). Similarly, the largest emission source in the current study contributing to total GHG emissions was enteric CH_4 (57-65%) from ruminal fermentation, emphasizing the potential for reduction in the GHG footprint of the cow-calf system through reductions in enteric CH_4.

5.2.1 Dietary manipulation

Dietary manipulation is a direct and effective means of lowering emissions from cattle in backgrounding and feedlot systems (Beauchemin et al. 2009), however, adoption of strategies such as use of feed additives including fats and use of ionophores into cow-calf systems can be difficult as these operations lack the necessary infrastructure for precision feeding. Therefore, dietary manipulation in these systems must focus on management strategies to improve forage quality through forage species selection and management for harvested feed as well as for grazing. Of particular interest is the use of stockpiled standing forage to extend the pasture grazing season into the late fall and early winter to reduce the cost of production compared to confinement feeding (McCartney et al. 2004; Larson et al. 2011; Kelln et al. 2011). Adoption of extended grazing systems can also generate measurable reductions in GHG emissions compared to confinement feeding due to lower CO_2 emissions from fuel use, and manure CH_4 from deposition of manure directly onto pastureland (Baron et al. 2018). To date, little research has been conducted to directly measure (Dickson 2022) or to model (Alemu et al. 2016) GHG emissions from late fall/early winter grazing. Dickson (2022) demonstrated CH_4 production did not differ significantly between the 4 stockpiled forage treatments (TFM, OGA, TAC, or COR) however, emissions were numerically lower for COR. In the current study, the high TDN of COR resulted in the lowest enteric CH_4 emissions of the 4 stockpiled treatments. These studies provide new information highlighting extended grazing as a management strategy to achieve emission reductions and cost savings. It is essential to compare these metrics concurrently, as on-farm adoption of GHG mitigation strategies will only occur if economically viable.

5.2.2 Reproductive management

Improved reproductive management including reducing the age and changing the time of calving is another avenue to potentially improve production efficiency and reduce emissions from the cow-calf system. Within the current study, systems with heifers calving at 2 yrs of age resulted in a higher number of calves produced each year compared to those in which heifers calved at 3 yrs of age, increasing the annual liveweight output (kg) of the system and reducing the GHG intensity (emissions per kg of liveweight output). Similarly, Beauchemin et al. (2011) explored strategies for reduction of GHG emission intensity including increased calf survival to weaning (4% reduction) and increased longevity of breeding stock by a single year (< 1% reduction) from a simulated beef production system in western Canada, demonstrating reductions to GHG emission intensities through improvements in production efficiency (calf output). Additionally, the current work estimated GHG emissions from cow-calf systems utilizing March- and June-calving. Although June-calving systems demonstrated cost savings compared to calving in March, the lowest GHG emission intensities were observed from March-calving systems, irrespective of age at calving or stockpiled forage treatment. This result was due to differences in energy requirements and DMI of mature cows grazing stockpiled forages, as well as an increased length of time required for June heifers to reach mature weight, increasing land area and associated fuel and fertilizer inputs. Although reductions in GHG emission intensity can be seen when management strategies are examined individually, there is potential for higher emission reductions when dietary and management-related strategies are combined (Beauchemin et al. 2011; Teranishi 2021).

5.3 Whole-systems approaches to emission mitigation and improved profitability

Models such as Holos enable examination of the entire production system to evaluate strategies for GHG emission mitigation, which is necessary as emission reduction in one area of the production system may result in an increase in another (Boadi et al. 2004). These models serve to identify management strategies which, if adopted, could potentially reduce on-farm emissions. However, adoption of GHG-mitigating practices will only occur if they are economically viable, therefore, it is important for models to include an economic analysis. The current work is novel as it compared the effects of changes to reproductive management and forages utilized for stockpiled grazing on GHG emissions concurrently, but also includes an economic component to evaluate net revenues, in order to ensure systems with lower GHG emissions produced are also economically sustainable. If not, programs and policies that incentivize producers to adopt these strategies must be developed by government or other organizations. The Rangeland Improvement Program developed by Ducks Unlimited Canada is an example of a program designed to incentivize producers to maintain grasslands and wetlands managed by beef producers and enhance biodiversity and other ecosystem services (CRSB 2022b). Through this program, producers identify BMPs that best support their own operations and receive a financial incentive to implement this practice or invest in infrastructure within their production system so long as grasslands are not broken, and wetlands are not drained throughout the agreed upon 10-yr period. Future programs may include financial compensation directed to producers for adopting practices that reduce GHG emissions, as well as other environmental metrics.

5.4 Conclusions and future direction

Beef cow-calf production systems are complex, with demands for land area to supply preserved feed, as well as pasture for cattle that compete with an increasing demand for cropland to feed the expanding human population. The continued advancement of models such as Holos will enable researchers and producers to better estimate impacts of changes in farm management on net farm GHG emissions, thereby improving the sustainability of the beef sector. Over the last

30 years, the cow-calf sector has made many improvements through research to improve production efficiency by increasing calf output (Beauchemin et al. 2011), feed efficiency, nutrition, growth implants, and genetics (Haugen-Kozyra 2021), as well as pasture management (Stewart et al. 2009). The current work has added new knowledge regarding improvements in reproductive efficiency (age and time of calving) and choice of forage species for stockpiled grazing. However, in order to achieve the ambitious goals established by industry and government, aggressive strategies will be required. Although many opportunities for improvement have been explored, opportunities exist to reduce the GHG footprint of beef production (Haugen-Kozyra 2021) improving profitability (Pogue et al. 2018). This includes adoption of existing management strategies that are known to improve production efficiency that have not been fully embraced by the cow-calf sector including: (i) improved forage selection and grazing management strategies; (ii) precision feeding for improved performance and reproductive outcomes; (iii) targeted breeding programs to improve feed efficiency, and (iv) the use of implants and vaccines. In addition, novel policy tools and programs that mitigate risk and incentivize adoption of sustainability practices are essential. Finally, new research initiatives that expand our knowledge in the area above including improved forage varieties for grazing, identification of tools for precision feeding in cow-calf systems including mechanized supplement delivery, rapid identification of feed quality, and utilization of food waste, with the goal to improve production efficiency, as well as environmental and economic sustainability. Continuous improvement in the beef sector will require multi-disciplinary stakeholder engagement to address the challenges facing these complex agro-ecosystems.

There is a need for continued expansion of whole-farm models to better estimate the effects of beef production on C sequestration and biodiversity in western Canada. Recent studies have examined the use of shelterbelts for sequestration of C to offset whole-farm GHG emissions and better develop the shelterbelt component of Holos (Mayrinck et al. 2019; Kröbel et al. 2020). Further, the C model within Holos (that assumes constant soil C until a change occurs in land use) has been updated (Holos version 4.0) to better respond to management changes and climate variation (Kröbel et al. 2016). Models that quantify the effects of human impacts on biodiversity and ecosystems currently exist (Alkemade et al. 2012), however, incorporation of models such as these into whole-system models such as Holos will be necessary to examine biodiversity impacts of beef production on rangelands and ecosystems within Canada and beyond.

6.0 List of references

Aasen, A., Baron, V.S., Clayton, G.W., Campbell Dick, A., and McCartney, D.H. 2004. Swath grazing potential of spring cereals, field pea and mixtures with other species. Can. J. Plant Sci. 84: 1051–1058. doi:10.4141/p03-143.

Adams, D.C., Clark, D., Sandberg, R., Carriker, G., and Klopfenstein, T.J. 2001. June versus March calving for the Nebraska sandhills: production traits. Nebraska Beef Cattle Reports. 284. https://digitalcommons.unl.edu/animalscinbcr/284.

Agriculture and Agri-Food Canada (AAFC). 2019. Description of soil MBSCK~~o~~A (Stockton). Canadian Soil Information Service (CanSIS). [Online] Available: https://sis.agr.gc.ca/cansis/soils/mb/SCK/~~o~~/A/description.html.

Alberta Agriculture and Rural Development (AARD). 2011. CowBytes Beef Ration Balancer

Program. Version 5. Alberta Agriculture and Rural Development, Edmonton, AB, Canada.

Alberta Carbon Registries. 2019. Reducing GHG emissions from fed cattle aggregation project pool 3. Trimble Canada Corporation. [Online] Available: https://alberta.csaregistries.ca/GHGR_Listing/AEOR_ListingDetail.aspx?ProjectId=229 [2022 Oct. 31].

Alberta Government. 2012. Quantification protocol for selection for low residual feed intake in beef cattle: Version 1.0. [Online] Available: https://open.alberta.ca/dataset/9780778596264 [2022 Oct. 31].

Alberta Government. 2016. Quantification protocol for reducing greenhouse gas emissions from fed cattle: Version 3.0. [Online] Available: https://open.alberta.ca/publications/9781460125533 [2022 Oct. 31].

Alemu, A.W., Ominski, K.H., and Kebreab, E. 2011. Estimation of enteric methane emissions trends (1990–2008) from Manitoba beef cattle using empirical and mechanistic models. Can. J. Anim. Sci. **91**: 305–321. doi:10.4141/cjas2010-009.

Alemu, A.W., Doce, R.R., Dick, A.C., Basarab, J.A., Kröbel, R., Haugen-Kozyra, K., and Baron, V.S. 2016. Effect of winter feeding systems on farm greenhouse gas emissions. Agric. Syst. **148**: 28–37. Elsevier B.V. doi:10.1016/j.agsy.2016.06.008.

Alemu, A.W., Janzen, H., Little, S., Hao, X., Thompson, D.J., Baron, V., Iwaasa, A., Beauchemin, K.A., and Kröbel, R. 2017. 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. Elsevier. doi:10.1016/j.agsy.2017.08.003.

Alexandratos, N., and Bruinsma, J. 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO.

Alkemade, R., Reid, R.S., Van den Berg, M., and Jeuken, M. 2012. Assessing the impacts of livestock production on biodiversity in rangeland ecosystems. PNAS. **110**(52):20900-20905. https://doi.org/10.1073/pnas.1011013108.

Anderson, B. 2020. Refining recommendations for grazing whole plant corn. Masters dissertation, University of Saskatchewan, Saskatoon, SK, Canada.

Baron, V.S., Dick, A.C., Bjorge, M., and Lastiwka, G. 2004. Stockpiling potential of perennial forage species adapted to the Canadian western Prairie Parkland. Agron. J. **96**: 1545–1552.

Baron, V.S., Dick, A.C., Bjorge, M., and Lastiwka, G. 2005. Accumulation period for stockpiling perennial forages in the western Canadian Prairie Parkland. Agron. J. **97**: 1508–1514. doi:10.2134/agronj2005.0021.

Baron, V.S., Doce, R.R., Basarab, J., and Dick, C. 2014. 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.

Baron, V.S., Doce, R.R., Basarab, J., Juskiw, P., Aljarrah, M., Swift, M-L., McKinnon, J., Kuipers, A., and Sheafer, A. 2018. Innovative swath grazing/increasing forage research capacity. BCRC Project Code FRG.04.13. [Online] Available: https://www.beefresearch.ca/fact-sheets/improved-swath-grazing-through-new-annual-forage-varieties-and-grazing-management/ [2022 Nov. 01].

Basarab, J., Baron, V.S., López-Campos, Ó., Aalhus, J., Haugen-Kozyra, K., and Okine, E. 2012.

Greenhouse gas emissions from calf- and yearling-fed beef production systems, with and without the use of growth promotants. Animals. **2**:195-220. doi: 10.3390/ani2020195.

Beauchemin, K.A., and McGinn, S.M. 2006. Enteric methane emissions from growing beef cattle as affected by diet and level of intake. Can. J. Anim. Sci. **86**:401-408. https://doi.org/10.4141/A06-021.

Beauchemin, K.A., McGinn, S.M., Grainger, C. 2008. Reducing methane emissions from dairy cows. WCDS Advances in Dairy Technology. **20**:79-93.

Beauchemin, K.A., McAllister, T.A., and McGinn, S.M. 2009. Dietary mitigation of enteric methane from cattle. CAB reviews: perspectives in agriculture, veterinary science. doi: 10.1079/PAVSNNR20094035.

Beauchemin, K.A., Janzen, H.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. Elsevier Ltd. doi:10.1016/j.agsy.2010.03.008.

Beauchemin, K.A., Janzen, H.H., Little, S.M., McAllister, T.A., 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. 166-167: 663-677. doi:10.1016/j.anifeedsci.2011.04.047.

Beauchemin, K.A., Ungerfeld, E.M., Eckard, R.J., and Wang, M. 2020. Review: fifty years of research on rumen methanogenesis: lessons learned and future challenges for mitigation. Animal. **14**:s2-s16. doi: 10.1017/S1751731119003100.

Biligetu, B., Jefferson, P.G., Muri, R., and Schellenberg, M.P. 2014. Late summer forage yield, nutritive value, compatibility of warm- and cool-season grasses seeded with legumes in western Canada. Can. J. Plant Sci. **94**: 1139–1148. doi:10.4141/cjps2013-269.

Boadi, D.A., Wittenberg, K.M., Scott, S.L., Burton, D., Buckley, K., Small, J.A., and Ominski, K.H. 2004. Effect of low and high forage diet on enteric and manure pack greenhouse gas emissions from a feedlot. Can. J. Anim. Sci. **84**:445-453. https://doi.org/10.4141/A03-079.

Canadian Round Table for Sustainable Beef (CRSB). 2020. CRSB Research Priorities & Recommendations - June 2020. [Online] Available: https://crsb.ca/wp-content/uploads/2021/11/CRSB-Research-Priorities-June-2020.pdf [2022 Oct. 21].

Canadian Round Table for Sustainable Beef (CRSB). 2022a. Goals & Progress. [Online] Available: https://crsb.ca/benchmarks/goals-progress/ [2022 Oct. 21].

Canadian Round Table for Sustainable Beef (CRSB). 2022b. Projects: Rangeland Improvement Program. Ducks Unlimited Canada. [Online] Available: https://crsb.ca/projects/rangeland-improvement-program/ [2022 Nov. 01]

Canfax. 2021a. The beef industry's contribution to the Canadian economy. Canfax Research Services. [Online] Available: https://www.beefresearch.ca/files/pdf/Multiplier-Summary-May-2021.pdf [2022 May 30].

Canfax. 2021b. Canadian cow-calf cost of production network 2020 results. Canfax Research Services. [Online] Available: https://www.canfax.ca/uploads/COP-Analysis/02_Summary_of_2020_Results.pdf [May 30 2022].

Carriker, G., Clark, D., Adams, D., and Sandberg, R. 2001. June versus March calving for the Nebraska sandhills: economic comparisons. Nebraska Beef Cattle Reports. 287. Available:

https://digitalcommons.unl.edu/animalscinbcr/287.

Chen, G., Elliott, J.A., Lobb, D.A., Flaten, D.N., Braul, L., and Wilson, H.F. 2017. Changes in runoff chemistry and soil fertility after multiple years of cattle winter bale feeding on annual cropland on the Canadian prairies. Agric. Ecosyst. Environ. **240**: 1–13. Elsevier B.V. doi:10.1016/j.agee.2017.02.003.

Christophersen, C.T., Wright, A-D. G., and Vercoe, P.E. 2014. In vitro methane emission and acetate:propionate ratio are decreased when artificial stimulation of the rumen wall is combined with increasing grain diets in sheep. J. Anim. Sci. **86**:384-389. doi:10.2527/jas.2007-0373.

Clark, R.T., Adams, D.C., Lardy, G.P, and Klopfenstein, T.J. 1997. Matching calving date with forage nutrients: production and economic impacts. Range Beef Cow Symposium. 166. https://digitalcommons.unl.edu/rangebeefcowsymp/166.

Damiran, D., Lardner, B., Larson, K., and McKinnon, J. 2016. Effects of Supplementing Wintering Beef Cows Grazing Barley Crop Residue on Performance and System. West. Beef Dev. Cent. - Fact Sheet: 1–6.

Dickson, J.M. 2022. Forage quality, animal performance, and behaviour of bred beef heifers grazing stockpiled perennial and annual forages in the late fall/early winter in Manitoba. Masters dissertation, University of Manitoba, Winnipeg, MB, Canada.

Diskin, M.G., and Kenny, D.A. 2014. Optimising reproductive performance of beef cows and replacement heifers. Animal. **8**:27-39. doi:10.1017/S175173111400086X.

Dove, H., and Mayes, R.W. 2005. Using n-alkanes and other plant wax components to estimate intake, digestibility and diet composition of grazing/browsing sheep and goats. Small Ruminant Research. **59**:123-139. doi: 10.1016/j.smallrumres.2005.05.016.

Durunna, O.N., Girardin, L.C., Scott, S.L., Robins, C., Block H.C., Iwaasa, A.D., Khakbazan, M., and Lardner, H.A. 2014. The effects of spring versus summer calving on beef cattle reproductive and growth performance in western Canada. Can. J. Anim. Sci. **94**:259-271. doi: 10.4141/CJAS2013-180.

Elolimy, A.A., Abdelmegeid, M.K., McCann, J.C., Shike, D.W., and Loor, J.J. 2018. Residual feed intake in beef cattle and its association with carcass traits, ruminal solid-fraction bacteria, and epithelium gene expression. J. Anim. Sci. Biotechnol. **9**:67. doi: 10.1186/s40104-018-0283-8.

Entz, M.H., Baron, V.S., Carr, P.M., Meyer, D.W., Smith, S.R., and McCaughey, J.W.P. 2002. Potential Forages to diversify Northern Great Plains Cropping System - a review. Agron. J. **94**: 240–250.

Environment Canada. 2022a. National Inventory Report 1990-2020: Greenhouse gas sources and sinks in Canada. Environment and Climate Change Canada. Gatineau, QC. Available: canada.ca/ghg-inventory.

Environment Canada. 2022b. Almanac Averages and Extremes for December 20. [Online] Available: https://climate.weather.gc.ca/climate_data/almanac_e.html?StationID=3471&period=15&searchMethod=contains&txtStationName=brandon&month=12&day=20&timeframe=4&month=12&day=20 [2022 Jun 10].

FAO, 2017. Strategic work of FAO for Sustainable Food and Agriculture. [Online] Available from: https://www.fao.org/3/i6488e/i6488e.pdf [2022 Oct. 28].

Fox, D.G., Sniffen, C.J., and O'Connor, J.D. 1988. Adjusting nutrient requirements of beef cattle for animal and environmental variations. J. Anim. Sci. **66**:1475-1495. https://doi.org/10.2527/jas1988.6661475x.

Frame, J. and Laidlaw, A. S. (2005). Prospects for temperate forage legumes. In Grasslands: Development, Opportunities, Perspectives (Eds S. G. Reynolds & J. Frame), pp. 3–28. Enfield, NH: Science Publishers, Inc.

Funston, R.N., Grings, E.E., Roberts, A.J., and Tibbitts, B.T. 2016. Invited review: Choosing a calving date. The Professional Animal Scientist. **32**(2):145-153. http://dx.doi.org/10.15232/pas.2015-01463.

Global Round Table for Sustainable Beef (GRSB). 2021. Global sustainability goals: June 2021. [Online] Available: https://wa.grsbeef.org/resources/Documents/2021%20Global%20Goals/GRSB_Global_Sustainable-Goals_062921.pdf [2022 Nov. 01].

Grainger, C., Clarke, T., McGinn, S.M., Auldist, M.J., Beauchemin, K.A., Hannah, M.C., Waghorn, G.C., Clark, H., and Eckard, R.J. 2007. Methane emissions from dairy cows measured using the sulfur hexafluoride (SF_6) tracer and chamber techniques. J. Dairy Sci. **90**:2755-2766. doi:10.3168/jds.2006-697.

Haugen-Kozyra, K. 2021. Market-based tools for accelerating cattle sustainability in Canada. Anim. Front. **11**(4): 17-25. https://doi.org/10.1093/af/vfab038.

Hewitt, B.S., McGeough, E.J., Cattani, D., Ominski, K.H., Crow, G.H., and Wittenberg, K.M.

2016. Evaluation of seven annual forages for fall stockpiled grazing in beef cattle. Proc. 10th International Rangeland Congress, Saskatoon, SK, July 2016.

Hewitt, B.S. 2018. Evaluation of annual and perennial forages for late fall/early winter stockpile grazing of beef cattle in Manitoba. Masters dissertation, University of Manitoba, Winnipeg, MB, Canada.

Hutton, G., Perillat, B., McCartney, D., and Ohama, A. 2004. Agri-facts: swath grazing in Western Canada. Alberta Agriculture Food and Rural Development [Online]. Available: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex9239/$file/420_56-2.pdf?OpenElement.

Intergovernmental Pannel on Climate Change (IPCC), Eggleston, S., Buendia, L., Miwa, K., Ngara, T.K., Tanabe, H., 2006. Guidelines For National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change. Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan.

Janzen, H.H., Angers, D.A., Boehm, M., Bolinder, M., Desjardins, R.L., Dyer, J., Ellert, B.H., Gibb, D.J., Gregorich, E.G., Helgason, B.L., Lemke, R., Massé, D., McGinn, S.M., McAllister, T.A., Newlands, N., Pattey, E., Rochette, P., Smith, W., VandenBygaart, A.J., and Wang, H. 2006. A proposed approach to estimate and reduce net greenhouse gas emissions from whole farms. Can. J. Soil Sci. **86**: 401–418. doi:10.4141/s05-101.

Janzen, H.H., Desjardins, R.L., Rochette, P., Boehm, M., and Worth, D., (eds). 2008. Better Farming Better Air - A scientific analysis of farming practice and greenhouse gases in Canada. Agriculture and Agri-Food Canada. Ottawa, Ontario.

Jégo, G., Rotz, C.A., Bélanger, G., Tremblay, G.F., Charbonneau, E., and Pellerin, D. 2015.

Simulating forage crop production in a northern climate with the Integrated Farm System Model. Can. J. Anim. Sci. **95**: 745-757. doi:10.4141/CJPS-2014-375.

Johnson, K.A., and Johnson, D.E. 1995. Methane emissions from cattle. J. Anim. Sci. **73**:2483-2492. https://doi.org/10.2527/1995.7382483x.

Jose, D., Damiran, D., Penner, G., McKinnon, J., Larson, K., Lardner, B. 2017. Effect of winter grazing system on beef cow performance and system costs. Western Beef Development Centre. Factsheet #2017.01.

Jung, H.G., and Allen, M.S. 1995. Characteristics of plant cell walls affecting intake and digestibility of forages by ruminants. J. Anim. Sci. **73**:2774-2790. doi:10.2527/1995.7392774x.

Jungnitsch, P.F., Schoenau, J.J., Lardner, H.A., and Jefferson, P.G. 2011. Winter feeding beef cattle on the western Canadian prairies: Impacts on soil nitrogen and phosphorus cycling and forage growth. Agric. Ecosyst. Environ. **141**: 143–152. Elsevier B.V. doi:10.1016/j.agee.2011.02.024.

Kallenbach, R.L. 2006. Reducing Losses When Feeding Hay to Beef Cattle. The Cattleman; September 2006. 93:4 pg. 128. [Online] Available: https://www.researchgate.net/publication/277996419.

Kasimanickam, R. K., Kasimanickam, V.R., and McCann, M.L. 2021. Difference in body weight at breeding affects reproductive performance in replacement beef heifers and carries consequences to next generation heifers. Animals. **11**(10):2800. https://doi.org/10.3390/ani11102800.

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. https://doi.org/10.4141/A05-010.

Kelln, B.M., Lardner, H.A., McKinnon, J.J., Campbell, J.R., Larson, K., and Damiran, D. 2011. Effect of winter feeding system on beef cow performance, reproductive efficiency, and system cost. Prof. Anim. Sci. **27**: 410–421. doi:10.15232/s1080-7446(15)30513-1.

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

Khakbazan, M., Durunna, O.N., Sirski, T.K., Brewin, D.G., Huang, J., Berry, N., Iwaasa, A.D., Scott, S.L., Robins, C.D., Block, H.C., and Lardner, H.A. 2015. The effects of spring versus summer calving on beef cattle economic performance in western Canada. Can. J. Anim. Sci. **95**: 475-486. doi:10.4141/CJAS-2015-046.

Komarek, A.M., Dunston, S., Enahoro, D., Godfray, H.C.J., Herrero, M., Mason-D'Croz, D., Rich, K.M., Scarborough, P., Springmann, M., Susler, T.B., Wiebe, K., and Willenbockel, D. 2021. Income, consumer preferences, and the future of livestock-derived food demand. Glob. Environ. Change. **70**. https://doi.org/10.1016/j.gloenvcha.2021.102343.

Kopp, J.C., McCaughey, W.P., Wittenberg, K.M. 2003. Yield, quality, and cost effectiveness of using fertilizer and/or alfalfa to improve meadow bromegrass pastures. Can. J. Anim. Sci. **83(2)**: 291-298. doi:10.4141/A01-074.

Kröbel, R., Bolinder, M.A., Janzen, H.H., Little, S.M., Vandenbygaart, and A.J., 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. https://doi.org/10.1016/j.agsy.2015.12.010.

Kröbel, R., Moore, J., Ni, Y.Z., McPherson, A., Poppy, L., Soolanayakanahally, R.Y., Amichev, B.Y., Ward, T., Laroque, C.P., Van Rees, K.C.J., and Akhter, F. 2020. Demonstration and testing of the improved shelterbelt component in the Holos model. Front. Environ. Sci. **8:**149. doi:10.3389/fenvs.2020.00149.

Kulathunga, R., Penner, G., Schoenau, J., Damiran, D., Larson, K., and Lardner, B. 2015. Effect of perennial forage system on forage characteristics, cow performance, and system economics. Western Beef Development Centre. Factsheet #2015-01.

Lardner, B., Larson, K., Pearce, L. 2012. Winter grazing beef cows with standing corn. Western Beef Development Centre. Factsheet #2012.03.

Lardner, H.A., Pearce, L., and Damiran, D. 2017. Evaluation of low heat unit corn hybrids compared to barley for forage yield and quality on the Canadian Prairies. Sustain. Agric. Res. **6**(1):90-102. doi:10.5539/sar.v6n1p90.

Larson, D.M., Cupp, A.S., and Funston, R.N. 2011. Heifer development systems: A comparison of grazing winter range or corn residue. J. Anim. Sci. **89**: 2365–2372. doi:10.2527/jas.2010-3767.

Larson, K. 2011. 2010 Low-cost cow-calf producers. Western Beef Development Centre. Factsheet #2011.02.

Legesse, G., Small, J.A., Scott, S.L., Crow, G.H., Block, H.C., Alemu, A.W., Robins, C.D., and

Kebreab, E. 2011. Predictions of enteric methane emissions for various summer pasture and winter feeding strategies for cow calf production. J. Ani. Feed Sci. **166-167**: 678-687. doi:10.1016/j.anifeedsci.2011.04.082.

Legesse, G., Beauchemin, K.A., Ominski, K.H., McGeough, E.J., Kröbel, R., MacDonald, D., Little, S.M., and McAllister, T.A. 2015. 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., Kröbel, 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. https://doi.org/10.1016/j.scitotenv.2017.11.194.

Little, S.M., Linderman, J., Maclean, K. and Janzen, H., 2008. Holos – A tool to estimate and reduce greenhouse gases from farms. Methodology and algorithms for versions 1.1.x. Agriculture and Agri-Food Canada, Cat. No. A52-136/2008E-PDF. 158 pp.

Little, S.M., Benchaar, C., Janzen, H.H., Kröbel, R., McGeough, E.J., and Beauchemin, K.A. 2017. Demonstrating the effect of forage source on the carbon footprint of a Canadian dairy farm using whole-systems analysis and the Holos model: alfalfa silage vs. corn silage. J. Climate. **5**:87. doi:10.3390/cli5040087.

Manitoba Agricultural Services Corporation (MASC). 2019. Yield Manitoba 2019. Farm Business Communications. Winnipeg, MB. [Online] Available: https://www.masc.mb.ca/masc.nsf/ym_2019_full_issue.pdf.

Manitoba Agriculture. 2021. Guidelines for estimating beef cow-calf production costs based on a

150 head cow herd. [Online] Not available.

Manitoba Agriculture. 2022a. Guidelines for estimating beef cow-calf production costs based on a 150 head cow herd. [Online] Available from: https://www.gov.mb.ca/agriculture/farm-management/production-economics/pubs/cop-beef-150-cow-calf.pdf.

Manitoba Agriculture. 2022b. Standing hay cost calculator. [Online] Available: https://www.gov.mb.ca/agriculture/farm-management/production-economics/cost-of-production.html.

Manitoba Agriculture. 2022c. Sustainable protein initiatives. [Online] Available: https://www.gov.mb.ca/agriculture/protein/sustainability/sus-pro-initiatives.html [2022 Nov. 01].

Manitoba Agriculture [undated a]. Winter rations for beef cows. [Online] Available: https://www.gov.mb.ca/agriculture/livestock/beef/winter-rations-for-beef-cows.html [2022 Nov 13].

Manitoba Agriculture [undated b]. Ration balancing checklist for cattle. [Online] Available: https://www.gov.mb.ca/agriculture/livestock/production/beef/ration-balancing-checklist-for-cattle.html [2022 Nov. 6].

Mata-Padrino, D.J., Felton, E.E.D., Bryan, W.B., and Belesky, D.P. 2017. Winter Grazing in a Grass-Fed System: Effect of Stocking Density and Sequential Use of Autumn-Stockpiled Grassland on Performance of Yearling Steers. Int. J. Agron. **2017**: 1–9. doi:10.1155/2017/2375954.

Mathison G.W. 1993. The beef industry. Animal production in Canada. (Eds J Martin, RJ

Hudson, BA Young). 35–74. University of Alberta, Faculty of Extension: Edmonton, Canada.

Mayrinck, R.C., Laroque, C.P., Amichev, B.Y., and Van Rees, K. 2019. Above- and below-ground carbon sequestration in shelterbelt trees in Canada: A review. Forests. **10**(10): 922. https://doi.org/10.3390/f10100922.

McCartney, D., Basarab, J.A., Okine, E.K., Baron, V.S., and Depalme, A.J. 2004. Alternative fall and winter feeding systems for spring calving beef cows. Can. J. Anim. Sci. **84**: 511–522. doi:10.4141/a03-069.

McCartney, D., Fraser, J. and Ohama, A. 2009. Potential of warm-season annual forages and Brassica crops for grazing: a Canadian review. Can. J. Anim. Sci. 89:431-440. https://doi.org/10.4141/CJAS09002.

McGeough, E.J., Cattani, D., Koscielny, Z., Hewitt, B., and Ominski, K.H. 2018. Annual and perennial forages for fall/winter grazing in western Canada. Can. J. Plant Sci. **98**:247-254. dx.doi.org/10.1139/cjps-2017-0228.

Meyer, A.M., Kerley, M.S., Kallenbach, R.L., and Perkins, T.L. 2009. Comparison of Grazing Stockpiled Tall Fescue Versus Feeding Hay With or Without Supplementation for Gestating and Lactating Beef Cows During Winter. Prof. Anim. Sci. **25**, 4; pg. 449. doi:10.15232/S1080-7446(15)30741-5.

Modongo, O., and Kulshreshtha, S.N. 2018. Economics of mitigating greenhouse gas emissions from beef production in western Canada. Agric. Syst. **162**:229-238. https://doi.org/10.1016/j.agsy.2017.12.008.

Moss, A.R., Jouany, J., Newbold, J. 2000. Methane production by ruminants: its contribution to global warming. Ann. Zootech. **49:**231-253. doi: 10.1051/animres:2000119.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H. 2013. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen,J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nelson, C.J., and Burns, J.C. 2006. Fifty years of grassland science leading to change. Crop Sci. **46**: 2204–2217. doi:10.2135/cropsci2006.04.0278gas.

National Research Council (NRC). 2000. Nutrient requirements of beef cattle. Seventh Revised Edition (Update 2000). National Academies Press. Washington, DC.

National Research Council (NRC). 2016. Nutrient requirements of beef cattle. Eighth Revised Edition (2016). National Academies Press. Washington, DC. https://doi.org/10.17226/19014.

Okine, E.K., Mathison, G.W., and Hardin, R.T. 1989. Effects of changes in frequency of reticular contractions on fluid and particulate passage rates in cattle. J. Anim. Sci. **67**(12):3388-3396. doi: 10.2527/jas1989.67123388x.

Peng, X. 2017. Potential of Stockpiled Annual and Perennial Forage Species for Fall and Winter Grazing in the Canadian Great Plains Region. Degree of Master of Science in the

Department of Plant Sciences. University of Saskatchewan, Saskatoon, SK.

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

Poore, M.H., Benson, G.A., Scott, M.E., and Green, J.T. 2000. Production and use of stockpiled fescue to reduce beef cattle production costs. J. Anim. Sci. **79**: 1. doi:10.2527/jas.00.079es1001i.

Poore, M.H., and Drewnoski, M.E. 2010. Review: Utilization of Stockpiled Tall Fescue in Winter Grazing Systems for Beef Cattle. Prof. Anim. Sci. **26**: 142–149. doi:10.15232/s1080-7446(15)30573-8.

Possberg, M., and Kulshreshtha, S. 2018. Beef enterprise profitability and greenhouse gas emissions on Manitoba farms. EC Agriculture. **4.1**:29-38.

Riesterer, J.L., Undersander, D.J., Casler, M.D., and Combs, D.K. 2000. Forage yield of stockpiled perennial grasses in the upper midwest USA. Agron. J. **92**: 740–747.

Rochette, P., Worth, D.E., Lemke, R.L., McConkey, B.G., Pennock, D.J., Wagner-Riddle, C., and Desjardins, R. L. 2008. Estimation of N_2O emissions from agricultural soils in Canada. I. Development of a country-specific methodology. Can. J. Soil. Sci. **88**: 641-654. https://doi.org/10.4141/CJSS07025.

Rotz, C.A., and Muck, R.E. 1994. Changes in forage quality during harvest and storage. Pages 828-868 in Fahey, G.C., eds. Forage Quality, Evaluation, and Utilization. American Society of Agronomy. Madison, WI. doi: 10.2134/1994.foragequality.c20.

Rotz, C.A., Buckmaster, D.R., and Comerford, J.W. 2005. A beef herd model for simulating feed intake, animal performance, and manure excretion in farm systems. J. Anim. Sci. **83**: 231–242.

Rotz, C.A., Isenberg, B.J., Stackhouse-Lawson, K.R., and Pollak, E.J. 2013. A simulation-based approach for evaluating and comparing the environmental footprints of beef production systems. J. Anim. Sci. **91**: 5427–5437. doi:10.2527/jas.2013-6506.

Rotz, C.A., Asem-Hiablie, S., Dillon, J., and Bonifacio, H. 2015. Cradle-to-farm gate environmental footprints of beef cattle production in Kansas, Oklahoma, and Texas. J. Anim. Sci. **93**: 2509–2519. doi:10.2527/jas.2014-8809.

Rotz, C.A., Asem-Hiablie, S., Place, S., and Thoma, G. 2019. Environmental footprints of beef cattle production in the United States. Agric. Syst. **169**: 1–13. Elsevier. doi:10.1016/j.agsy.2018.11.005.

Russell, J.B. 1998. The importance of pH in the regulation of ruminal acetate to propionate ratio and methane production in vitro. J. Dairy Sci. **81**:3222-3230. https://doi.org/10.3168/jds.S0022-0302(98)75886-2.

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. Beef cattle husbandry practices across Ecoregions of Canada in 2011. Can. J. Anim. Sci. **95**: 305–321. doi:10.4141/cjas-2014-158.

Shreck, A.L., Zeltwanger, J.M., Bailey, E.A., Jennings, J.S., Meyer, B.E., and Cole, N.A. 2021.

Effects of protein supplementation to steers consuming low-quality forages on greenhouse gas emissions. J. Anim. Sci. **99**(7):1-8. doi:10.1093/jas/skab147.

Sirski, T.K. 2012. The effect of calving season on economic risk and return in cow-calf operations in Western Canada. Masters dissertation, University of Manitoba, Winnipeg, MB, Canada.

Statistics Canada. 2017a. Table: 32-10-0424-01 Cattle inventory on farms, Census of Agriculture (2016), inactive. https://doi.org/10.25318/3210042401-eng.

Statistics Canada. 2017b. Table 32-10-0359-01 Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units. https://doi.org/10.25318/3210035901-eng.

Statistics Canada. 2017c. Table 32-10-0406-01 Land use, Census of Agriculture, 2011 and 2016, inactive. https://doi.org/10.25318/3210040601-eng.

Statistics Canada. 2022a. Table: 32-10-0130-01 Number of cattle, by class and farm type (x 1,000). https://doi.org/10.25318/3210013001-eng.

Statistics Canada. 2022b. Table 32-10-0077-01 Farm produce prices, crops and livestock. https://doi.org/10.25318/3210007701-eng

Stewart, A.A. 2008. Using a systems approach to examine net greenhouse gas emissions from beef production in Western Canada. Masters dissertation, University of Manitoba, Winnipeg, MB, Canada.

Stewart, A.A., Little, S.M., Ominski, K.H., Wittenberg, K.M., and Janzen, H.H. 2009. Evaluating greenhouse gas mitigation practices in livestock systems: an illustration of a whole-farm approach. J. Agric. Sci. **147**: 367-382. doi:10.1017/S0021859609008764.

Stewart, A.A., Alemu, A.W., Ominski, K.H., Wilson, C.H., Tremorin, D.G., Wittenberg, K.M., Tenuta, M., and Janzen, H.H. 2014. Whole-farm greenhouse gas emissions from a backgrounding beef production system using an observation-based and model-based approach. Can. J. Anim. Sci. **94**: 463–477. doi:10.4141/cjas2013-193.

Stonehouse, D. P., Gao, L., Hamilton, J. G., Buchanan-Smith, J. G. and Weersink, A. 2003. Improving the competitiveness of beef production in the northern contiguous United States and Canada. J. ASFMRA. **66**: 108-118. http://dx.doi.org/10.22004/ag.econ.198079.

Teranishi, R.E. 2020. Enteric methane emissions from pregnant beef heifers as affected by multiple dietary mitigation strategies. Masters dissertation, University of Manitoba, Winnipeg, MB, Canada.

Terry, S.A., Basarab, J.A., Guan, L. L., and McAllister, T.A. 2020. Strategies to improve the efficiency of beef cattle production. Can. J. Anim. Sci. **101**:1-19. doi: dx.doi.org/10.1139/cjas-2020-0022.

Time and Date. 2022. Past weather in Brandon, Manitoba, Canada. [Online] Available: https://www.timeanddate.com/weather/canada/brandon/historic?month=12&year=2014.

Thompson, L., Lardner, B., Iwaasa, A., Block, H., and Scott, S. 2012. Time of calving and feeding strategy effects on performance of feeder steers. Western Beef Development Centre. Factsheet #2012.01.

Thompson, L.R., Maciel, I.C.F., Rodrigues, P.D.R., Cassida, K.A., and Rowntree, J.E. 2021. Impact of forage diversity on forage productivity, nutritive value, beef cattle performance, and enteric methane emissions. J. Anim. Sci. **99(12)**:1-13. https://doi.org/10.1093/jas/skab326.

Thornely, J.H.M. and France, J. 2007. Mathematical Models in Agriculture: Quantitative methods for the plant, animal, and ecological sciences. CAB International. Wallingford, UK.

United Nations (UN). 2017. World Population Prospects: The 2017 Revision, Key Findings & Advance Tables. Working Paper no. ESA/P/WP/248. United Nations, Department of Economic and Social Affairs, Population Division.

United Nations (UN). 2022. Emissions Gap Report 2022: The Closing Window - Climate crisis calls for rapid transformation of societies. Nairobi. https://www.unep.org/emissions-gap-report-2022.

Van Soest, P.J., Sniffen, C.J., Mertens, D.R., Fox, D.G., Robinson, P.H. and Krishnamoorthy, U. 1982. A net protein system for cattle: The rumen submodel for nitrogen protein requirements for cattle. Okla. State Univ., Stillwater, Okla., MP-109 pp. 265-279.

Vergé, X. P. C., Dyer, J.A., Desjardins, R.L., and Worth, D. 2008. Greenhouse gas emissions from the Canadian beef industry. Agric. Syst. **98**:126-134. doi:10.1016/j.agsy.2008.05.003.

Volesky, J.D., Adams, D.C., and Clark, R.T. 2002. Windrow Grazing and Baled-Hay Feeding Strategies for Wintering Calves. J. Range Manag. **55**: 23. doi:10.2307/4003259.

Waghorn, G.C., Tavendale, M.H., Woodfield, D.R., 2002. Methanogenesis from forages fed to sheep. NZ Grassland Assoc. **64**:167–171. https://doi.org/10.33584/jnzg.2002.64.2462.

Warren, F.J. and Lemmen, D.S. 2014. Canada in a Changing Climate: Sector Perspectives on

Impacts and Adaptation. Government of Canada, Ottawa, ON. Available from: https://www.nrcan.gc.ca/climate-change/impacts-adaptations/canada-changing-climate-sector-perspectives-impacts-and-adaptation/16309.

Western Beef Development Centre (WBDC). 2015. Western Canadian cow-calf survey 2014. Western Beef Development Centre, Lanigan, SK. [Online] Available from: http://westernbeef.org/pdfs/economics/WCCCS_Summary_Overall_Jun2015.pdf.

Western Beef Development Centre (WBDC). 2018. Western Canadian cow-calf survey 2017. Western Beef Development Centre, Lanigan, SK. [Online] Available from: http://westernbeef.org/pdfs/wcccs/2017_WCCCS_Summary-FINAL.pdf.

Willms, W.D., Rode, L.M., and Freeze, B.S. 1993. Winter performance of Hereford cows on fescue prairie and in drylot as influenced by fall grazing. Can. J. Anim. Sci. **73**: 881–889. doi:10.4141/cjas93-090.

World Weather Online (WWO). 2022. Brandon, Canada annual weather averages. [Online] Available: https://www.worldweatheronline.com/brandon-weather-averages/manitoba/ca.aspx.

Zabel, F., Delzeit, R., Schneider, J.M., Seppelt, R., Mauser, W., and Václavík, T. 2019. Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. Nat. Commun. **10**, 2844. https://doi.org/10.1038/s41467-019-10775-z.

Zenobi, M.G., Lardner, H.A., Jefferson, P.G., and McKinnon, J.J. 2014. Blended by-product feed pellets for backgrounding cattle. Can. J. Anim. Sci. **94**: 533–543. doi:10.4141/cjas-2014-035.

7.0 Appendices

Table 1.A. Annual liveweights (kg) and greenhouse gas (GHG) emissions (kg CO_2e) for 16 beef production systems comparing age (2 vs 3 yrs) and time (March—MC; June—JC) of first calving and grazing 1 of 4 stockpiled forage treatments in the late fall/early winter.

Year	Liveweight output				Emissions total			
JC2	COR[a]	TFM[a]	OGA[a]	TAC[a]	COR[a]	TFM[a]	OGA[a]	TAC[a]
1	0	0	0	0	383,339	454,300	536,274	452,476
2	83,351	83,351	83,351	83,351	467,803	467,803	467,803	467,803
3	9,192	9,192	9,192	9,192	424,438	470,494	531,480	480,692
4	22,295	21,653	21,446	22,099	420,335	474,150	522,638	457,922
5	20,262	20,262	20,262	20,262	610,391	663,404	721,621	664,125
6	20,218	20,165	20,148	20,202	676,018	730,066	787,374	730,961
7	20,218	20,165	20,148	20,202	596,143	648,153	707,021	650,672
8	20,218	20,165	20,148	20,202	579,047	630,527	689,672	633,320
9	71,855	71,320	71,148	71,692	71,908	71,786	71,705	71,980
JC3								
1	0	0	0	0	383,339	454,300	536,274	452,476
2	83,351	83,351	83,351	83,351	418,602	418,602	418,602	418,602
3	0	0	0	0	476,660	533,035	608,356	546,461
4	11,354	10,316	9,973	11,088	472,762	501,233	567,726	484,503
5	22,817	22,817	22,817	22,817	550,884	615,645	672,519	615,116
6	19,833	19,833	19,833	19,833	578,822	632,516	688,458	631,864
7	18,306	18,207	18,175	18,281	526,293	573,744	633,272	576,424
8	18,529	18,430	18,398	18,504	513,220	561,026	620,139	557,623
9	18,306	18,207	18,175	18,281	536,128	584,597	643,922	586,644
10	69,560	69,016	68,836	69,420	71,347	70,892	70,845	71,056
MC3								
1	83,351	83,351	83,351	83,351	569,424	590,213	607,959	589,987
2	0	0	0	0	419,660	419,660	419,660	419,660
3	13,336	13,393	13,336	13,631	520,719	578,777	655,839	593,590
4	22,817	22,817	22,817	22,817	555,795	530,045	581,938	560,061
5	19,833	19,833	19,833	19,833	559,302	597,219	636,896	597,641
6	18,495	18,500	18,495	18,523	589,942	632,170	673,434	633,268
7	18,718	18,723	18,718	18,746	537,934	573,572	615,871	576,624
8	18,495	18,500	18,495	18,523	525,262	560,842	603,218	560,281
9	70,887	70,917	70,887	71,042	487,529	499,848	515,802	497,409
MC2								
1	83,351	83,351	83,351	83,351	579,654	601,349	619,029	600,421
2	10,354	10,411	10,354	10,649	417,087	468,303	530,509	480,605
3	22,817	22,300	22,039	22,817	427,857	456,645	500,788	483,075
4	20,373	20,378	20,209	20,401	538,338	462,117	558,890	585,842
5	20,373	20,378	20,209	20,401	546,924	592,720	639,392	596,728
6	20,373	20,378	20,209	20,401	592,672	631,321	685,053	643,251
7	20,373	20,378	20,209	20,401	540,132	577,976	628,560	589,302
8	72,955	72,987	72,955	73,124	474,435	485,560	505,461	496,118

[a] Stockpiled treatments included COR – standing corn, TFM – tall fescue/meadow bromegrass, OGA – orchard grass/alfalfa, and TAC – tall fescue/meadow bromegrass/alfalfa for late fall/early winter grazing.