Impact of productivity enhancing technologies on the environmental footprint of backgrounded and finished beef cattle

by

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ABSTRACT

The objective of this research was to examine the use of productivity enhancing technologies (PETs) and post-weaning management on the environmental impacts of beef steers in western Canada. The PETs considered included ionophores and hormone implants administered to steers raised in one of the three management systems: i) direct finishing (Heavy), ii) backgrounded in pens prior to finishing (Medium), and backgrounded in pens and on pasture prior to finishing (Light). Environmental parameters (greenhouse gas emissions (GHG), ammonia (NH_3) emissions, land requirements and water use) were modeled using a whole-farm perspective to better understand the environmental footprint of the Canadian beef industry. Use of PETs led to a 10-13% reduction in GHG emissions (CO_2e kg boneless beef^{-1}), a 10-32% decrease in NH_3 emissions (kg NH_3 kg boneless beef^{-1}), required 9-22% less land (ha kg boneless beef^{-1}) and used 12-25% less water (m^3 kg boneless beef^{-1}) compared to natural steers. Direct finishing compared to backgrounded, and 2-stage backgrounded steers reduced GHG emissions by 32% and 39% kg CO_2e kg boneless beef^{-1}, NH_3 emissions by 36% and 52% kg NH_3 kg boneless beef^{-1}, land requirements by 25% and 73% ha kg boneless beef^{-1} and water use by 18% and 51% m^3 kg boneless beef^{-1}, respectively. Varying post-weaning strategies allows producers to value-add (additional weight through backgrounding) and maximize the use of available feed, including grazing of grasslands. The full environmental impacts of removal of PETs from Canadian beef production must consider a whole-systems approach including economic viability, ecosystem services, as well as consumer demand and social acceptance.

FOREWORD

This thesis was written in accordance with the University of Manitoba Faculty of Graduate Studies thesis guidelines and follows the Canadian Journal of Animal Science manuscript style format. It consists of an abstract, introduction, material and methods, results, discussion, and conclusion and at this time has not been submitted for publication. The animal production data used to conduct the described research was sourced from Smith (2022).

CONTRIBUTION OF AUTHORS

S.S. Fortier: Conducted the modeling, data analysis and interpretation, writing of the thesis document and subsequent editing, K.H. Ominski: Supervision, conceptualization, reviewing, and editing; T.C. McAllister: Supervision, conceptualization, reviewing, and editing; G. Gizaw: Spreadsheet development, reviewing, and editing; M. Tenuta: Reviewing and editing; B. Lardner: Led initial field study, reviewing, and editing; Deanne Fulawka: Review of model input and output data.

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DEDICATION

This thesis is dedicated, with love, to my niece Ellie Ann Claire Shannon.

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ABBREVIATIONS

AAFC	Agriculture and Agri-Food Canada
ADG	Average daily gain
AET	Actual evapotranspiration
β-AA	Beta-adrenergic agonist
β-AR	Beta-adrenergic receptor
BW	Body weight
CAPI	Canadian Agri-Food Policy Institute
CETA	Comprehensive Economic Trade Agreement
CFIA	Canadian Food Inspection Agency
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
CP	Crude protein
DM	Dry matter
DMI	Dry matter intake
DOF	Days on feed
DP	Dressing percentage
EF	Emission factor
ET_c	Crop evapotranspiration
EU	European Union
GDP	Gross domestic product
GE	Gross energy
GHG	Greenhouse gas
GWP	Global warming potential
ha	Hectare
HCW	Hot carcass weight
HCON	Heavy conventional
HNAT	Heavy natural
LCON	Light conventional
LNAT	Light natural

IPCC	Intergovernmental Panel on Climate Change
K_c	Crop coefficient
$K_{c\ end}$	Crop coefficient, end
$K_{c\ init}$	Crop coefficient, initial
$K_{c\ mid}$	Crop coefficient, middle
LCA	Life cycle analysis
L_{dev}	Developmental phase
L_{init}	Initial phase
L_{late}	Late phase
L_{mid}	Middle phase
LW	Live weight
MCON	Medium conventional
MNAT	Medium natural
N	Nitrogen
N_2O	Nitrous oxide
NASEM	National Academies of Science, Engineering, and Medicine
NDM	National Drought Model
$NE_{activity}$	Net energy associated with activity
NE_{gain}	Net energy associated with growth
$NE_{maintenance}$	Net energy associated with maintenance
NH_3	Ammonia
NH_3-N	Ammoniacal nitrogen
OECD	Organization for Economic Co-operation and Development
P	Phosphorous
P_2O_5	Phosphate
PET	Productivity enhancing technology
PET_w	Potential evapotranspiration
PI	Protein intake
PR_{gain}	Protein retained for growth
REG	Ratio of dietary energy for growth to digestible energy consumed
REM	Ration of dietary energy for maintenance
TAN	Total ammoniacal nitrogen

TBA	Trenbolone acetate
TDN	Total digestible nutrients
TMR	Total mixed ration
WUI	Water use intensity

1.0 GENERAL INTRODUCTION

An increase in global human population from 7.3 billion to 9.6 billion in the next 30-years will result in a 33% increase in protein demand (Henchion et al., 2017). By 2030, the Organisation for Economic Co-operation and Development (OECD; 2022) predicts a 14% increase in protein consumption per capita compared to that predicted for 2018 and 2020. Paired with this increase in demand are increasing global pressures on the livestock industry to produce more beef with lower resource use and an overall reduced environmental impact (Henchion et al. 2022). Additionally, several studies suggest the carbon emissions associated with beef production (kg CO_2 equivalents (CO_2e) per kg of product) exceeds other animal-based protein sources such as chicken, pork, lamb, eggs, and milk (Dyer et al., 2010; Lesschen et al., 2011; Browne et al., 2011, Alemu et al., 2017). To meet the demand to reduce the environmental footprint of beef, the Canadian Roundtable for Sustainable Beef has set ambitious goals through Canada's National Beef Strategy to reduce greenhouse gas (GHG) emissions by 30%, food loss and waste by 50% and sequester an additional 3.4 million tonnes of carbon by 2030. Assessments of the current environmental footprint of the Canadian beef industry suggest that it contributed 12.0 kg carbon dioxide equivalents (CO_2e) kg LW^{-1} (Legesse et al. 2015), 18.4 kg NH_3 animal $^{-1}$ (Legesse et al. 2018b), required 104 m^3 kg LW^{-1} of land and required 7,989 L kg LW^{-1} of water at the time of slaughter (Legesse et al. 2018a).

Between 1981 and 2011, the industry was successful in reducing greenhouse gas (GHG) and ammonia emissions, and water use by 15%, 20%, and 17%, respectively (Legesse et al., 2015, 2018a, 2018b). These improvements in the environmental footprint of Canadian beef were achieved as a result of improved on farm management associated with reproductive and feed efficiency, increased weaning and carcass weight, and advances in animal and forage genetics (Brameld and Parr 2016; Alemu et al, 2017; Balafoutis et al. 2017). However, to meet the sustainability goals set by the industry, producers must continue to have access to existing mitigation strategies, including the use of productivity enhancing technologies (PETs) to improve the production efficiency of cattle (Ribeiro et al. 2020).

Productivity enhancing technologies are products, such as implants, β-adrenergic agonists (β-AAs), ionophores, melengestrol acetate and feed grade antibiotics that are used to increase average daily gain (ADG) and reduce days on feed (Ribeiro et al. 2020, Smith et al. 2022). In addition, several studies, including those conducted in Canada (Basarab et al., 2012; Aboagye et al., 2022; Boonstra et al., 2023) have demonstrated that use of these products also leads to a reduction in GHG and ammonia emissions, in addition to land and water use. Despite these positive benefits, the use of PETs is being increasingly scrutinized by consumers. Survey data indicated that North American consumers had a willingness to pay a premium for “natural” products, including beef produced without the use of PETs (Syrengelas et al., 2018). In Canada, this topic has received considerable interest. For example, the Canadian Centre for Food Integrity reported that in 2017 and 2019, 2.5 million and 950 thousand Canadians, respectively, engaged in discussion on agriculture and climate change, and the use of hormones in livestock production systems (Canadian Centre for Food Integrity 2019).

In addition to increased domestic demand for PET-free beef, there is also interest in this type of production system internationally. The 2017 Canada-European Union Comprehensive Economic Trade Agreement (CETA; AAFC 2018) was intended to increase tariff-free access of Canadian frozen and fresh beef from 20,000 tonnes in 2018 to 50,000 tonnes over 6 years (Global Affairs Canada, 2020).

While producers are cognisant and responsive to consumer demands, the environmental impact resulting from the complete removal of PETs from the Canadian beef industry for all types of production systems must be examined, including those with a backgrounding phase either in confinement or on pasture. There is also increased producer interest in non-conventional post-weaning management practices such as backgrounding of both calves and yearlings on pasture. These strategies provide an economic opportunity for cow-calf producers to retain ownership of their cattle for backgrounding or for custom grazing operations to purchase weaned cattle prior to finishing in a feedlot. Research conducted to date has focused primarily on confined backgrounding and feedlot production systems (Basarab et al., 2012; Abogaye et al., 2022; Boonstra et al., 2023; Capper and Hayes 2012; Cooprider et al. 2011; Stackhouse et al. 2012; Stackhouse-Lawson et al. 2013; Webb 2018), which has left a gap regarding the use of PETs in less intensive pasture-based backgrounding systems. Understanding the environmental impacts of PETs in all management scenarios, including forage-based post-weaning systems, is essential to identify potential opportunities to further improve the sustainability of the Canadian beef sector.

2.0 LITERATURE REVIEW

2.1 Overview of the Canadian Beef Industry

The Canadian beef industry produces, on average, 1.55 million tonnes of beef annually, of which more than 400,000 tonnes valued at $3.1 billion was exported to 62 countries in 2020 (AAFC, 2023). In 2022 Canada produced 2% of net global beef and veal and was the 8th largest exporter of beef worldwide (Canfax Research Services, 2023). Beef production is also a significant contributor to the Canadian economy, with 63.4% of Canadians consuming beef daily (OECD 2023), it is the second largest farm income source at 15% of total farm cash receipts (Kulshreshtha et al. 2021). Canada has approximately 60,000 beef farmers who contribute $21.8 billion to the gross domestic product (GDP; Kulshreshtha et al. 2021). For every dollar of income received by farm/ranch owners/employees, $6.22 is created elsewhere in the economy. Furthermore, for every job in the beef sector, another 3.9 jobs are created elsewhere in the Canadian workforce (Kulshreshtha et al. 2021).

Beef production in Canada is primarily compromised of three phases: i) cow-calf, ii) backgrounding and iii) finishing.

i) Cow-calf: This system is comprised of a breeding herd (cows, heifers and bulls) that produces an annual calf crop. There are two types of cow-calf operations: purebred and commercial. Purebred operations produce bulls (and heifers) to provide genetics to other purebred breeders or to commercial operators. Purebred cows and heifers are bred naturally or by artificial insemination (AI) to accelerate genetic improvements, to capitalize on the use of sexed-semen, and to generate more predictable calving dates with a condensed calving season. Most purebred breeders calve between January and February. Commercial operations use primarily crossbred cattle to take advantage of hybrid vigour. Commercial cow calf operations in Canada use bulls to breed naturally in early summer and calve between March and June. Calves will stay with the dam for 6-8 months and will typically be weaned between September and November at weights ranging from 230 kg to 400 kg. Breeding and calving dates are dependent on region and operation preference. Cow-calf operations are primarily forage-based, grazing through late spring and summer with some operations extending grazing into late fall and winter.

ii) Backgrounding: This management system occurs between weaning and the feeding of high-energy diets. The goal is to maximize the use of forages to encourage slower growth prioritizing muscle and frame development over fattening. Calves suited for backgrounding include those that are typically under 8 months of age and require extra time to facilitate bone and muscle growth and are offered low-grain, high-forage diets including hay, silage, and pasture with an average daily gain (ADG) of approximately1 kg hd^{-1} d^{-1}. Backgrounding calves can either be sourced from the cow-calf operation where they were born, purchased directly from another cattle operation or auction marts. These calves can be fed in a drylot, on pasture or using a combination of both to variable end weights depending on feed availability and operational goals.

iii) Finishing: These operations are focused on feeding high-energy diets to promote the deposition of fat until a “finishing” weight is achieved at which point animals will be shipped for slaughter. These diets are primarily grain-based total mixed rations (TMR) and consist primarily of barley in western Canada and corn in eastern Canada with cereal silage (i.e., barley, wheat, corn, triticale) and feed additives to formulate a balanced diet with an ADG of 1.5 kg hd^{-1} d^{-1}.

2.2 Performance Enhancing Technologies

Performance enhancing technologies (PETs) including in-feed additives and hormone implants are used in the cattle industry to improve feed intake, feed efficiency and ADG (Ribeiro et al. 2021; Smith 2022). These products, which include β-adrenergic agonists, ionophores, and hormones in the form of implants and in-feed additives, have been used for over 50 years to improve feed efficiency and capture indirect benefits through a reduction in negative environmental impacts (Legesse et al. 2018a; Legesse et al. 2018b; Legesse et al. 2015; Johnson et al., 2013).

Alternatively, natural beef is produced in the absence pf products designed to promote growth. As of 2023, there is no regulation or accepted standard definition of what constitutes “natural” beef in Canada (Ribeiro et al. 2020).

2.2.1 β-adrenergic agonists

β-adrenergic agonists are fed during the last 20 to 40 days prior to slaughter and function to decrease fat deposition while increasing ADG, gain to feed ratio and hot carcass weight compared to cattle not fed β-AAs (Ribeiro et al. 2021; Montgomery et al. 2009; Nichols et al. 2005;). These compounds are repartitioning agents that dramatically increase protein synthesis while reducing adipose tissue deposition and protein degradation by regulating cell metabolism (Pfau et al. 2023; Harsh et al. 2021). Specifically, skeletal muscle mass of animals fed β-AAs increases as these compounds are bound to beta-adrenergic receptors (β-AR) resulting in the inhibition of protein turnover and promotion of protein synthesis (Johnson et al., 2014). Additionally, supplementation of β-AAs to animals increases blood flow to muscle providing cells with greater access to nutrients and improving growth (Mersmann et al. 1998). Johnson et al. (2014) reported that feeding β-AAs to cattle resulted in a 11-39% increase in the cross-sectional area of the longissimus muscle (LM) and an 8-40% increase in skeletal muscles compared to cattle not fed β-AAs. Feeding L-644,969, a β2-AA, resulted in a 27% decrease in protein degradation compared to untreated steers (Johnson et al. 2014; Wheeler and Koohmaraie, 1992).

While information on β-AR for bovine species is relatively limited, there have been 3 subtypes found in: β_1-AR, β_2-AR and β_3-AR (Johnson et al. 2014). These subtypes are associated with specific muscles and tissues and β-AAs only have an effect on tissues in which a specific β-AR is located. For bovine skeletal muscle, over 99% of the β-AR subtype consists of β_2 with 90% of the β-AR subtype in bovine adipose tissues being β_2 (Sillence and Matthews, 1994).

The magnitude of response associated with β-AAs is dependent on several factors which include, the abundance of β-AR and the distribution of the varying subtypes, dose, and length of exposure. Studies show that more mature and heavier cattle will respond better to β-AAs compared to younger, lighter calves, with prolonged exposure resulting in desensitization of β-ARs (Johnson et al. 2014; Hausdorff et al. 1990). This desensitization can be avoided by continuously increasing the dose throughout the finishing period. However, chronic exposure will eventually result in β-AR internalization from the cell surface resulting in a reduced abundance of β-AR mRNA (Hausdorff et al., 1990).

Despite the positive benefits regarding growth, use of β-AAs have been seen to negatively impact meat tenderness in cattle and other ruminants (Miller et al., 1988; Schiavetta et al., 1990). Growth improvements arising from reduction in protein degradation which ultimately reduces the rate of post-mortem proteolysis in the muscle, are the driving factors adversely impacting meat tenderness (Koohmaraie, 2002). The issue of decreased meat tenderness has been shown to be related to dose. Schroder et al. (2003) noted that heifers and steers fed 200 mg hd^{-1} d^{-1} of ractopamine had no impact on meat tenderness compared to a control group while heifers fed 300 mg hd^{-1} d^{-1} had increased shear force compared to control heifers and those fed 200 mg hd^{-1} d^{-1}.

2.2.2 Ionophores

Ionophores were historically used in the beef industry as a coccidiostat but are also used to improve growth efficiency by i) increasing efficiency of energy metabolism by ruminal bacteria, ii) improving nitrogen metabolism by ruminal bacteria and iii) reducing the incidence of digestive disorders derived from abnormal rumen fermentation (Bergen and Bates, 1984). While antibiotics, ionophores are classified as category IV – low importance antibiotics, which means there is little use in human medicine, and a low risk of them promoting resistance to important antimicrobials (Cameron and McAllister 2016; Health Canada, 2009). Ionophores are fat-soluble and promote the transport of nutrients across the lining of the gut, thereby increasing the permeability of the gut wall, improving feed efficiency and growth compared to non-treated animals (Russell and Strobel, 1989; Pressman 1976). Use of these in-feed antibiotics has also been shown to reduce digestive disorders such as bloat, sub-acute acidosis and bovine emphysema (Callaway et al. 2003). Ionophores change the microbiome in the rumen, favouring Gram-negative bacteria which shifts the VFA production from acetate which results in the formation of hydrogen, to propionate which utilized hydrogen and thereby lowers methane emissions (Callaway et al., 2003). Given these attributes, ionophores have also been shown to reduce mortality and morbidity in feedlot cattle.

In North America, there are four licensed ionophores approved for commercial use: monensin, lasalocid, laidomycin propionate and salinomycin (National Academies of Sciences, Engineering, and Medicine, 2016). Lasalocid is marketed as Bovatec by Zoetis and monensin as Rumensin by Elanco Animal Health are licensed for use in Canada. These products have been adopted by the finishing industry, accounting for 85% of antibiotic use in feedlots to mitigate risk of acidosis associated with feeding cattle high-energy, gain-based diets (Brault et al., 2019). Feedlot adoption of ionophores can also be attributed to their ability to enhance growth efficiency (6.4%), reduce dry matter intake (DMI) (3%), increase ADG (2.5%), function as a coccidiostat, and reduce enteric methane (CH_4) emissions (Callaway et al., 2003; Duffield et al., 2012). Ionophores have been shown to reduce CH_4 emissions by 27% of gross energy intake (GEI) after initial supplementation and 30% after 2 weeks (Guan et al. 2006). However, these authors reported adaptation after 4 to 6 weeks to ionophores even when 2 difference ionophores were used in rotation. Consequently, it appears that if they occur, monensin-related reductions in methane emissions are only short-term.

2.2.3 Steroid implants

Natural steroids are compounds such as testosterone, estradiol and progesterone which are found naturally in beef cattle of both sexes. However, synthetic hormones in the form of implants are also used in cattle to promote growth (Ribeiro et al. 2020; Duckett and Pratt, 2014). In Canada, it is estimated that 80% of cattle in feedlots and 54% of backgrounded cattle are implanted to improve ADG, decrease the cost of production, and cost to consumers (Hiroven et al. 2020; Sheppard et al., 2015; Parr et al. 2011). According to industry data (Beef Cattle Research Council, 2019) 26.5% of producers in western Canada implant pre-weaned calves. However, the use of implants in pre-weaned calves is much lower in Ontario (2.4%) and Atlantic Canada (0.24%). Recent Canadian data has demonstrated that implanting steers significantly increases ($P = < 0.001$) DMI, final body weight (BW), hot carcass weight (HCW), ADG (21.8%) and the gain to feed ratio (G:F; 17.5%) as compared to non-implanted steers (Ribeiro et al., 2020). Previous North American data also documented an 8 -28%, 6% and 5-20% increase in ADG, DMI and G:F, respectively, of implanted as compared to non-implanted cattle (Basarab et al. 2012; Wileman et al. 2009). In addition, anabolic steroids do not require any withdrawal period as the timing of implantation is such that almost all of the hormones are released from the implant prior to slaughter.

Despite the merit and wide adoption of implants, they may result in reduced fat cover (5%), marbling (5%) and grade (Johnson et al. 2013; Duckett and Pratt 2014). These negative carcass outcomes are of specific concern when using implants containing trenbolone acetate (TBA) which are analogues of testosterone that produce anabolic activity that is 10 to 50 times that of naturally occurring testosterone (Willemart and Bouffault 1983). To minimize these negative carcass effects without losing the benefits, the most common types of implants used in the beef industry are those with a combination of TBA and estradiol (E2) (Johnson et al 2013).

2.3 Consumer Influence on Beef Production

Consumer preferences with regard to beef include taste, how it was produced and the cost in addition to sustainable practices, food security, healthiness, animal welfare, traceability, and transparency (Grebitus et al., 2015; Hocquette et. al., 2014). In a recent survey, 58%, 54%, and 41% of consumers articulated their concerns regarding health, cost of food and the affordability of healthy food, respectively (Canadian Centre for Food Integrity (CCFI) 2023).

For example, 58% of North Americans self reported that they would prefer beef raised without hormones and antibiotics (Nielsen Global Health and Ingredient-Sentiment Survey (2016). However, this does not reflect their buying habits. In addition to domestic interest in PET-free beef, international markets, including the EU in the form of the Comprehensive Economic and Trade Agreement (CETA), can offer incentive to producers to reduce PET use by offering potential premiums. Previous literature has demonstrated that PETs are safe (You and Lee 2023; Cameron and McAllister 2016; Jeong et al. 2010; Preston 1997; Smith 1998), contribute to environmental sustainability (Boonstra et al 2023; Aboagye et al. 2022; Aboagye et al. 2021), and reduce the cost to producers and consumers (Hiroven et al. 2020; Rogers et al. 2015; Capper and Hayes, 2012; Parr et al. 2011). However, their use in beef production continues to be scrutinized (Nielsen Global Health and Ingredient Sentiment Survey 2016; CAPI 2023).

2.4 Beef production and the environment

Today's industry stakeholders, consumers and thus beef producers are motivated to reduce the environmental impacts of the global, including the Canadian, food system (Layman 2018). The environmental concerns are largely centered around GHG emissions, especially CH_4, and their role in climate change, nutrient leaching (nitrogen (N) and phosphorus), ammonia (NH_3) emissions as well as the water and land use.

2.4.1 Greenhouse gas emissions

The three gases primarily responsible for GHG emissions in terms of beef production are Carbon dioxide (CO_2), CH_4 and nitrous oxide (N_2O).

Carbon dioxide

Carbon dioxide (CO_2) is cycled through the naturally occurring carbon cycle, with CO_2 capture facilitated by green vegetation through photosynthesis, which can serve as temporary or long-term carbon storage. Carbon dioxide is returned to the atmosphere by metabolic processes during cell metabolism by animals and plants as well as the decomposition of organic matter (Friedlingstein et al. 2006). Additionally, the burning of fossil fuels are a significant source of anthropogenic CO_2 emissions which elevate atmospheric CO_2 levels and promote climate change (Solomon et al. 2009).

Fossil fuel emissions occur on beef operations during activities that require the use of equipment such as, feeding, pen cleaning, building fence, seeding, harvest and manufacturing of crop inputs like fertilizer and herbicides. While this is a relatively low source of emissions on beef farms (5%; Beauchemin et al. 2010), CO_2 emissions account for 80% of all Canadian GHG emissions are derived from burning fossil fuels (Environment and Climate Change Canada 2023). Emissions associated with CO_2 due to fossil fuel burning would be greatly reduced if energy were sourced through renewable means that do not release CO_2 such as solar, wind, hydro and nuclear power (Khan et al. 2021; Muellner et al. 2021).

Methane

The primary GHG concerning the carbon footprint of beef production systems is enteric CH_4 derived from microbial fermentation of feed in the rumen. Manure is also a source of CH_4 emissions as a result of manure decomposition in storage, on pasture and after land application. Methane is of key concern in terms of climate change as it has a global warming potential (GWP^{100}) that is 28 times that of CO_2 (IPPC 2021). Until recently, GWP^{100} has been the standard to compare GHGs in carbon dioxide equivalence (CO_2e). However, this metric does not account for differing GHG persistence, specifically between CH_4 and CO_2. The recent development of GWP* considers the half-life of atmospheric CH_4 which is 9.1 years, compared to CO2 which can persist for thousands of years (Allen 2016; IPCC 2021; Lynch et al. 2020).

Nitrous oxide

Nitrous oxide (N_2O) is a potent GHG (GWP = 265-298 CO_2e) with an atmospheric life of 114 years and is derived from manure and urine on cattle operations (Waldrip et al. 2020). These emissions, which occur directly from storage of manure and deposition in pastures and indirectly from nitrogen volatilisation and leaching are highly influenced by cattle density, manure mass, manure pack density, temperature and moisture (Redding et al. 2015). Further, crude protein (CP) content of the diet determines the amount of N that is excreted and thus the potential N_2O emissions (Dijkstra et al., 2011). The production of crops for feed also contribute to N_2O emissions through the application of N-based fertilizers onto crop land (Venterea et al. 2012). While high inputs of fertilizer and protein-rich feeds can increase productivity, most of the N fed will not be retained by meat or milk and will be excreted at a relatively equal rate in urine and feces (Kebreab et al., 2002; Calsamigilia et al., 2010). While N_2O emissions are a natural component of the N cycle, agriculture N_2O emissions along with fuel combustion, chemical manufacturing and treatment of wastewater are also anthropogenic sources of this ozone depleting GHG (US EPA, 2015). That being said, N_2O emissions derived from beef production in Canada have decreased by 19% over the past 3 decades via increased on-farm efficiencies and adoption of best management practices (BMP; Legesse et al., 2015).

2.4.1.1 The carbon footprint of Canadian beef

Agriculture was Canada's 5th largest contributor of GHG emissions in 2021 (by sector) accounting for 10% of Canadian GHG emissions. These emissions are mostly associated with emissions from agricultural soils and enteric fermentation (82%), in addition to manure management (13%), and the burning of crop residue (0.1%; Environment and Climate Change Canada, 2023). Beef production accounted for 34% of total agricultural emissions and approximately 3% of total Canadian emissions (Environmental and Climate Change Canada, 2023).

Several studies have been conducted to capture the emissions associated directly with Canadian beef production using life cycle assessments (LCA). An LCA study examining a 120-hd cow-calf herd over an 8-year period including finishing calves, including bulls, replacement heifers and the associated cropland, inputs and pasture required to sustain the simulated herd was used to estimate the GHG emissions from western Canadian beef operations (Beauchemin et al. 2010). These authors reported an emission intensity of 22 kg CO_2e kg carcass weight^{-1} with the majority of emissions attributed to the cow-calf herd (61%). Breeding stock, backgrounders and finishers accounted for 19%, 8%, and 12% of total emissions, respectively. Enteric methane accounted for 63% of total GHG emissions. The majority of enteric CH_4 emissions were associated with cows (79%) with the remaining 21% attributed to bulls (3%), calves (2%), backgrounders (7%), and finishers (9%).

Similarly, Legesse et al. (2015) used the methods and algorithms of the Holos model to evaluate the GHG emissions associate with Canadian cattle production in 2011 compared to 1981. Over the course of 3 decades, total emissions have increase by 28%. However, when analyzed on an intensity basis, emissions decreased from 15.6 kg CO_2e kg LW^{-1} in 1981 to 12.7 kg CO_2e kg LW^{-1} in 2011 resulting in a 15% decrease. These results were linked to increased efficiencies in reproduction, increased weaning and carcass weights, as well as increased crop yields.

Alemu et al. (2017a) examined GHG emissions associated with the cow-calf sector, analyzing 295 farms across Canada reflecting differences in regional conditions and management practices on Canadian operations. On average, beef farms had an emission intensity of 23.9 kg CO_2 kg LW^{-1} ranging from 16.3 to 37.8 kg CO_2 kg LW^{-1} with the largest emissions arising from enteric fermentation (65%) and manure storage (23%). These authors reported that improving reproductive, nutrition, and grazing has the potential to reduce emission intensity by up to 31%.

Although the beef industry produces GHGs, the grasslands, grazed by beef cattle contain large stocks of carbon and serve as a carbon sink (Council of Canadian Academies 2022). It has been previously estimated that Canadian cattle producers were responsible for preserving 1.5 billion tonnes of carbon (Canadian Round Table for Sustainable Beef 2016; Gerber et al., 2013). Of these 1.5 billion tonnes, 964 million tonnes existed in natural pastureland and the other 589 million tonnes in cropland, tame pasture, hay, and other land used by the beef industry (Gerber et al., 2013). The Canadian Roundtable for Sustainable beef is in the process of publishing updated information associated with the carbon footprint of Canadian beef cattle production. When carbon sequestration was considered, the GHG footprint of the Canadian beef industry decreased by 8-10.5% (kg CO_2e year^{-1}) and when considered globally, reduced emissions by 20% (kg CO_2e year^{-1}; Smith et al. 2014; Gerber et al., 2013).

Overall, North America is highly efficient in their beef production and a low GHG producer on an intensity basis compared to all other global regions. Specifically, North American beef production on average produces 110 kg CO_2e kg protein^{-1} compared to other beef production regions including South America (365 kg CO_2e kg protein^{-1}), Oceania (158 kg CO_2e kg protein^{-1}), and Western Europe (152 kg CO_2e kg protein^{-1}) which produce 232%, 44%, and 38% more, respectively than Canadian beef on an intensity basis (CAPI 2023).

2.4.1.1.1 Estimating on-farm GHG emissions using the Holos model

Holos (V2.1, Research; www.agrc.gc.ca/holos-ghg), an empirical model based on IPCC (Intergovernmental Panel on Climate Change) Tier 2 methodology (IPCC 2006) that was developed by Agriculture and Agri-Food Canada and modified for Canadian conditions to allow environmental modeling using a whole-farm approach (AAFC, 2018). Holos outputs are on an annual timestamp, predicting monthly GHG emissions associated with livestock production, cropping systems, as well as land use change and management (Aboagye et al. 2022). The model estimates CH_4 emissions from enteric fermentation and manure, N_2O emissions from N leaching, N runoff from agricultural soils, and re-deposition of volatilized ammonia, CO_2 emissions from on-farm fuel combustion, and the manufacturing of crop inputs such as fertilizer and pesticides are also considered (Boonstra et al. 2023). Therefore, Holos, is a valuable tool to estimate the total and source of GHG emissions from Canadian beef production systems but can also be used to evaluate the change in emissions associated with different management practices (Boonstra et al. 2023; Aboagye et al. 2022; Guyader et al. 2017).

2.4.2 Ammonia emissions

Agriculture and agricultural activities have been cited as the main source of NH_3 pollution (Behera et al. 2013). Sources of agricultural based emissions are associated with NH_3 volatilization as a result of nitrogen (N) fertilizer application and the excretion of manure and urine in livestock housing as well as during the storage, and spreading of manure (Kupper et al. 2015; Hristov et al. 2011). These emissions have negative environmental consequences, including air and water pollution, eutrophication, soil acidity and secondary aerosol formation which can have health implications for both humans and livestock (Hristov et al. 2011; Parker, 2011). While a colourless gas, the pungent smell associated with NH_3 is cause for public concern when farms are located close to residential areas.

The process of ammonia volatilization is highly complex and poorly understood, though it is influenced by a multitude of factors including the quantity and quality of N in the feed, rumen N utilization, pH, temperature, and wind speed (Hristov et al. 2011; Sommer and Hatchings 1995). Ammonia emissions are primarily associated with the interaction of nitrogenous compounds (urea and ureases) found in the manure and feces of livestock (Neumeier and Mitloehner, 2013; Cole et al., 2009). The primary source of NH_3 is urea in urine, which is directly related to the concentration of N in the feed, with an increase in urea output proportional to an increase of N content in the feed (Hristov et al. 2011).

The complexity of quantifying NH_3 emissions is increased in grazing cattle as the body of research focused in NH_3 is limited, with large variations in emissions due to limitations in available measurement strategies which include chamber and wind tunnels which are limited in their ability to predict NH_3 emissions in extensive systems (Voglmeier et al. 2018). Nonetheless, grazing has been reported to produce 8 times lower NH_3 emissions compared to indoor and confined feeding systems as urine directly infiltrates into the soil prior to the hydrolysis of urea and release of NH_3 (Voglmeier et al. 2018). For example, NH_3 emissions from feedlot pen surfaces were 3.6 to 88 $\mu g\ m^{-3}\ s^{-1}$ (Hristov et al. 2011), while emissions of 4 to 15 $\mu g\ m^{-3}$ have been reported for pasture (Voglmeier et al. 2018).

A Canadian study conducted by Legesse et al. (2018b) evaluated the differences in NH_3 emission intensity from Canadian beef production between 1981 and 2011. These authors reported higher NH_3 emissions in 2011 compared to 1981 (18.4 and 16.0 kg NH_3 animal^{-1} year^{-1}, respectively), however, there was 20% decrease in emission intensity over this same time period (from 0.17 to 0.14 kg NH_3 kg beef^{-1}). For both years, 22% of total N intake was lost as ammoniacal nitrogen (NH_3-N) with an N excretion rate of 89% and 90% for 2011 and 1981, respectively. Sources of manure emissions included grazing (12%), confinement (40%), storage (28%), and land spreading (21%). Mature cows were the main source of NH_3 emissions accounting for almost half, followed by backgrounding (24%) and finishing cattle (28%). The remainder of NH_3 emissions were attributed to calves, bulls, and replacement heifers (Legesse et al. 2018b). These authors attributed the differences in NH_3 emissions intensity over three decades to improved reproduction efficiency, increased ADG and carcass weight.

2.4.3 Water usage

One of the most concerning consequences of global population growth is the depletion of fresh water sources due to pollution and climate change (Arto et al. 2016). With these increasing concerns, water usage by ruminants and other livestock is under public scrutiny. Agriculture's water footprint can be classified into 3 categories i) green water (rainwater and evapotranspiration from soils), ii) blue water (i.e., surface and ground water used for irrigation) and iii) grey water (water used by individuals, industry, agriculture etc. that has high concentrations of contaminates; Mekonnen and Hoekstra 2011). For beef production, water use is either attributed directly to animal consumption (directly via drinking or through the water portion consumed in feed) or what is required to produce crops for feed. While drinking water is essential for beef production in addition to animal health and welfare, it typically accounts for less than 1% of the water footprint of beef (Boonstra et al. 2023; Aboagye et al. 2022; Legesse et al, 2018a; Blümmel et al., 2014; Gerbens-Leenes et al., 2013).

Previously literature evaluated the water use of multiple livestock production systems on a global scale which included indirect water required to produce crops for feed, water that was drank by livestock, water that was consumed in feed and the water required to clean and maintain livestock facilities (grey water; Mekonnen and Hoekstra, 2011). These authors determined beef ultimately had the highest water footprint of the 8 livestock production systems analyzed ($7477 m^3 ton^{-1}$ or $1889\ m^3 hd^{-1}$) at an average finishing weight of 253 kg. The global average for beef water use intensity was found to be $15400\ m^3\ ton^{-1}$ carcass yield^{-1} of which green, blue, and grey water accounted for 94%, 4% and 3%, respectively. As with other studies analyzing water use, these authors found the largest share of water use intensity was attributed to the production of crops, as a result of the use of green water (Mekonnen Hoekstra 2011) with the water footprint being lower for crops that promoted higher feed conversion rates (i.e., barley vs. tame pasture), that enabled cattle to reach finishing weight faster.

Legesse et al. (2018a) evaluated the water footprint between 1981 and 2011. Of total water use, the breeding herd which include bulls, cows, replacement heifers and calves, accounted for 66% and 64% of water use in 1981 and 2011, respectively. This included the majority of water intake from drinking and feed with 70% attributed to consumption by the breeding herd. Legesse et al (2018a) also found that type of crop had an impact on the water use intensity on a DM basis, with barley grain (1093 L kg DM^{-1}) requiring more water than forages including native pasture (535 L kg DM^{-1}), tame pasture (468 L kg DM^{-1}) or grass hay (548 L kg DM^{-1}). However, as barley is typically higher yielding and forage accounted for a larger portion of the diet in Canadian beef systems, pasture had the highest rate of water use (Legesse et al. 2018a). Overall, between 2011 and 1981 total water use, and water use $steer^{-1}$ was 30% and 14% higher, respectively. Nonetheless, the amount of beef produced had significantly increased which resulted in a 17% decrease in water use on an intensity basis (L kg boneless $beef^{-1}$) in 2011 compared to 1981 (Legesse et al. 2018a).

2.5 Environmental impacts of removal of productivity enhancing technologies from Canadian beef systems

As previously described, increasing production efficiency via nutrition, reproduction and genetics has mitigated the environmental impacts of Canadian beef production over time (Legesse et al. 2015, 2018a, 2018b; Neumeier and Mitloehner 2013). More specifically, improvements in production efficiency achieved through the use of PETs have also led to demonstrated improvements in environmental sustainability. Using an LCA approach, several studies found that cattle treated with PETs, including steroid implants and feed additives like ionophores and β-AAs had a 1.1-28% decrease in GHG emissions (Boonstra et al. 2023, Aboagye et al 2021, 2022; Capper et al. 2021; Webb 2018), 9.9-19.5% reduction in land use (Boonstra et al. 2023; Aboagye et al. 2022), reduced NH_3 emissions by 7-18% (Boonstra et al. 2023; Aboagye et al. 2021; Capper at al. 2021), and water use by 10-19% (Boonstra et al. 2023; Aboagye et al. 2022; Capper et al. 2021) compared to cattle raised in absence of PETs. Additionally, the use of PETs resulted in a 6-18% decrease in N excretion (Boonstra et al. 2023; Aboagye et al. 2022; Capper et al. 2021) and a 4-16% reduction in CH_4 emissions (Boonstra et al. 2023; Aboagye et al. 2022; Stackhouse-Lawson et al. 2012). Lower environmental impacts are related to the dilution of maintenance requirements facilitated by PETs (Capper 2012) in which increased efficiency leads to an increase in output (i.e., kg boneless beef or kg LW) with a reduced environmental footprint.

2.6 Conclusion

Producers and consumers share the same goal, access to healthy, affordable food that is environmentally sustainable and harvested humanely. While international and domestic consumer demands are valid, and niche markets can provide valuable opportunities for beef producers, assessing the environmental benefits of employing these technologies is essential to inform consumers via science-based conclusions to promote informed food choices and ensure consumer trust. The research conducted in Canada in this area has focused on systems which are characterized by confined backgrounding and finishing systems but has not included those systems in which cattle are backgrounded on pasture, leaving a gap in knowledge regarding the environmental benefits the PETs may confer in more extensive production systems.

3 HYPOTHESIS AND OBJECTIVES

3.1 Hypothesis

The use of productivity enhancing technologies (PETs) will result in a reduction of the environmental footprint of steers directly finished, backgrounded before finishing and after two-phase backgrounding in confinement followed by pasture prior to finishing due to increased growth efficiency associated with the use of ionophores and implants. Increasing the length of time between weaning and slaughter via post-weaning management strategy will increase the environmental footprint as compared to direct finishing due to an increase in days on feed (DOF) and resources required to reach finish weight. Environmental indices to determine the environmental footprint include: i) greenhouse gas emissions (carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)), ii) land use, iii) water use and iv) ammonia emissions (NH_3).

3.2 Objectives

The objective of this research was to model and compare the environmental impacts (GHG and NH_3 emissions, land, and water use) off a multi-year study using three feeding management strategies: i) steers directly finished, ii) backgrounded before finishing and iii) two-phase backgrounding which included confined and pasture-based backgrounding prior to finishing, with and without PETs. Input data included diet and pasture quality, dry matter intake (DMI), average daily gain (ADG), body weight (BW), dry matter intake (DMI), hot carcass weight (HCW), dressing percent (DP), carcass grade, climatic information, and regionally-specific crop yields.

4 MANUSCRIPT

ENVIRONMENTAL IMPACTS ASSOCIATED WITH THE REMOVAL OF PRODUCTIVITY ENHANCING TECHNOLOGIES FROM THREE DIFFERENT BEEF STEER POST-WEANING FEED MANAGEMENT STRATEGIES IN SASKATCHEWAN: A CASE STUDY

4.1 ABSTRACT

Environmental impacts of post-weaning strategies to raise beef steers with (CON) or without (NAT) productivity enhancing technologies (PETs) were evaluated using a whole-farm system approach to estimate greenhouse gas (GHG) emissions via Holos, as well as ammonia (NH_3) emissions, land requirements and water use via spreadsheet models adapted to reflect the Canadian production environment. Post-weaning strategy was assigned by weaning weight (WW) and included direct finishing for Heavy steers (WW= 295 kg ± 11kg), confined backgrounding before finishing for Medium steers (WW= 250 kg ± 11 kg) and 2-stage backgrounding (confined feeding and summer grazing period) before finishing for Light (WW= 205 kg ± 11 kg) steers. Model inputs were sourced from a replicated production study (n=2 trials) comparing the performance of steers assigned to six management strategies (n=40 hd treatment^{-1} trial^{-1}): i) Heavy conventional (HCON); ii) Heavy natural (HNAT); iii) Medium conventional (MCON); iv) Medium natural (MNAT); v) Light conventional (LCON); and vi) Light natural (LNAT). Medium and Light steers were backgrounded in confinement for an average of 98-d ± 8-d and 195.5-d ± 7.5-d, respectively. In addition to being backgrounded in confinement, Light steers were also grazed for an average of 67.5-d ± 12.5-d, with duration in each year dependant on pasture forage availability. Cattle in all treatments were finished to a target final weight of 646 kg. Conventional steers had 10-13% lower GHG emissions (kg CO_2e kg boneless beef^{-1}), 10-32% lower NH_3 emissions (kg NH_3 kg boneless beef^{-1}), 9-22% lower land requirements (ha kg boneless beef^{-1}), and 12-25% lower water use (m^3 kg boneless beef^{-1}) compared to NAT steers. Comparatively, conventional direct finishing (HCON) had lower GHG (32% and 39% kg CO_2e kg boneless beef^{-1}) and NH_3 (36% and 52% kg NH_3 kg boneless beef^{-1}) emissions, land requirements (25% and 73% ha kg boneless beef^{-1}) and water use (18% and 51% m^3 kg boneless beef^{-1}) compared to MCON and LCON, respectively. Use of PETs, regardless of post-weaning management system, yielded lower environmental impacts than natural beef production systems. Additionally, based on estimated environmental indices, higher efficiency programs yielded the lowest environmental impact. However, sustainability metrics including habitat preservation and biodiversity were not included in the analysis. This research adds to the growing body of knowledge that use of PETs are a valuable tool to improve the environmental sustainability of beef production during confined backgrounding and finishing, and provides novel information regarding use in extensive backgrounding systems.

4.2 INTRODUCTION

Global protein demand is predicted to rise 14% by 2030 and 33% by 2050 as a consequence of increasing global population and incomes (OECD 2021; Henchion et al. 2017). Although this presents opportunities for Canadian beef production as the world's 8th largest exporter of beef and veal products (Canfax Research Services 2023), increased production must be achieved with an increased emphasis on food security while ensuring sustainability (Le Mouël and Forslund 2017). The latter is particularly important for the beef sector as several studies have reported a higher carbon footprint for beef compared to other animal-based protein sources including chicken, pork, lamb, eggs, and milk (Dyer et al., 2010; Lesschen et al., 2011; Browne et al., 2011). In response, the Canadian beef industry has set ambitious goals through Canada's National Beef Strategy to reduce GHG emissions by 30%, reduce food loss and waste by 50% and maintain the 14 million ha of native grasslands currently under the care of beef producers by 2030 (CRSB 2016).

Productivity enhancing technologies (PETs) including steroid implants, β-adrenergic agonists (β-AAs) and ionophores are widely employed in the confined feeding (backgrounding and finishing) sector in North America to improve feed and growth efficiency (Ribeiro et al. 2020; Smith 2022). Several studies have associated the use of these products to a reduction in GHG (1.1-28%; Boonstra et al. 2023; Aboagye et al. 2021, 2022; Capper et al. 2021; Webb 2018) and NH_3 (7-18%; Boonstra et al. 2023; Aboagye et al. 2022; Capper et al. 2021) emissions, as well as land (9.9-19.5% Boonstra et al. 2023; Aboagye et al. 2022) and water use (10-19%; Boonstra et al. 2023; Aboagye et al. 2022; Capper et al. 2021). However, little work has examined the link of the increased efficiencies and reduced environmental impacts of pasture-based backgrounding programs.

Diversifying calf management strategies, including the use of backgrounding in confinement and on pasture, are designed to achieve a slower rate of gain to build muscle and bone structure in lighter weight calves. Additionally, niche markets offer producers the opportunity to receive premiums by employing specific programs or management strategies, including the removal of PETs (Zimmerman et al. 2012; Seeger et al. 2011). Natural or free-from programs have been developed in response to consumer demand. Approximately 58% of North

Americans have indicated they prefer beef that has not been raised with antibiotics or hormones (Nielsen Global Health and Ingredient-Sentiment Survey 2016). Further, international trade agreements including the Canada-European Union Comprehensive Trade Agreement (CETA; AAFC 2018), were implemented to increase export opportunities to the European Union (EU). However, it is essential to understand the impacts of the removal of PETs on beef production in Canada to ensure that all stakeholders have access to the data required to make informed food choices and identify opportunities to reduce environmental impacts through increased efficiencies.

The purpose of this study was to understand the impact of PET removal on GHG and NH_3 emissions in addition to land and water use in steers raised in three post-weaning management systems including direct finishing, confined backgrounding prior to finishing and confined and pasture-based backgrounding prior to finishing. The use of PETs to reduce the environmental footprint of steers managed in a pasture-based backgrounding system has not previously been analyzed in western Canada.

4. 3 MATERIALS AND METHODS

4.3.1 Trial design

Description of experimental sites and climate

Animal performance and cropping system data used in the present study were collected from a replicated backgrounding and finishing study conducted by the University of Saskatchewan from November 28, 2017, to December 12, 2018 (Year 1) and December 11, 2018, to January 21, 2020 (Year 2; Smith 2022). Three sites were used for the backgrounding, grazing, and finishing phases of the study. Backgrounding and grazing phases were conducted at the Lanigan Livestock and Forage Centre of Excellence (LFCE) site (lat 51°51´N, long 105°02´W) for Year 1 and 2. In Year 1, receiving and finishing phases were conducted at the University of Saskatchewan Beef Research and Teaching unit (BCTRU) in Saskatoon (lat 52°09’N, long 106°37' W) and the LFCE BCTRU site in Clavet (lat 51°56’N, long 106°22' W) in Year 2.

Ecodistricts for the three sites were identified as follows: Lanigan - 745 (Quill Lake Plain), Saskatoon – 772 (Saskatoon Plain) and Clavet – 773 (Elstow Plains). The Saskatoon Plains and Elstow Plains ecodistricts were characterized by dark brown chernozem soils, 3B hardiness and was located in the moist mixed grasslands ecozone, while Quill Lake possessed black chernozem, 3A hardiness and was located in the aspen parkland ecozone (Saskatchewan Crop Planning Guide, 2017 and 2018; Saskatchewan Conservation Data Centre, 2023). Weather inputs, which included 30-year average (1990-2020) monthly temperature and precipitation (Table 4.1) from May to October (crop growing season) were obtained from Environment and Climate Change Canada (2020). More specifically, data was obtained from Saskatoon SRC (1990-2007) and Saskatoon RSC (2009-2020) Stations for ecodistricts 772 and 773 as these two stations were centrally positioned between the Saskatoon and Clavet locations. The 30-year average data did not include 2008 as Saskatoon SRC was only operational until 2007, being replaced by RCS in 2009. Data from the Watrous Station (1993-2020) was used to estimate temperature and precipitation for ecodistrict 745 (Lanigan, SK site).

Table 4.1 Long-term average (1990 to 2020) temperature and growing season (May to October) precipitation for Lanigan, SK and Saskatoon/Clavet, SK (Environment and Climate Change Canada 2020)

	Mean temperature (°C)		Mean growing season precipitation (mm)	
Month	Lanigan[b]	Saskatoon/Clavet[a]	Lanigan[b]	Saskatoon/Clavet[a]
January	-15.3	-14.7	-	-
February	-13.9	-11.9	-	-
March	-6.2	-5.7	-	-
April	3.0	3.6	-	-
May	10.3	11.2	43.7	45.9
June	15.3	16.0	71.7	81.6
July	17.7	18.6	74.5	56.3
August	16.9	17.6	42.6	37.2
September	11.7	12.4	41.8	30.2
October	3.6	4.1	28.9	21.3
November	-5.8	-5.5	-	-
December	-12.7	-12.6	-	-
Total	-	-	303.2	272.5

[a] Saskatoon weather stations (SRC and RSC)
[b] Watrous weather station

Description of steer production systems

As described by Smith (2022), 240 weaned Angus-cross steers that had not previously received hormonal implants were purchased and sorted into three groups by body weight: i) Heavy (*n* = 80; 295 kg ± 11 kg); ii) Medium (*n* = 80; 250 kg ± 11 kg), and iii) Light (*n* = 80; 205 kg ± 11kg; Table 4.2). The steers from all three weight groups were randomly assigned to a conventional (CON) or natural (NAT) production system (Table 4.3), resulting in six treatments (n=40 treatment^{-1}): i) Heavy weight steers finished conventionally (HCON); ii) Heavy weight steers finished naturally (HNAT); iii) Medium weight steers backgrounded and finished conventionally (MCON); iv) Medium weight steers backgrounded and finished naturally (MNAT); v) Light weight steers backgrounded, grazed, and finished conventionally (LCON) and vi) Light weight steers backgrounded, grazed, and finished naturally (LNAT). Backgrounding occurred in confinement and on pasture for Light steers. To differentiate these two feeding phases, the summer grazing period will henceforth be referred to as ‘grazing’ while backgrounding in confinement will be referred to as ‘backgrounding’.

Table 4.2 Weight of cattle assigned to Heavy, Medium and Light treatments during the feeding period (Smith 2022)

	Treatments		
	Heavy	Medium	Light
Weaning weight (kg)	295	250	205
Avg trial start weight (kg)	346	300	256
Backgrounding end weight (kg)	-	430	320
Finishing end weight (kg)	646	646	646

Heavy steers were not backgrounded to reflect a direct finishing system which is most common in Canadian feedlots.

Steer management

Upon arrival, all steers received Bovishield Gold (infectious bovine rhinotracheitis, bovine viral diarrhea Type 1 and 2, parainfluenza type 3, bovine respiratory syncytial virus, *Mannheimia* haemolytica; Zoetis, Kirkland, QC) and Ultrabac 7/Somnubac (*Clostridium chauvoei, Cl. septicum, Cl. novyi, Cl. sordellii, Cl. perfringens types C and D, and Haemophilus somnus;* Merck Animal Health, Kirkland, QC*)* and a topical antiparasitic product (Solmectin; Solvet, AB; Table 4.3). In addition, conventional steers were treated with Draxxin (Zoetis, Kirkland, QC) and implanted with Ralgro (36 mg zeranol; Merck Animal Health Ltd., Kirkland, QC). Steers in the natural treatments were not given any product until the finishing period where they again received Solmectin.

Table 4.3 Management of steers assigned to the natural (NAT) and conventional (CONV) treatments during the backgrounding, grazing and finished phases[a]

Phase	Treatment	
	CON	NAT
Receiving	Solmectin[b]	Solmectin
	Bovishield Gold One-Shot[c]	Bovishield Gold One-Shot
	Ultrabac 7/Somnubac[d]	Ultrabac 7/Somnubac
	Draxxin[e]	-
	Ralgro[f]	-
Backgrounding	Ralgro	
	Monensin (33 ppm)[g]	
	Tylosin (11ppm)[g]	-
		-
Grazing	Revalor-G[h]	-
Finishing	Solmectin	Solmectin
	Revalor-S[i]	-
	Monensin (33 ppm)[g]	-
	Tylosin (11 ppm)[g]	-

[a] Table modified from Smith (2022)
[b] Solmectin-Solvet, Calgary, AB, Canada
[c] Bovishield Gold One-Shot-Zoetis, Kirkland, QC, Canada
[d] Ultrabac 7/Somnubac-Merck Animal Health, Kirkland, QC, Canada
[e] Draxxin-Zoetis, Kirkland, QC, Canada
[f] Ralgro-36 mg zeranol; Merck Animal Health Ltd., Kirkland, QC, Canada
[g] Contained in the CON pellet processed at CO-OP Feed (Saskatoon, SK).
[h] Revalor-G-Merck Animal Health, Kirkland, QC, Canada
[i] Revalor-S-120 mg trenbolone acetate, 24 mg estradiol, Merck Animal Health, Kirkland, QC, Canada

Feeding strategy

Weaned steers were fed a total mixed ration (TMR) of grass hay (27.2% DM), barley silage (21.6% DM), barley grain (39.3 DM), canola meal (6.5% DM). Steers in the CON treatments received a pelleted supplement containing 11 mg/kg Tylosin; and 33 mg/kg Monensin (5.4% DM) while those in the NAT treatment received the same pellet without either of the medicated ingredients (5.4% DM) for a 40-d receiving period. Thereafter, Heavy steers were offered a finishing diet consisting of barley silage, dry-rolled barley grain and canola meal (Table 4.4) for 162-d to 219-d and 148-d to 191-d, in Year 1 and 2, respectively. Medium steers were offered a backgrounding diet consisting of barley greenfeed, barley grain, canola meal and a CON or NAT pellet (Table 4.4) in the drylot for 106-d and 90-d in Year 1 and 2 respectively, before transitioning to the finishing diet. Light steers were backgrounded in a drylot for 188-d and 203-d in Years 1 and 2, respectively, followed by an 80-d and 55-d summer grazing period in year 1 and year 2 respectively, and finished thereafter. Steers in the LCON and LNAT treatments were rotationally grazed on pastures comprised of the following three forage mixes: i) crested wheatgrass-smooth brome mix consisting of 75% crested wheatgrass (*Agropyron cristatum* L.), 15% smooth brome (*Bromus inermis* L.), and 15% other species, ii) meadow bromegrass-cicer milkvetch mix consisting of 45% meadow brome grass (*Bromus riparius* Rehm.) , 23% cicer milkvetch (*Astragalus cicer* L.), and 32% smooth bromegrass-alfalfa (*Medicago sativa* L.) iii) annual spring seeded Hazlet fall rye (*Secale cereale* L.).

Table 4.4. Backgrounding and finishing inclusion rates (%DM) for Year 1 and Year 2 for all feeding management strategies[a]

	Inclusion rate, % DM			
	Backgrounding diet	Finishing diet		
Item	Medium/Light	Heavy	Medium	Light
Barley greenfeed				
Year 1	59.4	-	-	-
Year 2	64.4	-	-	-
Barley silage				
Year 1	-	6.8	6.4	6.8
Year 2	-	7.2	6.3	6.8
Barley grain				
Year 1	29.9	84.4	84.9	84.1
Year 2	25.7	85.3	84.9	86
Canola meal				
Year 1	5.3	3.5	3.51	3.9
Year 2	4.3	2.3	3.46	2.2
Pellet				
Year 1	5.4	5.2	5.21	5.1
Year 2	5.5	5.2	5.3	4.9

[a]Smith (2022)

All diets offered during confinement were formulated to meet or exceed the nutrient requirements of growing and finishing cattle (NASEM 2016) with a targeted finish weight of 646 kg (Table 4.5). During backgrounding and finishing phases, diets were prepared as a TMR. “Slick bunk” management was used during confined feeding periods to limit feed remaining in the bunk and encouraging DMI. During backgrounding and finishing all pens were bedded with straw.

Feed samples were collected every 14 days, compiled monthly for grain and forage samples, by load for pellet and canola meal, and analysed as described by Smith (2022). Crude protein (CP; kg kg^{-1} diet dry matter (DM) and total digestible nutrients (TDN; %) values were pooled by phase (Table 4.5). Dry matter intake was calculated as the difference between feed offered and refused. As fed weights were recorded daily and refusals were collected every 14 days.

Table 4.5 Crude protein (CP) and total digestible nutrient (TDN) concentration of backgrounding, grazing, and finishing diets delivered to steers during Year 1 and Year 2[a]

	CP, % DM			TDN, % DM		
Item	Heavy	Medium	Light	Heavy	Medium	Light
Backgrounding diet						
Year 1	-	13.0	13.0	-	65.7	65.7
Year 2	-	12.3	12.3	-	63.9	63.9
Pasture composition						
Year 1	-	-	13.9	-	-	60.1
Year 2	-	-	12.1	-	-	62.0
Finishing diet						
Year 1	12.1	12.2	14.3	79.4	79.3	78.9
Year 2	12.7	13.4	14.1	80.5	80.1	78.8

[a]Smith (2022)

Body weight of each steer was measured on two consecutive days at the beginning, end, and at two-week intervals of each feeding phase. Average daily gain (ADG) was estimated monthly within each feeding phase.

Upon reaching finished weight, steers were slaughtered and processed at Cargill in High River, AB. Carcass characteristics including hot carcass weight (HCW), and dressing percentage (DP) were obtained post-slaughter (Table 4.6). Slaughter weight was used to estimate boneless beef (kg) as described in equation 1 (Agriculture Marketing Guide 2021).

$$Boneless\ Beef = DP * Slaughter\ Weight *0.73 \tag{1}$$

Where:

Boneless beef = the lean meat component from a beef carcass, kg;

DP = average dressing percentage, %;

0.73 = conversion rate from slaughter weight to boneless beef (Agriculture Marketing Guide 2021).

Table 4.6 Carcass outcomes including finished body weight (BW), hot carcass weight (HCW) dressing percentage (DP), and boneless beef of Heavy (H), Medium (M) and Light (L) steers raised with (CON) or without (NAT) productivity enhancing technologies

		Treatment					
Parameter	Year	HCON	HNAT	MCON	MNAT	LCON	LNAT
Finished BW, kg	1	646.3	652.1	651.4	639.7	674.0	672.7
	2	638.2	646.3	640.4	656.0	655.9	654.6
HCW, kg	1	366.5	367.3	369.2	363.5	366.9	377.2
	2	376.9	365.1	360.7	372.2	357.0	367.7
DP, %	1	59.1	58.7	58.5	59.4	56.7	58.5
	2	61.1	58.7	58.3	59	57.3	59.1
Boneless beef, kg	1	244.5	245.0	246.3	242.5	244.8	251.6
	2	251.4	243.5	240.6	248.3	238.1	245.3

Land use requirements

Land use requirements (ha treatment^{-1}) were calculated by using inclusion rate of ingredients (DM %), dry matter intake (DMI), number of days on feed (DOF), number of steers, as well as feeding and storage losses (Eq 2; Rotz and Much 1994).

$$L = \frac{\left(\frac{\mathrm{DMI} \text{ x } n \text{ x } \mathrm{DOF} \text{ x } i}{\mathrm{DM}}\right) \text{ x } (1+wf)}{\mathrm{y}} \tag{2}$$

Where:

L = Land requirement for specified feed ingredient (ha)
DMI = Average dry matter intake for the treatment (kg/day)
n = number of steers in the treatment group
DOF = number of days the steers in each treatment were on feed
i = Inclusion rate of feed ingredient in the diet (%)
DM = Dry matter of the feed ingredient (%)
wf = Waste factor of ingredient (%)
y = Yield of the feed ingredient (kg/ha)

Dry matter intake for tame pasture was estimated by assuming steers consumed 2.5% of their body weight in DM and multiplied by DOF to determine intake per head during the grazing period (National Academies of Sciences, Engineering and Medicine 2016). Utilization percentage was estimated by multiplying DMI hd^{-1} by 40 to account for all animals and dividing by measured pasture yields (Smith 2022). To determine the land area used to produce canola meal, it was assumed it accounted for 55% of the seed DM after processing (Canola Council of Canada 2020).

Cropping system inputs and yields

Canola and barley grain were assumed to be grown locally within the LFCE Clavet with low-till management. Inputs, seeding rate and yield were obtained from the 2017 and 2018 Saskatchewan Crop Guides for Dark Brown soil zones, while barley silage, barley greenfeed and tame pasture were all grown at the LFCE Lanigan with known inputs, seeding rates and yields (Table 4.7).

Inputs of nitrogen (N) included synthetic N fertilizer (anhydrous and granular), N deposited by grazing steers and above- and below ground residue decomposition. Rate of synthetic N fertilizer application and total land it was applied to was provided by the growers for silage, greenfeed and Hazlet fall rye (56 kg N/ha; Smith 2022), while barley grain and canola were estimated by land requirements and fertilizer application recommendations provided by the Saskatchewan Crop Report for the area, soil type and year (Government of Saskatchewan 2017; Government of Saskatchewan 2018). Annual phosphorus (P) fertilizer application rates for canola and barley grain were obtained from the Saskatchewan Ministry of Agriculture Crop Planning Guide (2017; 2018), when grown in dark brown soil zones and averaged for both years. No irrigation was considered for the feed crops.

Table 4.7 Average yield, dry matter (DM, %), harvest and storage losses, and fertilizer inputs associated with production of the feed ingredients included in backgrounding, grazing, and finishing diets during Year 1 and 2

Feed ingredients	Yield (kg ha^{-1} as fed)	DM (%)[a]	Feeding and storage loss (%)[b]	Land applied nitrogen (kg N ha^{-1})	Land applied phosphorus (kg P_2O_5 ha^{-1})
Barley greenfeed	6747.1[a]	80.8	20.0	93.4[a]	24.3[a]
Barley silage	14044.5[a]	35.5	5.0	0.5[a]	0.0[a]
Barley grain	3604.0[c]	90.0	0.0	77.4[c]	33.6[c]
Canola meal[d]	1888.4[c]	89.5	0.0	98.6[c]	53.8[c]
Tame pasture	2499.4[a]	-	0.0	0.0[a]	0.0[a]

[a] Obtained from Smith (2022)

[b] Rotz and Muck (1994)

[c] Saskatchewan Crop Planting Guides (2017; 2018)

[d] Canola meal was assumed to account for 55% of the canola yield after processing (Canola Council of Canada 2020).

4.3.2 Estimating greenhouse gas emissions

The Holos model (V3.0.5, Research; www.agr.gc.ca/holos-ghg), developed by Agriculture and Agrifood Canada, was used to estimate greenhouse gas (GHG) emissions from weaning to finishing including all processes involved in growing feed and feeding steers in each of the six treatment groups (Little et al., 2008; Krobel et al., 2012). Holos is an empirical model based on IPCC Tier II methodology (Intergovernmental Panel on Climate Change, IPCC, 2006) and modified for Canadian conditions (Alemu et al., 2017a). Holos has been used in previous studies to estimate whole-farm GHG emissions of Canadian cattle operations (Alemu et al. 2017b; Beauchemin et al. 2010; Guyader et al. 2017; Little et al. 2017). Recently, Holos has been used to estimate and compare the GHG emissions associated with commercial Canadian beef production systems finished with and without PETs (Aboagye et al. 2022; Boonstra et al., 2023).

The GHG emissions estimated in Holos included: i) methane (CH_4) from enteric fermentation and manure decomposition; ii) direct nitrous oxide (N_2O) emissions from soils associated with cropping and pasture; iii) carbon dioxide (CO_2) from on-farm energy consumption and manufacturing of fertilizer and herbicide iv) CO_2 sequestration or storage from perennial pastures and iv) indirect N_2O emissions from N leaching, runoff, and re-deposition of volatilized ammonia. Emissions contributed by transportation of animals, feed, supplements, PET products or other goods required for the production of beef steers, as well as processing and manufacturing were not included in the scope of this analysis.

Methane emissions from enteric fermentation were estimated using a CH_4 conversion factor of the diet, total digestible nutrients (TDN) and crude protein (CP) content in the diet. Manure CH_4 emissions were estimated from the type of manure handling practices utilized on farm and the associated conversion factor (MCF). Manure was managed using deep bedding during backgrounding and finishing (MCF = 0.17) and directly deposited on pasture with no storage or intervention during grazing (MCF = 0.01).

Total N inputs which included crop residues, manure application, manure deposited on pasture and above- and below-ground residues were used to estimate direct N_2O emissions which resulted from nitrification and denitrification of agricultural N using a Canadian specific algorithm (Rochette et al., 2018). Growing season, precipitation, and potential evapotranspiration, soil variables including soil type and texture, tillage management, and geography were adjusted within the model. Average temperature and soil N_2O conversion were included as monthly variables to compile the annual soil N_2O emissions allocated to each month (%). Direct N_2O emissions (manure storage and deposition) were estimated using the emissions factor (EF; kg N_2O-N $(kgN)^{-1}$) which coincided with the manure handling system. Factors contributing to indirect N_2O included N leaching and volatilization fractions, were estimated using the EF of 0.0075 and 0.01, respectively.

The primary sources of on-farm CO_2 emissions were fossil fuel consumption and energy required to produce crops including machinery use and animal feeding. Secondary sources of CO_2 emissions were from manufacturing of crop inputs (e.g., fertilizer and herbicides). In addition to estimating CO_2 emissions, Holos also estimated CO_2 stocking exchange associated with management practices that induce changes in carbon storage including tilling, grazing management and crop species. Soil carbon storage or sequestration associated with the perennial pasture was estimated during the pasture-based backgrounding period. Seeded or tame grasslands were assumed to be converted from annual crop land with carbon storage from existing stands estimated based on time since management change, the carbon change rate for the seeded perennials, ecodistrict and total area.

Total emissions were estimated for each feeding period (backgrounding, grazing, and finishing) and summed in CO_2 equivalents (CO_2 eq) is based on methodology described by the Intergovernmental Panel on Climate Change (IPCC; 2006) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). This approach was utilized by multiplying the global warming potential (GWP^{100}) of the gas by the total emissions of the individual GHG using CO_2 as a base unit to evaluate the emission intensity of a particular activity (e.g., livestock production). The GWP^{100} of the above described GHGs were: CO_2: 1, CH_4: 28, and N_2O: 265 to 298 (IPPC, 2021). System boundary and scope used values of 23 and 296 for CH_4 and N_2O, respectively in the Holos model Version 3.0.6. Emission intensities were expressed as kg total LW at time of slaughter (kg CO2e, kg LW^{-1}), per kg HCW (kg CO_2e, kg of HCW^{-1}), and per kg of boneless beef (kg CO_2e, kg of boneless $beef^{-1}$).

4.3.3 Estimating ammonia emissions

N intake and total ammoniacal nitrogen excretion

Excreted total ammoniacal N (TAN) was assumed to be contributed by NH_3, urea within urine and other sources of hydrolysable N associated with steer production, as described by Legesse et al. (2018a). The difference between daily N intake and daily N retention was calculated to estimate the quantity of N excreted by steers on a daily basis ($N_{\text{excretion rate}}$). Daily N intake (IPCC, 2006); Eq 3) was estimated using protein intake (PI), gross energy intake (GE), and the net energy required for maintenance ($NE_{\text{maintenance}}$).

$$N\ intake = PI / 6.25 \qquad \text{(IPCC, 2006; 3)}$$

Where:

N intake = Daily N intake, kg N hd^{-1} d^{-1};

PI = protein intake, kg hd^{-1} d^{-1} (Eq. 4);

6.25 = the coefficient to convert from dietary protein to dietary N.

$$PI = (GE / 18.45) \times CP \qquad \text{(IPCC, 2006; 4)}$$

Where:

GE = gross energy intake, MJ hd^{-1} d^{-1} (Eq. 5);

18.45 = the conversion factor for gross energy kg^{-1} DM, MJ kg^{-1};

CP = crude protein of feed, kg kg^{-1}

$$GE = [(NE_{maintenance} + NE_{activity}) / REM) + (NE_{gain} / REG)] / (DE / 100) \quad \text{(IPCC, 2006; 5)}$$

Where:

$NE_{maintenance}$ = the net energy required for maintenance, MJ hd^{-1} d^{-1} (Eq. 6);

$NE_{activity}$ = the net energy required for feeding, MJ hd^{-1} d^{-1}. Confined-backgrounding and finishing $NE_{activity}$ was assumed to be negligible as a result of limited space during those feeding periods however, grazing steers on pasture had a $N_{activity}$ of 0.17 (IPCC, 2006);

REM = the ratio of net energy available in the diet for maintenance to the digestible energy consumed, MJ hd^{-1} d^{-1} (Eq. 7);

NE_{gain} = the net energy for gain, MJ hd^{-1} d^{-1} (Eq. 8);

REG = the ratio of net energy available to steers in the diet for gain to the digestible energy consumed, MJ hd^{-1} d^{-1} (Eq. 9);

DE = the digestible energy of feed, % TDN.

$$NE_{maintenance} = Cf_{adjusted} \times BW_{average}^{0.75} \quad \text{(IPCC, 2006; 6)}$$

Where:

$Cf_{adjusted}$ = the temperature adjusted baseline maintenance coefficient (IPCC, 2006);

$BW_{average}$ = average body weight, kg.

$$REM = 1.123 - (4.092 \times 10^{-3} \times DE) + (1.126 \times 10^{-5} \times DE^{2}) - (25.4 / DE) \qquad \text{(IPCC, 2006; 7)}$$

$$NE_{gain} = 22.02 \times (BW_{average} / (C_{d} \times BW_{final}))^{0.75} \times ADG^{1.097} \qquad \text{(IPCC, 2006; 8)}$$

Where:

C_d = the coefficient related to cattle description (IPCC, 2006);

BW_{final} = final body weight, kg;

ADG = average daily gain, kg d^{-1}.

$$REG = 1.164 - (5.160 \times 10^{-3} \times DE) + (1.308 \times 10^{-5} \times DE^{2}) - (37.4 / DE) \qquad \text{(IPCC 2006; 9)}$$

The daily N retention included the protein fraction which was retained for growth (PR_{gain}) described by Eq. 10.

$$PR_{gain} = ADG \times ((268 - (29.4 \times (RE / ADG)) / 1000) \qquad \text{(NRC, 2000; 10)}$$

Where:

PR_{gain} = Protein retained for growth, kg hd^{-1} d^{-1};

RE = retained energy, Mcal hd^{-1} d^{-1} (NASEM 2016; Eq. 11).

$$RE = 0.0635 \times EBW^{0.75} \times EBG^{1.097} \qquad (11)$$

Where:

EBW = empty body weight, kg hd^{-1} (NASEM 2016; Eq. (12);

EBG = empty body gain, kg hd^{-1} d^{-1} (NASEM 2016; Eq. (13).

$$EBW = BW_{average} \times 0.891 \qquad (12)$$

$$EBG = ADG \times 0.956 \qquad (13)$$

Eq. 14 and Eq. 15 were used to estimate N excreted through urine ($TAN_{excreted}$), with the remaining N assumed to be excreted in the feces ($FecalN_{excreted}$), respectively (Dämmgen and Hutchings 2008).

$$TAN_{excreted}, = N_{excretion\ rate} \times Fraction_{Urinary\text{-}N} \tag{14}$$

Where:

$TAN_{excreted}$ = the N excreted from the urine, kg TAN hd^{-1} d^{-1};

$Fraction_{Urinary\text{-}N}$ = the fraction of N excreted from the urine.

$$FecalN_{excreted} = N_{excretion\ rate} \times (1 - Fraction_{Urinary\text{-}N}) \tag{15}$$

Where:

$FecalN_{excreted}$ = the excreted N from the feces, kg fecal N hd^{-1} d^{-1}.

Quantification of NH_3 emissions based on source

Animal housing

Emissions associated with grazing steers while on pasture were estimated for the LNAT and LCON steers using Eq. 16. Pasture-free-grazing refers to the period of time when steers were grazing on pasture.

$$NH_{3\ emissions,\ g} = TAN_{excreted} \times EF_{Pasture\text{-}\ free\text{-}grazing\ adjusted} \times 17/14 \tag{16}$$

Where:

$NH_{3\ emissions,\ g}$ = NH_3 emissions from grazing steers on pasture, kg NH_3 hd^{-1} d^{-1}

$EF_{Pasture\text{-}free\text{-}grazing\ adjusted}$ = the temperature-adjusted emission factor associated with steers grazing on pasture

$17/14$ = the coefficient for the conversion of ammoniacal nitrogen (NH_3-N) to NH_3.

$$EF_{Pasture\text{-}free\text{-}grazing\ adjusted} = Pasture\text{-}free\text{-}grazing\ adjustment \times EF_{pasture\text{-}free\text{-}grazing} \quad (17)$$

Where:

Pasture-free-grazing adjustment = the adjusted temperature when cattle were housed on pasture, kg (NH_3-N) kg^{-1} (Eq. 18)

$EF_{pasture\text{-}free\text{-}grazing}$ = 0.1, kg (NH_3-N) kg^{-1}

$$Pasture\text{-}free\text{-}grazing\ adjustment = 1.041^{average\ temperature,\ ℃}) \div 1.041^{15} \quad (18)$$

Steers were housed in confinement during the backgrounding and finishing phases. Emissions from housing in confinement during these times were estimated using Eq. 19.

$$NH_{3\ emissions,\ h} = TAN_{excreted} \times EF_{Feedlot\ adjusted} \times 17/14 \quad (19)$$

Where:

$NH_{3\ emissions,\ h}$ = NH_3 emissions from confined animal housing, kg NH_3 hd^{-1} d^{-1}

$EF_{Feedlot\ adjusted}$ = the temperature-adjusted emission factor for confined feeding housing

17/14 = the coefficient to convert NH_3-N to NH_3.

$$EF_{Feedlot\ adjusted} = feedlot\ adjustment \times EF_{feedlot} \quad (20)$$

Where:

Feedlot adjustment = the adjusted temperature when steers were housed in confinement, kg (NH_3-N) kg^{-1} (Eq. 21)

$EF_{feedlot}$ = 0.9, kg (NH_3-N) kg^{-1}

$$Feedlot\ adjustment = 1.041^{average\ temperature,\ ℃}) \div 1.041^{15} \quad (21)$$

Periodic TAN excreted (Mg TAN hd^{-1} $period^{-1}$) and periodic NH_3 emissions (Mg NH_3 hd^{-1} $period^{-1}$) from steers fed in confinement ($PTAN_{excreted, h}$, and $PNH_{3emissions, h}$ respectively) and grazing steers ($PTAN_{excreted, g}$, and $PNH_{3emissions, g}$ respectively) were estimated by multiplying by the days in the feeding period.

Manure storage

Manure from grazing steers was deposited and remained on pasture, therefore the emissions from manure storage during the grazing period was assumed to be zero. However, during backgrounding and finishing, steers housing and periodic TAN associated with moving manure to a storage system ($PTAN_{storage}$) was estimated by calculating the difference between periodic NH_3 volatilization and the periodic TAN excreted. Housing, in this study, does not refer to steers being housed indoors, but rather the emissions from steers in confined feedlot pens during backgrounding and finishing. NH_3 emissions attributed to wasted feed or bedding were assumed to be negligible and were not considered in the analysis (Legesse et al. 2018b).

$$PTAN_{storage} = PTAN_{excreted,h} - (PNH_{3emission,h} \times 14/17) \tag{22}$$

Where:

$PTAN_{storage,}$ = the periodic TAN from stored manure, mg TAN hd^{-1} feeding $period^{-1}$;

$PTAN_{excreted, h}$ = the periodic TAN from manure excreted by housed (confinement or pasture) steers (Mg TAN hd^{-1} feeding $period^{-1}$);

$PNH_{3emission, s}$ = the periodic emission rate of NH_3, temperature adjusted from housed (confinement or pasture) steers (Mg NH_3 hd^{-1} feeding $period^{-1}$);

$14/17$ = conversion of NH_3-N to NH_3.

NH_3 volatilization from stored manure was estimated using total ammoniacal nitrogen and specific EF. Eq. 23 defines the variation in TAN during the time manure was being stored. Further, by subtracting nitrified N, TAN during storage and TAN that was mineralized from organic N were complied.

$$PTAN_{storage2} = PTAN_{storage} \times (1\text{-}F_{immob})(1\text{-}F_{nitrify}) + (PON_{storage} \times F_{minneralize}) \tag{23}$$

Where:

$PTAN_{storage2}$ = the adjusted TAN during manure storage used to calculate NH_3 emissions hd^{-1} during manure storage, Mg TAN hd^{-1} feeding $period^{-1}$;

F_{immob} = the fraction of TAN immobilized to organic N during manure storage;

$F_{nitrify}$ = the fraction of TAN which was nitrified during manure storage;

$PON_{storage}$ = the periodic organic N mass flow of excreted fecal N from the confined housing to manure storage per steer, Mg organic N hd^{-1} feeding $period^{-1}$;

$F_{minneralize}$ = the fraction of organic N that was mineralized as TAN during manure storage.

The estimation assumed no TAN immobilization during the storage of manure ($F_{immob} = 0$) for backgrounding and finishing steers, the nitrified TAN fraction from stockpiled manure was 0.14 (C= 0.14; Chai et al., 2014) and the organic N fraction mineralized as TAN was 0.28 ($F_{minneralize} = 0.28$). For grazing steers, it was assumed that there was no TAN immobilization ($F_{immob} = 0$), no nitrified TAN ($F_{nitrify} = 0$) and no mineralization of the organic N fraction ($F_{minneralize} = 0$) as manure was nit stored on pasture.

Manure land application

The manure associated with grazing steers was directly applied to the untilled pastureland during grazing. Although, the leaching and run-off fraction was assumed to be 0 for deep bedding manure $N_2O\text{-}N_{leaching}$ rate was calculated (Holos Manual Table 14; eq. 24) to estimate the indirect N_2O emission from manure on pasture.

$$Frac_{leach} = 0.3247 * \frac{P}{PE} - 0.0247 \qquad \text{(Holos Manual Table 14; 24)}$$

Where:

$Frac_{leach}$ = Fraction of N lost by leaching and runoff (kg N) with a range from 0.05 – 0.3. Values lower than 0.05 were assumed to be 0.05 and values higher than 0.3 were assumed to be 0.3.

P = Growing season precipitation by ecodistrict (May-October)

PE = Growing season potential evapotranspiration by ecodistrict (May-October)

P and PE were obtained using previously described weather data (Environment and Climate Change Canada, 2020).

Based on observations of management practices on Canadian beef operations and methodology from previous literature (Legesse et al., 2018b), it was assumed that of the manure, 57% was spread on tilled land while 43% was spread on untilled land. Further, NH_3 emissions from land applied manure were estimated using the combined average temperatures from April to May and September to November to account for the spreading of manure in the spring or fall (Shappard, 2015). Available TAN and EF from manure application, type of land, tillage intensity, and month of application, were used to estimate the quantity of volatized NH_3. The monthly TAN associated with the transfer of manure from storage to land application was estimated using quantity of land where manure was applied and the remaining NH_3 following storage (Eq. 25).

$$PTAN_{land,tillage} = F_{till/untill} \times (PTAN_{storage2} - MNH_{3emissions,s} \times 14/17 \qquad (25)$$

Where:

$PTAN_{land,tillage}$ = the periodic TAN from manure application to tilled or untilled land during a specific timespan, Mg NH_3 hd^{-1} $month^{-1}$;

$MNH_{3emissions,s}$ = NH_3 emission rate during manure stockpiling, Mg NH_3 hd^{-1} $month^{-1}$;

$F_{till/until}$ = the manure fraction that was applied on tilled or untilled land.

4.3.4 Estimating water use

Drinking water and processing

The daily water intake estimation considered animal category, average BW (Smith, 2022) and ambient temperature during each feeding phase (Environment and Climate Change Canada, 2020) as described by Legesse et al. (2018a; Eq 26).

$$\text{Total drinking water use} = WU_{coeff} \times n_d \times n_{hd} \tag{26}$$

Where:

WU_{coeff} = the water use coefficient (litres hd^{-1} d^{-1}; National Academies of Sciences, Engineering, and Medicine, 2016);

n_d = the number of days in the feeding phase;

n_{hd} = the number of steers (hd treatment^{-1} yr^{-1}).

Water consumption by steers was assumed to not change at temperatures of ≤ 4.4 °C and were assumed to increase with an ambient temperature > 4.4°C (Table 4.8). Previous studies (Beaulieu, 2007; Legesse et al., 2018a) have deemed the water use requirement associated with cleaning cattle and facilities were negligible when determining the water footprint of beef production systems and therefore it was not considered in this study.

Table 4.8 Estimated total daily water intake (liters hd^{-1} d^{-1}) of growing and finishing steers[a]

	Temperature, °C					
Weight, kg	4.4	10.0	14.4	21.1	26.6	32.2
Growing steers						
182	15.1	16.3	18.9	22.0	25.4	36.0
273	20.1	22.0	25.0	29.5	33.7	48.1
364	23.0	25.7	29.9	34.8	40.1	56.8
Finishing steers						
273	22.7	24.6	28.0	32.9	37.9	54.1
364	27.6	29.9	34.4	40.5	46.6	65.9
454	32.9	35.6	40.9	47.7	54.9	78.0

National Academic of Sciences, Engineering, and Medicine (2016)

The value of 16.5 L kg boneless beef^{-1} was used to estimate the water requirement of at processing and was based on average water use efficiency at processing facilities in western Canada of (Legesse et al. (2018a)

Estimating water use: Crop production

Water use derived from the production of feed and tame pasture were estimated using water demand of specific crops and the consumption (kg DM) of each feed ingredient (Legesse et al. (2018a). Crop yields specific to feed ingredients were used to estimate the total volume of water evapotranspired required to produce one kg of crop (L kg^{-1} DM).

Potential (PET_w) and actual evapotranspiration (AET) data were estimated using the National Drought Model and precipitation data from Environment and Climate Change Canada for the following weather stations: Saskatoon SRC (1990-2007) and Saskatoon RSC (2009-2020) and Watrous (1993 – 2020; Figure 4.2; Environment and Climate Change Canada, 2020). Crop and tame pasture water demand were calculated as follows (Eq. 28):

$$\textit{Crop water demand} = PET_w \times K_c \tag{28}$$

Where:

PET_w = potential evapotranspiration;

K_c = the respective crop coefficient (ASCE 1996)

Water that originated from precipitation and the exchange of water between soil, land surface and the atmosphere (IPCC 2006) is described as green water and was estimated by Eq. 29

$$\textit{Green water} = AET \times K_c \tag{29}$$

Where:

AET = actual evapotranspiration, estimated using data from the National Drought model (NDM);

K_c = the respective crop coefficient (ASCE 1996).

Crop coefficients (K_c) describe the influence of plant species on the evapotranspiration as it deviates from the reference crop in term of crop characteristics, crop development, canopy cover, height, density, and management during the growing season to estimate crop water demand (Pokorny 2019). Previous literature (Allen et al., 2007, 1998; ASCE, 1996) was used to acquire crop coefficients (K_c) and used to develop a K_c curve for each crop, including tame pasture (Figure 4.1). K_c curves considered the length of time between germination and harvest along with developmental stage ($K_{c\ init}$, $K_{c\ mid}$, and $K_{c\ end}$). Growing season was assumed to occur from May to October. Developmental stages specific to each crop (Allen et al., 2007, 1998) were based on location and associated growing conditions and management practices to attribute each growing stage with the appropriate K_c. Four stages of development (Allen et al., 1998) specific for each crop were assumed, in order of occurrence, as follows: i) initial development (L_{init}), corresponding to $K_{c\ init}$, ii) rapid development (L_{dev}) which K_c corresponded to the rate from $K_{c\ init}$ to $K_{c\ mid}$, iii) maturity (L_{mid}), in correspondence to K_c mid, and iv) late-season period (L_{late}) which K_c corresponded to the rate of $K_{c\ mid}$ to $K_{c\ end}$. Planting date (Huffman et al., 2015) was also considered when developing the K_c curves to signify the initiation of the growing season. These values were sourced from Saskatchewan Crop Planning Guides (2017 and 2018) for barley grain, and canola production and from on-site data for barley silage and greenfeed. Growing season length specific to each annual crop (d) was calculated as the sum of the lengths of all crop development stages (L_{init}, L_{dev}, L_{mid}, L_{late}). Crop specific developmental stages for canola were not defined by Allen et al. (2007 and 1998) and were assumed using the descriptions of developmental stages (Allen et al. 1998; Britton 2019).

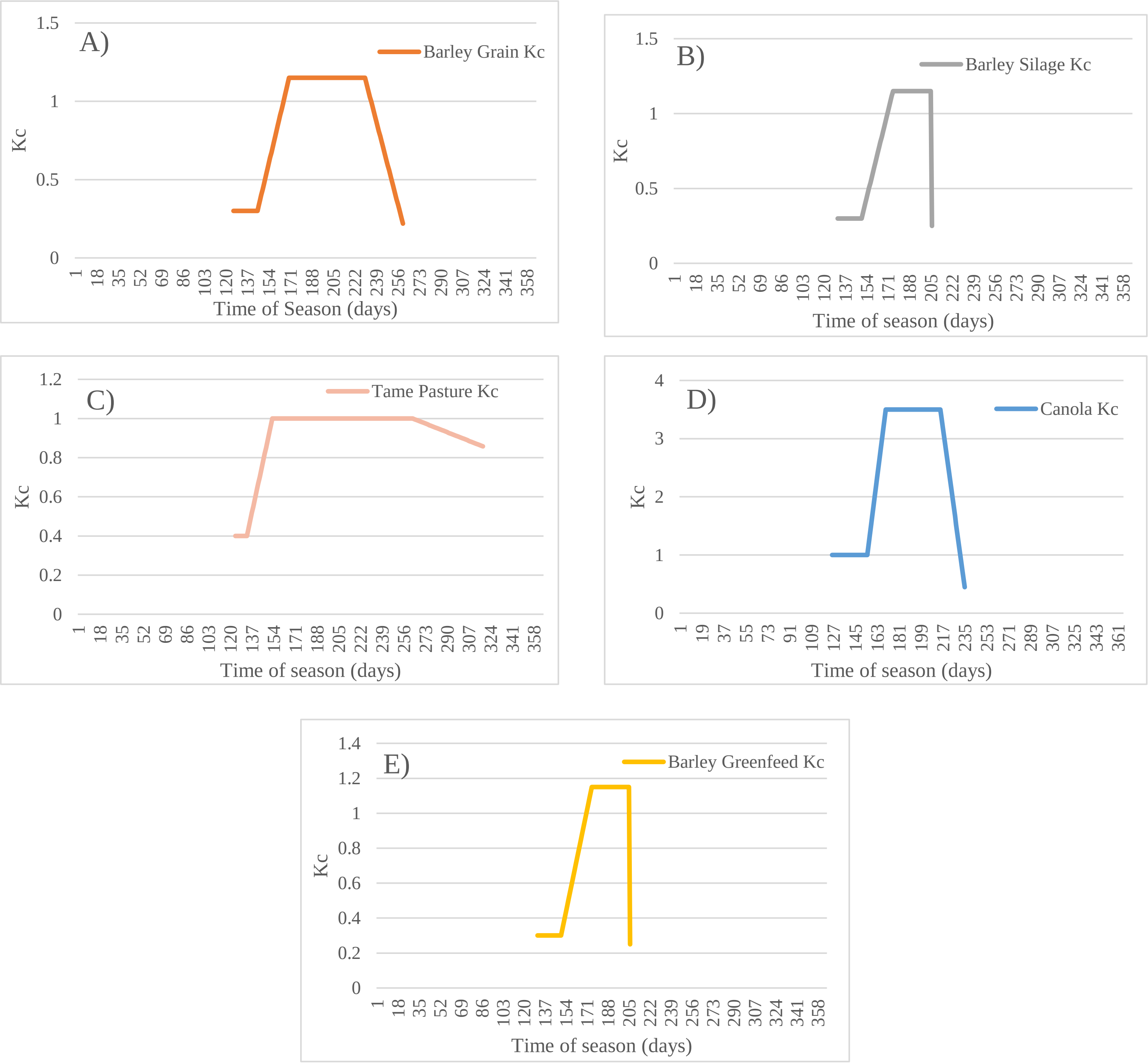

Figure 4.1 Crop coefficient (K_c) curves for A) barley grain B) barley silage C) tame pasture D) canola meal, and E) barley greenfeed.

The growing season crop evapotranspiration (ET_c; Eq 31) is described as the amount of water required by the crop during the course of the growing season to develop and reach maturity by the date of harvest.

$$ET_c = Crop\ water\ demand \times yield \tag{30}$$

Where:

Yield = the amount of crop produced (kg DM ha^{-1}).

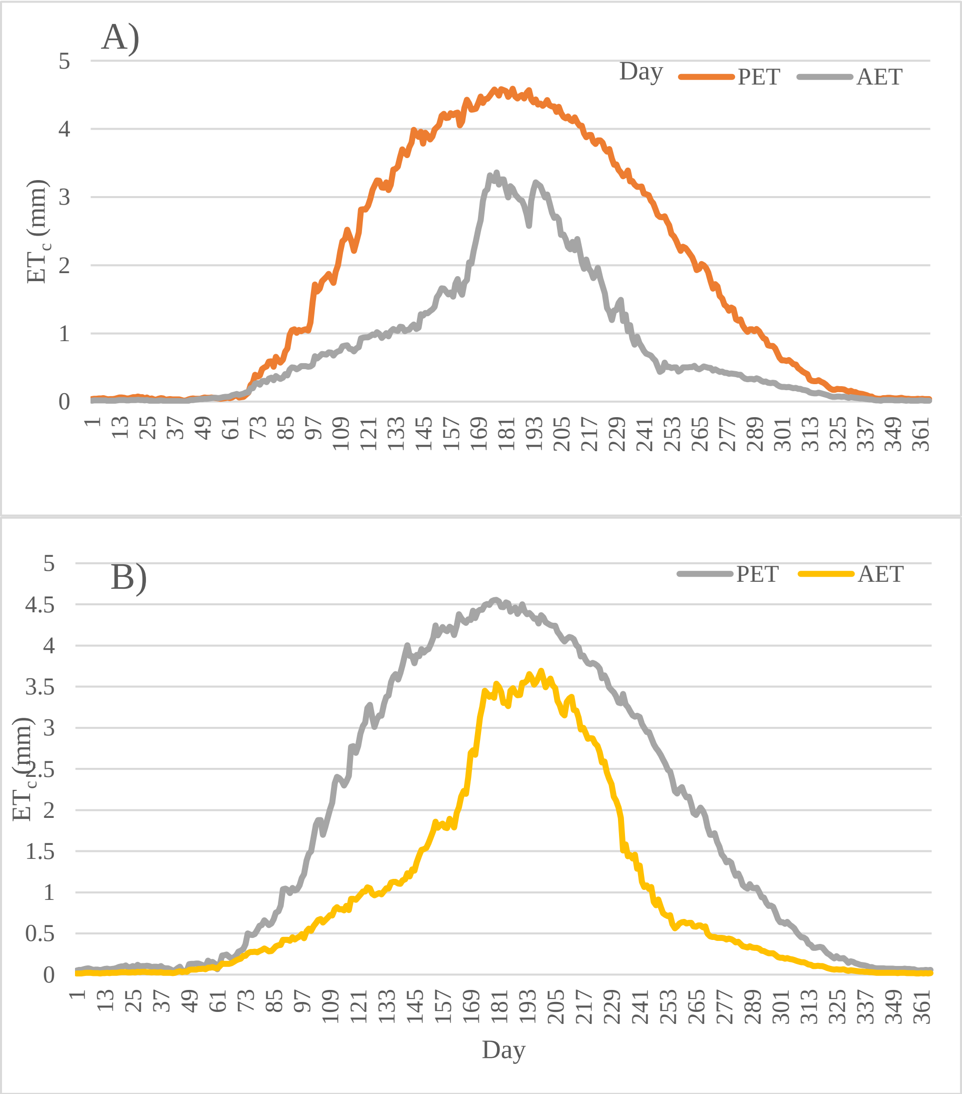

Figure 4.2 Average annual potential evapotranspiration (PET, mm) and actual evapotranspiration (AET, mm) over 10 years (2009 to 2019) measured at the Saskatoon RSC weather station, Saskatoon, SK (A) and the Watrous Weather station in Watrous Saskatchewan, AK (B).

4. 4 RESULTS

4.4.1 Impacts of PET removal on days on feed (DOF)

Average days on feed (DOF) to reach the targeted finish weight of 646 kg ranged from 155-339-d for conventional steers and 205-398-d for natural steers (Table 4.9). Steers in the LNAT treatment had the highest DOF in both years while HCON had the lowest. Steers in HCON, MCON and LCON treatments required 24%, 25% and 15% fewer days to reach the targeted finishing weight, respectively as compared to the natural treatment for each of the feeding strategies. Overall, the average reduction in DOF across all treatments as a result of PET treatment was 22%.

When examined by feeding phase, DOF were lowest for the Heavy, intermediate for Medium and highest for Light steers for both CON and NAT steers. Grazing days were lower in Year 2 compared to Year 1 due to decreased forage production as a result of drought. Therefore, Light steers were backgrounded approximately one month longer in Year 1 compared to Year 2.

Table 4.9 Days on feed by feeding phase in Year 1 and Year 2 for steers managed in six management scenarios (HCON = Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

	HCON	HNAT	MCON	MNAT	LCON	LNAT
			Days			
Backgrounding[a]						
Year 1			106	106	188	188
Year 2			90	90	203	203
Grazing						
Year 1					80	80
Year 2					55	55
Finishing						
Year 1	162	219	116	173	74	124
Year 2	148	191	105	190	78	146
Total						
Year 1	162	219	222	279	342	392
Year 2	148	191	195	280	336	404

Average Total	155	205	208.5	279.5	339	398

[a]Backgrounding in confinement

4.4.2 Impact of management strategy and feeding phase on GHG emissions

Average total GHG emissions (n= 2 trials) during the feeding period ranged from 1,648.0 to 3,993.8 kg CO_2e hd^{-1} for CON steers and 1,854.2 to 4,270.0 kg CO_2e hd^{-1} for NAT steers (Figure 4.3). Therefore, HCON, MCON, and LCON treatments had 11.2%, 10.0% and 9.8% lower GHG emissions, respectively, compared to NAT steers raised with the same feeding management strategy. The highest emissions were from the LCON and LNAT treatments. When carbon sequestration associated with the grazing phase was considered GHG emissions decreased from 3,993.8 to 2,551.3 and 4,270.0 to 2,829.5, kg CO_2eq hd^{-1}for LCON and LNAT, respectively. Nonetheless, emissions for the Light group remained higher than their Heavy and Medium counterparts for both the conventional and natural management strategies.

When examined by feeding phase, backgrounding accounted for 44%, 35%, 44% and 37% of GHG emissions while finishing accounted for 56%, 65%, 30% and 39% of GHG emissions for MCON, MNAT, LCON, and LNAT treatments respectively. Grazing accounted for 25% and 24% of total emissions for LCON and LNAT, respectively. More specifically, GHG emissions for MCON and LCON were both 13% higher than MNAT and LNAT steers during backgrounding . In addition, LCON steers had 1% higher emissions than LNAT steers during grazing (1,009.6 vs 1,017.5 kg CO_2eq hd^{-1}). Conversely, during finishing, HCON, MCON, and LCON had 11%, 10% and 28% lower emissions than steers in the respective NAT treatments (Figure 4.3).

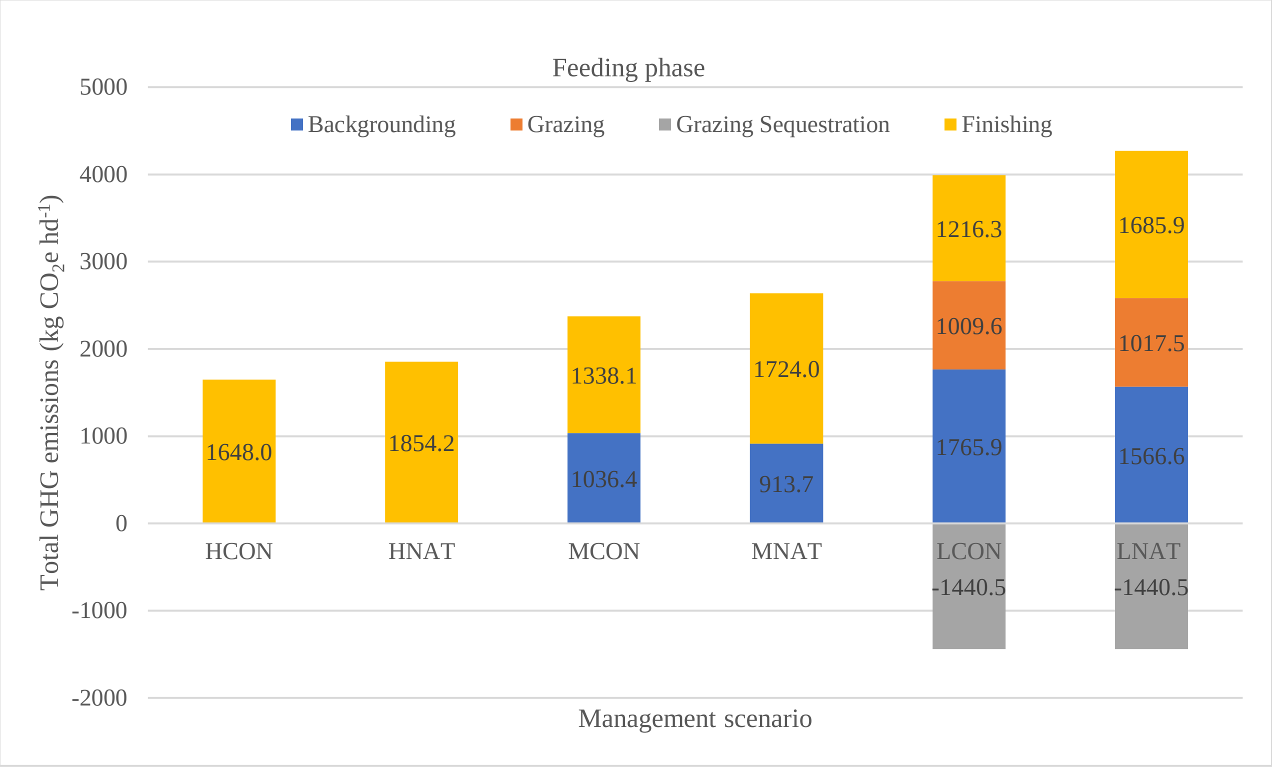

Figure 4.3 Total mean greenhouse gas emissions (CO_2e hd^{-1}; n=2 trials) for each phase of production (backgrounding, finishing, and grazing) and carbon sequestration during the grazing phase for steers managed in six management scenarios (HCON = Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural).

4.4.2.2 GHG emissions by source

As a proportion of all GHG emissions over the feeding period, enteric CH_4 was the largest source of emissions regardless of feeding strategy, followed by direct N_2O, manure CH_4 and energy CO_2. Further, HCON, MCON and LCON steers had lower CH_4 (9%, 5%, 3%), manure CH_4 (8%, 6%, 4%), direct N_2O (13%, 16%, 10%), indirect N_2O (13%, 16%, 11%) and CO_2 (19%, 24%, 12%) emissions, respectively, as compared to NAT steers with the same feeding strategy (Figure 4.4).

For LCON and LNAT treatments, the grazing period accounted for 22% of total enteric CH_4 emissions (both treatments), 2% of manure CH_4 (both treatments), 37% and 33% of direct N_2O, 31% and 27% of indirect N_2O and 47% and 41% of CO_2 emissions, respectively. Backgrounding accounted for 47% of enteric CH_4 and 52% of manure CH_4 emissions with LCON having the highest proportion of CH_4 emissions at 51% for enteric and 63% for manure. The majority of CO_2 emissions for MCON and MNAT were from backgrounding (74% and 80% respectively). Backgrounding and finishing each accounted for 50% of total enteric CH_4 emissions for MCON and 58% and 42% respectively, for MNAT.

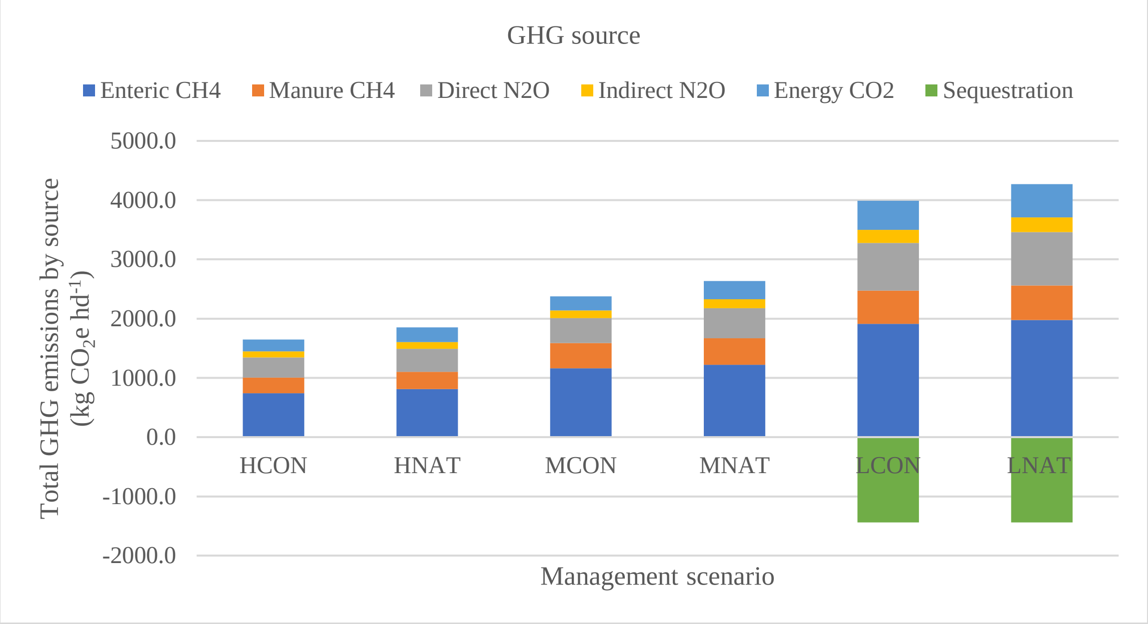

Figure 4.4 Total mean greenhouse gas emissions by type (kg CO_2eq hd^{-1}; n=2 trials) for six management scenarios (HCON = Heavy conventional, HNAT = Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; and LNAT = Light natural).

Emissions associated with crops were lower for CON steers compared to NAT steers raised on the same diet. Further, emissions were influenced by the level and type of dietary ingredients with barley grain having the highest emissions for steers in the Heavy and Medium treatments (HCON 87%; HNAT 88%; MCON 79%; MNAT 81%). However, barley grain only accounted for 36% and 43% of emissions in the Light treatments while pasture accounted for 50% and 44%.

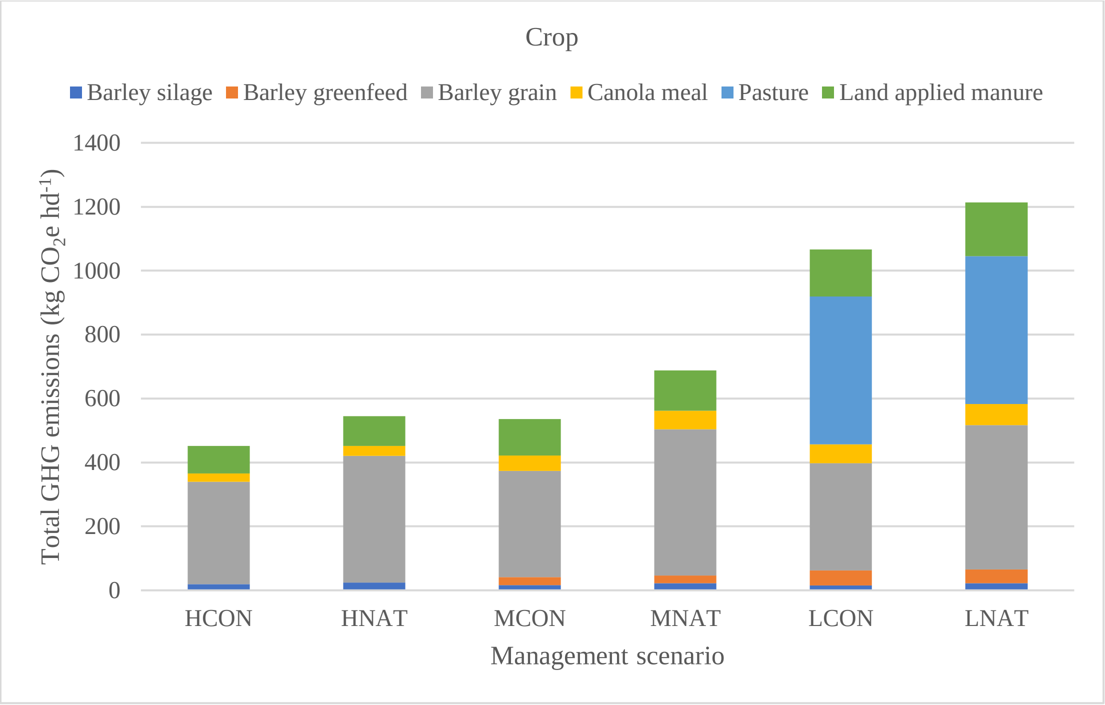

Figure 4.5 Total mean GHG emissions **(**kg CO_2eq hd^{-1}; n =2 trials) associated with production of feed ingredients for the diets of six management scenarios (HCON = Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT= Medium natural; LCON = Light conventional; LNAT = light natural)

In summary, GHG emissions from the steers accounted for 71 to 77% of emissions across all feeding strategies (Figure 4.6). Further, HNAT, MNAT and LNAT treatments had a higher proportion of emissions associated with the production of feed crops (29%, 26% and 28%, respectively) compared to the HCON, MCON, and LCON (27%, 23% and 27%, respectively).

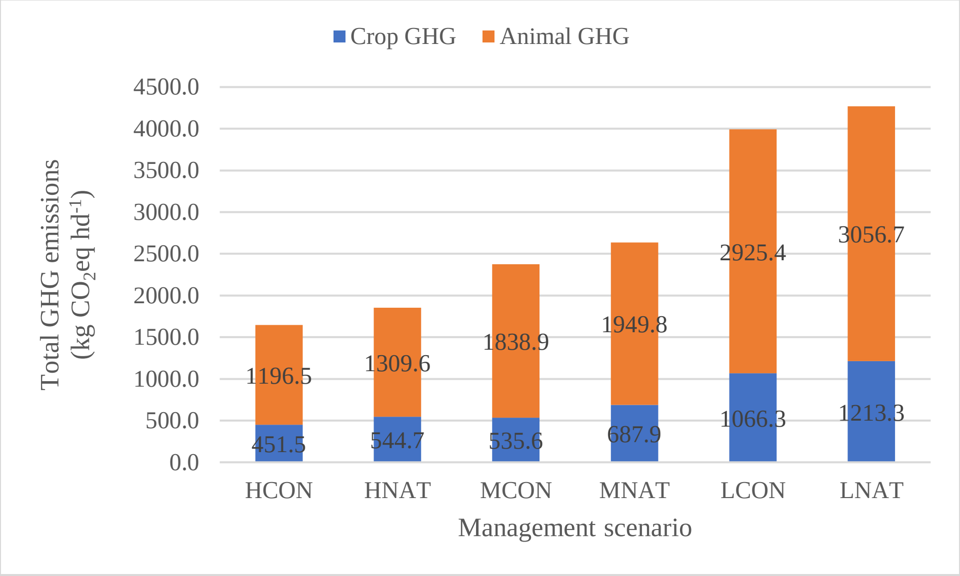

Figure 4.6 Total mean GHG emissions (kg CO_2eq hd^{-1}; n = 2 trials) excluding carbon sequestration from crops or steer sources for six management scenarios (HCON = Heavy conventional; HNAT = Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

When expressed on an intensity basis, emissions for NAT steers were higher than CON steers across all feeding strategies, regardless of the unit of expression. Steers in HCON had 10%, 13% and 13% lower emissions compared to HNAT when expressed as kg CO_2eq kg LW^{-1}, kg CO_2eq kg HCW^{-1} or kg CO_2eq kg boneless beef^{-1}, respectively (Figure 4.7). Similarly, steers in MCON had 10% lower CO_2eq kg LW^{-1} and 9% lower GHG emissions than MNAT for other intensity metrics (kg CO_2eq kg HCW^{-1} and kg CO_2eq kg boneless beef^{-1}). Steers in LCON had 10% lower GHG emissions per kg CO_2eq kg LW^{-} and 7% less kg CO_2eq kg HCW^{-1} and per kg CO_2eq kg boneless beef^{-1}.

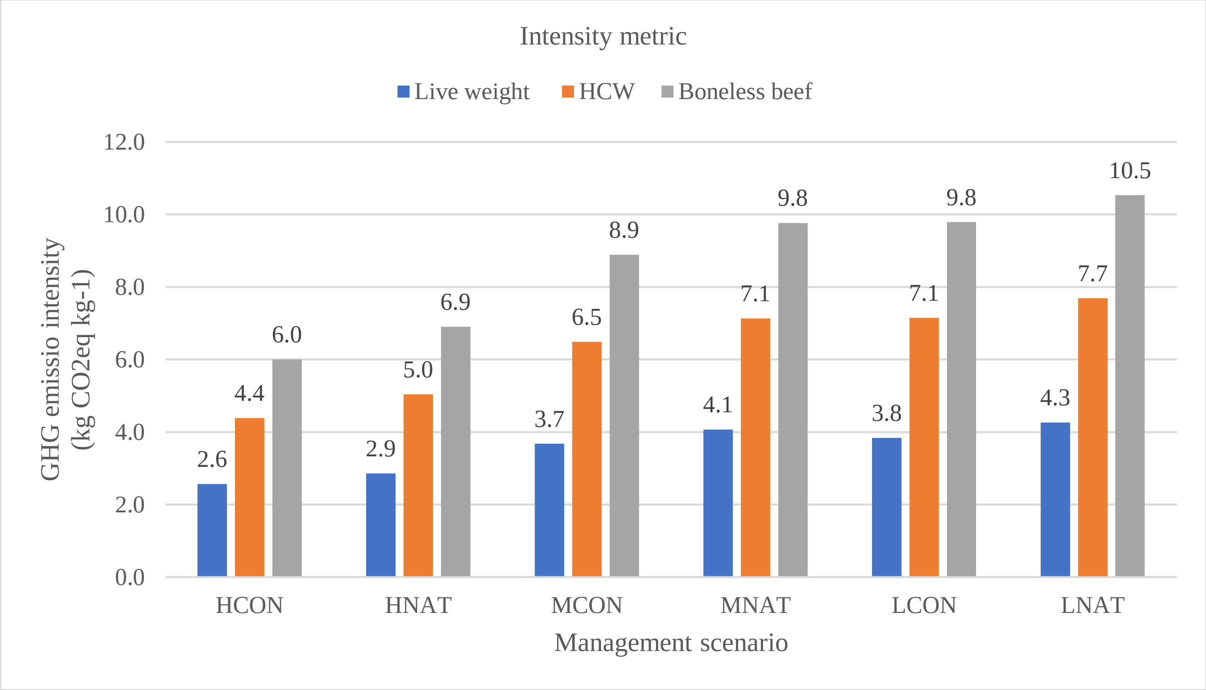

Figure 4.7 Greenhouse gas emissions expressed on an intensity basis (kg CO_2e kg^{-1} live weight, HCW, and boneless beef head^{-1}) for six management scenarios (HCON = Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

4.4.3 Impacts of PET removal on land requirements

Land requirements ranged from 0.46 to 1.6 ha head^{-1} for CON and 0.57 to 1.7 ha head^{-1} for NAT (Figure 4.8). When compared to the NAT treatments with the same feeding strategy, LCON, MCON and HCON required 20%, 22% and 9% less land, to produce the feed consumed by the steers from weaning to finish. Further, LNAT had the highest land requirement during the feeding period while HCON required the least. HCON, MCON, and LCON required 19%, 17% and 35% less land for barley silage, 20%, 28% and 26% less land for barley grain and 20%, 19% and 11% less land for canola meal compared to NAT steers raised with the same feeding strategy. In addition, MNAT and LNAT steers required 7% and 8% less barley greenfeed, than the CON steers of the same feeding strategy.

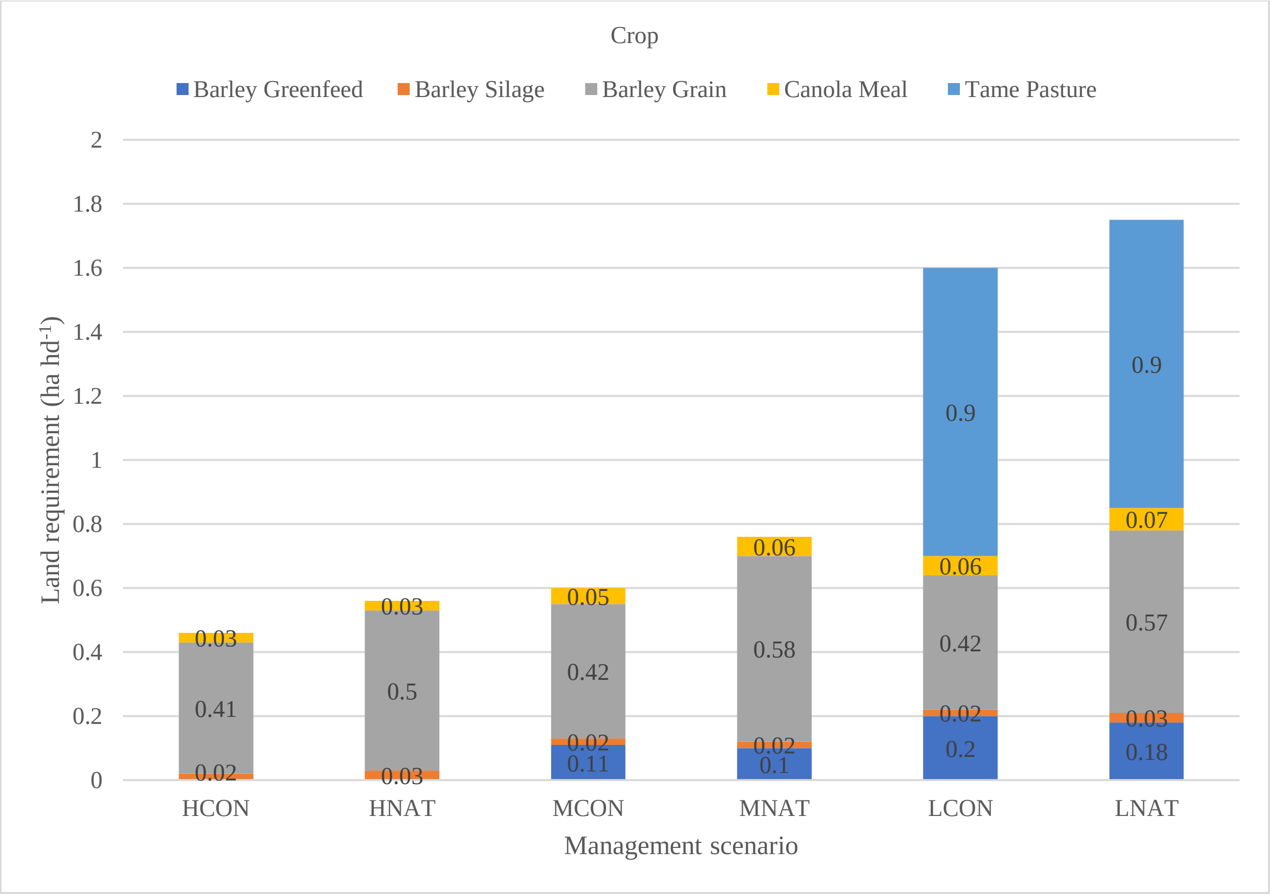

Figure 4.8 Total land required (ha hd^{-1}; n=2 trials) for production of feed ingredients for six management scenarios (HCON = Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

During backgrounding, MCON and LCON required 7% and 8% more land than MNAT and LNAT, respectively (Figure 4.9). During finishing HCON, MCON and LCON required 20%, 32% and 34% less than HNAT, MNAT, and LNAT, respectively. During grazing, both LCON and LNAT steers required 0.9 ha hd^{-1}.

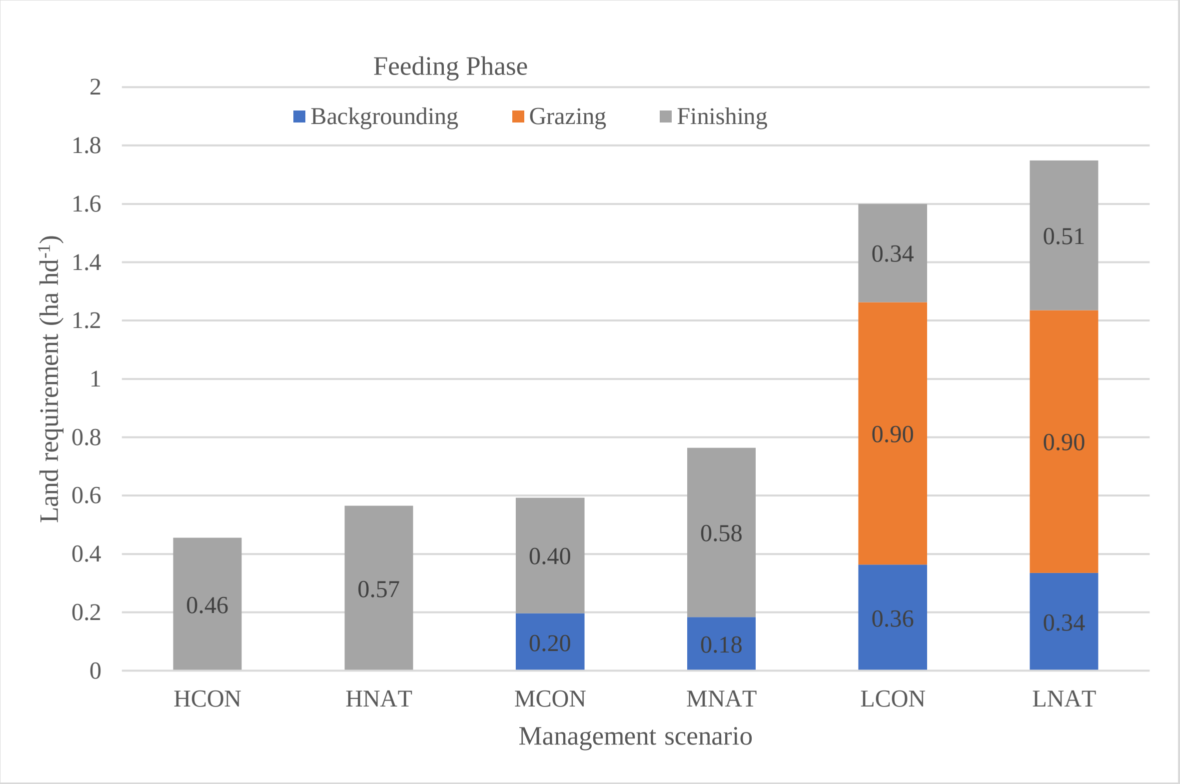

Figure 4.9 Average total land required (ha head^{-1}; n=2 trials) by feeding phase for six management scenarios (HCON = Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT= Medium natural; LCON = Light conventional; LNAT = Light natural)

Expressed on an intensity basis, HCON, MCON and LCON required 19%, 22% and 9% less land (ha^{-1} kg liveweight^{-1}; Figure 4.10.) compared to the respective NAT treatment. Land requirements expressed on an intensity basis were lowest for Heavy steers, intermediate for Medium steers and highest for Light steers across all intensity metrics in both NAT and CON systems.

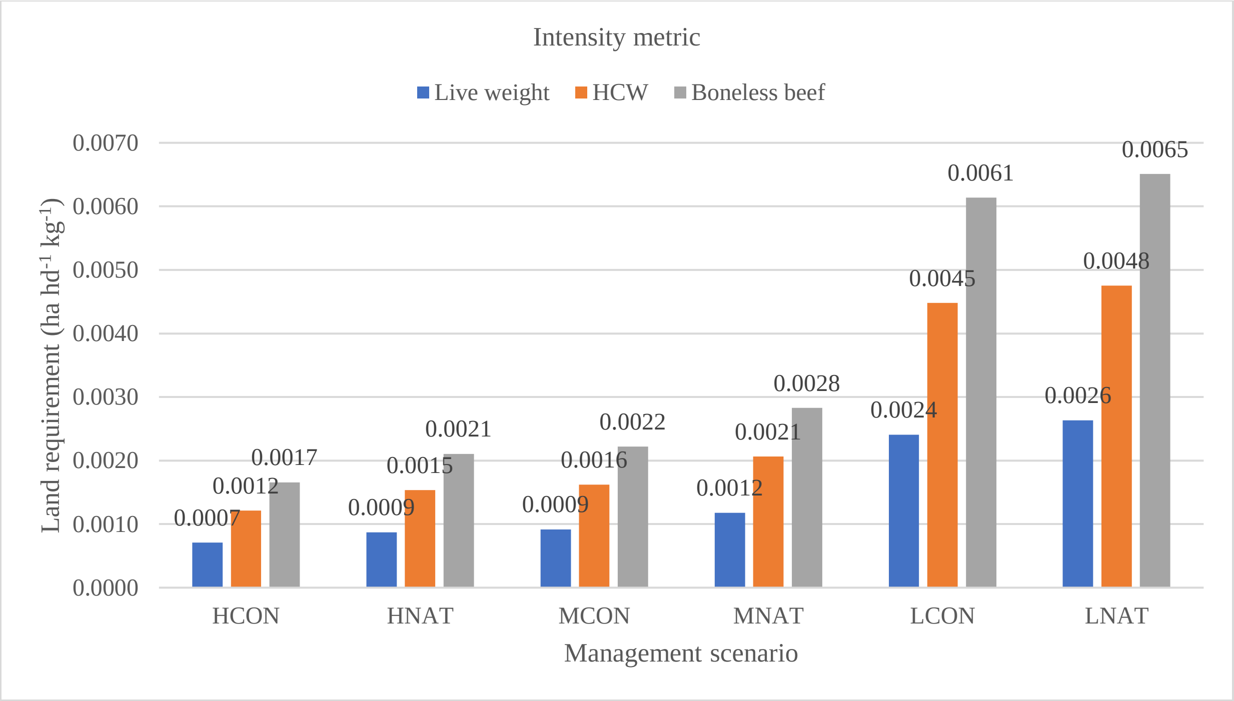

Figure 4.10 Average land requirement (ha kg^{-1} live weight, HCW, and boneless beef head^{-1}; n=2 trials) for six management scenarios (HCON - Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

4.4.4 Impacts of PET removal on ammonia emissions

4.4.4.1 Nitrogen Excretion

Average N excretion during backgrounding and finishing phases (n=2 trials) was 21%, 25% and 35%, lower for HCON, MCON, and LCON compared to the respective NAT treatment (Figure 4.11). Similarly, proportion of N lost as a percentage of consumed (Figure 4.12) was also lower for CON vs. NAT steers. In addition, N excretion was lowest for Heavy, intermediate for Medium and highest for Light steers for both CON and NAT steers during the backgrounding and finishing phases. Nitrogen excretion during the grazing period was not reported as intake was not measured.

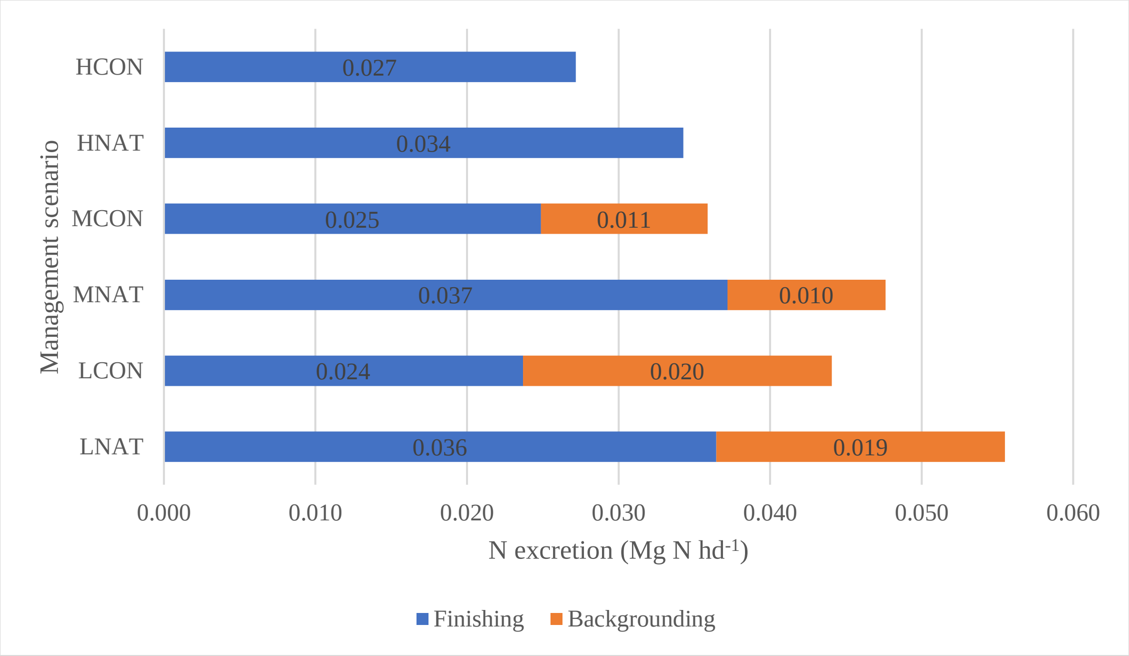

Figure 4.11 Average total N excretion (Mg N hd^{-1}) during finishing and backgrounding (n = 2 trials) for six management scenarios (HCON = Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT= Medium natural; LCON = Light conventional; LNAT = Light natural).

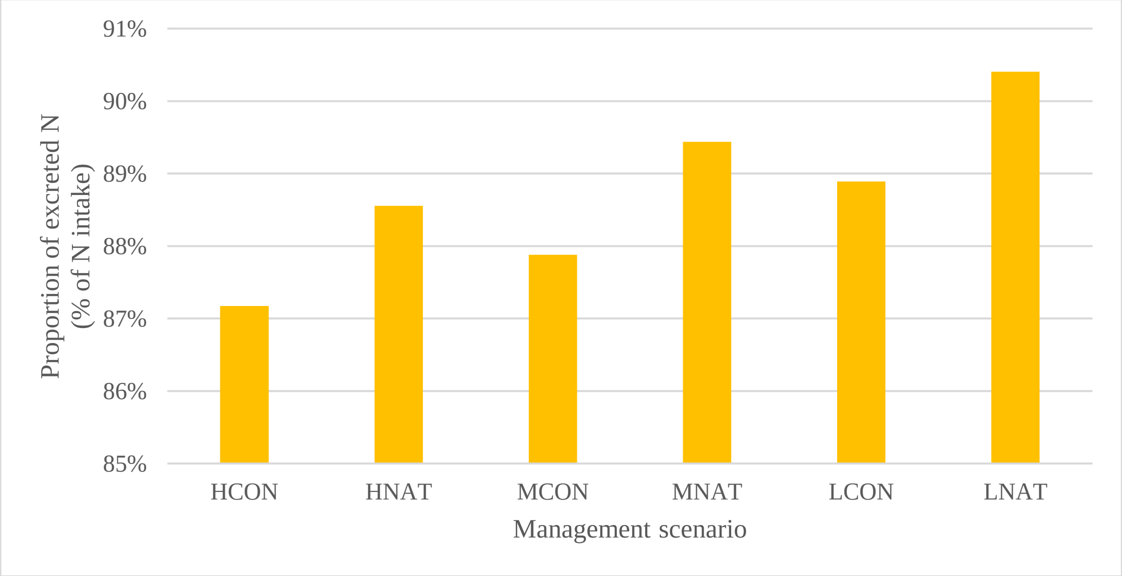

Figure 4.12 Proportion of N intake excreted by steers (n = 2 trials) for six management scenarios (HCON = Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural) during finishing and backgrounding phases.

4.4.4.2 Ammonia emissions

On average, 33-39% of N intake was lost as NH_3-N for conventional steers and 35-37% for natural steers; with a more NH_3 loss during the finishing phase (100% Heavy steers, 29% MCON; 37% MNAT; 23% LCON; 25% LNAT) as compared to the backgrounding phase (0% Heavy steers; 9% MCON; 6% MNAT; 16% LCON; 12% LNAT).

Conventional treatments had 25%, 32% and 13% lower ammonia (NH_3 hd^{-1}) emissions for Heavy, Medium and Light steers compared to the respective NAT steers (Figure 4.13). Overall, finishing accounted for the majority of ammonia emissions (Heavy steers, 100%; MCON, 77%; MNAT, 85%; LCON, 58%; LNAT, 67%). During finishing, HNAT, MNAT, and LNAT steers had higher NH_3 emissions (4.2, 9.3, and 4.6 kg NH_3 hd^{-1}) than CON steers of the same feeding strategy. Backgrounding accounted for 23%, 15%, 39%, and 32% of emissions for MCON, MNAT, LCON and LNAT steers, respectively, with MNAT and LNAT having lower emissions (0.2 and 0.6 kg NH_3 hd^{-1}, respectively), than CON steers. Grazing accounted for 4% and 2% of NH_3 emissions for LCON and LNAT steers, respectively, with LNAT having lower emissions (0.3 kg NH_3 hd^{-}1) than LCON.

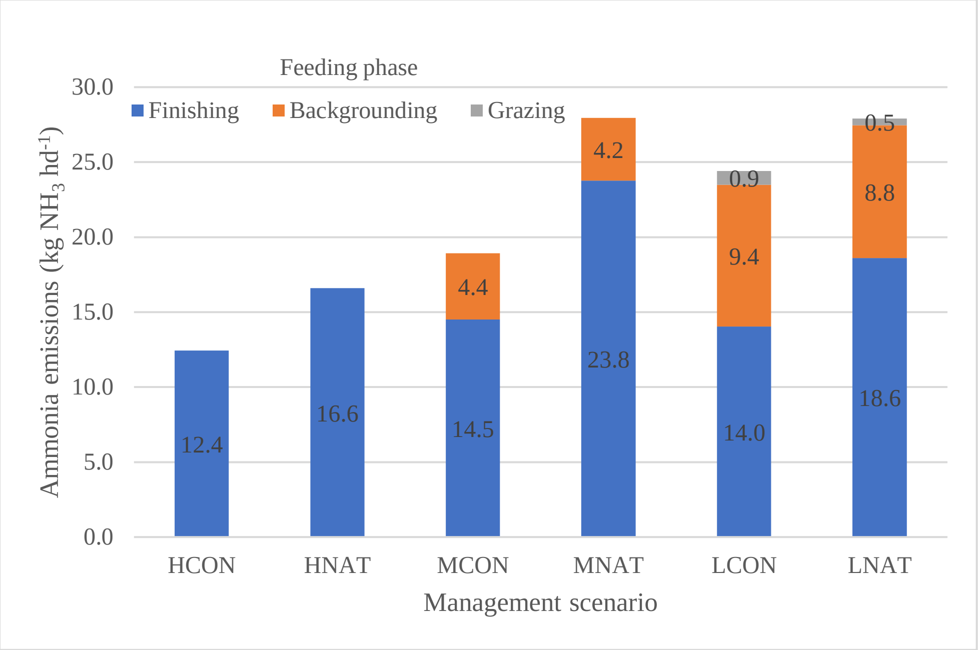

Figure 4.13 Total average ammonia emissions (kg NH_3 hd^{-1}) from steers during backgrounding, grazing, and finishing (n=2 trials) for six management scenarios (HCON = Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

The greatest proportion of NH_3 emissions (kg NH^3 hd^{-1}) were associated with confined feeding emissions (54.7% HCON, 57.8% HNAT, 63.1% MCON, 69.7% MNAT, 63.8% LCON and, 59.27% LNAT; Figure 4.14). Lowest emissions (kg NH^3 hd^{-1}) were associated with grazing for Light steers (0.06% LCON and 0.01% LNAT).

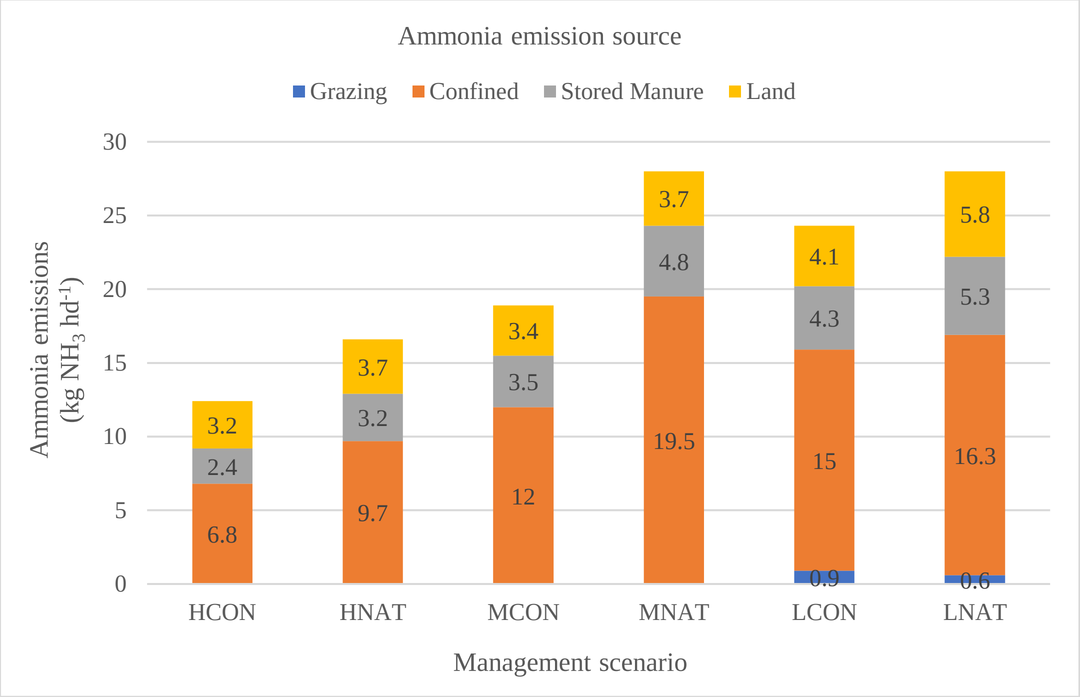

Figure 4.14 Average ammonia emissions (kg NH_3 hd^{-1}; n=2 trials) by source for six management scenarios (HCON = Heavy conventional; HNAT = Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

4.4.4.3 Ammonia emissions on an intensity basis

On an intensity basis, HCON steers had 24% and 27% lower emissions when expressed as kg NH_3 kg liveweight^{-1} and kg NH_3 kg HCW^{-1}/kg boneless beef compared to HNAT steers (Figure 4.15). Similarly, MCON had 32% lower emissions (kg NH_3 than MNAT kg liveweight^{-1}, kg HCW^{-1} and kg boneless beef^{-1}) compared to MNAT. Finally, LCON produced 13% and 10% lower emission (kg NH_3 kg liveweight^{-1} and less kg NH_3 kg HCW^{-1} kg boneless beef^{-1}) compared to LNAT.

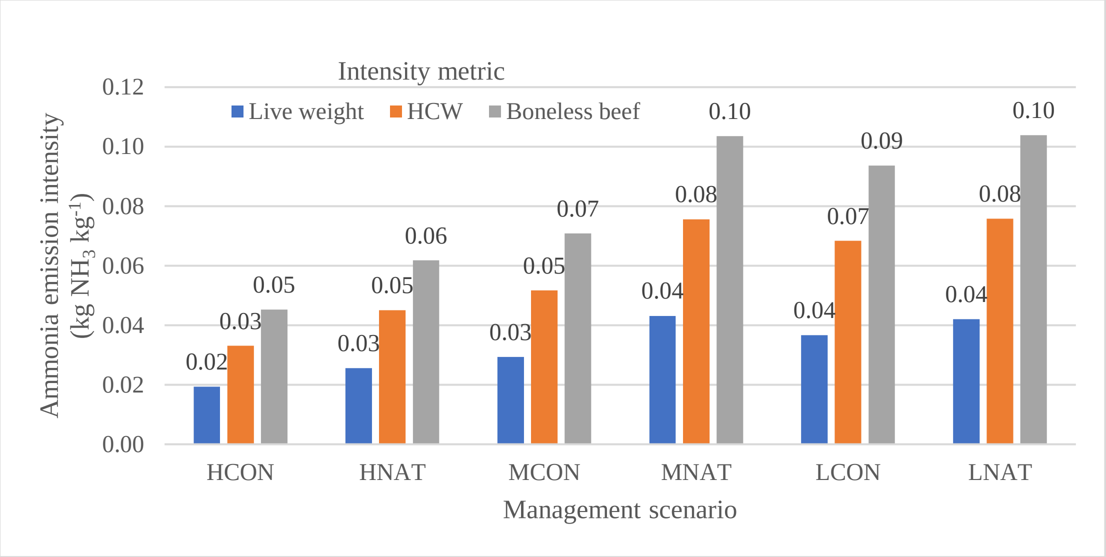

Figure 4.15 Average ammonia emissions on an intensity basis (kg NH_3 kg liveweight^{-1}, kg HCW^{-1} and kg boneless beef^{-1}; n=2 trials) for six management scenarios (HCON - Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

4.4.5 Impacts of PET removal on water use

Feed production accounted for more than 99% of total water use for all treatments (Table 4.10). Further, HCON, MCON, and LCON used 19%, 24% and 11% less water than the natural treatment of the same feeding strategy. Drinking water (m^3 hd^{-1}) was also 25%, 31% and 18% lower in HCON, MCON and LCON, respectively, compared to the NAT treatments with the same feeding strategy. There was a less than 1% difference for water use associated with processing between CON and NAT steers of the same feeding strategy (Table 4.11).

Table 4.10 Proportion of water use (L; n=2 trials) required by steers for drinking, feed production, and processing for 6 management scenarios (HCON - Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

	HCON	HNAT	MCON	MNAT	LCON	LNAT
Drinking water	0.5%	0.5%	0.5%	0.5%	0.4%	0.4%
Crop production	99.1%	99.1%	99.2%	99.2%	99.4%	99.4%
Beef processing	0.4%	0.4%	0.4%	0.3%	0.2%	0.2%

Of the water used for feed production (Table 4.11), barley grain accounted for 88%, 88%, 73%, 77%, 43% and 52% of the total water use for HCON, HNAT, MCON, MNAT, LCON, LNAT, respectively. Water requirements for LCON and LNAT on pasture accounted for 34% and 27% of total water use. Barley greenfeed was not included in the diet of the Heavy steers but accounted for 12%, 8%, 13%, and 10% of the total water required to produce feed crops for MCON, MNAT, LCON, and LNAT, respectively. Barley silage accounted for 3% of water required for crop production for both HCON and HNAT, 2% for both MCON and MNAT, 1% for LCON and 2% for LNAT steers. Canola meal accounted for 9% of the water required for feed crops for both HCON and HNAT, 13% for MCON, 12% for MNAT, and 9% for both LCON and LNAT steers, respectively.

More specifically, water use for barley grain was 19%, 28% and 26% less for HCON, MCON, and LCON compared to NAT treatments (Table 4.11). Water for barley silage was 19%, 26% and 35% less for HCON, MCON and LCON compared to NAT steers. Water for canola meal was 20%, 19% and 11% less for HCON, MCON and LCON compared to NAT steers. Water for greenfeed was 7% and 8% less for MNAT and LNAT than MCON and LCON. Further, LNAT treatments used 10% less water on pasture than LCON.

4.4.5.1 Total water use

Conventional steers had 20%, 24%, and 12% lower water requirements, resulting in a difference of 260.7 m^3 hd^{-1},413.5 m^3 hd^{-1} and 295.7 m^3 hd^{-1} for Heavy, Medium, and Light steers compared to their respective NAT treatments. Total water use was lowest for Heavy steers, intermediate for Medium steers and highest for Light steers for both CON and NAT treatments.

Table 4.11 Mean total water use (m^3 hd^{-1}, n=2 trials) including drinking, feed production, and processing, required by steers for six management scenarios (HCON - Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

Water use,	Management scenario[a]					
m^3 hd^{-1}	HCON	HNAT	MCON	MNAT	LCON	LNAT
Drinking water	5.1	6.7	6.4	9.2	8.6	10.5
Crop Production						
Green water						
Barley grain	942.7	1,171.0	972.1	1342.8	977.8	1,321.3
Barley silage	33.2	41.2	26.7	36.0	25.4	38.8
Barley greenfeed			153.6	143.8	285.6	264.1
Canola meal	91.9	114.7	1,75.2	215.8	213.1	238.5
Pasture					762.3	695.3
Total green water	1,067.7	1,326.8	1,327.7	1,738.3	2,264.2	2,558.0
Beef Processing	4.6	4.7	4.7	4.7	4.8	4.8
Total water use	1,077.4	1,338.2	1,338.8	1,752.2	2,277.6	2,573.3

During backgrounding, MCON and LCON steers required 7% and 8% more water per head than MNAT and LNAT while LCON required 10% more water per head during grazing than LNAT. During finishing HCON, MCON and LCON required 20%, 32% and 34% less water than HNAT, MNAT and LNAT steers, respectively (Figure 4.16).

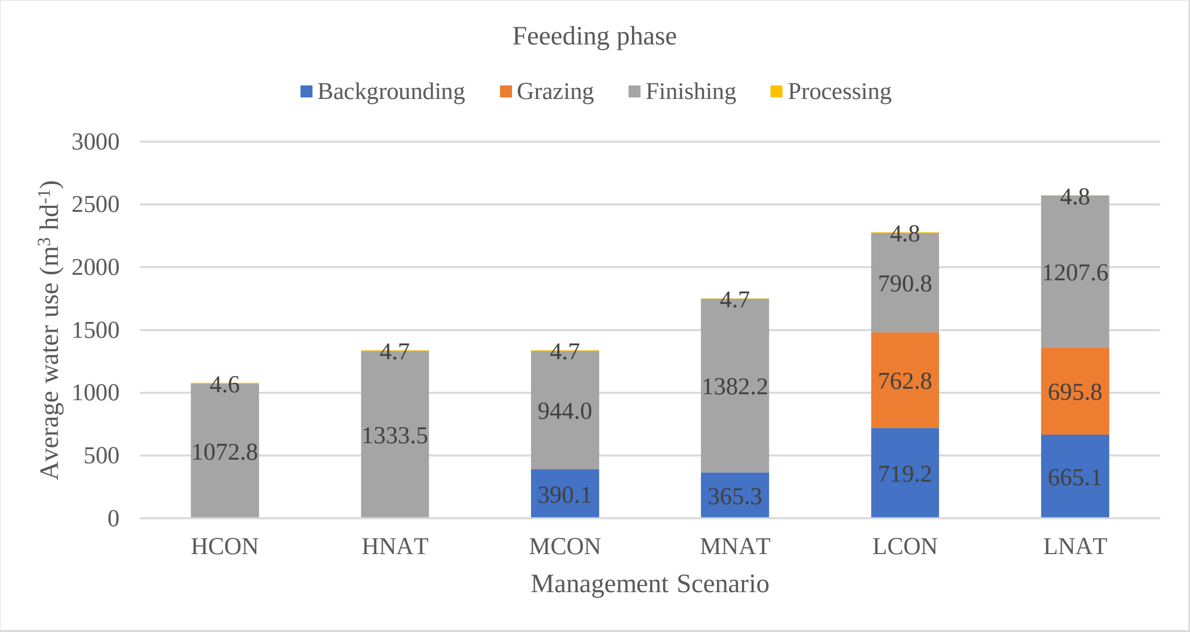

Figure 4.16 Water use (m^3 hd^{-1}) by steers during backgrounding, finishing, and grazing (n = 2 trials) for six management scenarios (HCON - Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

On an intensity basis (m^3 H_2O kg boneless $beef^{-1}$), HCON, MCON and LCON had a 19%, 25% and 12% lower water use intensity than HNAT, MNAT, and LNAT, respectively (Figure 4.17). When compared by feeding management strategy, HCON required 18% and 51% less water than MCON and LCON, respectively with MCON steers requiring 39% less water than the LCON steers. Similarly, HNAT required 25% and 46% less water than MNAT and LNAT steers respectively, with MNAT steers requiring 28% less water than LNAT steers.

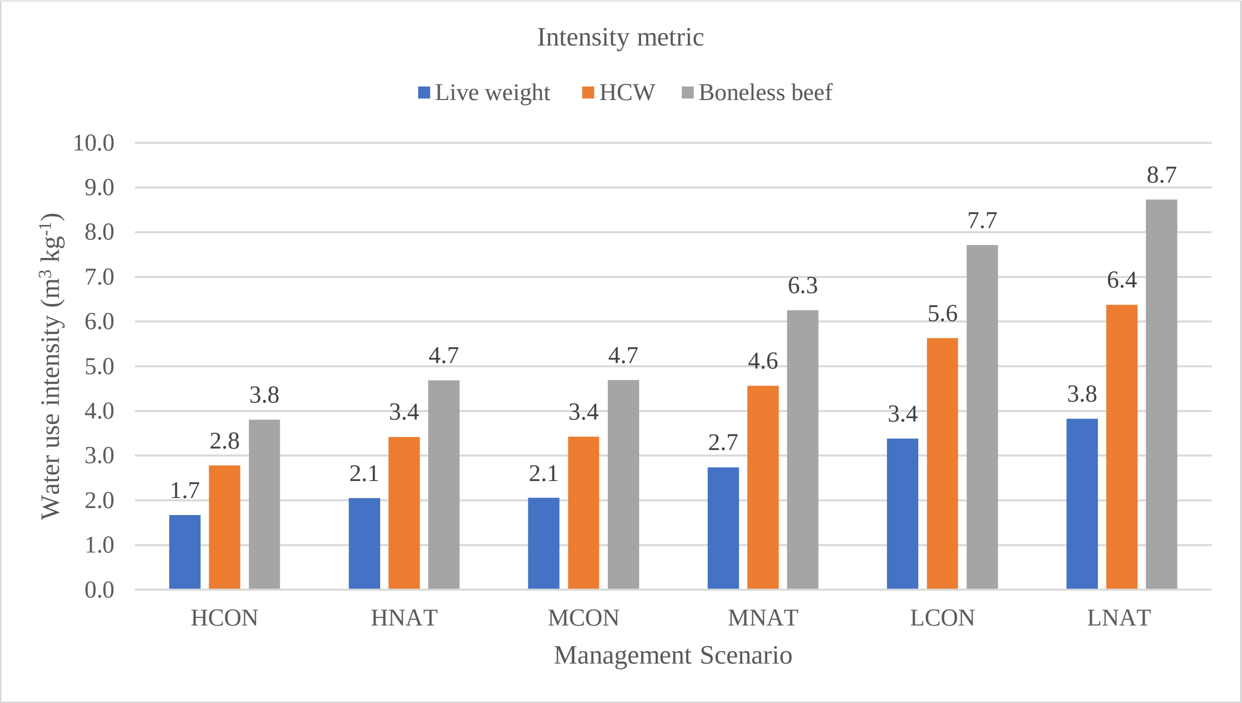

Figure 4.17 Average water use intensity (m^3 kg live weight^{-1}, kg HCW^{-1}, and kg boneless beef^{-1}; n=2 trials), for steers raised in six different management scenarios (HCON - Heavy conventional; HNAT =Heavy natural; MCON = Medium conventional; MNAT = Medium natural; LCON = Light conventional; LNAT = Light natural)

4.5 DISCUSSION

Days on feed

The observed 15-25% reduction in DOF from CON vs NAT steers can be attributed to an increase in ADG in the former (Smith 2022) as a result of the use of PETs. Further, HCON had 26% and 54% fewer DOF compared to MCON and LCON steers, respectively with MCON having 30% fewer than LCON. Similarly, HNAT had 27% and 48% fewer DOF compared to MNAT and LNAT, respectively with MNAT having 30% fewer than LNAT steers.

The reduction in DOF is attributed to HCON steers having higher ADG (1.93 kg d^{-1}) compared to MCON (1.90 kg d^{-1}) and LCON (1.24 kg d^{-1}) as well as heavier weaning and trial start weights. Therefore, Heavy steers reached the target weight of 646 kg in an average of 155 days compared to 208.5 and 339 days for the later two treatments. Similarly, steers in the HNAT had higher ADG (1.62 kg d^{-1}) compared to MNAT (1.51 kg d^{-1}) and LNAT (0.99 kg d^{-1}) and therefore reached the target weight of 646 kg in an average of 205 days compared to 279.5 and 398 days for the later two treatments. Increased ADG for steers in the Heavy treatment can be attributed to the increased energy density of the diet (> 85% barley grain; average TDN = 79.95%) throughout the finishing period compared to the lower energy diets associated with the Medium and Light treatments which included lower energy feeds during backgrounding (average TDN= 64.8%) and grazing (average TDN= 61.0%), for 41% and 75% of the feeding period, respectively (Table 4.5). Improved production efficiency leading to reduced DOF because of PET use in steers compared to natural steers has been reported elsewhere (Capper et al. 2012; Cooprider et al. 2011).

Total greenhouse gas emissions and emission intensity

Overall, GHG emissions (kg CO_2e kg LW^{-1}) were 9.8% to 11.2% lower for CON compared to NAT which translated to a 7.1-13% reduction in overall GHG emission intensity (kg CO_2e kg boneless $beef^{-1}$). The observed reduction in emissions and emission intensity can be directly attributed to the reduction in DOF associated with use of PETs in the CON compared to NAT steers produced using the same feeding strategy. However, higher rates of GHG emission associated with MCON and LCON steers during the backgrounding and grazing phases were due to heavier body weights and therefore higher DMI in CON steers compared to NAT steers. Use of PET's resulted in an overall reduction in GHG emissions regardless of feeding management strategy as all CON treatments (Heavy, Medium, and Light) had lower DOF compared to their respective NAT treatment.

The reduction in emission intensity estimated in the present study are comparable to those reported elsewhere in western Canada (4.9-5.1% Basarab et al. 2012; 15.8% Aboagye et al., 2022; 3-7% Boonstra et al., 2023), Brazil (1.1-28% Capper et al., 2021), and the United States (31.4% Cooprider et al. 2011; 6.6-8% Stackhouse et al. 2012; 22% Stackhouse-Lawson et al. 2013; 1.1-7.7% Webb, 2018). Differences in the magnitude of reduction of emissions associated with PET use between studies can be assumed to be related to diet, DOF, class of cattle, cattle breed, weaning and final weights and the delivery method, timing, and length of time of PET treatment. For example, steers in the study by Boonstra et al. (2023) received three TBA/estradiol implants with or without the addition of ractopamine. However, in the present study, Heavy and Medium steers received two TBA/estradiol implants during finishing, while Light steers received one. During the backgrounding phase, Medium and Light steers received 2 and 3, zeranol implants respectively. In addition, Light cattle received one TBA/estradiol implant while grazing. A portion of the lower GHG emissions from PET-treated steers observed in Boonstra et al. (2023) may be attributed to the fact that the PET-free steers still received ionophores in their diet. In contrast, NAT steers in the current study did not receive any PETs. Boonstra et al. (2023) is used throughout the discussion as a comparison to our study as it is a recent western Canadian study using similar metrics.

Aboagye et al. (2022) reported a 15.8% decrease in GHG emissions in steers which received a 120 mg TBA and 24 mg estradiol implant, as well as tylosin and monensin compared to those who did not receive any PETs. Other differences from the present study include higher initial weights and lower targeted finish weights, as well as increased DOF for HCON (162 to 148) compared to the finishing period reported by Aboagye et al. (2022; 66 to 99). Further, Aboagye et al. (2022) only examined environmental impacts during the finishing phase while the present study examined weaning to slaughter.

Few studies have examined the impacts of GHG emissions of implanted cattle backgrounded on pasture. Capper et al. (2021) estimated a 9.4% reduction in GHG emissions in implanted cattle raised in a Brazilian production system which relied heavily on extensive grazing. These authors used an excel-based LCA model as previously described by Capper (2012), and Capper and Cady (2020). However, unlike our study system boundaries of these studies included cow-calf production and finishing of bulls and heifers (no steers), as well as transport emissions from farm to slaughter. Other differences include total DOF which was over two years vs an average of 339-d for LCON.

Greenhouse gas emissions by source

Regardless of feeding strategy, enteric CH_4 emissions accounted for the highest portion of total emissions (Heavy = 44.3%; Medium = 47.6%; Light = 47.1%; Figure 4.4) with a reduction of 3% to 9% when comparing CON and NAT steers. Manure CH_4, direct N_2O and indirect N_2O were the remaining emissions from each of the production systems. These values are comparable to Boonstra et al. (2023) who reported 44.9% of emissions were associated with enteric CH_4, and with TBA implants resulting in a 4% reduction in enteric CH_4 emissions in steers that were backgrounded and finished as compared to non-implanted cattle.

High-energy diets also resulted in a lower proportion of enteric CH_4 emissions with HCON steers having 62% of total animal associated emissions (kg CO_2e) attributed to CH_4 compared to MCON and LCON which had 63% and 66% attributed to enteric CH_4, respectively. Similarly, during backgrounding enteric CH_4 accounted for 66% of animal associated emissions for MCON and LCON, and 74% of animal associated emissions during grazing. This trend was also apparent in Boonstra et al. (2023) in which enteric CH_4 accounted for a lower proportion (75%) of emissions during finishing compared to backgrounding (84%).

Methane from manure, direct N_2O, indirect N_2O and CO_2, were reduced by PETs by 4-6%, 10-16%, 11-16%, and 12- 24%, respectively) compared to NAT steers. Boonstra et al. (2023) reported a comparable reduction in emissions with PETs by source of 3-7% for enteric CH_4 but a slightly lower reduction in emissions of 6-7%, 6-7%, and 9% for direct N_2O, indirect N_2O and CO_2. These differences may be attributable to regional variation in temperature and precipitation (Central Saskatchewan vs. Lethbridge, AB) as well as diet and other management factors that influenced DOF.

GHG emissions from feed production

Production and delivery of feedstuffs resulted in 27-29% of total GHG emissions, with the quantity produced for each ingredient determined by its inclusion rate in the diet (Vergé et al. 2008; Figure 4.6). As expected, barley grain had the highest proportion of emissions (62% to 73% of crop emissions) for Heavy and Medium steers during the backgrounding and finishing phases. Pasture accounted for the highest proportion of feed emissions (38% to 43%) for Light steers when carbon sequestration was not considered due to the large land base required to grow forages that had a comparatively lower yield to other feed ingredients (Table 4.7).

Overall, there was 12-25% lower emissions associated with feed from CON compared to NAT steers. Additionally, Heavy treatments had reduced emissions associated with feed compared to the Medium and Light treatments as a result of higher energy diets (H avg TDN= 79.9%; M avg TDN= 72.1%; L avg TDN= 68.4%; Table 4.5) leading to reduced DOF.

Aboagye et al. (2022) and Boonstra et al. (2023) also reported a reduction in emissions associated with crops as less feed was required as a result of the use of PETs in steers. However, Boonstra et al. (2023) reported a higher proportion of crop emissions compared to the present study (42% of total emissions) which could be attributed to differences in cop management including yield, fertilizer rates, herbicide application and rates of inclusion of feedstuffs in the diets (corn vs. barley and silage vs. greenfeed/silage) in the different regions (Lethbridge, AB vs. Clavet, SK). In our study, as well as those cited above, increased feed efficiency and ADG leads to a reduction in emissions associated with crop production as less feed was required to bring PET-treated steers to finishing weight regardless of the post-weaning management strategy.

Improvements to carbon sequestration estimation in Holos 4 vs. 3

Carbon sequestration was estimated in the Holos model (V3.0.6.) which resulted in negative emissions during the grazing period. It is important to note that carbon sequestration in this version of the Holos model is estimated using the same methodology used previously by the National Inventory Report: Greenhouse Gas Sources and Sinks (NIR; ECCC 2020) based on the Century model described by Patron et al. (1987;1988). It is a single-year soil carbon model which employs annual soil organic carbon (SOC) change factors to estimate the change of SOC with changing management practices including tillage to no-till or shifting from annual crop production to perennial pasture stands. Alternatively, the most recent version of Holos (V4) utilizes two multi-year soil carbon models: i) IPCC Tier 2 model (current methodology of the NIR; ECCC 2023) and ii) the Introductory Carbon Balance Model (ICBM; Andrén and Kätterer 1997). These models allow for the annual estimations of soil carbon based on carbon inputs and outputs. An annual timestep estimating over multiple years including soil dynamics is used for both crops and perennial land use systems including a polygon scale in response to the change of management practices including annual crop residue and manure inputs, inclusion of a cover crop rotation, tillage practices, and climatic conditions among other factors to estimate past, present and future carbon sequestration changes.

Land requirements

Annual variation in feed ingredient yield and land required for the production of feed was minimized by averaging crop yields and fertilization rates (2017 to 2019), temperature (1990 to 2020) and precipitation (1990 to 2020) over multiple years. The observed decrease in land requirements for growing feed for the steers during each of the three feeding phases (finishing << backgrounding < grazing) occurred as a result of a decrease in DOF in CON vs NAT steers. It is important to note than during backgrounding and grazing, CON steers required slightly more land than NAT steers (Figure 4.9) due to increased ADG, BW and DMI (Smith 2022) associated with the use of PETs. Similarly, although the same quantity of land was allocated to LCON and LNAT steers during grazing, Smith (2022) reported that PET-treated steers had higher ADG.

Improved efficiencies as a result of the use of PETs resulted in a land use reduction of 9-22% (ha kg boneless beef^{-1}) for CON compared to NAT steers. Boonstra et al. (2023) reported a 9.9-10.5% decrease in land required for steers treated with PETs. In addition, Aboagye et al. (2022) reported a 19.5% increase in the land required to raise cattle without PETs.

Nitrogen excretion

The observed reduction (0.007 - 0.012 Mg N hd^{-1}; 21%-25%; Figure. 4.11) in total mean N excretion between CON and NAT steers was associated with increased nitrogen use efficiency linked to improved feed efficiency and ADG with use of PETs, resulting in fewer DOF (Stackhouse et al., 2012 and Capper et al., 2012). The finishing phase had a higher rate of N excretion (0.037 to 0.024 Mg N hd^{-1}) than backgrounding (0.010 to 0.020 Mg N hd^{-1}) for both Medium and Light steers despite MCON (110.5-d vs 98-d) and MNAT (181.5-d vs. 98-d) having more DOF during backgrounding. On average, the finishing phase had high dietary CP compared to backgrounding (13.1% vs 12.6%, respectively; Table 4.5). Additionally, Light steers had more average DOF during backgrounding (195.5-d) than finishing (LCON= 76-d, LNAT=135-d). While Heavy and Medium steers are consistent with the established trend of increasing DOF increased the environmental footprint, MNAT had a higher N excretion rate than LCON and LNAT (28.0 kg NH_3 hd^{-1} vs. 24.3 and 27.9, respectively).

The observed reduction of N excretion from CON compared to NAT is higher than that reported by Boonstra (2022) who reported a 6% reduction (2.88-2.81 Mg N and 2.99-3.05 Mg N for steers treated with TBA and RAC, respectively). However, the overall excretion rate was comparable to our study (92.2-93.2% vs. 87-90% respectively).

Total NH_3 emissions and NH_3 emission intensity

A decrease in total NH_3 emissions of 25%, 32% and 13% for HCON, MCON and LCON, respectively (Figure 4.13) and emissions intensity (27%, 32% and 10%, for HCON, MCON and LCON; Figure 4.15) as a result of the use of PETs is supported by other literature. Aboagye et al. (2022) reported an11% decrease in emissions from implanted steers compared to non-implanted steers when adjusted for weight. Further, Capper et al. (2021) reported a 17.7% reduction in GHG emissions in Brazilian cattle as a result of the use of PETs in a pasture-based system. Boonstra et al. (2023) reported much lower differences in NH_3 emissions (7.4% to 7.6%) between PET treated and natural steers, as result which may be attributed to differences in DOF, as well as differences in the types of PETs employed and climatic conditions.

NH_3 emissions by source and phase

Confined emissions were the largest source of NH_3 emissions for all treatments (6.8 to 19.5 kg NH_3 hd^{-1}; Figure 4.14). Second highest NH_3 emissions were from stored manure for all Medium and Light steers (3.5 to 5.3 kg NH_3 hd^{-1}), land for the Heavy steers (3.2 to 3.7 kg NH_3 hd^{-1}) while third highest was stored manure for Heavy steers (2.4 to 3.2 kg NH_3 $hd^{-}1$) and land for the Medium and Light steers (3.4 to 5.8 kg NH_3 hd^{-1}). HCON represented the lowest rate of emissions from all sources compared to the other CON treatments, due to increased efficiency from a higher energy diet resulting in fewer DOF while LCON represented the highest rates of NH_3 emissions from all sources, compared to the other CON steers due to the inverse. Grazing resulted in the lowest NH_3 emissions attributed to the fewest DOF and direct application of manure to the land as opposed to it being stored. Boonstra (2022) also reported the highest proportion of emissions (66% ± 1%) in confinement as compared to stored and land applied manure NH_3 emissions. Differences in proportion of emissions by source between Boonstra (2022) and our study can be attributed to higher dietary CP content during backgrounding (13.2%) compared to our study (12.6%) and climate.

It is important to note that the magnitude of difference in emissions from steers in the MNAT treatment was proportionally larger than of the other two treatments. A possible explanation for this difference may be associated with the time of finishing which occurred from March to September (spring and summer) compared to other treatments in which finishing occurred during fall/winter to early spring. Therefore, the MNAT treatment had a 30-y average ambient temperature of 10.5 °C during the finishing period as compared to the other treatments which had 30-y average ambient temperatures range of -5°C to 7°C. Increased temperatures promote ammonia volatilization (Wang et al. 2023; Sommer and Hatchings 1995) and stockpiling-adjusted emissions factors consider temperature as described by Sheppard and Bittman (2012). In this model NH_3 emissions increase 1.5-fold for every 10°C increase above the reference temperature of 15°C and decrease by an equal amount for every 10°C below the 15°C reference temperature (Legesse et al. 2018b). There is potential concern, that higher ambient temperatures as a result of climate change will lead to higher NH_3 emissions.

Water requirements

Feed production was the primary use of water accounting for 99.1% to 99.4% of total water use. This aligns with previous literature examining PET use (99.3% Boonstra et al., 2023; 99% reported by Legesse et al. 2018a). Average steer water intake ranged from 0.5% to 0.4% of total water use across management scenarios which is consistent with previous literature (0.4% and <1%; Boonstra et al. 2023 and Legesse et al. 2018a, respectively). Water required for meat processing (4.6 to 4.8 m3 hd^{-1}) was also comparable to Boonstra et al. (2023) and Legesse et al. (2018a).

A reduction in total water use (m^3 water hd^{-1}) between CON and NAT treatments can be attributed to lower DOF for CON due to increased feed efficiency as compared to NAT. Similar reductions have been observed by Aboagye et al. (2022; 19.4%) as well as Capper et al. (2021; 15%) and Boonstra et al. (2023; 10%; 183 m^3 hd^{-1} to184.7 m^3 hd^{-1}). However, total water use for Heavy treatments and MCON though comparable by management were lower than use reported by Boonstra et al. (2023; 2,090.1 m^3 hd^{-1} and 2,596.7 m^3 hd^{-1} vs. 1,077.4 m^3 hd^{-1} and 1,338.7 m^3 hd^{-1}, respectively) as blue water associated with irrigation was considered by the Boonstra et al. (2023) and not in the current study.

During confined and pasture-based backgrounding, MCON and LCON steers required more water than MNAT and LNAT as a result of heavier weights and therefore an increase in DMI and drinking water requirement (Table 4.8; NASEM 2016). However, when adjusted for BW (data not shown), MCON and LCON consumed less water compared to the NAT steers of the same feeding strategy, as was the case for Light steers during the grazing period. This same phenomenon was observed by Capper et al (2021) for pastured bulls and Boonstra et al. (2023) for steers during the backgrounding phase.

On an intensity basis, HCON, MCON and MCON had a water use intensity of 3.8 m^3 H_2O kg boneless beef $^{-1}$, 4.7 m^3 H_2O kg boneless beef $^{-1}$, and a 7.7 m^3 H_2O kg boneless beef $^{-1}$, representing a 19%, 25%, and 12% reduction compared to their respective NAT treatments (Figure 4.17). This is comparable to Boonstra et al. (2023) who reported a 5.9 m^3 H_2O kg boneless beef $^{-1}$ for both STBA and SRAC treatments resulting in a 11% to 12% decrease in water use m^3 H_2O kg boneless beef $^{-1}$ compared to the weight-adjusted control steers. Other Canadian studies (Aboagye et al. 2022) found weight adjusted steers to have a 19.4% increase in water usage (m^3 H_2O kg boneless beef $^{-1}$). These same authors reported implanted steers had a water use intensity of 6.42 m^3 H_2O kg boneless beef $^{-1}$ which is comparable to the less efficient MNAT treatment in the present study which is expected as the previously mentioned authors considered blue water associated with irrigation while the present study did not.

4.6 CONCLUSIONS

The results from this study confirm that utilization of PETs in Canadian beef production systems (including direct finishing, backgrounding prior to finishing and backgrounding, summer grazed and finished cattle) resulted in lower land use, GHG and NH_3 emissions, and water use on an intensity basis, compared to NAT treatments. Further, this study adds to previously published results which demonstrate a lower environmental footprint when using PET's due to increased ADG resulting in reduced DOF to reach a target end weight. Average environmental and crop data over a 30-year period was used to ensure that short-term variation in temperature and precipitation would not impact outcomes. In addition, the study design which included 80-hd per each of six treatments over two replicate years, resulting in 960 observations provides further confidence regarding the observed outcomes.

Although LNAT and LCON had greater GHG and ammonia emissions, as well as land and water use compared to Medium and Heavy treatments, important sustainability metrics including biodiversity and other ecosystem services associated with grazing yearling steers were not included in our evaluation. Carbon sequestration data was estimated using Holos v3. While this measurement provides an estimate to compare systems, it is likely that the extent of carbon storage was underestimated as carbon sequestration is difficult to predict and conservative estimates were employed. However, Holos v4 has a more refined equations to estimate carbon sequestration, though it was not available when this project was conducted. Other ecosystem services associated with the preservation of grassland ecosystems were not included in the analysis as these metrics are yet to be quantified and reliably measured. However, there is optimism as this type of work is being done by research institutions and NGOs including Ducks Unlimited Canada and the Nature Conservancy of Canada, among others.

Lastly, while there are higher adoption rates of PET use in feedlot and backgrounding systems compared to cow-calf and other extensive systems, this project is the first in Canada to report a reduced environmental footprint can be achieved on pasture-based systems through the use of PETs.

5 GENERAL DISCUSSION

This study adds to an existing body of literature which demonstrates that that the use of PETs in post-weaned steers can reduce the environmental impacts (GHG and NH_3 emissions, land, and water use) of beef production compared to NAT steers. This study is unique in that it is the first to examine the value of using PETs in multiple post-weaning feeding strategies including a two-phase backgrounding system with a grazing phase prior to entering the feedlot.

The observed decrease in the estimated environmental impacts in CON compared to NAT cattle can be attributed to an increased ADG resulting in a decrease in DOF. As a result, on an intensity basis, HCON consistently had the lowest environmental impacts compared to MCON and LCON as these steers had either a one or two backgrounding phases respectively, in which they were fed lower energy diets that resulted in a longer feeding period. Therefore, PETs and directly finishing of cattle are strategies to reduce the environmental impact of beef production in Canada. The data demonstrated that the Light management scenario consistently had the highest environmental footprint in terms of GHG and ammonia emissions, as well as land and water use. However, pastureland used for grazing stored large quantities of carbon with the potential for additional carbon sequestration in the systems used to produced both LCON and LNAT steers. These results must be interpreted with caution as the carbon module in Holos v3, used to estimated GHG emissions in this study, is basic compared to the new Holos v4 and therefore has limitations. Nonetheless, although some aspects of the forage-based diets resulted in a greater environmental impact than direct grain-fed cattle, grasslands also supply additional ecosystem goods and services including supporting biodiversity by providing habitat for Canadian wildlife and many species at-risk and the perseverance of the quality of ground and surface water.

Gaps in Knowledge

Although we possess the capacity to measure and estimate several sustainability metrics including GHG and NH_3 emissions, land use, and water use, we are only learning to accurately assess the impact of other metrics including habitat preservation, biodiversity, connectivity of landscapes, carbon sequestration and circularity within agriculture systems, which are not considered in the current study. Recent studies have made attempts to quantity these parameters (Pogue et al. 2018, 2020) and conservation groups acknowledge the success of agricultural land conservation programs in preserving the habitats of species at risk (Reiter et al 2022). For example, Abel Moneim et al. (2022) recently demonstrated that conversion of grasslands to annual cropland restricted ecological flow. Their work emphasizes the importance of grasslands in maintaining landscape connectivity in Alberta, thereby sustaining biodiversity and gene flow for Alberta's wildlife species.

There are concerns regarding the potential loss of PETs and negative impacts that this could have on Canadian cattle production including soil erosion, run-off, and air pollution. However, tracing metabolites and waste from feedlots that may flow with run-off and impact living organisms in adjacent ecosystems is complex. However, emerging studies are beginning to assess if PETs have other ecosystem impacts when they are employed in intensive feedlot systems. Recent studies (Challis et al. 2021) found that feeding ractopamine (RAC) to cattle over 42 days resulted in detectable levels of this β-AA within manure on the pen floor after 13 days. The pen floors even at that time were contaminated at levels well beyond what has been shown to physiologically impact certain fish species native to the area (Challis et al. 2021). However, the extent to which RAC flows from the feedlot to surrounding waterways still needs to be determined.

Identifying strategies to mitigate the environmental impacts of beef production systems must consider the whole system including geographical location, feed availability and economically viability (Capper et al., 2021). Use of PETs offer a low-cost strategy to reduce the environmental footprint of cattle, which requires limited management and is of limited risk to environmental health and food safety

(Capper et al., 2021). Additionally, the use of PETs has been shown to reduce the cost of beef for consumers from US$ 15.50 to 13.80/kg (Hiroven et al. 2020).

Banning the use of PETs to Canadian producers could impact Canada's position as one of the lowest emitters of GHGs per kg beef on a global scale with North American beef producing 110 kg CO_2e kg protein^{-1}, which is on average 43% less than other developed regions (CAPI 2023). Further, removal of PETs would lead to increased competition for land to produce livestock, feed, and human food. With the margins for cow-calf producers constantly thinning, the economic viability of the Canadian beef industry could be threatened without access to technologies that increase growth efficiency, reduce days on feed and reduce resource inputs.

Although the natural cattle market exists, its demand is largely saturated at the domestic level and the auditing procedures required for its exports can cause contracting delays that lead to over-finishing, more DOF and reduced meat quality (Personal communication: Brenna Grant, Canfax Research Services, Lyle Adams, Alberta Cattle Feeders' Associate and 6A Cattle Company Ltd, Dr. Ron Stevenson Metzger Veterinary Services and Copper Creek Ranch). Additionally, whether producers are seeing the proposed premiums associated with the natural market is questionable (Personal correspondence: Shannon Argent, VBP+ and Brenna Grant, Canfax Research Services).

A survey conducted by Nielsen Global Health and Ingredient-Sentiment Survey (2016) which spanned 69 countries and 30,000 consumers reported that the majority of respondents from North America (58%) would choose beef products that are free from hormones and antibiotics. While online surveys are not always a reflection on in-store purchasing behaviour (Tait et al. 2018) restaurants that sell beef and beef products, including A&W, have used this perceived preference as a marketing tool. It has been demonstrated that the information consumers are exposed to will influence whether or not they will consume beef products (Katare et al. 2022).

The international demand for “free-from” beef resulted in barriers to export of Canadian beef to EU countries. In order to enter this market, the CETA agreement was negotiated and signed to allow free-trade of beef products between Canada and the EU provided cattle were raised by standards set by the EU which includes abstaining from the use of PETs. Although the CETA agreement was expected to generate millions of dollars in trade and export to support the Canadian natural cattle market, trade/management barriers still exist to enter the European market and producers are yet to see the benefit from CETA (Arnason, 2020). According to Statistics Canada, the Canadian beef industry currently uses less than 5% of the quota allocated under CETA. In 2022, exports to the EU and UK accounted for less than 1% of total beef export volume (1,158 tonnes) with no Canadian beef export to the UK in 2022 or in the first four months of 2023. Despite this, the EU represents 11% (16,452 tonnes) of Canada’s total beef import volume in 2022 (AAFC, 2023). The price of beef imported from the EU as of June of 2023 was $6.25/kg compared to Canada’s export price of $18.94/kg, suggesting Canada is exporting higher valued products to the EU and UK and importing lower-value products from these same countries. In the first 6 months of 2023, imports from the EU was down 7% by volume compared to 2022 which was valued at $92 million.

Encouraging science-based discussion and engagement with producers and consumers

Further investment in extension and knowledge transfer is necessary to support producers in the adoption of the use of PETs beyond the feedlot and pre-weaning. Many provinces (i.e., Alberta and Ontario) have cut back or decreased funding for extension which has created a gap in extension of best management practices to producers. This valuable source of information is particularly important for cow-calf producers who unlike large scale-feedlots, do not rely heavily on nutrition or consulting companies for management advice. Furthermore, providing information regarding types of implants available, administration techniques, as well as economic and environmental outcomes will ensure that they are able to make informed decisions regarding adoption of PET’s.

Further, this study has provided data to inform consumers to better understand the environmental implications of their food choices. It is apparent that developing effective and creative solutions to encourage dialogue between consumers and producers regarding shared values is essential to improve environmental sustainability and promote science-driven decision-making regarding food choices.

6 GENERAL CONCLUSIONS

Study conclusions:

- Data presented in this study support the hypothesis that the use of productivity enhancing technologies (PETs) post-weaning reduces environmental impacts associated with backgrounding of steers on pasture or in confinement as well as during finishing.
- Across all three management strategies, PETs resulted in a 7-13% decrease in GHG emissions (kg CO_2eq kg boneless beef^{-1}), a 13-32% reduction in ammonia emissions (NH_3; kg NH_3 kg boneless beef^{-1}), a 9-22% reduction in land requirement (ha kg boneless beef^{-1}), a 11-24% reduction in water use (m^3 H_2O kg boneless beef^{-1}) and on average, reduced DOF by 22%.
- This study adds to existing North American literature that demonstrates that the removal of PETs from beef production has negative environmental consequences.
- To the authors knowledge, this was the first study in Canada to use production data to model the environmental impacts of beef calves raised with or without PETs in which a grazing period was included as part of a backgrounding/yearling grasser finishing program. Further research regarding the environmental benefits (biodiversity, carbon sequestration, and habitat preservation) associated with the use of PETs during the grazing period is necessary.

Future considerations:

- Further understanding the environmental and efficiency benefits of utilizing PETs in forage-based systems including cow-calf and pre-weaned calves are needed.

- Further work understanding the demand for naturally-raised cattle in international and domestic markets as well as the cost-benefits to producers is an important next step.
- Finding strategies and forums to better engage with consumers including students who are the next generation of decision-makers is essential. Further support to organizations including Ag in the Classroom, and venues including the Farm and Food Discovery Centre and Discover the Farm could encourage knowledge sharing regarding the role of beef in our food system.

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