Characterization of manure management, nutrient composition, and greenhouse gas emissions from cow-calf operations in Manitoba

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ABSTRACT

This research was conducted to characterize management practices on Manitoba cow-calf operations, as well as nutrient composition and greenhouse gas emissions from solid beef cow manure during summer storage. A survey of management practices, including animal and manure management, was conducted on 10 cow-calf operations across Manitoba, which were known to generate stored solid manure from beef cows. Physical characteristics and nutrient composition of manure were measured on 2-3 dates, and manure greenhouse gas emissions (CO_2, CH_4, N_2O, NO_2, and NH_3) were measured approximately biweekly over four months using a steady-state, flow-through hood with an in-line FTIR multi-gas analyzer. Farm calving season and manure disturbance (piling and/or mixing) were management practices which influenced the quantity and timing of GHG emissions, in that manure stored in piles had higher CH_4, N_2O, and reactive N gas, NO_2 emissions, than manure in bedding packs, on a per area of manure basis (CO_2-e m^{-2}). Average cumulative CO_2 flux for manure stored in piles ranged from 4,319.0-25,276.1 g m^{-2} per month, as compared to 375.3-1,628.3 g m^{-2} for manure stored as a bedding pack. Across all farms, CH_4 was responsible for the largest proportion of emissions, with a mean whole-period cumulative flux of 771.9 g m^{-2} or 19,298.0 g CO_2-e m^{-2} across all farms. Understanding the influence of management practices on manure composition, degradation, and GHG emissions will help position the cow-calf sector towards sustainability through the development of GHG emission models, improved emissions estimates, and the development of best management practices for producers. Not all manure storage types were captured (e.g., true composting of manure) and therefore additional research in this area will allow for improved understanding of chemical processes/mechanisms responsible for observed GHG emissions.

CONTRIBUTION OF AUTHORS

Manuscript: H.C. Keenes: Conducted field research, sample and statistical analysis, writing of original draft and editing of manuscripts; D.N. Flaten: Interpretation, reviewing and editing; M.R.C. Cordeiro: Interpretation, reviewing and editing; M. Tenuta: Supervision, conceptualization, reviewing and editing; K.H. Ominski: Supervision, conceptualization, reviewing and editing.

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ABBREVIATIONS

°C	Degrees Celsius
ADF	Acid detergent fibre
AOAC	Association of Official Agricultural Chemists
BD	Bulk density
C:N	Carbon-to-nitrogen ratio
CH_4	Methane
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalents
CRSB	Canadian Roundtable for Sustainable Beef
CV	Coefficient of variation
DM	Dry matter
ECCC	Environment and Climate Change Canada
FTIR	Fourier-transform infrared spectroscopy
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	International Panel on Climate Change
L	Litres
MM	Micrometeorological methods
N_2O	Nitrous oxide gas
NDF	Neutral detergent fibre
NH_3	Ammonia
NH_4^+	Ammonium
NO	Nitric oxide gas

NO_2	Nitrogen dioxide gas
NO_2^-	Nitrite
NO_3^-	Nitrate
OM	Organic matter
SAS	Statistical Analysis Software
cm	Centimetres
d	Days
g	Grams
ha	Hectares
kg	Kilograms
m	Metres
mg	Milligrams

FOREWORD

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

1.0 GENERAL INTRODUCTION

With rising public interest in climate change and greenhouse gas (GHG) emissions, a focus on sustainable agricultural systems has emerged. The agriculture sector accounts for 10% of anthropogenic GHG emissions in Canada (ECCC 2024). Cattle are significant contributors to agricultural emissions, notably methane (CH_4) and nitrous oxide (N_2O), from enteric fermentation and manure management (ECCC 2024). The cow-calf sector accounts for 36% of the beef cattle inventory in Canada (Statistics Canada 2023), and 61% of GHG emissions (in CO_2 equivalents, CO_2-e) from the beef cattle industry in Western Canada (Beauchemin et al. 2010). While cow-calf manure alone contributes 22% of total GHG emissions (CO_2-e) from the Western Canadian beef cattle industry (Beauchemin et al. 2010), there is limited knowledge of manure management practices on Canadian cow-calf operations (Sheppard et al. 2015). As such, there may be great potential to reduce GHG emissions from this sector of the industry.

Greenhouse gas emissions and nutrient transformations occurring in manure stores (i.e., feces, urine, and bedding materials) are influenced by animal management (diet, bedding, housing), manure management (storage, handling), and environmental conditions (temperature, moisture). Studies related to manure emissions have largely focused on feedlot operations (Hao et al. 2004; Larney et al. 2006; Flesch et al. 2007; Rahman et al. 2013; Bai et al. 2015; McGinn and Flesch 2018; Bai et al. 2020), where the aforementioned factors differ significantly from cow-calf operations. These parameters also vary across the globe, therefore research findings from outside of Canada (Bai et al. 2015; Bai et al. 2020) may not be representative of Canadian production systems. As management practices across the Canadian cow-calf sector are also extremely diverse, understanding these management practices and how they influence nutrient transformation and

GHG emissions is important when quantifying emissions and developing GHG mitigation strategies.

Recent efforts to describe livestock manure storage and the associated GHG emissions, including the DATAMAN database (Hassouna et al. 2023), which is a global database of GHG emissions, further highlight the knowledge gap regarding GHG emissions from the Canadian beef sector and cow-calf operations in particular. The objective of the current study was to survey management practices, manure nutrient, and manure greenhouse gas (CO_2, CH_4, N_2O, NO_2, and NH_3) emissions from stored manure on cow-calf operations in Manitoba, and to quantify as well as understand drivers of these emissions. The information collected can be used to refine emissions estimates, including those associated with the DATAMAN database (Hassouna et al. 2023) and Canada's National Inventory Report (ECCC 2024), leading to improved policy development, and GHG mitigation strategies for cow-calf producers. These efforts will ultimately help the cow-calf sector realize GHG emission reduction targets.

2.0 LITERATURE REVIEW

2.1. GHG emissions from the cattle industry

In 2022, the agriculture sector accounted for 10% of total anthropogenic greenhouse gas emissions in Canada (ECCC 2024). The agriculture industry is a notable source of methane (CH_4) and nitrous oxide (N_2O) emissions, emitting 31% of CH_4 and 75% of anthropogenic emissions, respectively (ECCC 2023). Livestock production contributes significantly to agricultural CH_4 and N_2O emissions through enteric fermentation (CH_4) and manure management (CH_4 and N_2O emissions), with beef cattle being the largest source of enteric CH_4 emissions and manure N_2O, and second largest contributor to manure CH_4. A life cycle assessment of Western Canadian beef production by Beauchemin et al. (2010) showed that cow-calf operations produced 80% of all GHG emissions in a beef cattle production system, with 22% of total emissions attributed to beef cow manure CH_4 and N_2O alone. Beef cows are the largest animal class in the Canadian beef sector, with 84% of beef cows located in the Prairie provinces (Statistics Canada 2023a).

2.2. Characterization of cow-calf production systems

Cow-calf production systems are the first stage of the beef production cycle where a permanent cow herd is maintained to produce a yearly calf crop. The majority of calves are born between February and April (Sheppard et al. 2015; University of Saskatchewan 2018; Waldner et al. 2024), and cow-calf pairs graze perennial grasslands throughout the summer months. Calves are weaned in the fall and cows may be moved to intensive, confined overwintering areas when: i) available grazing sites have been fully utilized, ii) weather conditions prevent further grazing (i.e., excess snow, crusted snow, etc.) or iii) when they are close to parturition. Extended-grazing systems have gained in popularity, particularly in the Prairies (Sheppard et al. 2016), and therefore the time at which cows are brought in from pasture has moved later into the winter months.

Approximately 79% of all cattle operations in the Prairies will utilize "seasonal feeding areas," such as pens with little or no potential for grazing, for some amount of time (Sheppard et al. 2015). These intensive overwintering areas allow for ease of management of pregnant cows, including monitoring for calving difficulties and the potential to offer higher-quality feed.

Approximately 86% of Canadian cattle producers provide bedding materials (Sheppard et al. 2015) as it provides insulation and keeps pens dry, thereby lowering cow maintenance energy requirements and improving calf survival. The most common type of bedding is cereal straw (Sheppard et al. 2015), which may be added to the overwintering area at scheduled intervals (i.e., weekly) or may be added in response to cold temperatures or precipitation.

2.2.1. Manure management

Intensive overwinter areas result in an accumulation of manure, bedding, and waste feed (Hao et al. 2001). When cows return to pasture in spring, a manure pack, which consists of deposited feces and bedding, may remain in place in the pen before removal. This period of passive management of the stored manure is often referred to as "stockpiling" or "passive composting". The removal of solid manure from the overwintering area typically occurs once annually in the Prairies (Sheppard et al. 2015), with 94% of producers storing manure outdoors in uncovered piles or bunks (Sheppard and Bittman 2012), where the contents of manure pack are collected or pushed and piled. During this period of storage as a pile, producers may intermittently aerate manure via turning, which accelerates decomposition.

In contrast, in extensive overwintering areas, manure is deposited on pasture. As such, there is no collection and/or mass storage of solid manure and bedding materials, as is characteristic of intensive overwintering areas. Nutrient cycling is therefore distinctly different

between these management types (Jungstitch et a. 2011). The focus in the present study is on intensive overwintering.

2.2.2. Nutrient cycling

Nutrients excreted in livestock manures, such as N, P, as well as organic matter (OM)/volatile solids, have the potential to influence soil, air, and water quality through nutrient transformations, GHG emissions, and leaching into surface and groundwater (Boyd et al. 2005; CRSB 2016a). These losses may occur throughout manure storage, handling, and application to cropland as fertilizer. Nutrient losses, including direct and indirect GHG emissions, such N_2O, CH_4, and carbon dioxide (CO_2) and ammonia (NH_3) emissions, contribute to climate change and potentially degrade air quality (Chai et al. 2014; CRSB 2016a). The processes by which these losses occur will be discussed below in further detail.

2.3. Characterization of stored solid manure

2.3.1. Physical profile of stored solid manure

Moisture content (MC) of fresh manure in straw-bedded beef feedlots is dependent on several factors, including weather conditions and quantity of bedding, with average reported MC values of approximately 43% (Larney et al. 2006). Generally, MC of stored manure decreases throughout storage, resulting in an overall decrease in manure mass. Total mass loss throughout storage has been found to range from 35% in static manure piles to 66% in aerated piles of beef feedlot manure (Larney et al. 2001; 2006). Total mass reduction is related to a decrease in manure dry matter (DM) and aerobic decomposition of OM, which is higher in composted than stockpiled manure (Larney et al. 2006). These same authors reported a total DM loss of 22.5% for stockpiled manure and 39.8% for composted manure. Together, the combined effects of drying and

decomposition can result in a total manure volume reduction of 66%, leading to a subsequent increase in manure bulk density (Larney et al. 2001).

2.3.2. Chemical profile of stored solid manure

A characterization of solid beef manure across farm types in Manitoba (primarily cow-calf with a smaller number of backgrounding and finishing operations) conducted by Loro (2005) reported an average total N content of 0.53% (ranging from 0.27-0.85%) and total C content of 7.34% by wet weight (ranging from 3.54-11.40%). Stockpiled and composted feedlot and dairy manure have been reported to have substantial C- and N-based losses during storage, ranging from 11-46% and 26-70% in total N and C content, respectively (Chadwick 2005; Larney et al. 2006; Mulbry and Ahn 2014; Niu et al. 2017). The observed variability in nutrient profile and subsequent loss during storage may be attributed to differences in animal and manure management. Moreover, as these values have been derived from beef (Chadwick 2005; Larney et al. 2006) and dairy manure (Mulbry and Ahn 2014; Niu et al. 2017), where management strategies including diet and frequency of bedding lead to differences in manure nutrient concentrations, and presumably do not represent nutrient losses from cow-calf operations. Given the scarcity of information regarding nutrient profiles and loss of cow-calf manure, there is need for further study and quantification for this sector of the cattle industry.

2.3.2.1. Carbon dioxide emissions

Carbon dioxide is produced in stored manure through microbial digestion of OM. Eghball et al. (1997) observed that 46-62% of total C in composted feedlot manure was lost as CO_2, primarily from the aerobic portion of the manure storage system. The rate of CO_2 loss is highest in early storage – typically the first week – for both stockpiled and composted manure, and generally

decreases with increasing length of storage (Pattey et al. 2005; Bai et al. 2020). This pattern of emissions, combined with increasing pile temperatures over time (Pattey et al. 2005; Bai et al. 2020), suggests that CO_2 emissions are initially associated with high levels of microbial decomposition and begin to slow as easily degradable organic compounds are consumed. Carbon dioxide production, which occurs through oxidation of manure OM, may be limited when O_2 concentration in the manure pile is low, such as in water-saturated piles or piles without sufficient aeration. As O_2 concentration in the pile decreases, there is a shift towards anaerobic decomposition (Sommer 2013). Consumption of O_2 occurs originally from the surface of the pile and moves downwards towards the centre of the pile, resulting in shift in CO_2 profile, whereby the bottom of the pile produces the most CO_2 as time progresses (Hao et al. 2001).

2.3.2.2. Methane emissions

Methane emissions from stored manure are a product of anaerobic fermentation of manure and bedding materials via methanogenic microorganisms. Solid manure packs/piles are characterized by the presence of anaerobic zones, neutral pH, and adequate N, P, K, and OM for methanogensis (Kebreab et al. 2006). The magnitude of CH_4 emitted is a function of manure composition, climate, and manure management strategies (Jun et al. 2001). Further, CH_4 release from the manure pile depends not only on CH_4 production within the manure, but also the rate of CH_4 oxidation and transport within the pile (Kebreab et al. 2006). Approximately 80% of C transformation in a deep-bedded cattle manure pack or pile occurs in the aerobic portion, which comprises the top 20 cm (Sommer 2013). Below depths of 20 cm, manure packs/piles are likely to be anaerobic (Sommer 2013). Hao et al. (2001) found maximum CH_4 concentrations in composted feedlot manure piles occurred at maximum depth (107 cm), decreasing uniformly towards the manure surface. At increasing depths, there is potential for CH_4 produced by methanogenic

organisms at the bottom of a manure pile to be oxidized before reaching the surface (Hao et al. 2004; Kebreab et al. 2006; Sommer 2013), limiting the release of CH_4 from the pile. Thus, pile depth will influence CH_4 emissions released and measured. Turning/aerating manure piles will also reduce the amount of CH_4 produced due to the incorporation of oxygen (Bai et al. 2020).

As with CO_2 emissions described above, CH_4 emissions from piled solid beef feedlot manure stores are highest during the first few weeks of storage (Hellebrand and Kalk 2001; Hao et al. 2004; Yamulki 2006; Moral et al. 2012), and decrease as duration of storage increases (Pattey et al. 2005). However, for CH_4, this may be attributed to high rates of O_2 consumption early in microbial decomposition, creating anaerobic pockets within the manure (Hao et al. 2004). Gaseous emissions of CH_4 then cause these pockets to physically collapse (Hellebrand and Kalk 2001), thus emissions slow. Throughout storage, CH_4 makes up 0.03-9.7% of total C emissions from deep-bedded cattle systems (Sommer 2001; Chadwick 2005). Though seemingly small, these emissions are significant as CH_4 has 28x the global warming potential of CO_2 (Parchauri et al. 2015).

2.3.2.3. Nitrogen transformation and losses

Typically, 10% of consumed N is excreted in manure as organic N via a combination of undigested feed N and microbial N in feces, and as urea in urine (Tamminga 2006). Nitrogenous compounds in manure may undergo a variety of transformations during storage. Chemical transformations, including nitrification, denitrification, mineralization, and N-fixation, are carried out by the microbial population in the manure, whereas physical transformations include the movement of gaseous forms of N between manure and the atmosphere (Agnew 2010). The C:N ratio and aeration of manure determine the type of N transformation that will occur (Hellebrand and Kalk 2001; Chai et al. 2014), with nitrification and denitrification serving as the major pathways of N_2O production in manure (Kebreab et al. 2006).

Nitrification is an aerobic, 2-step process, whereby NH_3 or ammonium (NH_4^+), existing in the manure and/or produced during N mineralization, is oxidized to nitrite (NO_2^-), which is then converted to nitrate (NO_3^-) (US EPA 2002).

$$NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$$

Ammonia-oxidizing bacteria first oxidize ammonia to nitrite, followed by oxidation of nitrite to nitrate by nitrite-oxidizing bacteria (US EPA 2002).

$$NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-$$

$$NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^-$$

Both NO_2 and N_2O may be released as by-products (Kebreab et al. 2006). Denitrification is an anaerobic process, which occurs when a lack of O_2 leads to the use of NO_3^- as a source of oxygen (Kebreab et al. 2006). The process of denitrification consists of a sequential reduction of NO_3^- or NO_2^- to nitrogen monoxide (NO), N_2O, or di-nitrogen gas (N_2), where NO and/or N_2O may be released through incomplete denitrification (Kebreab et al. 2006).

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

These two processes can occur simultaneously within manure, with the rate at which they occur dictated by the availability of O_2 and OM (Agnew 2010). Due to the inherent heterogeneity of stored manure, different N-transformative processes will dictate N_2O production in different areas of the pile. Other nitrogenous emissions include NH_3 volatilization, the largest source of N-based emissions (Hellebrand and Kalk 2001; Chadwick 2005; IPCC 2019) and NO_3^- leaching.

2.3.2.3.1. Nitrous oxide emissions

Nitrous oxide is a potent greenhouse gas with 265x the global warming potential of CO_2 (Parchauri et al. 2015), and a precursor to NO, an ozone-depleting gas. In Canada, agricultural N_2O emissions make up 75% of total N_2O emissions (ECCC 2023), with 17% of agricultural

emissions stemming from livestock manure storage (ECCC 2023). In a study by Tenuta et al. (2000) examining livestock manure of various species and storage types, only 3 of 20 manure sources produced large quantities (>18 μg N kg^{-1} h^{-1}) of N_2O – two of these were solid beef manure from cow-calf drylot housing. These data suggest beef cow manure stores can be significant contributors to total livestock manure N_2O emissions. Indeed, ECCC (2024) has reported that beef cattle manure is responsible for 41% of national manure-related N_2O emissions.

Nitrification in manure contributes to N_2O emissions as N_2O is produced as an intermediate, and also supplies NO_2^-/ NO_3^- for denitrification. Tenuta et al. (2000) observed that N_2O emissions were correlated to NO_2^- and NO_3^- concentrations in livestock manure (cow-calf, dairy, and poultry manure), and therefore a significant source of N_2O if storage conditions favour the production of NO_2^- and/or NO_3^-. The heterogenous nature of stored manure with the presence of both aerobic and anaerobic patches within the pack/pile suggests that either nitrification or denitrification may predominate, however, the latter is commonly the leading source of N_2O in stored manure or compost (Hellebrand 1998; Tenuta et al. 2000).

Temporal patterns of N_2O emissions from stored solid manure are also variable. Generally, N_2O production is highest in early stockpiling or composting of solid beef (Hellebrand and Kalk 2001; Hao et al. 2004; Chadwick 2005; Pattey et al. 2005) and dairy cattle (Yamulki 2006) manure, declining by the mid-storage period. This decrease in emissions often occurs 3-9 weeks from the beginning of the manure storage period (Hellebrand and Kalk, 2001; Hao et al. 2004; Chadwick 2005; Pattey et al. 2005; Yamulki 2006). This is consistent with findings by Tenuta et al. (2000), who reported that the O_2 concentration was at its highest during early storage of cow-calf drylot manure, promoting nitrification and thus the formation of NO_2^- and NO_3^- for denitrification. In contrast, Bai et al. (2020) observed a decrease in N_2O concentrations throughout storage of solid

beef cattle feedlot manure, while Pattey et al. (2005) found low emissions throughout storage of stockpiled and slurry beef manure stores. While total N_2O production is generally low, ranging from 1-4.3% of total N lost (Chadwick 2005; Chadwick et al. 2011; IPCC 2019), this variation exemplifies the need for further study of N_2O emissions from stored beef cattle manure, particularly from beef cows, which have been underrepresented in studies of manure emissions.

2.3.2.3.2. Ammonia emissions

While not a direct contributor to climate-warming, NH_3 emissions are a concern due to their association with fine particulate matter in the atmosphere, surface water eutrophication, and nitrate contamination of ground waters (Chai et al. 2014; US EPA 2004). Manure contains two primary forms of N, NH_4^+ and organic N, both of which may contribute to NH_3 production through volatilization and mineralization, respectively (Johnson et al. 2005).

Ammonia is primarily produced at the surface of manure through NH_3 volatilization, the conversion of urea or NH_4^+ to NH_3, and released into the atmosphere. Ammonia losses occur as soon as feces are excreted, and continue throughout manure handling, storage, and application (Powell et al. 2008a).

Ammonia losses are associated with manure total ammoniacal nitrogen (TAN), a highly volatile fraction of manure N which consists of NH_3, NH_4^+, urea and uric acid (Chai et al. 2014). Factors influencing manure NH_3 emissions include manure temperature and pH, wind speed, aeration and exposed surface area (Hellebrand and Kalk 2001; Hristov et al. 2011; Sommer 2013). Approximately 19-45% of total manure N in beef feedlot manure may be lost as NH_3 during storage (Eghball et al. 1997). Emissions are typically highest during the first 2-3 weeks of the storage period (Hellebrand and Kalk 2001; Chadwick, 2005) and decrease with time (Hellebrand

and Kalk 2001; Chadwick 2005; Bai et al. 2020), ceasing when urea has been totally hydrolyzed (Hellebrand and Kalk 2001). The most comprehensive study of NH_3 emissions from beef cattle manure stores in Canada was conducted by Sheppard and Bittman (2012), whereby a beef-specific TAN-flow model (Sheppard and Bittman 2011) was used to model NH_3 emissions from all beef classes across 11 Canadian ecoregions. Building upon the knowledge generated by Sheppard and Bittman (2012), an on-farm characterization of NH_3 losses from beef cow manure will help to improve NH_3 emission inventories and modeling, components of Canada's Inventory Improvement Plan (ECCC 2021a).

Studies of NH_3 emissions from dairy cattle are more numerous than for beef cattle, highlighting a gap in current emissions estimates associated for the latter. Hristov et al. (2011) reported that emissions from beef cattle manure (animal class not specified) are typically similar, but may be greater than those from dairy, due to a variety of factors including: i) increased dietary N retained in milk as compared to muscle (beef), leading to potential for greater N excretion and loss via urine and feces from a beef animal; ii) lower OM content of the feces of a beef animal due to differences in dietary composition; and iii) beef housing (feedlots, drylots, and pasture) allows for greater air movement over the manure and thus increased rates of NH_3 volatilization compared to indoor housing of dairy cattle. However, production practices and diet composition for beef cows differ from feedlots and therefore only the latter points may apply to cow-calf production. As such, further exploration of NH_3 emissions from the cow-calf sector is needed to fill this gap in knowledge.

2.3.2.3.3. Nitrate leaching

Nitrate is a product of nitrification and is the most soluble N ion in manure (Agnew 2010). It can contribute to contamination of surface and groundwater via leaching and manure runoff (Boyd 2005; Chadwick 2005; Agnew 2010). Nitrate leaching can be a concern in confined housing or other areas with high stocking density where concentrated areas of nutrient can occur, such as those used for beef cows during the winter months (Boyd 2005; Sheppard et al. 2015). However, collection and piling of manure from overwintering pens reduces the potential for nitrate leaching, provided the storage area is managed appropriately. This includes minimizing exposure to precipitation when possible, avoiding pack establishment on coarse textured soils (Boyd 2005), and use of passive aeration (Hristov et al. 2011). However, the latter may increase the potential for nitrification and leaching in subsequent application of manure to cropland (Hristov et al. 2011). Given the limited knowledge of NO_3^- leaching from beef manure confinement, further research is required, as identified in the CRSB (2016a) Environmental Sustainability Assessment, for accurate estimation of NO_3^- losses from cow-calf manure.

2.4. Factors influencing GHG emissions from stored solid manure

2.4.1. Diet

As mentioned above, the nutrient composition of manure inherently varies with composition of the diet. Nutrients supplied in excess of animal requirements are excreted in the urine and feces (Erickson et al. 2003). As beef cow diets differ locally and regionally, nutrient excretion is highly variable for beef cows fed in confinement (Erickson et al. 2003). Animal dry matter intake, digestibility of feed ingredients, and crude protein (CP) content (Anele et al. 2014; CRSB 2016a) are key drivers of N transformation and losses from manure thereby influencing N excretion. Nitrogen excretion from stored solid beef cow manure is estimated at 222 g N and 5.4

kg of volatile solids per head per day, as compared to 180-215.3 g N and 2.0-2.3 kg volatile solids per head per day for solid manure from finishing animals (CRSB 2016a, using N excretion equations from Anele et al. (2014)).

Given that nutrients supplied in excess of requirements has been shown to increase N-based emissions from manure (Hristov et al. 2011), precision ration formulation to avoid feeding excess protein can reduce NH_3 emissions from manure (Tamminga, 2006; Powell et al. 2008a). This is particularly relevant in the cow-calf sector, as only 36% of cow-calf producers in Western Canada (University of Saskatchewan 2018) and 6% of cow-calf producers in Manitoba (Undi et al. 2011) balance diets provided to beef cows to meet nutrient requirements.

In addition to reducing dietary CP, other potential strategies to reduce emissions in feedlots include increased dietary roughage (potentially impacting rate of gain), as well as changes in source and quantity of dietary N, such that the site and rate of protein digestion shift N excretion from the urine to feces, thereby limiting N losses through NH_3 volatilization (Hristov et al. 2011).

Much of the research regarding dietary strategies as a means of GHG mitigation has focused on enteric CH_4 emissions. While strategies such as low-forage, high-grain diets have been observed to decrease enteric CH_4 emissions (Tamminga, 2006; Beauchemin et al. 2009), decreasing the C:N ratio of the diet has been theorized to result in higher CH_4 production from manure (Boadi et al. 2004). In contrast, Boadi et al. (2004) and Niu et al. (2017) saw no effect of high vs. low forage diets on physiochemical properties of manure including DM content, volatile solids, total N and total C content. Further, low-forage, high-grain diets are not typical for mature beef cows in Canada (Sheppard et al. 2015), highlighting the importance of considering class- or farm-specific dietary composition and the resultant manure nutrient profile when conducting

manure emissions studies, to better understand the relationships between animal diet and manure emissions, and to develop comprehensive best management practices for GHG mitigation.

2.4.2. Bedding

The amount of bedding provided in confined animal housing impacts the chemical and physical properties of the manure. Yamulki (2006) found that a 50% increase in straw added to fresh dairy manure prior to storage decreased N_2O and CH_4 emissions by 40% and 45%, respectively. Tamura and Osada (2006) also observed a reduction in CH_4 and N_2O emissions with increased bedding, as the reduction in bulk density encouraged aerobic decomposition, limiting methanogenesis and promoting rapid reduction in NH_4^+ concentration, which would otherwise be available for N_2O losses by nitrification. Reduced NH_3 emissions have also been observed with straw-bedded solid manure systems compared to slurry systems, as the straw is able to absorb mineralized TAN from manure (Sommer 2013).

While bedding may increase C:N ratio and seemingly reduce CH_4 and N_2O emissions, as described above, the addition of straw may also increase aeration, aiding gas diffusion and thus increasing NH_3 emissions (Kebreab et al. 2006), as observed by Tamura and Osada (2006) in composted dairy manure. In contrast, the addition of straw on top of a manure pile may decrease NH_3 emissions by reducing airflow at the surface of the pile (Sommer 2013). Given that multiple mechanisms impact stored emissions, it is clear there is a need for further research regarding the influence of bedding materials on manure pack emissions.

While straw is the primary bedding material used on Canadian beef operations, type and particle size of bedding may also affect manure nutrient profile and GHG emissions. Bedding materials of large particle size, such as woodchips, increase air flow through the pile, which may

subsequently increase O_2 concentration, resulting in increased aerobic decomposition of manure OM and thus increased CO_2 and decreased CH_4 and N_2O emissions (Hao et al. 2004). However, bedding materials such as cereal straw, with a more easily degradable hemicellulose structure (Eklind and Kirchmann 2000) and smaller particle size, result in increased decomposition during storage, leading to increased CO_2 emissions (Hao et al. 2004). Use of other bedding materials such as newspaper and pine shavings have been shown to result in lower total manure N concentrations than straw- or non-bedded dairy housing manure packs, although N losses as NH_3 were similar among newspaper, straw, and non-bedded manure packs (Powell et al. 2008a). Therefore, there are numerous factors consider when examining stored manure GHG emissions studies in different geographic areas or farm types (dairy vs. beef, cow-calf vs feedlots, etc.) where type and amount of bedding may differ.

2.4.3. Manure storage types

2.4.3.1. Stockpiled manure storage

Stockpiling manure, also referred to as static stockpiling, is a common form of solid manure storage in the beef cattle industry. Stockpiled manure is not disturbed by either turning or aeration throughout the storage period; rather it is a passive form of manure storage. Approximately 60-70% of all beef producers in the Western provinces store manure using stockpiling (Sheppard and Bittman 2012). Owing to the lack of aeration, stockpiled manure is largely anaerobic, which leads to increased CH_4 flux from stockpiled manure, as compared to turned manure (Bai et al. 2020).

2.4.3.2. Composted manure storage

Composting is an alternative management strategy for solid manure storage prior to field application. The composting process is accomplished by microbial degradation of manure OM, facilitated by turning or forcibly aerating the pile, which creates an aerobic environment in which these microorganisms thrive (Chen et al. 2011). The composting process is comprised of active (mesophilic and thermophilic stages) and curing (mesophilic and maturation stages) phases (Chen et al. 2011). In the early stages of manure composting, microorganisms use C-rich substrates such as starches and fibres for energy, producing CO_2 (Chen et al. 2011). As OM is broken down, the compost pile condenses, resulting in anoxic conditions and therefore the continual aeration of the pile prevents the compost from becoming anaerobic (Chen et al. 2011; Sommer 2013). During this stage of rapid, active decomposition, compost temperatures increase to 55-65°C which can persist for weeks depending on pile composition and conditions (Chen et al. 2011). This phase continues until easily digestible C is limiting, at which point decomposition is slower and pile temperatures decrease with microbial activity (Chen et al. 2011). Mesophilic microorganisms become dominant once again, and the compost pile enters the curing phase, during which O_2 consumption is low, and OM is converted into stable products resulting in finished compost (Chen et al. 2011).

Composting of livestock manure offers benefits such as a reduction of pathogens and weed seeds, due to the high temperatures associated with microbial decomposition, increased nutrient density, reduced odours, and reduced moisture content (Bai et al. 2020). Only 13% of all beef operations on the Prairies were composting solid manure in 2011, a decrease from 23% in 2005 (Sheppard and Bittman 2012; Sheppard et al. 2016). Despite the benefits, manure composting presents a concern due to increased potential for direct and indirect GHG emissions (Hao et al. 2001). Due to the aerobic nature of composted manure, the increase in GHG emissions is largely attributed to an increase in N_2O and NH_3 emissions when manure is composted rather than

stockpiled (Chai et al. 2014; Bai et al. 2020). In contrast, CH_4 emissions are largely reduced due to pile aeration (Bai et al. 2020), and instead the majority of manure C is lost as CO_2 (Hao et al. 2001). The turning process associated with manure composting also increases pile porosity, which promotes diffusion of GHGs from the pile to the atmosphere (Hao et al. 2001).

2.4.4. Environmental conditions

Gaseous emissions from stored manure may be influenced by environmental conditions, such as ambient temperature and wind speed, resulting in apparent diurnal (Khan et al. 1997; Flesch et al. 2007; Harper et al. 2009; Leytem et al. 2011; McGinn and Flesch, 2018) and seasonal fluctuations (Powell et al. 2008a; Harper et al. 2009; Leytem et al. 2011). Emissions of N_2O, NH_3, and CO_2 are positively correlated to increased environmental temperatures in both solid beef (Hellebrand and Kalk 2001; Pattey et al. 2005; McGinn and Flesch 2018; Bai et al. 2020) and dairy manure (Pattey et al. 2005; Powell et al. 2008a), with NH_3 and CO_2 emissions also correlated with increasing wind speeds (Bai et al. 2020). These responses to increasing temperatures and wind speed explain diurnal flux patterns that have commonly been observed from stored manure. Typically, GHG emissions are highest in mid-afternoon, when temperature and wind speed are at their highest, and lowest in the evening through to early morning. This has been observed for N_2O (Bai et al. 2015), NH_3 (Flesch et al. 2007; Powell et al. 2008b; Harper et al. 2009; Leytem et al. 2011; Bai et al. 2015; Bai et al. 2020), CH_4 (Leytem et al. 2011; Bai et al. 2015; Bai et al. 2020), and CO_2 (Leytem et al. 2011) emissions from manure. While it may be inferred that temperature and wind speed dictate diurnal flux, Bai et al. (2015) noted that animal and management activities are also at their highest mid-day, such that pile aeration or disturbance may inadvertently influence emission patterns.

Precipitation patterns may also influence gaseous emissions from manure. Ammonia emissions from beef cattle feedlot pens were observed to decrease after rainfall and increase again as the pen surface dried (Flesch et al. 2007). A similar effect was observed in spread dairy manure, where NH_3 emissions decreased with rainfall as soluble ammoniacal-N leached into the soil (Beauchamp et al. 1982). This too may occur in stored manure if NO_3^- leaches to the bottom of the pile where anoxic conditions predominate, and N_2O emissions through denitrification may increase (Hao et al. 2001). Similar emissions patterns were observed by Bai et al. (2020), where N_2O emissions increased following rainfall, as saturation led to anaerobic conditions resulting in denitrification losses. These newly formed anaerobic conditions may lead to simultaneous increases in CH_4 emissions.

As well as diurnal fluctuations, an understanding of seasonal variation of manure GHG emissions is essential for accurate emissions estimates and policy development, however, this may be challenging as manure stores typically do not exist year-round. Despite this, some longer-term emissions studies have been able to capture seasonal variation/fluctuation (Powell et al. 2008a; Powell et al. 2008b; Leytem et al. 2011; McGinn and Flesch 2018). Given the effects of temperature and wind speed on emissions, as described above, it may be expected that gaseous emissions from manure are highest during the summer months. This seasonal variation has been observed for NH_3 emissions from dairy manure (Harper et al. 2009; Powell et al. 2008a; 2008b). However, as these operations used indoor animal housing, the observed variation may not be representative of emissions from the cow-calf sector where manure stores exist outdoors. In outdoor housing environments, McGinn and Flesh (2018) observed that NH_3 emissions from beef feedlots were highest during the month of August, while Leytem et al. (2011) observed that emissions of CO_2, CH_4, N_2O, and NH_3, from solid manure compost on an open-lot dairy farm were

highest in June. In addition, pile aeration and other farm activities that may cause disturbance often increase during the summer months, leading to increased emissions from manure (Leytem et al. 2011).

Seasonal variation in manure emissions may also be associated with changes in management strategies. For example, diets that change with season (feed availability, stage of production, etc.) may result in differences in nutrient content of manure entering the storage pile. In addition, the time of year that the pile is formed/added to may also influence emissions. This effect was noted in fresh dairy manure by Powell et al. (2008a) who reported significantly lower NH_3 emissions in dairy manure in winter than in summer/fall due to lower dietary N intake and excreted manure N, but also decreased urease activity at colder temperatures. Therefore, it is essential to consider management decisions such as diet, time animals spend in overwintering areas and duration of storage, as well as environmental conditions when comparing manure GHG emissions between studies, to understand seasonal variation in emissions and develop best management practices for producers.

2.5. Emissions from land application

A long-used fertilizer, livestock manure contains valuable nutrients for plant growth, including N, P, K, S, and offers other benefits not provided by synthetic fertilizer such as OM, encouragement of soil microbial activity, promotion of nutrient recycling within the farm, as well as addition of OM to the soil (Agnew 2010). However, if not properly managed, application of manure can have negative impacts on soil and water quality and therefore and should be considered in the development of best management practices.

The rate of GHG emissions from applied manure varies from farm to farm based on manure management practices, including type/rate of application and incorporation into the soil. A survey of Manitoba beef cattle management practices discovered that while 81% of producers spread collected manure as fertilizer, only 9% of producers test manure for nutrients prior to application, 24% soil test prior to application, and 7% know the rate at which they apply manure (Undi et al. 2011). This indicates that producers are generally unaware of the quantity of nutrient being recycled through manure application, and the subsequent GHG emissions that may occur from the applied manure. Loro (2005) attempted to characterize solid beef manure, and noting the heterogeneity of nutrient content, revealed that solid manure from beef cattle is not a balanced fertilizer. These authors reported that to achieve a recommended 78.5 kg N ha^{-1} application rate, a wide range of 20-99 tonnes manure/ha would be required, due to the variability in manure nutrient profile. However, even when application rates are calculated on an N basis, P would be commonly over-applied (Loro 2005). These authors reported that application at an average rate of 78.5 kg N ha^{-1} resulted in application of P in excess of what can be utilized by most annual and alfalfa crops (97% and 82%, respectively). This over application of P may then contribute to eutrophication of surface water through runoff and leaching (Boyd 2005). This is of particular concern when applying composted manure, as the composting process results in substantial N and C losses and negligible P loss (Larney et al. 2006). Due to the concurrent decrease in MC in composted manure, Larney et al. (2006) found that composted manure provides 1.4x the P of fresh or stockpiled manure when applied to meet a crop's N requirements. This has implications regarding the use of composted manure when calculating application rates on an N-basis (Loro 2005; Woodbury et al. 2014), particularly where fertilizer application regulations demand compliance with P-based application rates (Larney et al. 2006), such as in Manitoba. Overapplication of nutrients can be

avoided with soil and manure testing. However, the difficulty associated with obtaining representative samples of a manure pile may make characterization challenging. Collecting manure samples over time is necessary to prevent application of excess nutrients and, may also facilitate the development of standard manure nutrient "book" values for an operation, animal class, or manure storage type (Loro 2005).

2.6. GHG measurement techniques

Techniques to measure gaseous emissions from manure have primarily been developed from those used to measure emissions from soils (Kebreab et al. 2006). These methods generally fall under two categories: chamber and micrometeorological methods (MM; Lapitan et al. 1999). Chamber methods involve placing an enclosed unit (chamber) over the emission source of interest, where emitted gases are captured within the headspace of the chamber (Kebreab et al. 2006). How the gas flux is measured will depend on if a "closed" (non-steady state) or "open" (or steady state) chamber is used. In a closed chamber, gas flux from the emitting surface is proportional to the increase in headspace gas concentration over time, whereas in open chambers, gas flux is proportional to the difference in gas concentrations between incoming and outgoing air (Kebreab et al. 2006). Gas sampling occurs at known intervals, and chamber dimensions and gas densities can be used to determine a change in gas flux over time (Agnew 2010). Chambers are typically small ($< 1m^2$; Husted 1994), making them portable and easy to use. Chambers have been utilized in both dairy (Powell et al. 2008a; 2008b) and beef manure emissions studies, including windrows (Hellebrand and Kalk 2001) and feedlot manure stores (Hao et al. 2001). Despite their ease of use, chamber studies have been criticized for altering ambient conditions, as the environment within the chamber differs from that outside, preventing true in situ measurements (Flesch et al. 2007;

McGinn et al. 2009). While the small size also makes chambers portable, this requires many measurements to be taken to achieve a representative sample from a large area (Flesch et al. 2007). This may be of concern with manure stores, as the inherent heterogeneity may be difficult to capture using this method.

Micrometeorological methods for measurement of gas flux are non-invasive techniques which do not alter environmental conditions as chambers do (Flesch et al. 2007), and are suitable for continuous or long-term measurement of gas flux (Kebreab et al. 2006). There are two main categories of MM, those that measure horizontal/downwind flux, and those that measure vertical flux above the emission source (Flesch et al. 2007). An integrated horizontal flux measurement technique was utilized by Sommer et al. (2004), where upwind and downwind horizontal measurements were used to calculate vertical flux. However, horizontal flux measurements may not be suitable for manure emissions, as the surrounding terrain may be variable and disturb air flow (Flesch et al. 2007). A micrometeorological mass balance method (Khan et al. 1997; Wagner-Riddle et al. 2006) may be more suitable for study of manure stores, as this method is not influenced by surrounding air flow. In this method, gas flux is quantified by the difference in horizontal flux upwind and downwind from the emitting surface, where horizontal airflow (wind) carries emitted gases such that concentration increases with distance over the emitting surface (Wagner-Riddle et al. 2006). While MM allow for analysis of a larger area than chambers (Agnew 2010), analysis may be limited by the size of storage area, as small manure stores may be too small for deployment (Wagner-Riddle et al. 2006), and larger areas will require multiple gas sensors downwind and thus incur greater costs (Flesch et al. 2007). The use of these techniques on-farm may also be limited by the proximity of other emissions sources, which if upwind of sensors can influence apparent emissions.

Both chamber and MM can be combined with gas quantification techniques such as Fourier-transform infrared (FTIR) spectroscopy (Galle et al. 1994; Hellebrand and Kalk 2001; Bai et al. 2020). Molecules of different gases have a unique atomic structure which produce different spectra when exposed to infrared light. When analyzing the spectra produced, absorption strength can indicate gas concentration. The use of FTIR spectroscopy allows for multiple gases to be analyzed simultaneously (Griffith and Galle 2000; Bjorneberg et al. 2009; Bai et al. 2015; McGinn and Flesch 2018; Bai et al. 2020), an important attribute for use in measuring emissions from manure. This ability of FTIR spectroscopy allows for observation of interactions between gaseous emissions (McGinn and Flesch 2018), which is currently lacking in many studies (Bai et al. 2015). This technique for gas quantification is also suitable for use on-farm, as minimum gas detection limits of the technology are in the range of values observed in feedlot emissions studies obtained using other GHG measurement techniques (Hristov et al. 2011).

2.7. Summary

Livestock manure is a significant source of anthropogenic CH_4 and N_2O emissions in Canada, and is also a source of CO_2 and NH_3 emissions. These gaseous emissions are influenced by animal and manure management decisions, as well as environmental conditions. While it is known that these factors influence GHG emissions from manure, not all animal class/farm types, which drive many of these management decisions, are equally represented in research. As beef cows are the largest contributors to manure GHG emissions in Western Canadian beef production, there is a need to consider class-specific emissions estimates, which consider the animal and manure management factors typical of cow-calf operations.

3.0 HYPOTHESES AND OBJECTIVES

3.1. Hypotheses

1. Cow-calf farms are highly heterogenous in feed quality and manure storage conditions. Thus, nutrient composition of stored solid manure is significantly different across farms.
2. Decomposition of organic materials, such as manure, progresses over time and is influenced by storage conditions. Therefore, nutrient composition of stored solid manure is significantly different within a farm over time.
3. Stored solid manure from beef cows is a source of CO_2, CH_4, N_2O, NO_2, and NH_3 emissions. The quantity of these greenhouse gas emissions from stored solid manure is influenced by manure nutrient composition and storage conditions.

3.2. Objectives

1. Understand management practices of "typical" cow-calf operations in Manitoba by surveying producers.
2. Characterize nutrient composition, physical characteristics, and GHG flux from stored manure from 10 beef cow overwintering pens.
3. Examine relationships between manure management, manure composition/characteristics, and GHG flux to determine driving factors of GHG emissions from stored solid manure.

4.0 MANUSCRIPT

Survey of cow-calf operations to characterize manure management, nutrient composition, and greenhouse gas emissions

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4.1 ABSTRACT

A survey of 10 cow-calf operations in Manitoba was conducted to characterize farm management practices, manure composition, and greenhouse gas (GHG) emissions from stored manure bedding packs of overwintering beef cows. Producers were asked about animal and manure management decisions from August 2019 to September 2020. Manure characterization occurred from June to September 2020, and involved sampling for manure nutrients 2-3 times, bi-weekly physical analysis in situ, and bi-weekly determination of CO_2, CH_4, N_2O, NO_2, and NH_3 fluxes using a steady-state, flow-through hood with an in-line FTIR multi-gas analyzer. Farm operations that piled manure bedding packs had greater CO_2-equivalent (CO_2-e) GHG emissions, on a per area of manure basis, than those where manure packs were undisturbed with no piling. Average cumulative CO_2 flux for manure stored in piles ranged from 4,319.0-25,276.1 g m^{-2} per month, as compared to 375.3-1,628.3 g m^{-2} for manure stored as a manure pack. Calving season and mixing of piled manure affected the quantity and timing of emissions. Overall, the highest GHG emissions (CO_2-e) across all farms were from CH_4, with a mean whole-period cumulative flux of 771.9 g m^{-2} or 19,298.0 g CO_2-e m^{-2} across all farms, with greater sources of CH_4, N_2O, and NO_2 from manure piles than bedding packs.

4.2 INTRODUCTION

With an increasing public awareness of climate change, the agricultural sector, and notably livestock production, have received growing attention. In Canada, the agriculture industry contributes 31% of national methane (CH_4) emissions and 75% of national nitrous oxide (N_2O) emissions, of which the beef cattle sector is a significant contributor through enteric fermentation (CH_4) and manure management (CH_4 and N_2O; ECCC 2023). The cow-calf production cycle in the Prairies, which is home to 84% of Canada's beef cow herd, has traditionally resulted in large volumes of stored solid manure, which contributes approximately 22% of total GHG emissions (CO_2-e) from the beef sector (Beauchemin et al. 2010).

Solid manure is a rich source of N and organic C (Sommer 2013), serving as a source of nutrient excretion to air, water, and soil. Nutrient concentration of manure is influenced by animal management (i.e., feeding and housing practices) and manure management practices on-farm (CRSB 2016a). Despite being a significant source of GHG emissions, limited knowledge of manure management practices on Western Canadian cow-calf operations exists (Sheppard et al. 2015). For Canada to meet industry- and government-led goals for GHG reduction, including Canada's Methane Strategy (ECCC 2022), it is essential to improve our knowledge of manure management practices, manure composition, and subsequent GHG emissions, from cow-calf operations. With this knowledge, geographically- and sector-appropriate best management practices can be developed, such that the cow-calf sector can best position itself towards sustainability.

The objectives of this study were to: i) understand management practices of "typical" cow-calf operations in Manitoba, by surveying producers for animal and manure management practices; ii) characterize nutrient composition, physical characteristics, and GHG flux from stored solid manure originating from beef cow overwintering pens; and iii) examine the relationships between

manure management, manure composition, and manure GHG flux to determine driving factors of emissions from stored solid beef cow manure.

4.3 MATERIALS AND METHODS

4.3.1. Cow-calf management practices survey

A farm management practices survey was developed to gather information regarding cow-calf herd and manure management. Criteria for selection included those farms that represented "typical" Western Canadian cow-calf operations, including confinement of close-up (i.e., nearing parturition) cows and/or heifers during the overwintering period such that a solid manure bedding pack (bedding, waste feed, and feces as deposited in the overwintering pen) and/or piled manure storage (the contents of a manure pack are pushed into a pile) was generated. The surveys were distributed electronically in May 2020 to 16 Manitoba cow-calf producers, such that a range in herd sizes, management practices, and local environmental conditions were represented. Surveys were completed over the phone to ensure questions were correctly interpreted. Survey results were summarized, and 10 producers were selected to participate in the on-farm manure and GHG measurement phase of the project.

Survey questions were focused in three areas: i) characterization of the operation, including farm type, classes and number of animals, and calving season; ii) overwintering management of the herd, including housing, use of diet formulation software, and feed ingredients during each month of the period of study (September 2019 – August 2020); and iii) manure management including manure removal, storage and application.

4.3.2. Manure characterization

4.3.2.1. Physical characterization of solid manure

Physical characteristics of solid manure including dry matter (DM), temperature, and bulk density, were determined from cow overwintering pens located on nine farms and from a heifer overwintering pen on one farm (Farm 8), which did not store manure from cows. Measurements were taken on six of 10 farms (Farms 1, 2, 3, 4, 5, 6, 8) beginning in June 2020, two additional farms (Farms 7, 9) in July 2020, and a tenth farm (Farm 10) in August 2020. Sampling occurred approximately every two weeks until September 2020, or until manure was removed from the pen, whichever occurred first. This sampling schedule resulted in 4-7 visits per farm, dependent on start date and time of manure removal/spreading. An overview of the manure sampling schedule, including dates, duration, and number of visits on each farm, is reported in Table 1.

Manure DM was determined for each of three depths – surface, mid, and deep – which were easily distinguishable by colour/texture in the manure pack. Surface manure was dry, pale, and consisted mostly of straw/bedding materials. Mid-pack/mid-pile manure was noticeably wetter than the surface, and orange in colour. Deep manure was dark brown in color. At each depth, five grab samples obtained from random locations across the pack/pile, composited, subsampled and stored in plastic bags at -20°C. Thereafter, samples were then dried at 60°C to a constant weight to determine DM.

Long stem (36”) compost thermometers were inserted into three locations evenly distributed across the pack/pile and temperature, as well as corresponding manure depth, were recorded at each location. Manure bulk density was determined using a bucket drop test which is a mass per unit volume technique described by the ASTM Standard D4531-15 (ASTM International 2015). In brief, a 21.4 L pail of known weight was filled halfway with manure collected from a mix of surface, mid, and deep manure depths, as described above, from a centrally located core of the

pack/pile. Thereafter, the bucket was dropped three times from a height of 15 cm to allow the material to settle. The pail was then filled completely and dropped again three times. The fill and drop process was repeated an additional three times. The pail was then loosely filled to the top with manure and weighed; manure mass was determined by subtracting bucket mass. Manure bulk density was then calculated using the general density equation:

$$Bulk\ density\ (kg\ L^{-1}) = \frac{Manure\ mass\ (kg)}{Bucket\ volume\ (L)} \quad (1)$$

4.3.2.2. Chemical analysis of solid manure

4.3.2.2.1. Sample collection

Solid manure samples for chemical analyses were collected at: i) early storage - the first visit to a farm during the sampling period; ii) at piling - if manure originally stored as a pack was piled, and formation of the manure pile occurred more than two weeks post-initial chemical analysis; and iii) at end of storage - when manure was removed/spread or at conclusion of the sampling period in September.

During each sampling period, 15 grab samples from three regions of the pile (five surface, five mid, and five deep) were collected in triplicate from random locations within the pack/pile. The 15 grab samples from each subset were composited, mixed by hand in a large bucket, and homogenized in a food processor to reduce particle size. Each composited sample was split into two 1L sample duplicates. One duplicate from each of the three composited manure samples was sent to Central Testing Laboratory Ltd. (Winnipeg, MB) for analysis of manure nutrient concentration, while the remaining samples were retained for nitrate analysis.

4.3.2.2.2. Manure nutrient analysis

Solid manure samples were analyzed for DM content, ash, total N, ammonium (NH_4^+), total P, acid detergent fibre (ADF), and neutral detergent fibre (NDF) by Central Testing Laboratory Ltd. In brief, DM was determined by drying at 135°C to a constant weight (AOAC 2005, Official Method 930.15). Ash content was determined by dry ashing at 600°C (AOAC 2005, Official Method 942.05). Total N content was determined by the combustion method (AOAC 2005, official method 990.03) and ammoniacal nitrogen (NH_4^+-N) content using the Kjeldahl method (AOAC 2005, official method 941.04). Organic nitrogen content was then calculated as the difference between total N and NH_4^+-N content. Total P content was determined by wet acid digestion and ICP-OES analysis (AOAC 2005, official method 985.01). Acid detergent fibre and NDF content were determined by ANKOM Technology analytical methods 14 and 15, respectively (ANKOM Technology 2020a; ANKOM Technology 2020b) using an ANKOM Delta Fiber Analyzer (Macedon, NY).

Additional manure nutrient analyses were conducted at the University of Manitoba. Solid manure samples were analyzed for total C, total N, and C:N ratio by high temperature combustion using a vario MAX cube elemental analyzer (Elementar, Langenselbold, Germany). In brief, a 150 mg sample of dried and ground manure was combusted at 900°C and auto analyzed with aspartic acid as the daily factor sample (a standard concentration used for calibration of the instrument) and homogenous ground alfalfa as an organic analytical standard. Elemental concentration was determined in Microsoft Excel from the measured absolute element content and sample weight using the following equation:

$$c = \frac{a \cdot 100 \cdot f}{w} \tag{2}$$

Where:

c = elemental concentration (%)

a = absolute element content (mg)

f = daily factor measurement

w = sample weight (g).

Total C and total N content was used to determine C:N ratio of the manure sample.

Nitrate (NO_3^--N and NO_2^--N) concentrations were determined from water extractions of manure. Fifteen grams of processed manure was placed in a 250 mL Erlenmeyer flask and covered with approximately 150 mL distilled water, to obtain a 1:10 manure:extract ratio. This mixture was shaken for 30 min at 150 rpm. A 40-45 mL sample of extract was collected and centrifuged at 2800 rpm for 3 min. The supernatant was then filtered with Watman No. 40 filter paper into a plastic scintillation vial, and analysed using a Technicon Autoanalyzer (Seal Analytical, Mequon, WI). The NO_3^--N concentration of the extract was then used to calculate manure NO_3^- on a DM basis using the following equation:

$$mg\ {NO_3}^- - N/_{kg\ dry\ manure} = \frac{[{NO_3}^- - N]_{extract} \cdot \left[volume_{extract} + \left(wt_{manure} - \left(\frac{wt_{manure}}{(1 + \%DM_{manure})}\right)\right)\right]}{(wt_{manure}/(1 + \%DM_{manure})} \quad (3)$$

where $[NO_3^-\text{-N}]_{extract}$ is reported in mg NO_3^--N L^{-1}. The same calculation was used to determine manure NO_2^--N on a DM basis.

Table 1. Sampling dates, sampling period and number of GHG measurements taken from the 10 cow-calf operations surveyed in 2020.

	Farm									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Initial sampling date	June 12	June 23	June 16	June 23	June 24	June 18	July 10	June 19	July 31	Aug 19
Mid-storage sampling date	-	Aug 20	July 6	-	Aug 21	July 16	-	-	-	-
Final sampling date	Aug 27	Sept 17	Aug 17	Sept 17	Sept 18	Sept 8	Sept 16	Aug 31	Sept 23	Sept 23
Sampling period (d)	76	86	62	86	86	82	68	73	54	35
# GHG measurements	6	7	5	7	7	7	6	6	5	4

4.3.3. GHG measurements

4.3.3.1. GHG sampling

A steady-state flow-through wind tunnel (Zhang et al. 2007) with an in-line FTIR (Gasmet DX4015, Vantaa, Finland) spectrometer was used to determine carbon dioxide (CO_2), CH_4, N_2O, nitrogen dioxide (NO_2), and ammonia (NH_3) emissions from stored manure (Figure 1). The wind tunnel was made from galvanized mild steel with a rust-resistant zinc coating. It contained internal baffle plates and covered an area of 0.32 m^2 (0.8 m x 0.4 m) on the manure surface. The tunnel had a PVC pipe inlet (10.16 cm OD) and outlet (7.62 cm OD). The inlet pipe was equipped with an in-line bilge blower (SEACHOICE Products, Pomano Beach, FL) to force ambient air through baffles and evenly across the manure surface. Average air velocity of the blower was set to 0.3 m s^{-1} by manual adjustment, and measurement of wind velocity using a hot wire anemometer (HHF1001R, Omega Environmental, St-Eustache, QC). A thermocouple (Type-T, Omega Environmental) in the inlet and outlet connected to a data logger (CR3000, Campbell Scientific Canada, Edmonton, AB) recorded temperature of the air streams.

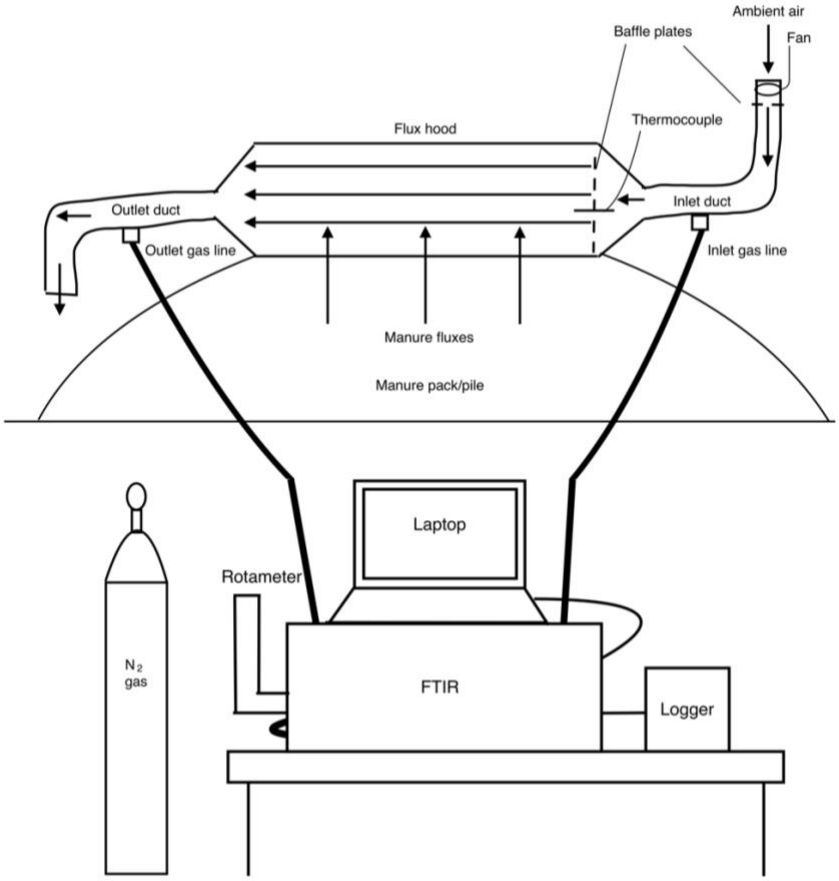

Figure 1. Steady state wind tunnel for measurement of greenhouse gas emissions from manure.

Gas sample lines (1/8" ID x 1/4" OD Bev-A-Line B-5 IV Tubing, Cole-Parmer, Montreal, QC) were attached to the inlet and outlets using stainless steel 1/4" OD tube fittings (Swagelok, Solon, OH). Sample air (1.5 L min^{-1}) was drawn using the analyzer's pump through the tubing and passed through a solenoid valve controlled by the data logger that switched between the inlet and outlet lines every 4 min before passing into a 500 mL Erlenmeyer flask. The flask was included to prevent condensation reaching the analyzer. The analyzer was fitted with a 0.01-micron Balson gas and liquid sample analyzer filter (9922-05-DQ Parker Hannifin Corp., Lancaster, NY) to also protect the analyzer from moisture.

Gas sampling occurred approximately bi-weekly from June – September 2020, on the same dates physical characteristics were measured. Upon arrival to each farm, the FTIR flowcell was allowed to reach an operating temperature for 30 min prior to sampling. On each sampling day, the FTIR was zeroed with an N_2 reference gas. Where multiple farms were sampled in a day, the zeroing procedure occurred only at the first farm. Following the zeroing procedure, if performed, and before beginning gas measurement on each farm, a two-minute continuous measurement of ambient gas concentrations was taken. Two 30-minute continuous measurements of manure gas emissions were then taken at each farm, from two different, randomly selected locations on the manure pack/pile. While random, effort was made to sample across the manure surface throughout the sampling period. Location of the chamber (cardinal direction) and wind direction were recorded for each location. Gas concentrations of CO_2, CH_4, N_2O, NO, NO_2, and NH_3 in parts per million (μL gas L^{-1} air) of inlet and outlet streams were recorded every 7 seconds.

4.3.3.2. Determination of gas flux

Mixing of sampled inlet and outlet atmosphere was evident between solenoid switches, thus 90 seconds from the beginning of a measurement period and 30 seconds at the end of a measurement period were discarded. This left four, 120-second periods to average concentrations for the inlet and outlet for each solenoid switch over the 30-minute sampling period.

The analyzer was controlled by a laptop computer running the Calcmet computer software (Gasmet). Raw gas concentration determinations from the Calcmet software were then processed using an in-house developed Microsoft Excel (Microsoft Corp., Redmond, WA) FTIR Data Processing Macro to determine gas flux.

To determine daily average flux, it was assumed that GHG flux measured during the 30-minute period was representative of a whole day. Daily average fluxes were determined using the following equation adapted from Zhang et al. (2007, Equation 4):

$$F_{GHG}\ (g\ GHG\ m^{-2}d^{-1}) = (C_{outlet} - C_{inlet}) \cdot AF \cdot (Density/CA) \quad (4)$$

Where:

C_{outlet} = average outlet gas concentration (ppmV)

C_{inlet} = average inlet gas concentration (ppmV)

AF = air flow ($m^3\ s^{-1}$), calculated as velocity ($m\ s^{-1}$) * duct area (m^2)

Density = gas density ($kg\ m^{-3}$), derived using the ideal gas law:

$$\frac{MW * P}{R * T} \Big/ 1000$$

Where:

MW = molecular weight of the gas ($g\ mol^{-1}$)

P = air pressure (Pa)

R = ideal gas constant ($8.314\ J\ K^{-1}\ mol^{-1}$)

T = temperature (K)

CA = chamber area (m^2)

Gas fluxes were also reported in g C or N $m^{-2}\ d^{-1}$, by multiplying flux (g GHG $m^{-2}\ d^{-1}$) by the weight of C or N per molecular weight of the respective gas. The two 30-min flux measurements taken per farm per day were averaged and assumed representative of that day's flux, as indicated above.

Emissions in CO_2 equivalents (CO_2-e) were then calculated using IPCC 4th Assessment Report GWP factors of 25 and 298 for CH_4 and N_2O, respectively (Solomon et al. 2007). Nitrogen dioxide and ammonia were also considered as sources of indirect N_2O emissions as per

Environment Canada's National Inventory Report (ECCC 2021b), where 1% of emitted NO_2-N and NH_3-N are assumed to be volatilized, deposited, and re-emitted as N_2O.

In addition to daily emissions estimates per farm, cumulative emissions were estimated for each gas. All measurements taken on a single farm were averaged to determine an average emission value (g of gas m^{-2} d^{-1}) for that farm and multiplied by 104 d to yield an estimate of cumulative emissions (g of gas m^{-2}) over the entire sampling period. Values from each farm were used to examine summary statistics for each gas. Results were reported in both g of gas m^{-2}, and in g CO_2-e m^{-2}, as per the methods above.

To compare emissions between manure storage types (bedding pack vs. pile), cumulative emissions per month from each storage type were also estimated. A monthly basis was chosen to capture changes in farm sample size and manure storage (piling, removal) as they occurred. For each of June, July, August, and September, all measurements taken from a manure/bedding pack (across all farms) were averaged, and all measurements taken from a manure pile were averaged; the average values for each storage type were then multiplied by the number of days in that month to yield average cumulative emissions estimates per month per storage type. Results were reported in both g of gas m^{-2}, and in g CO_2-e m^{-2}, as per the methods described above.

In addition to the above methods to report GHG flux on an area basis, flux was also determined on a kg^{-1} of manure basis. In brief, manure depth and bulk density were used to determine mass per area of manure.

$$Depth\ (m) * \ Bulk\ density\ (kg\ m^{-3}) = Mass\ per\ area\ (kg\ m^{-2}) \quad (5)$$

This value was then used to convert flux from an area to a mass basis.

$$\frac{Flux\ (g\ d^{-1}\ m^{-2})}{Mass\ per\ area\ (kg\ m^{-2})} = Flux\ (g\ d^{-1}\ kg^{-1}) \quad (6)$$

Cumulative emissions for each gas, as well as cumulative monthly emissions by storage type, were then calculated as above.

There are limitations associated with the methods used to estimate flux per kg of manure. Notably, only depth measurements associated with the temperature probes used were available for all farms. As such, maximum depth is that of the length of the probe, 0.91m, rather than actual manure depth; the estimation of flux on a mass basis therefore does not account for manure at a depth greater than 0.91m. All farms with piled manure (Farm 1, 2, 3, 5, 6) were associated with the maximum depth, though actual depth may exceed 0.91m. This method also assumes uniform bulk density throughout the manure pile, though manure bulk density is expected to increase at greater manure depths due to compaction caused by piling and settling. Finally, as these are estimated values, as opposed to measured values, these should be considered supplemental to the original flux per area of manure measurements.

4.3.4. Statistical analysis

For manure physical characteristics, nutrient composition, and cumulative emissions, summary statistics were derived using the UNIVARIATE procedure in SAS On Demand for Academics (SAS Inst., Cary, North Carolina). Sources of variation in manure nutrient values (between farms, dates within farms, and residual) were analyzed using the MIXED procedure. Type 3 analysis of variance was used to record covariance parameter estimates, from which %CV was derived; residual maximum likelihood (REML) estimation was used to assess statistical significance. Farms and dates within farms were considered random variables. Spearman rank correlations were derived using the CORR procedure.

4.4 RESULTS

4.4.1. Cow-calf management practices survey

Surveyed farms were distributed across the southern portion of Manitoba (Figure 2). Five farms were located in the Southwest, two near the city of Winnipeg, one in the Interlake region, and one in the Southeast area of the province. All farms self-identified as cow-calf operations; five farms sell most calves at weaning, and five farms retain the majority of calves for further feeding.

An overview of the classes and numbers of animals present on surveyed farms is reported in Table 2. The number of beef cows, the main animal class of interest, ranged from 20-425, with a mean of 127 head. In addition to beef cows, breeding bulls (ranging from 1-16 head) were present on all 10 farms surveyed.

The typical calving season on each of the surveyed farms is presented in Figure 3. In general, winter to spring calving was most prevalent; one farm began calving in January, with the majority beginning calving in February-March, and finishing calving by May-June. The exception to this trend is Farm 1, which practiced fall calving, from August through October. Regardless of the time of calving, all farms maintained a 60-90 d calving season.

Feedstuffs were primarily forage-based, with seven of 10 farms providing straw as feed, six providing annual forage with >50% legume content, four providing annual forage with 25-50% legume content, and four providing cereal hay or silage (Figure 4). Screenings were also a common supplement, provided on four of 10 farms. All farms provided cows with salt, and nine of 10 provided supplemental mineral. The “other” category was comprised of feed ingredients not listed as options on the survey and included native grass hay (1) and oat greenfeed (2). One producer also provided cows with Rumensin (Elanco, Grayfield, IN), an ionophore. All farms provided feed during confinement periods; five provided feed in confinement areas only, and five farms (Farms 1, 2, 3, 6, 9) provided supplemental feeds during months when forage via grazing was available

(pasture or paddock). Salt was provided year-round on six farms, and supplemental mineral was provided year-round on seven farms. Only four of 10 producers utilized ration balancing software or collaborated with a nutritionist to formulate balanced diets for the cow herd.

Location of the cow herd on surveyed farms throughout the period of September 2019 – August 2020 is detailed in Figure 5. Pen or drylot housing (depicted in grey) are periods in which cows were in confined areas and solid manure stores were generated. Across the 10 farms, cows spent from 2-6 months overwintering in confinement.

In confinement, all farms provided animals with bedding. All farms utilized cereal straw bedding, while Farm 4 also used flax straw. Five producers also considered waste feed as bedding, and thus a component of the manure/bedding pack. Producers were also asked to provide the rationale used to decide when to add bedding to confinement areas. Eight of 10 producers provided bedding based on weather or pen conditions, where excessive moisture (rain, snow) or pen cleanliness prompted the addition of bedding. The remaining two producers provided bedding on a timed schedule – Farm 6 provided bedding weekly, while Farm 5 added fresh bedding to cow pens daily.

As indicated in Figure 5, when not confined, cows grazed pasture (depicted in green), paddocks (depicted in yellow; smaller, enclosed parcels of land), or were managed using extended grazing practices (depicted in orange; swath grazing and corn stubble grazing on Farms 2 and 8 respectively). In these environments, manure was deposited on land and not collected or stored.

An overview of management of solid manure from beef cow overwintering pens from September 2019 – August 2020, including time spent as a pack and/or pile, and timing of manure spreading, is provided in Figure 6. Additional manure handling practices are reported in Figure 7. On all farms, manure was stored initially as a manure pack. Producers reported maintaining the

bedding pack for as little as 4 months (Farms 2 and 4) and up to 10 months (Farm 7). Nine of 10 farms report clearing solid manure from overwintering pens annually, with one farm removing manure every two or more years. Nine of 10 farms reported piling manure after cows left the winter confinement areas in spring; eight stockpiled manure after collection, and one farm (Farm 4) reported managing solid manure as compost. The remaining farm, Farm 8, cleaned cow pens and spread manure in spring after cows were turned out on pasture, thus sampling on this farm occurred when manure was removed from bred heifer overwintering pens. Including the farm which composted manure, two farms (4, 6) reported frequently turning or aerating the manure piles. These manure piles were reported to be maintained anywhere from 2-12 months prior to removal and application to land. In practice, manure management over the sampling period differed from practices initially reported on the management survey due to labor availability and weather conditions. Farms 1, 2, 3, 5, and 6 piled manure, with the latter piling manure in windrows. Farms 4, 7, 8, 9, and 10 maintained manure as a manure/bedding pack in the confinement area throughout the sampling period. Farm 1 frequently turned manure, with turning events in early July and mid-August 2020. There was also frequent disturbance on Farm 6, as additional manure was added to the length of the windrow throughout the sampling period.

Following storage, manure from all farms was applied to the land. Prior to application, only eight of 10 producers reported nutrient testing manure, and only two of 10 producers also nutrient tested soil (Figure 7). Only one producer reported using nutrient testing as their rationale for deciding which land was to receive manure. Distance to fields was indicated as a factor when deciding where to apply manure on seven of 10 farms. Five of 10 farms considered field conditions such as moisture or erosion when selecting land for manure application, and four of 10 selected the area to received manure based on crop type alone. Three producers indicated that rotation of

land receiving manure (2) and volume of other materials or debris present in the field (1) influenced decisions regarding manure application. Six of 10 farms reported that manure is typically applied to annual cropland only, two of 10 applied manure to hay or pastureland only, and two producers applied manure to a combination of both annual and hay/pastureland (Figure 7). A summary of land anticipated to receive manure during the sampling period is reported in Table 3. Manure application decisions are described in Figure 8.

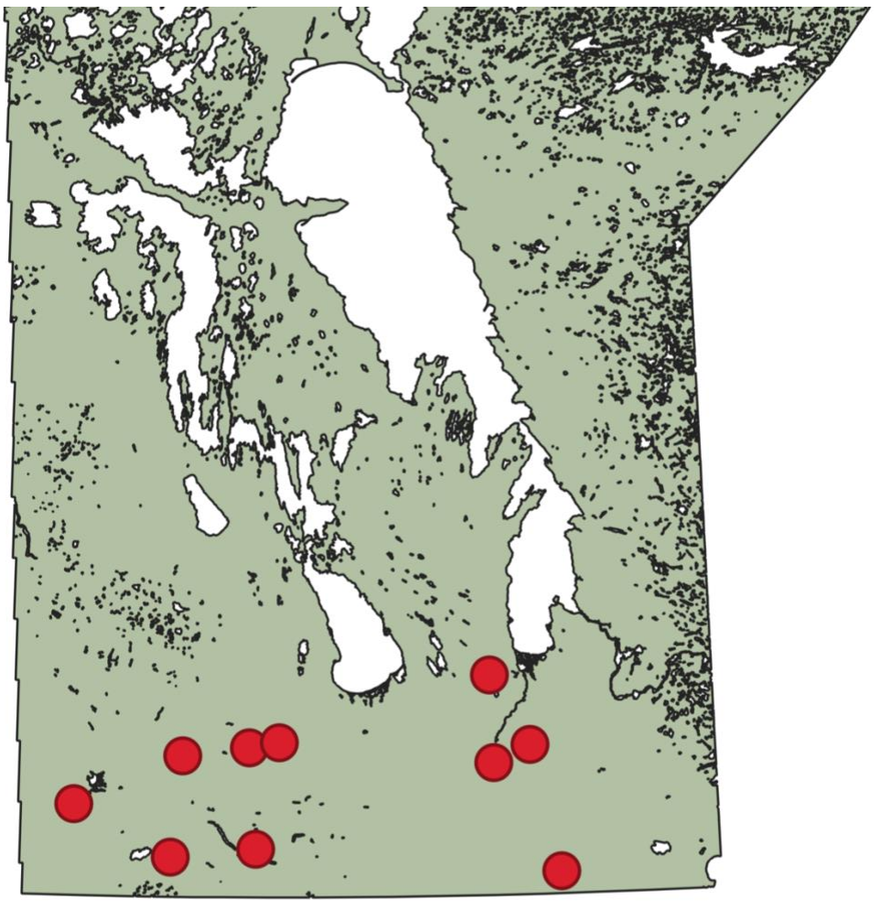

Figure 2. Location of the 10 Manitoba cow-calf farms surveyed.

Table 2. Mean, minimum and maximum number and classes of animals present at the time of survey across all 10 Manitoba cow-calf farms.

	Mean	**Min.**	**Max.**	**SD**
Beef cows	127	20	425	116
Calves (<1 year of age)	113	0	400	109
Replacement heifers (yearling)	28	0	130	40
Replacement heifers (2 year old bred)	5	0	18	8
Mature breeding bulls	6	1	16	5
Yearling breeding bulls	5	0	25	8
Backgrounded cattle	18	0	145	46
Finishing cattle	1	0	11	3

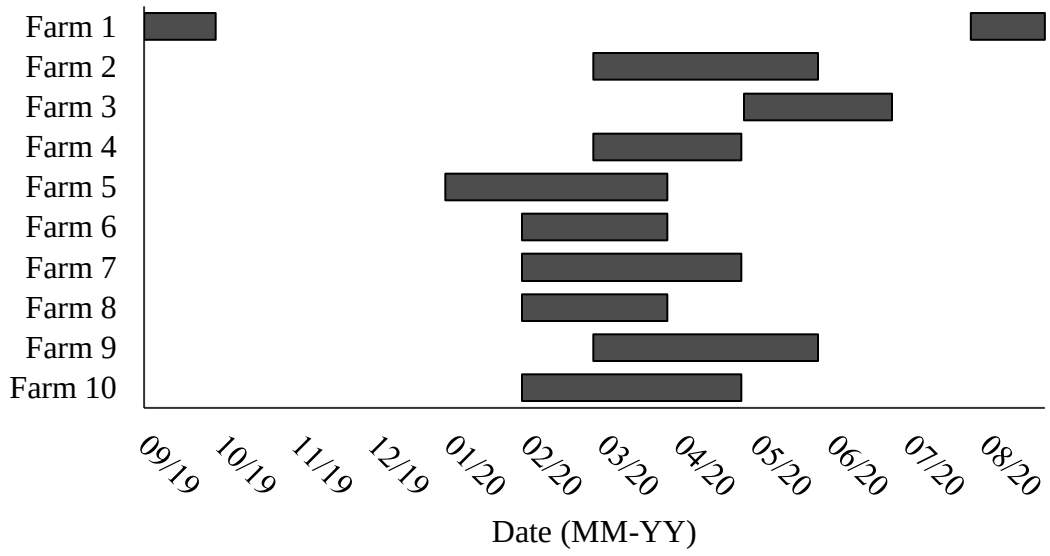

Figure 3. Calving season for each of the 10 Manitoba cow-calf farms surveyed.

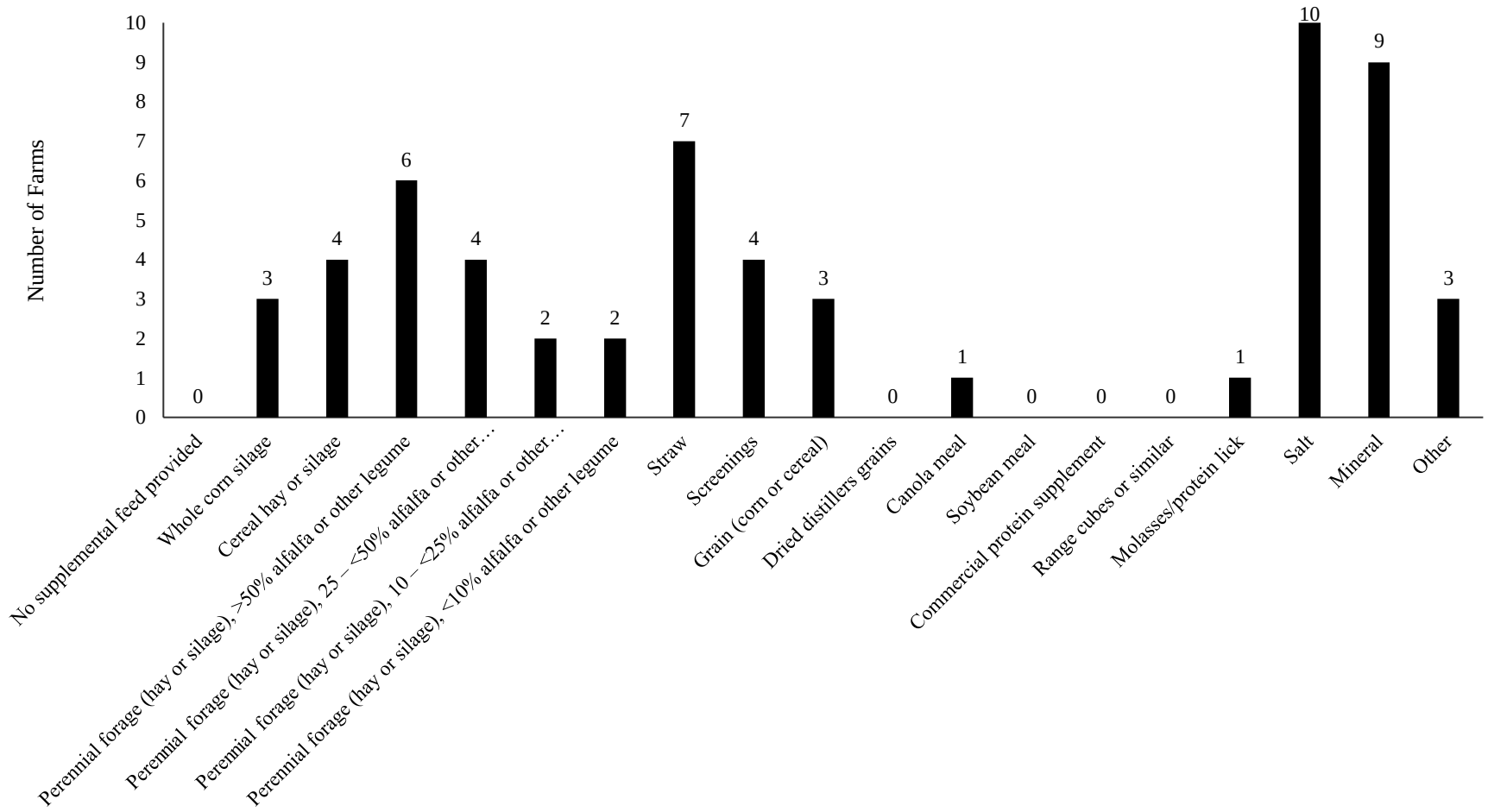

Figure 4. Feedstuffs used in beef cow diets during the overwintering period on the 10 Manitoba cow-calf farms surveyed.

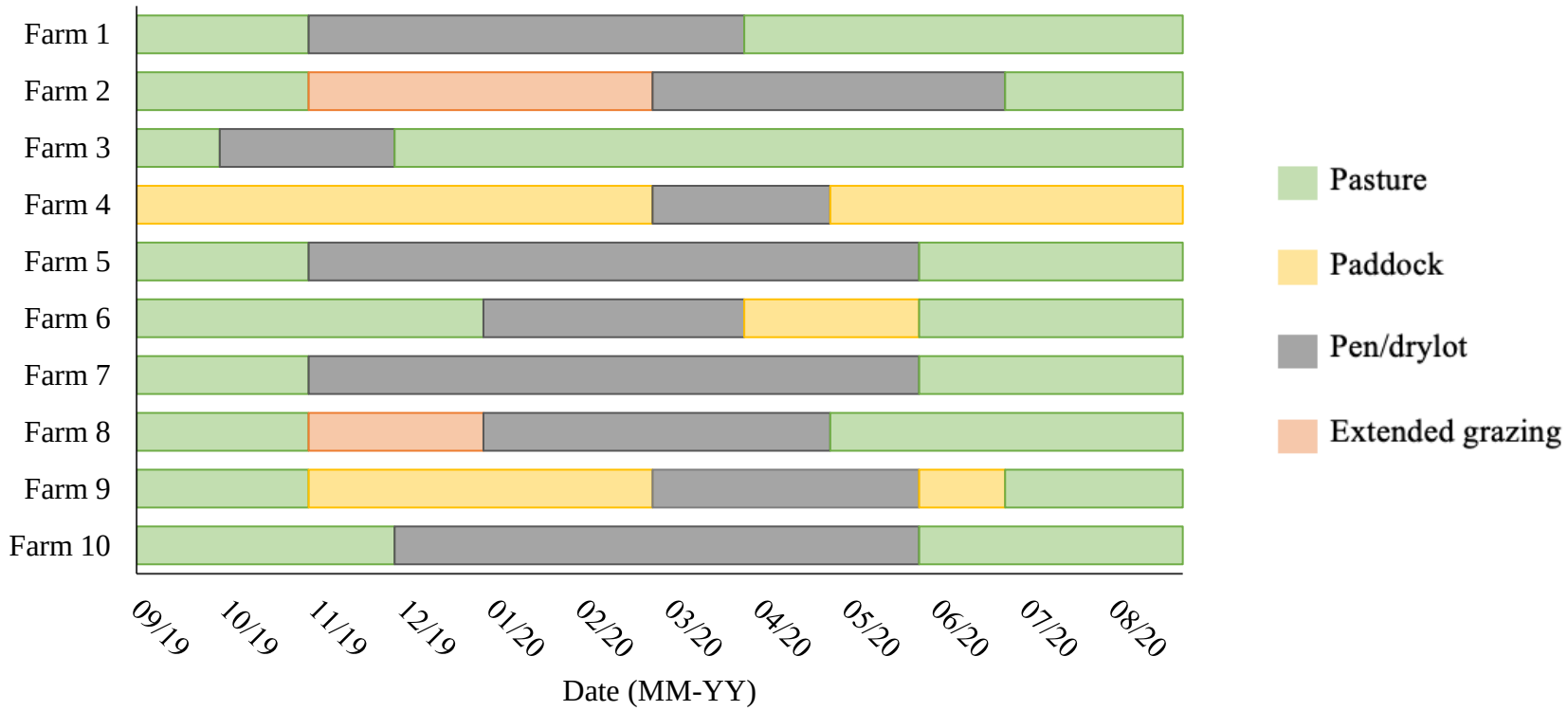

Figure 5. Location of beef cows during the overwintering period (September 2019 – August 2020) on the 10 Manitoba cow-calf farms surveyed.

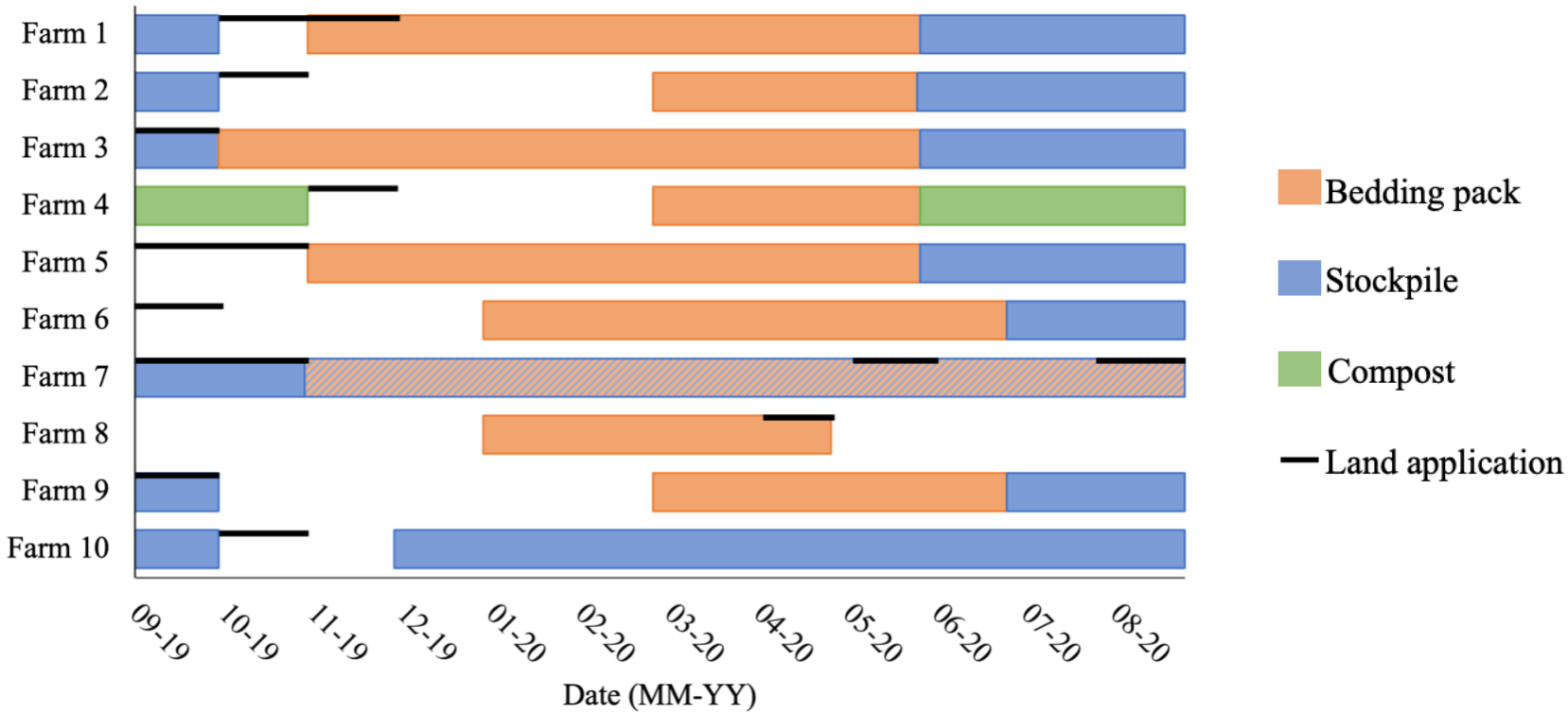

Figure 6. Solid manure management (September 2019 – August 2020) from beef cow overwintering pens and timing of spreading on the 10 Manitoba cow-calf farms surveyed.

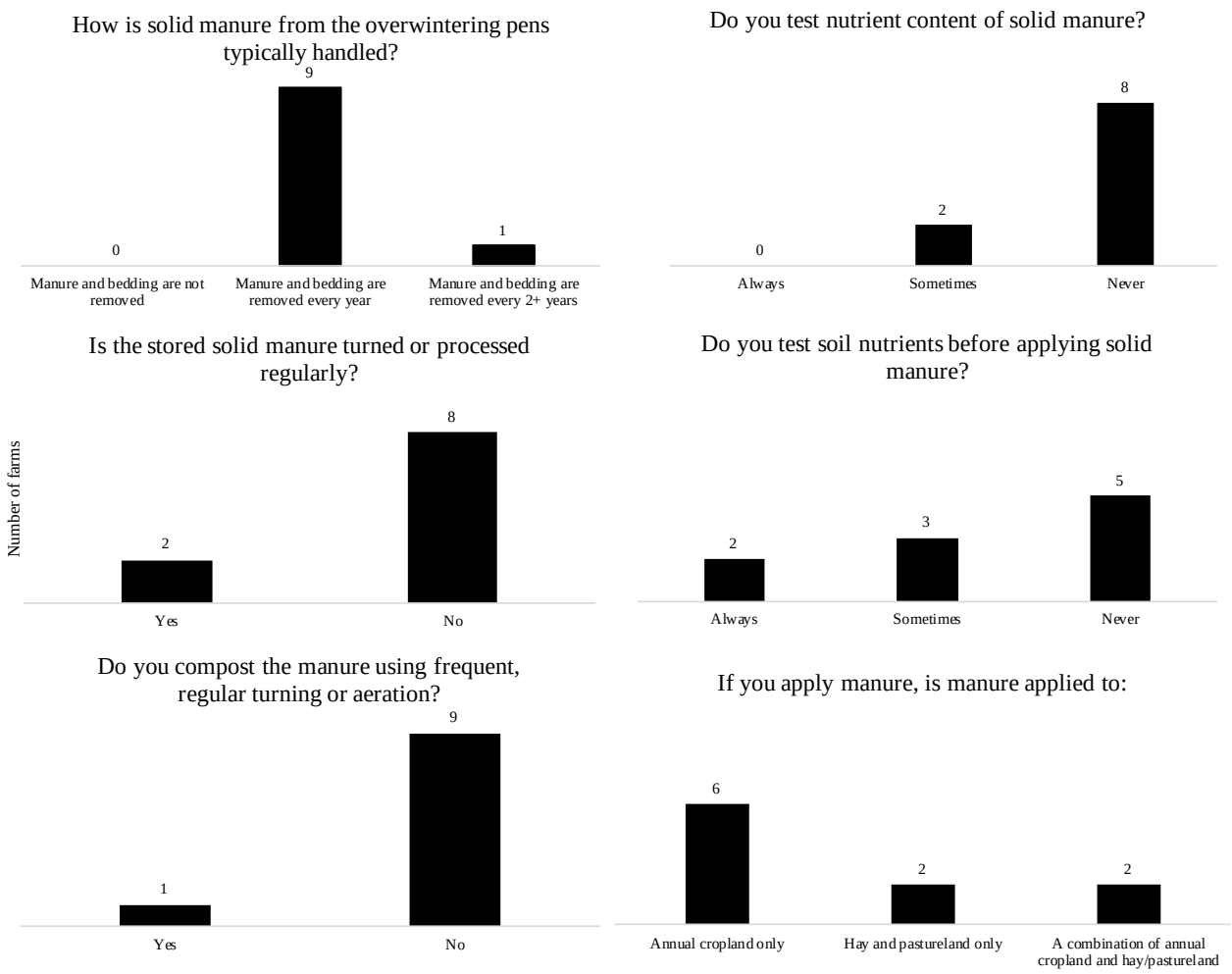

Figure 7. Characterization of manure handling practices on the 10 cow-calf farms surveyed.

Table 3. Anticipated land area (ha) to which solid beef cow manure was to be fall-applied on the 10 Manitoba cow-calf farms surveyed.

	Mean	Min.	Max.	SD
Annual cropland (n=8 farms)	48	10	100	29
Hay or pastureland (n=4 farms)	16	4	41	17

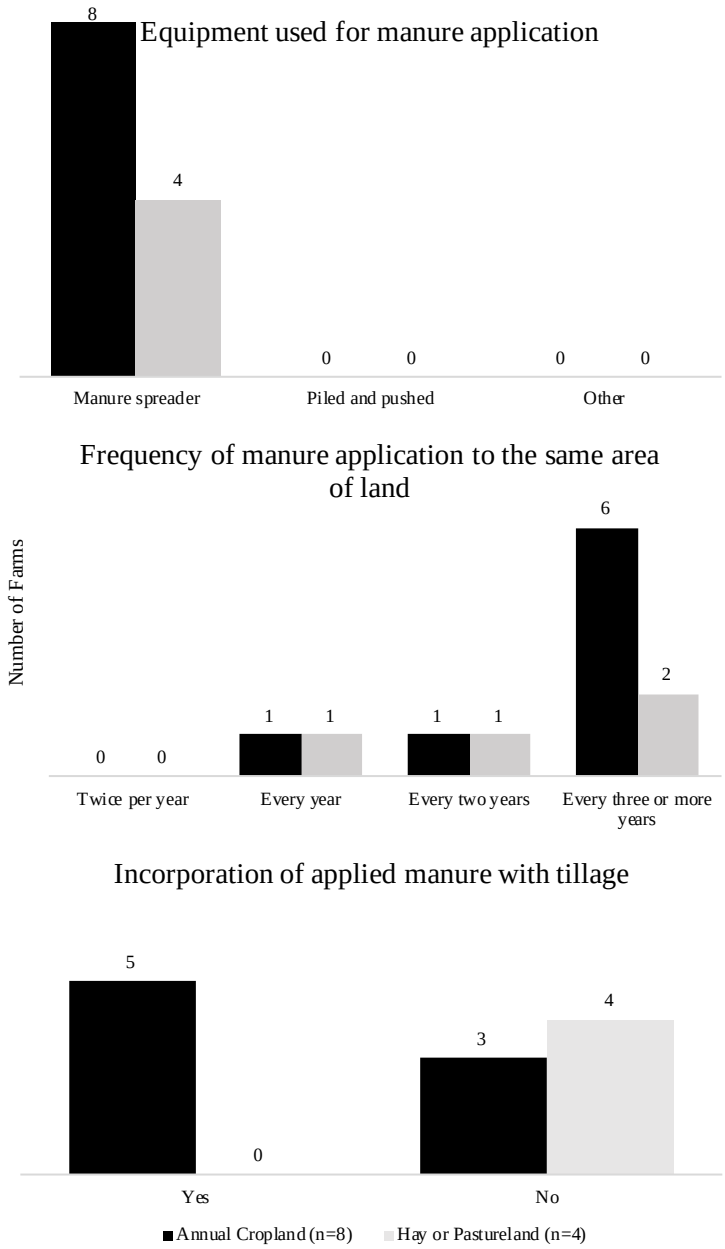

Figure 8. Characterization of manure application practices on the 10 Manitoba cow-calf farms surveyed.

4.4.2. Manure characteristics and composition

A summary of bi-weekly physical manure characteristics is provided in Table 4. Mean DM content across all farms and dates was 33%, with a range of 15-68%. Manure temperature, which can be interpreted as a marker of microbial activity within the manure, was also highly variable, ranging from 14-55°C. Bulk density, as an indication of free pore space and oxygen content in the manure, ranged from 0.09-0.83 kg L^{-1}.

Mean, minimum, maximum, standard deviation, and coefficient of variation values for manure nutrient composition are reported in Table 5. Manure DM content derived from nutrient analyses was slightly lower, at a mean of 30% with smaller variation (25%) than those derived from samples for physical analysis. Carbon-rich fractions of manure such as total C, ADF, and NDF had the lowest coefficients of variation across all components, at 14%, 10%, and 8%, respectively. Nitrogen fractions, in contrast, were the most variable. While total N had a coefficient of variation of 19%, manure NH_4^+-N and nitrate-N had coefficients of variation of 112% and 240%, respectively. However, mean content of these components in the manure is relatively low, at 1,332 ppm and 66 ppm (DM basis) for NH_4^+-N and NO_3^--N, respectively.

The source of variation in manure components can be attributed to changes in manure composition between dates within a farm (i.e., changes in composition over time; Table 6), where variation was significant for all components, rather than variation between farms. Variation in nutrient content between farms was significant only for total P content, with a coefficient of variation of 16.6%.

Table 4. Physical characteristics of solid beef cow manure on the 10 Manitoba cow-calf farms surveyed (n=60 samples).

Characteristic	Mean	Min.	Max.	SD	CV (%)
DM (%)	34	15	68	11	33
Temperature (°C)	28	14	55	12	42
Bulk density (kg L^{-1})	0.52	0.09	0.83	0.15	28

Table 5. Composition of solid beef cow manure on 10 Manitoba cow-calf farms surveyed (n=72 samples).

Component	Mean	Min.	Max.	SD	CV (%)
DM (%)	30	17	48	7	25
ADF (% DM)	54	45	67	5	10
NDF (% DM)	65	47	75	5	8
Ash (% DM)	26	12	73	12	45
Total P (% DM)	0.33	0.16	0.63	0.09	28
Total C (% DM)	38	12	47	5	14
Total N (% DM)	2.10	0.98	2.95	0.40	19
NH_4^+-N (ppm)	1,332	115	9,183	1,495	112
Organic N (% DM)	1.97	0.91	2.86	0.46	23
Nitrate N (ppm)	66	0	1,006	159	240
C:N	20	12	32	4	23

Table 6. Coefficient of variation (%) for manure components between farms and sampling dates within farms.

Component	Coefficient of Variation (%)		
	Farms	Dates within farms	Residual
DM	2.3	20.1***	14.3
Ash	10.4	35.2***	27.6
ADF	2.3	7.0***	6.5
NDF	0.0	5.3*	6.35
Total P	16.6*	14.9*	18.0
Total C	4.3	10.2***	13.2
Total N	0.0	13.6***	101.3
NH_4-N	0.0	49.0*	16.7
Organic N	0.0	16.7***	159.5
Nitrate	0.0	181.9***	9.1
C:N	0.0	84.8***	54.9

*, *** indicate significant relationships at $P < 0.05$, $P < 0.001$, respectively

4.4.3. Manure GHG emissions

4.4.3.1 Daily average flux

Plots of daily average in CO_2, CH_4, N_2O, NO_2, and NH_3 flux for all farms are shown in Figures 9 (g m^{-2} d^{-1}) and 10 (mg kg^{-1} d^{-1}). Two general patterns in CO_2 flux were apparent. A mid-period flux event occurred on Farms 2, 3, 5, and 6. The farms that exhibited these spikes piled manure, with the increase occurring at either of the next two gas measurement days following the piling event. Farms 4, 7, 8, 9, and 10, in contrast, maintained relatively low, steady emissions across the sampling period. On these farms, solid manure was maintained as a manure/bedding pack. These general patterns indicate that those farms with piled manure (Farms 1, 2, 3, 5, and 6) had higher emissions than farms that maintained manure as a manure or bedding pack (Farms 4, 7, 8, 9, and 10).

Farm 1 showed a distinct decrease in CO_2 emissions across the sampling period from the first sampling date until the turning event in early August, after which emissions increased on the final measurement date. This increase in activity was not observed following the first turning event in July. These turning events, along with the fall calving season on this farm, create a distinct farm typology for Farm 1 with the highest CO_2 emissions occurring on this farm.

The same trends in emissions as per daily average CO_2 flux were observed for CH_4, N_2O, and NO_2 flux. Farms 3 and 6 exhibited significant spikes in CH_4, N_2O, and NO_2 emissions following piling events, while Farms 2 and 5 showed apparent, but less exaggerated, spikes in emissions after piling. Nitrous oxide emissions differed in the magnitude of the spike observed after piling on Farm 3, as this farm surpassed the highest emissions observed from Farm 1, which was typically the most active (i.e., highest CO_2 flux as a general indicator of microbial activity) pile. Farm 1 exhibited the same decreasing trend in emissions until the August turning event for

both CH_4 and N_2O emissions. Farms 4, 7, 8, 9, and 10 maintained low emissions of CH_4, N_2O, and NO_2 throughout.

Across all farms and dates, NH_3 emissions remained close to zero, except for Farm 1, which exhibited a brief period of NH_3 emissions at the beginning of the sampling period.

4.4.3.2. Cumulative gas flux

Mean, median, minimum, and maximum values, standard deviation, and coefficient of variation for cumulative emissions of CO_2, CH_4, N_2O, and NO_2 across all farms are presented in grams of the specific gas m^{-2} (Table 7), and in grams of CO_2-e m^{-2} (Table 8). Average cumulative flux across all farms was: 12,308.5 g CO_2 m^{-2}; 771.9 g CH_4 m^{-2}; 5.4 g N_2O m^{-2}; 1,25.8 g NO_2 m^{-2}; and 6.7 g NH_3 m^{-2}. The low average value of NH_3 produced across all farms and dates is consistent with the plots of daily average flux discussed above.

This overall assessment of all farms in Table 8 also shows that CH_4 was emitted in the largest quantity, in terms of warming potential, at an average of 19,298.0 g CO_2-e m^{-2}, followed by CO_2 at 12,308.5 g CO_2-e m^{-2}, and N_2O at 1,594.0 g CO_2-e m^{-2}. Indirect N_2O emissions from NO_2 and NH_3 were less significant, at 374.7 g CO_2-e m^{-2} and 20.1 g CO_2-e m^{-2}, respectively. Coefficients of variation across the gases ranged from 99-309%.

Grouping farms by storage type (pack vs. pile) monthly from June through September shows the difference in average emissions between the storage types. These results are presented in grams of individual gas m^{-2} (Table 9), and in grams of CO_2-e m^{-2} (Table 10). Average monthly emissions for all gases, across all months, were higher for piled manure. Considering the warming potential of the individual GHGs, farms with manure packs had the greatest proportion of emissions from CO_2, while farms with manure piled had the greatest proportion of emissions as

CH_4. Piled manure also exhibited higher average N_2O and NO_2 emissions than manure packs across all months.

4.4.3.3. Gas flux per kg of manure

Gas flux expressed per kg of manure (Table 11) was similar to those measured per manure area, described above. Mean cumulative emissions across all farms were: 39,670.0 mg CO_2 kg^{-1}; 2,007.9 mg CH_4 kg^{-1}; 14.6 mg N_2O kg^{-1}; 329.9 mg NO_2 kg^{-1}; and 11.9 mg NH_3 kg^{-1} (Table 11). In CO_2-e (Table 12), cumulative emissions across all farms were again highest from CH_4, at an average of 50,196.6 mg CO_2-e kg^{-1}, and CO_2, at an average of 39,670.0 mg CO_2-e kg^{-1}. Coefficients of variation remained high, ranging from 62-391% across the individual gases. Manure piles were consistently more biologically active than manure packs, having higher GHG flux for CO_2, CH_4, N_2O, and NO_2 in both g of individual gas per kg manure (Table 13), and in g CO_2-e per kg manure (Table 14).

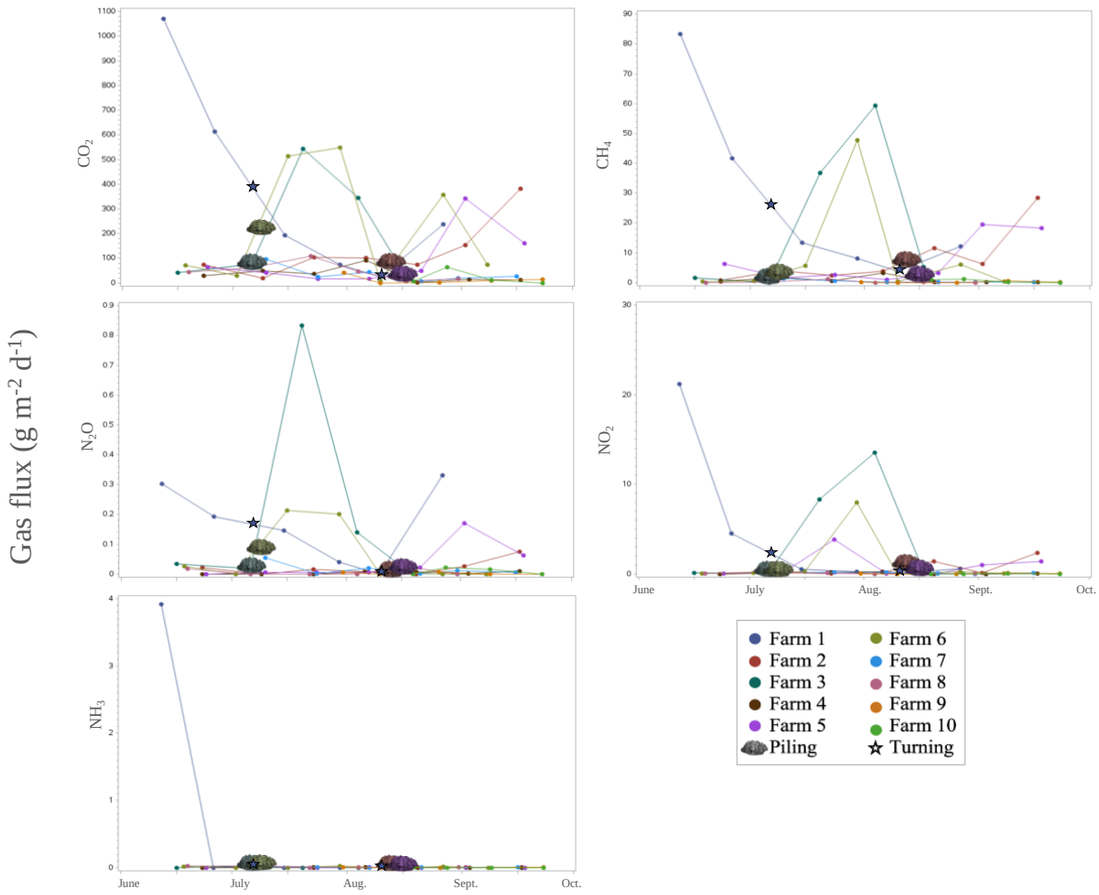

Figure 9. Daily average CO_2, CH_4, N_2O, NO_2, and NH_3 flux (g m^{-2} d^{-1}) from stored solid manure in overwintering pens.

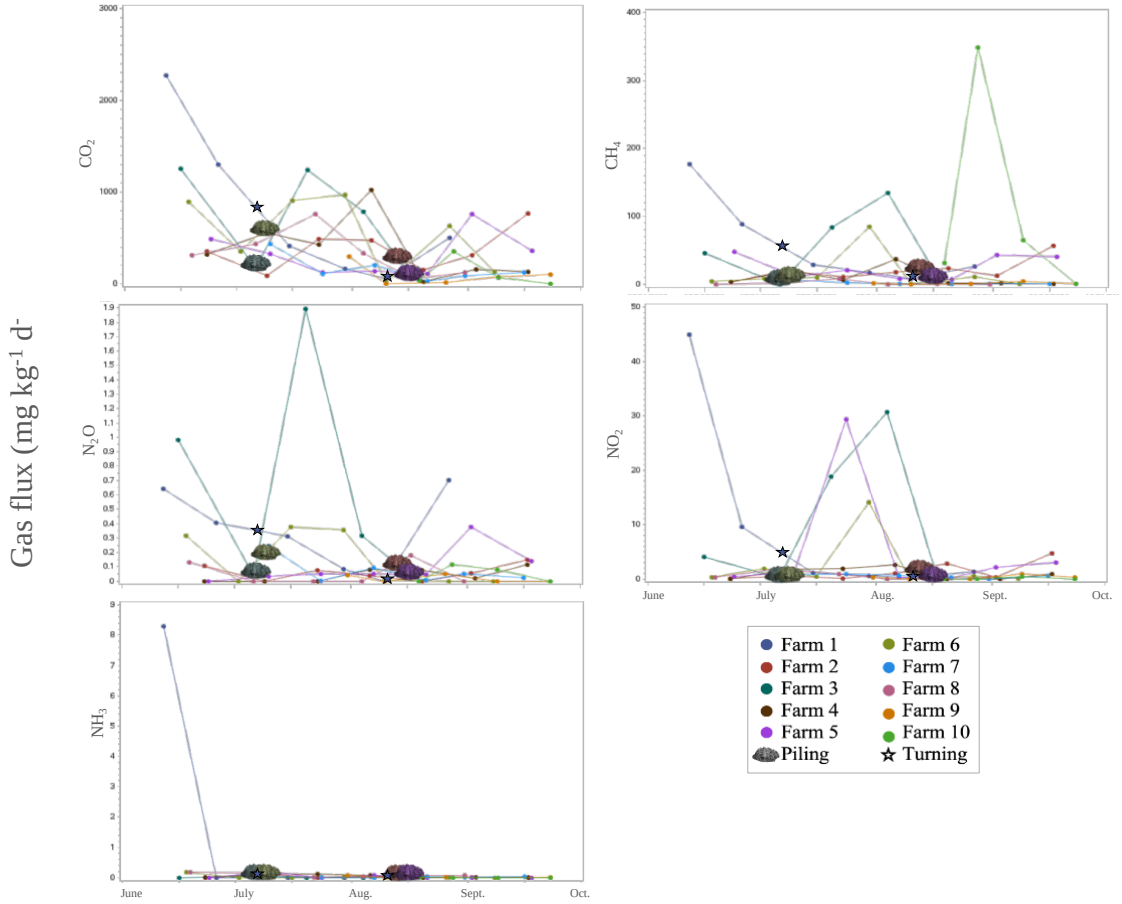

Figure 10. Daily average CO_2, CH_4, N_2O, NO_2, and NH_3 flux (mg kg^{-1} manure d^{-1}) from stored solid manure in overwintering pens.

Table 7. Average cumulative gas flux (g m^{-2}) from stored manure on the 10 Manitoba cow-calf farms from June - September 2020.

Gas	Mean	Median	Min.	Max.	SD	CV (%)
CO_2	12,308.5	7,612.0	1,413.1	38,397.4	12,144.9	99
CH_4	771.9	435.8	19.0	2,815.7	981.9	127
N_2O	5.4	1.9	-0.2	21.6	7.8	147
NO_2	125.8	37.5	-1.6	470.6	186.2	148
NH_3	6.7	0.3	-1.3	65.8	20.8	309

Table 8. Average cumulative gas flux (g CO_2-e m^{-2}) from stored manure on the 10 Manitoba cow-calf farms from June - September 2020.

Gas	Mean	Median	Min.	Max.	SD	CV (%)
CO_2	12,308.5	7,612.0	1,413.1	38,397.4	12,144.9	99
CH_4 [a]	19,298.0	10,893.8	476.0	70,391.3	24,546.5	127
N_2O [a]	1,594.0	551.1	-54.3	6,447.7	2,335.4	147
NO_2 [b]	374.7	111.8	-4.6	1,402.4	555.0	148
NH_3 [b]	20.1	0.8	-3.4	196.2	61.0	309

[a] Assumes a global warming potential (GWP) of 25 for CH_4, 298 for N_2O

[b] Assumes 1% of emitted NH_3-N and NO_2-N are volatilized, deposited, and re-emitted as N_2O

Table 9. Average cumulative flux (g m^{-2}) by month for solid manure stored as a bedding pack or pile on the 10 Manitoba cow-calf farms.

Gas	June		July		Aug.		Sept.	
	Pack (n=6)	**Pile (n=1)**	**Pack (n=7)**	**Pile (n=3)**	**Pack (n=7)**	**Pile (n=5)**	**Pack (n=4)**	**Pile (n=3)**
CO_2	1,628.3	25,276.1	1,215.2	10,076.5	1,015.3	4,319.0	375.3	6,685.3
CH_4	46.1	1,875.6	35.3	574.5	25.8	394.2	4.9	435.9
N_2O	0.5	7.4	0.2	7.5	0.2	1.9	0.0	2.0
NO_2	1.3	385.8	12.9	89.5	1.3	63.5	1.6	29.4
NH_3	-0.2	58.0	0.2	-0.2	0.1	0.0	0.0	0.0

Table 10. Average cumulative flux (g CO_2-e m^{-2}) by month for solid manure stored as a bedding pack or pile on the 10 Manitoba cow-calf farms.

Gas	June		July		Aug.		Sept.	
	Pack (n=6)	Pile (n=1)	Pack (n=7)	Pile (n=3)	Pack (n=7)	Pile (n=5)	Pack (n=4)	Pile (n=3)
CO_2	1,628.3	25,276.1	1,215.2	10,076.5	1,015.3	4,319.0	375.3	6,685.3
CH_4 [a]	1,151.3	46,889.3	882.0	14,363.1	644.4	9,853.8	123.0	10,898.4
N_2O [a]	139.9	2,217.5	60.7	2,233.8	59.8	572.5	13.2	587.6
NO_2 [b]	3.9	1,149.5	38.3	266.6	3.9	189.2	4.8	87.7
NH_3 [b]	-0.6	172.8	0.6	-0.7	0.3	0.1	-0.1	0.1

[a] Assumes a global warming potential (GWP) of 25 for CH_4, 298 for N_2O

[b] Assumes 1% of emitted NH_3-N and NO_2-N are volatilized, deposited, and re-emitted as N_2O

Table 11. Average cumulative gas flux (mg kg^{-1} manure, below 1 m^2 surface area of manure, up to a maximum depth of 0.91m) from stored manure on the 10 Manitoba cow-calf farms from June - September 2020.

Gas	Mean	Median	Min	Max	SD	%CV
CO_2	39,670.0	36,842.9	9,885.2	81,327.9	24,518.8	62
CH_4	2,007.9	1,409.0	133.2	5,963.7	2,205.5	110
N_2O	14.6	6.6	-1.0	67.9	21.8	150
NO_2	329.9	117.5	-8.4	1,138.0	421.2	128
NH_3	11.9	1.4	-35.4	139.5	46.4	391

Table 12. Average cumulative gas flux (mg CO_2-e kg^{-1} manure, below 1 m^2 surface area of manure, up to a maximum depth of 0.91m) from stored manure on the 10 Manitoba cow-calf farms from June - September 2020.

Gas	Mean	Median	Min.	Max.	SD	CV (%)
CO_2	39,670.0	36,842.9	9,885.2	81,327.9	24,518.8	62
CH_4 [a]	50,196.6	35,225.1	3,329.9	149,092.8	55,137.9	110
N_2O [a]	4,339.3	1,956.9	-291.9	20,237.5	6,506.0	150
NO_2 [b]	983.2	350.1	-24.9	3,391.1	1,255.2	128
NH_3 [b]	35.4	4.3	-105.5	415.6	138.3	391

[a] Assumes a global warming potential (GWP) of 25 for CH_4, 298 for N_2O

[b] Assumes 1% of emitted NH_3-N and NO_2-N are volatilized, deposited, and re-emitted as N_2O

Table 13. Average cumulative flux (mg kg^{-1} manure, below 1 m^2 surface area of manure, up to a maximum depth of 0.91m) by month for solid manure stored as a bedding pack or pile on the 10 Manitoba cow-calf farms.

Gas	June		July		Aug.		Sept.	
	Pack (n=6)	Pile (n=1)	Pack (n=7)	Pile (n=3)	Pack (n=7)	Pile (n=5)	Pack (n=4)	Pile (n=3)
CO_2	18,081.4	53,536.2	8,474.6	19,913.8	6,814.0	8,855.5	2,710.2	13,880.2
CH_4	526.2	3,972.6	240.8	1,149.1	185.1	859.7	35.4	916.9
N_2O	7.4	15.8	0.8	15.8	1.3	4.2	0.5	4.2
NO_2	25.4	817.0	98.9	181.3	9.6	141.6	10.1	61.6
NH_3	-7.3	122.8	1.2	-0.5	0.5	0.0	-0.3	0.0

Table 14. Average cumulative flux (mg CO_2-e kg^{-1} manure, below 1 m^2 surface area of manure, up to a maximum depth of 0.91m) by month for solid manure stored as a bedding pack or pile on the 10 Manitoba cow-calf farms.

Gas	June		July		Aug.		Sept.	
	Pack (n=6)	Pile (n=1)	Pack (n=7)	Pile (n=3)	Pack (n=7)	Pile (n=5)	Pack (n=4)	Pile (n=3)
CO_2	18,081.4	53,536.2	8,474.6	19,913.8	6,814.0	8,855.5	2,710.2	13,880.2
CH_4 [a]	13,155.1	99,314.2	6,019.4	28,726.3	4,627.6	21,492.6	884.7	22,922.3
N_2O [a]	2,198.4	4,696.7	250.6	4,706.3	398.9	1,245.2	146.4	1,261.5
NO_2 [b]	75.5	2,434.8	294.7	540.2	28.6	422.0	30.1	183.6
NH_3 [b]	-21.8	365.9	3.5	-1.6	1.4	0.1	-0.8	0.1

[a] Assumes a global warming potential (GWP) of 25 for CH_4, 298 for N_2O

[b] Assumes 1% of emitted NH_3-N and NO_2-N are volatilized, deposited, and re-emitted as N_2O

4.4.4. Spearman rank correlation coefficients

Spearman rank correlation coefficients for gas flux and manure composition and nutrient variables are depicted in Table 15. The most significant relationships were between gas flux and manure temperature, at 0.68 (P = 0.0002), 0.76 (P <0.0001), and 0.64 (P = 0.0008) for CO_2, CH_4, and NO_2 flux, respectively. The relationship between N_2O flux and manure temperature was also significant, though less strongly correlated (0.48, P = 0.0184). Total N (-0.54, P = 0.0059) and organic N (-0.53, P = 0.0075) were also highly correlated to CO_2 flux, as was total C to NO_2 (-0.56, P = 0.0047). Other significantly correlated variables were CO_2 and ash, CO_2 and total C, CH_4 and DM, and CH_4 and total C. Scatter plots for correlation analysis are provided in Appendix A.

Table 15. Spearman rank correlation coefficients between daily average gas flux (g d^{-1} m^{-2}) and manure characteristic and nutrient variables.

Gas	Variable														
	Temp.	**BD**	**Depth[a]**	**Mass[b]**	**DM**	**ADF**	**NDF**	**Ash**	**TP**	**TC**	**TN**	**NH_4^+-N**	**Organic N**	**NO_3^--N**	**C:N**
CO_2	0.68***	NS	0.43*	0.56**	NS	NS	NS	0.41*	NS	-0.60*	-0.54**	NS	-0.53**	NS	NS
CH_4	0.76***	NS	NS	0.41*	0.42*	NS	NS	NS	NS	-0.43*	NS	NS	NS	NS	NS
N_2O	0.48*	NS	0.63**	NS	NS	NS	NS	NS	NS	NS	NS	NS	. ANS	NS	NS
NO_2	0.64***	NS	NS	0.61**	NS	NS	NS	NS	NS	-0.56**	NS	NS	NS	NS	NS
NH_3	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, *** indicate significant relationships at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively; NS indicates relationships that are not significantly correlated ($P > 0.05$)

[a] Manure pack or pile depth up to a maximum of 0.91m

[b] Manure mass up to a maximum depth of 0.91m

4.5 DISCUSSION

4.5.1. Cow-calf management practices survey

The purpose of the manure management survey was to confirm that management practices used on the 10 cow-calf farms selected for characterization of nutrient and GHG emissions were representative of the broader cow-calf class. The observed calving season is typical of the prairie provinces where most calves are born from February-April (Sheppard et al. 2015). The mean cow herd size of 127 head on surveyed farms is larger than the average of 74 head on a cow-calf operation in Manitoba (Statistics Canada 2023b). The mean number of two-year-old bred heifers (5 head or 4% of the cow herd) was smaller than the typical replacement rate of 12% (Canfax Research Services 2023; Manitoba Agriculture 2023), or 12 head for a herd size of 127 cows. This is likely due to the timing of the survey in relation to calving season; in May, when the survey was conducted, most farms have finished calving, and thus first calf heifers were considered as part of the cow herd.

Farm 1, in contrast to the other surveyed farms, practiced fall calving. Fall calving may be advantageous as the nutritional demands of pregnancy can be met on pasture during summer, however the period of highest nutritional demands due to lactation occur during winter confinement (Manitoba Agriculture, n.d.). As such, diets fed to fall-calving beef cows during winter confinement may have higher energy and CP content, with the latter influencing N excretion in manure. All farms maintained a calving season of 2-3 months, consistent with the typical 66-90 d calving season reported in surveys by Sheppard et al. (2015) and the University of Saskatchewan (2018).

Feedstuffs provided on surveyed farms were consistent with primarily forage-based feed ingredients as characterized by Sheppard et al. (2015), which included perennial forage, cereal hay/silage, corn silage, and mineral supplements. In Manitoba, Undi et al. (2011) found alfalfa

hay/silage, straw, and unfertilized grass hay were the most common forages fed during the winter confinement period, with 83-100% of cow-calf producers also providing mineral supplement. Also consistent with previous surveys was the rate of ration balancing when preparing supplemental diets for cows. Forty percent of producers surveyed used ration balancing software; the University of Saskatchewan (2018) previously reported that 59% of cow-calf operations fed balanced rations.

As per study design, only farms that confined cows and/or bred heifers were included in the survey and the on-farm sampling study, as it is in confinement areas that solid manure stores are generated. During the summer, 100% of farms utilized grazing (nine of 10 farms on pasture, 1 of 10 in grazing areas that producers defined as paddocks, i.e., smaller parcels for grazing, but were not formally defined in the study) which was consistent with a previously reported rate of 95% of animals on pasture (Sheppard et al. 2015). It has previously been reported that use of winter seasonal feeding areas for beef animals in Canada is highest in the Prairies (Sheppard et. al 2015), with the rate of winter grazing increasing in all regions of Canada (Sheppard et al. 2016). Winter grazing is utilized to lower winter feed costs while also improving nutrient recycling (McCartney et al. 2004; Jungnitsch et al. 2011; Kelln et al. 2012; Jose et al. 2020). The use of extended grazing including may continue to increase as a means to access alternative sources of feed, thereby addressing feed shortages caused by drought, flooding, or excessive heat due to climate change. For example, Southern Manitoba experienced drought in 2020, and feed challenges were raised by numerous respondents in the written portion of the survey.

The movement of cows to confined areas on the surveyed farms was consistent with Sheppard et al. (2015), who also reported that movement of animals to winter confinement typically begins in October. The provision of straw bedding in confined areas on 100% of surveyed farms in this study is consistent with findings from Undi et al. (2011), wherein 86% of cow-calf

producers in Manitoba provided bedding in confined areas, with cereal straw the most common bedding material (Undi et al. 2011; Sheppard et al. 2015).

All 10 farms stored manure outdoors as bedding packs, piles, or windrows, for between 4-12 months of the year, which is consistent with Sheppard and Bittman (2012) who surveyed 1,380 cow-calf, backgrounding, and finishing operations. These researchers reported that 94% of farms stored solid manure collected from confinement areas as uncovered, outdoor piles or bunkers, exposing manure to heat, rain, and wind, and the respective effects of these elements on nutrient loss and GHG emissions, such as drying, saturation, disturbance, volatilization, etc. Sheppard and Bittman (2012) have noted that Prairie beef producers store manure for longer periods of time than in Eastern Canada; 27% of producers in the Prairies stored manure for >12 months, as compared to 3% in the Eastern provinces, where the majority of producers (51%) store manure for only 1-6 months. Undi et al. (2011) found a 3-6 month storage period was most common on cow-calf operations in Manitoba, shorter than that reported by Sheppard and Bittman (2012). Immediate application of manure to land, as opposed to storage as a bedding pack, pile, or windrow, has been reported on 21-43% of cow-calf operations in Canada (Undi et al. 2011; Alemu et al. 2016).

Only 10% of producers in the current study reported composting of stored manure, which is similar to the 13% reported by Sheppard et al. (2016). While manure composting provides benefits such as increased DM content and reduction of parasites, weed seeds, and pathogens (Larney and Hao 2007), the ability of an operation to practice composting may be constrained by available labour and equipment. The observed 50% occurrence of manure disturbance (piling and/or turning) in the current study is consistent with Sheppard and Bittman (2012), who found that 30-40% of stored manure piles in Western Canada were disturbed (turned, moved, etc.) during storage.

In actual practice, only 50% of producers stored manure as a pile during the sampling period. Much of southern Manitoba experienced dry conditions in the summer of 2020 (Manitoba Agriculture 2020). As manure piling is typically utilized as a means to reduce manure moisture content prior to hauling and land application, the already dry conditions experienced may have mitigated the need for manure piling as excess moisture was not a concern.

The response by surveyed farms of 0% and 20% for "always test manure and soil nutrients" was similar to that observed by Undi et al. (2011), where 91% and 76% of cow-calf producers in Manitoba did not nutrient test either stored manure or soils, respectively, before manure application. These results imply that overall, cow-calf producers in Manitoba are not aware of nutrient rate applied, or rate required, when applying manure to cropland. These practices have environmental as well as economic implications, where nutrient provided in excess may result in leaching and runoff, leading to concerns with eutrophication (Boyd 2005; Tamminga 2006), thereby preventing recycling of valuable nutrient within the farm system.

Although manure was applied to annual cropland by 60% of farms surveyed, 20% of respondent farms, generally those with smaller herd sizes, applied manure to hay/pastureland only. Undi et al. (2011) found that land type to which cow-calf operations in MB applied manure varied by region. In Central and Southwest regions of Manitoba, where most of the farms sampled in the current study are located, manure was more commonly applied to annual cropland than hay or pastureland. In all other areas of the province, manure was applied to the two land types in equal proportion. Undi et. al (2011) also found that the amount of land to which manure is applied is largely related to herd size (Undi et al. 2011), as both manure volumes and farm land base typically increase with herd/farm size. Application of manure typically occurred in fall on farms in the

current study, consistent with spreading of solid manure from Prairie feedlot operations as observed by Sheppard et al. (2016).

Comparing the results of this survey to previous surveys, it is evident that farms in the current study are generally representative of typical Western Canadian/Prairie cow-calf operations with regards to the herd size and management practices (calving season, supplemental feedstuffs, overwintering period, bedding practices, and manure storage type, location, and nutrient testing) used. As such, it is reasonable to use data from the surveyed farms to represent the cow-calf class, identify trends, and subsequently draw conclusions regarding nutrient and GHG flux profile.

4.5.2. Manure characteristics and composition

4.5.2.1. Physical characteristics

Manure DM content, in both nutrient and physical analyses samples, was considerably higher than that reported elsewhere for solid livestock manure (≥ 10-15% DM; Lorimor et al. 2004; ASAE 2005; Sommer 2013), and may be attributed to the large volumes of bedding used in cow-calf pens, as well as the high-moisture conditions of external animal housing in Manitoba compared to other locations which receive less precipitation. Manure from most farms maintained mesophilic temperatures (<40°C; Hao et al. 2004), although thermophilic temperatures (55-65°C; Chen et al. 2011) were approached on Farm 1, 2, and 5, all of which experienced disturbance events. Temperatures of 50-72°C have been achieved in manure compost (Hao et al. 2001; Pattey et al. 2005), where the increase in oxygen availability and distribution of labile C caused by pile turning accelerate the rate of decomposition (Hao et al. 2001; Larney et al. 2006; Sommer 2013). . Manure in the current study was more dense than previously reported values from solid beef cattle manure (0.069-0.099 kg L^{-1}; Hao et al. 2001; Pattey et al. 2005). As bulk density can be interpreted as an estimate of free pore space and oxygen availability (Poulsen and Moldrup 2007),

the density of piles observed here may be attributed to the infrequent disturbance and subsequent settling of most stored manure.

4.5.2.2. Manure nutrient analysis

Average total C observed (38% DM) was higher than values reported by Eghball et al. (1997; 11.7%, DM basis), Hao et al. (2004; 27.68%, DM basis), and Larney et al. (2006; 24.8%, DM basis) for stored solid feedlot manure, and Loro (2005; 7.34% as-is basis), for stored solid beef cattle manure from various animal classes. A total C content of 42.6-43.4% was reported by Moral et al. (2012), where cattle were straw-bedded and fed forage-based diets, which are characteristic of the cow-calf operations in the current study. As with total C content, mean total N content was also higher (2.10% DM) in the present study than previously reported values ranging from 0.98-1.8% DM basis (Eghball et al. 1997; Hao et al. 2004; Larney et al. 2006; Moral et al. 2012) for feedlot manure, and 1.31% for beef cow manure (Tenuta et al. 2000). Nitrogen excretion in manure is related to CP composition of the diet, and dietary CP/N in excess of animal requirements (Cole et al. 2005; Powell et al. 2008b; Hristov et al. 2011). While little information on diets fed on surveyed farms was acquired from producers, only 40% of producers in this study balanced rations, and that high-legume forages, which would have higher CP content than grass-based forages, were commonly used.

The observed average manure C:N ratio of 20:1 was within the general range of 10:1-30:1 for cattle manure as a soil amendment (USDA 2011; Wortmann and Shapiro 2012), though higher than previously reported values of 13.4:1-16.6:1 (Hao et al. 2004; Loro et al. 2005; Larney et al. 2006) from feedlot manure. This suggests that there should be relatively fast decomposition of

manure (Robertson and Groffman 2015) with C:N decreasing significantly as decomposition progresses (Taylor and Sinsabaugh 2015).

In the present study, significant farm-to-farm variation was only noted for manure total P content. Previous manure characterizations have focused on only one or two sites (Hao et al. 2001; Pattey et al. 2005; Larney et al. 2006; Bai et al. 2020) or have averaged nutrient composition across sites (Loro 2005). Larney et al. (2006) examined changes in nutrient concentration over time in fresh, stockpiled, and composted feedlot manure in Manitoba and Alberta. For all manure treatments, significant location effects were only observed for manure N:P ratio (Larney et al. 2006), a metric which can be used as an index of potential soil P loading for land application of manure (Sharpley et al. 2001). Little information regarding dietary, and thus manure P content is available (CRSB 2016a), highlighting knowledge gaps relating to effects of animal management (i.e., dietary composition) on nutrient excretion and resultant environmental effects. The lack of significant variation across other nutrient fractions may indicate that differences in dietary composition, manure storage and handling, and environmental effects on manure composition and progression of decomposition were not significant enough to lead to changes in nutrient fractions. It is possible the small geographic range of the present study (Southern Manitoba) is a factor in this, however Larney et al. (2006) also found no difference in manure nutrient content other than N:P between sampling location (Manitoba vs Alberta), as mentioned above.

In contrast, there was significant variation for all nutrient fractions within farms over time. This variation can be associated with changes in composition as decomposition of manure OM progresses. It is possible that the temporal variability observed was large enough to obscure the ability to detect differences between farms. Overall, a limitation to the coefficient of variation

approach used in this study is that the direction of change is not accounted for, only the magnitude and significance of the variation over time.

A decrease in moisture content over time is characteristic of the composting process, as continuous aeration and temperature increases caused by accelerated microbial activity help to remove moisture from the manure (Wang et al. 2019). Reported DM losses from straw-bedded feedlot manure range from 30.1-39.8% for active compost, and 20.6-22.5% for passively composted/stockpiled manure for 99-132 d storage periods (Larney et al. 2001; Hao et al. 2004; Larney et al. 2006). The rate of moisture or mass loss compared to the rate of the various nutrient fractions within the manure will dictate if the relative concentration of the nutrient increases or decreases. This again reiterates the disadvantage of using the % CV approach, which addresses source and magnitude of variation, but does not account for directionality of the changes in nutrient concentration (i.e., if a nutrient fraction is increasing or decreasing in concentration over time).

Of the manure nutrients, total C, ADF, and NDF had the smallest coefficients of variation within-farms over time. Acid detergent fibre is comprised of cellulose and lignin, less-degradable fractions of the manure, coming from both bedding materials and dietary forages. Cereal straw, which accounted for all bedding materials on all farms surveyed and was a common ingredient in beef cow diets in the present study, has an average cellulose and lignin (ADF) content of 50% (National Research Council 2001). High lignin content limits the rate of decomposition of manure C during storage (Veeken et al. 2001; Hao et al. 2004; Arriaga et al. 2017). The composition of bedding materials, large volumes of bedding typical of cow-calf overwintering pens, and the consistency of bedding materials used across farms, may explain the low variation seen across manure total C and other carbon-rich fractions. Other possible reasons for the small variation in manure total C include the following: i) early-storage nutrient samples are likely older than the

"fresh" manure in literature, thus decomposition of labile C had already begun before sampling, and less readily degradable C remains while early losses were not accounted for, and ii) potential bias of farms joining the study late in the sampling period (i.e., Farms 7, 9, 10), and therefore early C decomposition was not accounted for; or alternatively, iii) stockpiling manure, as practiced on most farms, limited decomposition of labile C.

The coefficient of variation for total N content within farms over time was relatively low (13.6%), although significant. A decrease in total N observed in stored manure in other studies range from 4.9% (Eghball et al. 1997) to 42.5% (Hao et al. 2004) following 99-110 d of composting. Several studies have demonstrated that NH_4^+-N tends to decrease following manure storage, while NO_3^--N increases (Eghball et al. 1997; Larney et al. 2006), indicating the occurrence of nitrification in the manure. This again highlights a disadvantage of the CV approach to quantifying sources of variation, as these processes cannot be closely tracked. However, scatter plots of NO_3^--N vs. NH_4^+-N (Figure A.1) show a curvilinear decreasing relationship ($R = -0.50$, $P = 0.01$), suggesting nitrification has occurred in manure with high NO_3^--N and low NH_4^+-N This response may be expected in older piles, as nitrifiers (aerobic), which are not present in the anaerobic environment of the animal rumen, take time to establish in the manure pack.

As within-farm nutrient concentrations were significantly variable over time, this highlights the need for nutrient testing of manure prior to application as fertilizer. As suggested by Loro (2005), continuous manure testing over a number of application seasons would allow producers to develop a farm-specific nutrient database leading to informed decision-making regarding nutrients applied to soils, improve within-farm nutrient cycling, and ensure compliance with any nutrient application policies. This study helps to establish standard values for cow-calf manure, which can aid in appropriate manure spreading and improvement of whole-farm nutrient cycling.

The above differences in physical and nutrient values between the cow-calf manure sampled here and previous characterization studies of feedlot manure, indicate that management factors associated with cow-calf vs. finishing operations, including bedding volume, diet composition and subsequent N retention can impact manure nutrient profile. In conclusion, limited data regarding manure and animal management practices (manure storage type, bedding materials, feed ingredients, etc.), as well as failure to nutrient test manure and soils prior to application, illustrate potential shortcomings in understanding nutrient management by cow-calf producers.

4.5.3. Manure GHG emissions

4.5.3.1. CO_2 emissions

As emissions of CO_2 from manure originate from the decomposition of labile C under aerobic conditions, production and emissions are increased by the incorporation of oxygen and redistribution of organic matter (Hao et al. 2001), via turning and/or disturbing the manure. This response explains the observed pattern of CO_2 emissions, with consistently low emissions from manure packs, and spikes in emissions from piled or turned manure. While this effect has been noted in composted manure (Bai et al. 2020), the disturbance caused by pile formation on otherwise undisturbed manure (Farms 2, 3, 5, and 6) would likely result in similar increases in emissions following the piling event, as observed in Ahn (2011) for CO_2 and CH_4. However, neither Ahn (2011) or Pattey et al. (2005) observed statistical differences between CO_2 emissions from stockpiled and composted (i.e., many disturbance events) manure.

Carbon dioxide emissions in the current study were found to be significantly correlated to manure temperature. This relationship was also observed by Pattey et al. (2005), where CO_2 emissions and manure core and surface temperatures, for both stockpiled and composted manure, were significantly and positively correlated, which is indicative of increased microbial respiration.

Overall, CO_2 emissions from stored beef cow manure were lower than previous studies of solid manure storage over a similar storage length (Hao et al. 2001; 2004). The lack of regular manure disturbance resulted in cumulative emissions lower than those previously observed by Hao et al. (2001; 2004) for composted feedlot manure (73,800-168,000 mg kg^{-1} wet manure and 195-239 g m^{-2} d^{-1}, respectively) over a 99 d storage period. As 60% of producers in the current study utilized manure stockpiling by maintaining stored manure as a bedding pack, this reveals an important manure storage type for cow-calf producers previously unrepresented in the literature (i.e., deep bedding from beef cows in empty pens under outdoor storage conditions) and enhances the knowledge of manure emissions from this farm/animal class.

When expressed on a CO_2-e basis, CO_2 emissions were the second largest source of GHG emissions per unit of manure, despite the relative inactivity of undisturbed manure in the current study. In other studies which examined multiple gases of interest concurrently, including Pattey et al. (2005), Ahn et al. (2011), Moral et al. (2012), McGinn and Flesch (2018), and Bai et al. (2020), CO_2 was the largest source of GHG emissions (CO_2-e basis) from stored manure. However, CO_2 emissions are excluded from the carbon footprint for manure (CRSB 2016a). Consideration of CO_2 from stored manure may be necessary to ensure total GHG emissions are estimated and accounted for.

4.5.3.2. CH_4 emissions

Methane is produced under anaerobic conditions, from the degradation of hydrolyzed C products by methanogenic microorganisms (Kebreab et al. 2006). As such, CH_4 emissions are often lower for turned/aerated manure than for stockpiled manure (Hao et al. 2001; Pattey et al. 2005; Bai et al. 2020), thus the observed increase in CH_4 emissions after piling in this study was

not expected. This observed increase in CH_4 emissions following disturbance likely occurred where manure depth was large enough to maintain anaerobic conditions within, such that the increase in functional pore space following the disturbance event encouraged gas diffusion from the pile (Hao et al. 2001; Ahn et al. 2011), i.e., transport, rather than production, of CH_4 was enhanced. Methane efflux from these deeper manure stores may not have otherwise occurred, due to the increased potential for methane oxidation as it travels toward the manure surface (Hao et al. 2001; Kebreab 2006).

Although Ahn et al. (2011) hypothesized that delaying disturbance events decreases CH_4 emission potential from manure, Mulbry and Ahn (2014) found no significant difference between emission spikes for CO_2, CH_4, and N_2O when the first turning event following pile formation was delayed. The disturbance event in Mulbry and Ahn (2014) was pile mixing, rather than pile formation, with a maximum delay in mixing of 5 weeks post-piling. However, this knowledge combined with the response pattern of Farm 1 indicates the potential for manure emissions to occur even at increasing pile age, as long as total pile drying/composting has not occurred. This is of particular importance when adverse weather conditions or other farm activities (i.e., limited time/labour available) result in manure being maintained in pen as a manure pack, and infrequent disturbance events over the course of the manure storage period. Therefore, frequency of disturbance should be considered when developing GHG mitigation strategies for manure management.

Cumulative CH_4 emissions from June-September ranged from 19.0-2,815.7 g CH_4 m^{-2} across all farms. Over a 53 d compost period, Hellebrand and Kalk (2001) found average cumulative emissions of 1,346 g CH_4 m^{-2} from feedlot manure, which is within the range of CH_4 emissions observed in the present study, although over a significantly shorter storage period. On a per-mass

basis, Hao et al. (2001) observed May-August cumulative emissions from composted feedlot manure in the range of 6,300-8,000 mg kg^{-1}, which is greater than the 133.2-5,963.7 mg kg^{-1} observed here. This is interesting, considering that CH_4 is produced anaerobically, and both Hellebrand and Kalk (2001) and Hao et al. (2001) employed turning (both studies) and/or forced aeration (the latter) composting treatments. In continually aerated piles, emissions were generally highest in the first 1-3 weeks of storage and decreasing over time to low or ambient levels (Hao et al. 2001; Hellebrand and Kalk 2001; Moral et al. 2012; Ahn et al. 2012; Mulbry and Ahn 2014; Bai et al. 2020). Yamulki (2006) reported cumulative CH_4 emissions of 102.41 g kg^{-1} and 55.86 g kg^{-1} from stored dairy manure with and without the addition of straw bedding, respectively, over a 4-month storage period. Although their study was of similar length to the current study, cumulative emissions were considerably lower than those observed here. On a daily emissions basis, Hao et al. (2004) reported daily average emission rates of 12.3 g CH_4 m^{-2} d^{-1} from composted feedlot manure, which when compared to the current study, was higher than that reported for manure packs but lower than the peaks observed on farms with disturbed manure. Together, these results indicate that piles surveyed in the current study were relatively biologically inactive, with even less activity in the manure packs, and highlight the effect of manure disturbance on CH_4 emissions despite the necessity of anaerobic conditions for CH_4 production. Overall, this indicates that manure management factors such as pile disturbance and depth, which together allow for CH_4 diffusion, may be important factors to consider for GHG mitigation.

Despite low cumulative and average emissions in comparison to previous studies, CH_4 was the largest contributor of GHG on a CO_2-e basis across all surveyed farms. Characterizations of composted manure by Hao et al. (2001; 2004) and Hellebrand and Kalk (2001) also observed that CH_4 was the largest source of emissions from stored beef manure. This magnitude of CH_4

emissions was unexpected, considering the use of turning or aeration as a means of CH_4 mitigation (Pattey et al. 2005; Szanto et al. 2007; Jiang et al. 2013; Hou et al. 2015; Bai et al. 2020).

Based on manure management practices of the surveyed farms, including stockpiling of manure, it is reasonable for CH_4 to be the dominant source of GHG emissions in the current study, as disturbance events (piling, turning) were infrequent, and occurred on only five of 10 farms. In the remaining farms, manure was largely untouched throughout the storage period, allowing for anaerobic conditions to be maintained within the manure. Because the GWP of CH_4 is approximately 28 times that of CO_2, CH_4 mitigation by maintenance of aerobic conditions, whether by turning, minimizing compaction, and covering (Sommer, 2001; Chadwick, 2005), or addition of bedding materials (Yamulki 2006), has been a popular research focus. However, the potential for increased emissions of CO_2, N_2O, and NH_3 may occur with maintenance of aerobic conditions. This is an important consideration given the half-life of CH_4 of approximately 10.5 years, compared to 120 and 114 years for CO_2 and N_2O, respectively (US EPA 2022). The prevalence of CH_4 as the largest source of emissions on a CO_2-e basis, for both stockpiled and composted treatments, in this and other studies (Hao et al. 2001; Hellebrand and Kalk 2001; Hao et al. 2004) indicates the need to continue investigating CH_4 mitigation strategies for beef cattle manure management.

4.5.3.3. N_2O emissions

Pile turning/aeration on Farms 2, 3, 5, and 6, and the August turning event on Farm 1 resulted in apparent increases in N_2O emissions as it served to stimulate the aerobic nitrification process as well as improve the rate of GHG diffusion from manure (Hao et al. 2001; Ahn et al. 2011; Bai et al. 2020). The compounding effects of pile disturbance have resulted in higher N_2O

emissions from composted vs. stockpiled manure stores, as described in Hao et al. (2001), Pattey et al. (2005), and Bai et al. (2020). The mixing action of pile disturbance has a subsequent two-fold effect on N_2O emissions: NO_3^- produced in aerobic areas by nitrification moves to anaerobic zones lower in the pile, where it can be reduced by denitrification; and NH_4^+-N from within the pile is brought to aerobic zones the surface for nitrification (Hao et al. 2001; Ahn et al. 2011).

Interactions between N_2O emissions and NH_4^+ and/or NO_3^- in the current study were not significant, although the number of nutrient samples obtained was small. As such, mechanisms contributing to N_2O emissions, and the high coefficients of variation observed for NO_3^- and NH_4^+ can only be speculated. The decreasing curvilinear relationship seen between NO_3^- and NH_4^+ (Figure A.1) suggest that nitrification as a likely source of emissions across all farms. This hypothesis is supported by the decrease in NH_4^+-N (Farms 1, 2, and 6) and increase in NO_3^- (Farms 1, 2, 3, 5, 6) over time on farms experiencing disturbance events and subsequent increases in N_2O emissions (Figure A.2), but cannot be confirmed from the data presented. In contrast, the significant positive associations between N_2O and manure depth as well as NO_2 and manure mass may indicate denitrification as a source of emissions, where deeper, more dense piles may encourage formation of anaerobic zones. Nitrous oxide produced in these areas can then be released by pile disturbance events (El Kader et al. 2007; Mulbry and Ahn 2014).

The range of whole-period cumulative N_2O emissions observed in the current study are lower than those reported by Hao et al. (2001) and Yamulki (2006; 59.66-102.05 mg kg^{-1} for composted beef and dairy manures, respectively), over a 4-month storage period, and by Moral et al. (2012; 76.93 mg kg^{-1}) for stockpiled beef cattle manure over a shorter 52 d measurement period. This again points to relatively inactive piles in the current study.

As Farm 1 had the highest GHG emissions, it is interesting that the post-turning emissions spike from Farm 3 resulted in emissions that were larger than that of Farm 1. This increase in emissions occurred immediately following the piling event on this farm, as well as a period of excessive heat and rainfall in the days previous (weather data not shown). Similar increases in N_2O emissions following rainfall were observed by Moral et al. (2012) and Bai et al. (2020). It is interesting, however, that Moral et al. (2012) attributed the observed increase to enhanced levels of nitrification, due to the added moisture and pile disturbance caused by rainfall, while Bai et al. (2020) attributed this increase to production through denitrification, where saturation and decreased pore space in the manure lead to anaerobic environments conducive to the process. A similar explanation, whereby the saturation caused by rainfall "plugs" the surface of the manure, preventing diffusion, was given by Hao et al. (2001) to describe a decrease in N_2O emissions regarding GHG production resulting from composting of feedlot manure. Chadwick (2005) also observed a decrease in N_2O emissions from manure following rainfall, attributing this decrease to loss of NO_3^- by leaching, which would otherwise be available for denitrification. These discrepancies regarding emissions and the impact of environmental effects highlight the many challenges associated with study of livestock manure which is typically stored outdoors and therefore subjected to changes in temperature and precipitation. As a result, care should be taken when data from laboratory-level studies, which may not capture whole-system complexities, are used to establish manure emissions estimates and develop programs and policies.

4.5.3.4. NO_2 emissions

As with N_2O, NO_2 is produced as a by-product of nitrification and denitrification processes. While NO_2 does not have a direct effect on climate warming, nitric oxide (NO) and NO_2,

collectively referred to as NO_x, are important players in atmospheric trace gas chemistry (Yamulki and Jarvis 2002; Akiyama and Tsuruta 2003), as they are precursors to tropospheric ozone and nitric acid, a component of acid rain, respectively. These gases can also be deposited on manure/soil surfaces and re-emitted as N_2O, which is assumed to occur at a rate of 1%, as described in the IPCC Guidelines (Nevison 2001) and ECCC's National Inventory Report (2021b).

While NO_2 emissions may be a concern for environmental quality, characterization of emissions from manure is scarce. Where such emissions estimates are reported, they do not account for species, class, storage type, regional production differences, or other related effects which will influence nutrient composition and nitrification/denitrification processes, leading to differences in NO_x emissions. Using generic values from the European Environment Agency (2019), the CRSB (2016) estimated that solid manure from beef animals generates 0.000395 kg NO_x $animal^{-1}$ d^{-1}, however as stated, this value does not account for animal class, diet, or manure storage type. As identified by the CRSB (2016a) Environmental LCA, further study of NO_x from manure is required to improve modelling efforts and emissions estimates. Results from this study are an important first step in developing species- and class-specific NO_x emissions values from manure.

4.5.3.5. NH_3 emissions

As the action of pile turning and aeration resulted in increased emissions for the other gases, as discussed above, it was anticipated that NH_3 would also increase. Pile disturbance has been reported to increase microbial decomposition, and improve functional pore space and gas diffusion, as well as redistribute NH_4^+ produced by mineralization to areas where volatilization can occur (Parkinson et al. 2004; Sommer 2013). Instead, NH_3 emissions from farms in the current

study remained near zero across the entire storage period, regardless of manure storage type or disturbance, with the exception of Farm 1.

The main source of NH_3 emissions from cattle manure is from urea (Bussink and Oenema 1998). In manure, urea present in the urine is rapidly hydrolyzed to CO_2 and NH_3 (Bussink and Oenema 1998). As there is immediate mixing of urine and feces within the bedding pack of confined animals, the highest NH_3 emissions likely occurred prior to the start of the sampling period. This is supported by several studies (Hellebrand and Kalk 2001; Sommer 2001; Chadwick 2005; El Kader et al. 2007; Moral et al. 2012) in which peak NH_3 emissions from animal manure occurred within the first 2 weeks of composted storage, then decreasing sharply to almost zero within three weeks of the start of manure composting.

While the period of NH_3 emissions from Farm 1 appears to occur at the beginning of the sampling period, this was not the beginning of the manure storage period on this farm, as manure was piled sometime before the commencement of the sampling period (date unknown). Manure on this farm was disturbed twice during the sampling period, however, on-farm activities causing disturbance prior to the sampling period were unknown. A mid-storage (50 d post-pile formation) increase in NH_3 emissions following successive turning events was observed from a manure windrow by Bai et al. (2020), illustrating the possible effect of turning in a mature manure pile. Observed NH_3 emissions on Farm 1 early in the sampling period may be associated with active composting, as evidenced by the temperature of the manure and CO_2 flux measured. During active composting, the decomposition of labile C, leading to a decrease in C:N ratio, results in net mineralization of organic N in the manure (Larney et al. 2006; Chai et al. 2014) whereby NH_3 is released. This highlights differences in potential NH_3 emissions from disturbed vs. undisturbed (stockpiled) manure, which should be considered in emissions estimates from stored manure.

Low overall NH_3 emissions in the current study may also be related to the high volume of bedding used, which is typical of cow-calf operations. A straw bedding cover can limit airflow to the NH_3-emitting surface below, as well as increase NH_4^+ immobilization in the manure, reducing emissions (Sommer 2013). Pattey et al. (2005) implemented pile covering (using stable compost as a cover) to minimize NH_3 emissions from beef and dairy manure stores when studying other GHG (CO_2, CH_4, and N_2O) emissions. Elsewhere, pile covering has been shown to numerically but not significantly reduce (Chadwick 2005) or to have no effect on NH_3 emissions (Sommer 2001).

4.5.4. Drivers of GHG emissions

4.5.4.1. Manure temperature

Temperature of a substrate is a key determinant of microbial growth and activity. For this reason, strong positive correlations between gas flux and temperature are expected. Carbon dioxide, as a general measure of microbial respiration, has previously been correlated to manure core and surface temperatures (Pattey et al. 2005). As microbial activity decomposes manure organic matter, temperature within the pile increases (Hao et al. 2001). This increase in heat may subsequently result in a drying effect, which may explain the positive relationship between manure DM and CH_4 emissions in the current study; a phenomenon that is opposite to what might be expected as CH_4 is produced under anaerobic (i.e., saturated) conditions. Methane emissions from manure have previously been observed to increase with core temperature in composted dairy manure piles (Yamulki 2006), and in stockpiled and composted beef manure piles (Pattey et al. 2005). While N_2O emissions from manure have previously been found to be correlated with increasing temperatures (Jaderborg 2020), this relationship was less strongly correlated than with

other gaseous emissions in the present study, likely because nitrifiers are not thermophilic (Hellman et al. 1997).

4.5.4.2. Manure depth and mass

Manure depth (up to 0.91 m) was significantly and positively correlated with CO_2 and NO_2 emissions. An inherent feature of manure stored as a pile, as opposed to a bedding pack, is greater manure depth as well as an increase in the number of disturbance events (i.e., piling). Boadi et al. (2004) previously observed that the highest CO_2 and CH_4 emissions from a solid beef manure pile were recorded from those areas in the centre of the pile which had the greatest depth. Areas of deep manure have been reported to have increased temperature, moisture, and nutrient density, creating conditions favourable for microbial activity (Husted et al. 1994; Janzen et al. 1999; Boadi et al. 2004

In the current study, manure depth was significantly and positively correlated with manure temperature and DM, although DM content was not measured at the manure core as in Boadi et al. (2004). The association between manure depth and CH_4 observed by Boadi et al. (2004) was not observed here, which may be due to CH_4 oxidation along the path of CH_4 diffusion towards the surface of the stored manure. Manure mass was also significantly positively correlated with manure temperature (Figure A.1), and CO_2, CH_4, and NO_2 emissions. Given that manure bulk density was not correlated with GHG emissions, the significant effect of manure mass (which was estimated from manure depth and bulk density) on GHG emissions was explained by manure depth, rather than bulk density. However, these attempts to relate flux to manure characteristics may be influenced by the limitations associated with manure depth measurements and mass calculations, as described.

4.5.4.3. Manure C and N

A significant relationship was found between CO_2 and total C, total N, and organic N. Manure total C was also significantly correlated with CH_4 and NO_2 emissions. Despite the statistical significance, assessing the scatter plots for these relationships (Figure A.1) shows that these plots are consistently skewed by data points from Farms 1, 2, 3, 5, 6 obtained post-piling. While this complicates the inference of nutrient transformation occurring, these results also suggest mechanistic differences in nutrient transformation occurring in the different manure storage types. The negative Spearman rank correlations between manure total C and gas flux are not expected, and may indicate more structural carbon (as opposed to readily available carbon) present in the manure, which could be attributed to large volumes of straw bedding material, an increase in manure DM with increasing total C, or N immobilization occurring due to increasing total C, however these are speculations that cannot be confirmed from the data presented.

4.5.4.4. Management

Based on the description of GHG emission patterns above, there is an obvious relationship between manure disturbance and emissions. Farm 1, a pile with multiple disturbance events during the sampling period, had the highest daily average and cumulative emissions across all farms and a distinct farm management typology. Notably, this manure pile was the most frequently turned, with two documented turning events during the sampling period. This farm exhibited an increase in CO_2 emissions following the August turning event, typical of turned or composted manure as described above. Bai et al. (2020) also observed a peak in CO_2 emissions, on day 135 of the manure storage period, followed by a decrease until the end of the measurement period. Sommer (2001)

attributed these late-storage emissions to an increase in cellulose and hemicellulose decomposers, as most labile C would have been degraded earlier. However, the general decrease in CO_2 emissions with time observed in the present study can likely be attributed to a decrease in labile C (Pattey et al. 2005; Bai et al. 2020), as decomposition progressed.

In addition to manure management, animal management in Farm 1 also differed from the other farms in that it was also the only herd which calved in fall (August/September). Therefore, during the winter confinement period which began in November on this farm, dietary requirements were increased due to the increased demands of suckling a calf (Manitoba Agriculture, n.d.), and potentially the resumption of estrus and rebreeding (Statham 2023). Therefore, these diets may have been higher in energy and protein as compared to those for winter- or spring-calving animals confined during late mid to late gestation (Merck 2022). Bedding requirements during the winter confinement period are also higher for fall-calving herds (Manitoba Agriculture, n.d.), to keep both cows and calves clean and comfortable. In addition to calving season, bedding amounts also vary based on weather conditions, availability, or producer preference. Increased nutrients, whether by nutrient excretion, waste feed, or added bedding, may influence emission potential from stored manure. The timing and total duration of animal confinement and manure storage, may also be influenced by farm calving season, and therefore impact manure nutrient composition, transformation, and losses. While the increased emissions from Farm 1 cannot be definitively attributed to any of these factors, they should be considered as potential drivers of emissions, and should be further investigated to examine impact of calving season, as well as dietary and manure nutrient composition.

Farm 1 is also unique in that manure was maintained as a pile for the entirety of the sampling period. Other farms that piled manure (Farms 2, 3, 5 and 6) also had large emissions,

though manure piling was the only major disturbance event on these farms. In contrast, those farms that maintained manure as a bedding pack had lower emissions, which together suggest that maintaining stored manure as a bedding pack may be a means for cow-calf producers to mitigate emissions from manure stores. It should be noted, however, that a large surface area is characteristic of a manure pack. This should be considered more closely if maintaining solid manure as a bedding pack is explored as a potential GHG mitigation strategy, particularly as manure emissions were measured on a per surface area of manure basis.

4.6 CONCLUSIONS

In this study, 10 cow-calf operations in Manitoba were surveyed and sampled in-situ to characterize manure management practices, manure nutrient profile, and GHG emissions from stored solid beef cow manure. This characterization demonstrated that surveyed farms are representative of the broader Western Canadian cow-calf class and that emissions data gathered from them are representative of cow-calf farms in the Prairie region.

This characterization of cow-calf manure nutrient profiles improves current "standard book" manure nutrients values. The new knowledge generated in this study will prove useful for cow-calf producers as they do not typically test manure stores or soils prior to manure application. This information is key to improving whole-farm nutrient cycling, wherein management of manure nutrients has both environmental and economic implications for the cow-calf producer.

Variation in manure nutrients between-farms was only significant for total P content. Rather, variation within a farm over time (dates within farm) was significant for all nutrients, indicative of the process of decomposition occurring over the course of the manure storage period. The lack of variation in nutrient content between farms supports the use of this dataset as representative of manure nutrients for the broader cow-calf class.

Of the GHG measured, CH_4 was the largest source of emissions across all farms, followed by CO_2. Emissions of N_2O, NO_2, and NH_3 were considerably smaller. Large differences in emissions patterns of all gases were observed for undisturbed (manure packs) vs. disturbed (piled and/or turned) manure stores. Increased emissions followed disturbance events were observed, with manure emissions remaining otherwise relatively stagnant. These findings demonstrate that manure management strategies of storage manure and disturbance are key drivers of GHG emissions from manure. Farm 1, which had the most numerous manure disturbance events, had the largest GHG emissions. Farm 1 was also unique in that cows calved in the fall rather than the spring, which influenced other management decisions that may have affected manure emissions, including dietary composition, bedding materials/amounts, timing of pile establishment and disturbance events, and length of storage.

This study identified that the manure pack is an important form of manure storage for cow-calf producers in Manitoba, and the dataset collected helps to fill knowledge gaps related to manure GHG emissions from Canadian cow-calf and confinement housing systems. Due to the lack of manure disturbance in this storage type, and the low emissions compared to previous characterizations of composted cattle manure, storage of manure as a bedding pack may be a tool for GHG mitigation on cow-calf operations.

While this study expands current knowledge of manure nutrient and GHG emissions, further understanding of the mechanisms driving GHG emissions is required. This may be accomplished by more frequent sampling of manure to better understand nutrient profiles and concurrent changes in GHG emissions. More detailed information related to the diets fed to cows during confinement may also be beneficial in identifying how management factors (diet, calving season, etc.) may influence GHG emissions. Further examination of true composted manure stores, as well as the

manure packs and piles as measured here, are required to facilitate the development of best management practices (BMPs) for cow-calf producers.

5.0 GENERAL DISCUSSION

The Beef Cattle Research Council's (BCRC) National Beef Research Strategy (BCRC 2012) indicated that only 12% of research related to cow-calf production systems focused on GHG mitigation; this metric includes both enteric methane and manure management studies. Study of manure management includes not only those management decisions regarding storage and transport, but also the application of manure as a fertilizer/soil amendment. However, there appears to be a disconnect between these phases in the manure life cycle. Manure management prior to field application is often associated with animal production systems, while field emissions are attributed to crop production systems, as per FAO LEAP Guidelines (FAO 2016). The CRSB (2016a) used this approach for their National Beef Sustainability Assessment. Although stored manure and manure excreted on pasture have inherently different courses of decomposition and emission potential, the dissociation of manure amongst different phases of the cow-calf production system may contribute to an incomplete understanding of manure nutrient cycling including loss via emissions. Extensive production environments including pasture and winter grazing systems for beef cows (Sheppard et al. 2016), where manure is deposited on pasture rather than collected and stored, pose challenges related to manure sample collection and study, as manure is not deposited in or collected as a bedding pack or pile.

The study of manure management and nutrient cycling is essential not only for environmental sustainability, but also the economic viability of a cow-calf operation. Where nutrient lost to soil, air, and waterways are a risk for climate change and environmental quality, as has been discussed, these losses also reduce the potential quality of manure as fertilizer for crop production. Nitrogen lost from the manure represent a financial loss as synthetic N fertilizers are purchased to support plant growth. Plant-available forms of N, NO_3^- and NH_4^+, are actively lost from manure through leaching, nitrification/denitrification, and volatilization, when not managed

appropriately. Thus, the financial benefits of mitigating nutrient losses, including GHG emissions, becomes apparent to producers.

Further, examination of manure management strategies and the subsequent development of GHG mitigation strategies related to manure aligns with industry goals targeting GHG emission reductions. The BCRC has outlined a goal to achieve a 33% reduction in GHG intensity from primary beef production by 2030 (BCRC 2021). Improvement in management of manure nutrient was previously included in the National Beef Research Strategy (BCRC 2012), under feed grains and feed efficiency research. The CRSB (2016b) has also set a target to reduce the GHG footprint per unit of production (CO_2-e kg^{-1} beef) and has included manure management as part of this goal. Promotion of BMPs for manure nutrient is a current extension goal for the beef industry (BCRC 2021). It has been acknowledged that previous efforts to mitigate GHG emissions from the Canadian beef sector have focused on feedlot operations, leaving cow-calf systems an "untapped" opportunity for research and mitigation (BCRC 2021).

This project also aligns with broader government targets. The new Sustainable Canadian Agricultural Partnership, launched in April 2023, aims for a 3-5 MT reduction in GHG emissions from the agricultural sector (AAFC 2022). Similar goals have also been set under the Climate Change & Environment priority of the Guelph Statement (AAFC 2021), a framework for strengthening Canada's agriculture industry through 2028. Under this priority, Canada aims to reduce GHG emissions and improve carbon sequestration, as well as respond to changing climate with the development of best management practices for agricultural producers. The dataset generated in the present study may contribute to the development of BMPs that will lead to GHG mitigation from the cow-calf sector.

As discussed throughout, there have been few studies that have compared GHG emissions and nutrient composition of stockpiled vs. composted manure, such as Pattey et al. (2005), Larney et al. (2006), Ahn et al. (2011), and Bai et al. (2020). While fresh manure (Larney et al. 2006) and stored manure slurry (Pattey et al. 2005) have also been examined, there has been little research conducted to quantify and compare emissions from cow-calf confined overwintering areas. Previous studies were primarily focused on feedlot manure, where diets are typically higher in CP, less bedding is provided than for overwintering beef cows, and manure clearing may be more frequent due to pen conditions, stocking density, and shorter turnaround time between animal groups. Depending on available labour, other farm activities (i.e., the need for usage of the pen), weather conditions (i.e., excessive moisture limiting the ability to enter the pen, or conversely, dry conditions eliminating the need to pile and manure as a means to reduce moisture content prior to spreading), etc., the manure pack on a cow-calf operation may be left untouched for several months. As identified in the current survey, this is a common method of manure storage prior to application. The data presented here indicates that maintaining an undisturbed manure pack (i.e., not piled or turned) may minimize the opportunity for emissions from the manure. Further study of deep-bedded cow-calf manure packs in confinement as well as shallow-depth bedding in extensive overwintering sites require further examination of anaerobic processes and related emissions to develop science-based BMPs.

The observation that manure packs remain relatively inactive throughout storage, as compared to the increased emissions spikes resulting from piling or turning, is of particular interest as manure composting is often touted as an avenue for GHG mitigation. As such, it would be of interest to compare emission patterns and quantities from manure packs, stockpiles, and compost piles from cow-calf operations, as the former appears to be a common manure “storage” type with

conditions unique to this management system. Due to differences in environmental conditions (indoor vs. outdoor housing), animal traffic (disturbance, compaction, and urination leading to urea volatilization), and manure characteristics, manure packs from beef cow overwintering pens can be assumed to behave differently from dairy cattle or swine, which have been more frequently studied (Hassouna et al. 2023).

Data collected in the current study (management survey, manure nutrient characterization, and manure GHG measurements) may also be useful when comparing measured vs. modelled GHG emissions from cow-calf operations. This information can be used in model development and validation. The breadth of information collected would be particularly useful for whole-systems models that estimate GHG emissions, such as the Holos model (AAFC, Ottawa, ON) or Integrated Farm System Model (IFSM; Agriculture Research Service, United States Department of Agriculture, Washington, DC). Previously, Holos has been used to determine whole-farm emissions from cow-calf operations, including stockpiled and composted manure (Beauchemin et al. 2010; Alemu et al. 2017), and IFSM has been used for estimation of GHG emissions from composted beef cattle manure windrows (Bonifacio et al. 2017a; 2017b). Use of the information generated herein may present an opportunity to refine existing models and more accurately predict GHG emissions leading to necessary improved goal setting and reporting as well as policy development. This data may also improve current Canadian GHG estimates from the beef industry, which are based on mathematical models, such as ECCC's National Inventory Report (2021b) and the CRSB (2016a) National Sustainability Assessment. The dataset will also prove useful to modelling improvements outlined in Canada's Methane Strategy (ECCC 2022), including the simultaneous study of gases of interest, and modelling of various agricultural mitigation measures.

The present study also helps to fill gaps identified in the DATAMAN database (Hassouna et al. 2023), a robust, global database of GHG and NH_3 emissions from the livestock manure management lifecycle. Hassouna et al. (2023) has indicated that GHG emission studies were lacking for several important livestock production systems. Of these, beef cattle production systems, particularly confined systems (the closest system to a cow-calf seasonal feeding area identified in this study were “feedlots”), were notably underrepresented in the literature. The present study meets the criteria for inclusion in the DATAMAN database (Hassouna et al. 2023), and therefore may be used to develop more accurate emission factors for manure from confined beef animal systems.

6.0 GENERAL CONCLUSIONS

Study conclusions:

- Nutrient composition of stored manure on cow-calf operations was *not* significantly different between farms, except for total P content. Nutrient composition of stored manure was significantly different across dates within farms (i.e., changes in composition over time) for all nutrients.
- Stored solid beef cow manure on the surveyed operations had average cumulative emissions of 12,308.5 g m^{-2} CO_2, 771.9 g m^{-2} CH_4, 5.4 g m^{-2} N_2O, 125.8 g m^{-2} NO_2, and 6.7 g m^{-2} NH_3 from June – September 2020. On a CO_2-e basis, CH_4 was the largest source of GHG emissions across all farms, followed by CO_2.
- Manure storage type (manure pack vs. stockpile) and calving season, which directly affects other management decisions (i.e., diet, bedding, timing of disturbance, storage period, etc.), are management factors which influence GHG emissions from stored manure.
- The dataset collected as part of the manure nutrient characterization builds upon previous characterizations of manure nutrients and GHG emissions, for the establishment of "book" values for manure nutrient and emissions estimates.
- Manure packs, generated in confinement areas and stored under outdoor storage conditions, are an important manure storage type for cow-calf producers. These manure stores are disturbed minimally, and may be used as a manure GHG mitigation strategy for cow-calf producers.

Future considerations:

- As manure packs may be a method to reduce manure GHG emissions, a comparison of GHG emissions from storage types including manure packs, stockpiles, and composted manure, as well as manure stored in extensive overwintering areas, would improve knowledge of emissions from stored manure, the effects of manure management on emissions, and aid in the development of manure GHG mitigation strategies for the cow-calf sector.
- Dietary composition related to stored manure may improve understanding of nutrient excretion, and influence of animal management (diet, calving season and related effects) on manure composition.
- More frequent sampling of manure nutrient concurrent with GHG measurement would allow for further evaluation of processes/mechanisms leading to GHG emissions, beyond what could be hypothesized here.
- Manure characteristics, nutrient transformations, and GHG emissions are influenced by environmental conditions. Closer study of weather events and environmental conditions during the storage period would also allow for further evaluation of processes/mechanisms leading to GHG emissions. Further, as cow-calf producers experience and adapt to climate change, the influence of extreme weather events on stored manure (directly, or indirectly through changing farm management practices) should be considered.
- The dataset generated in this study contributes to the current knowledge of manure GHG emissions and has potential for incorporation in the DATAMAN database (Hassouna et al. 2023), or for use in modelling efforts to compare measured vs. modelled emissions and develop mitigation strategies/BMPs for cow-calf producers.

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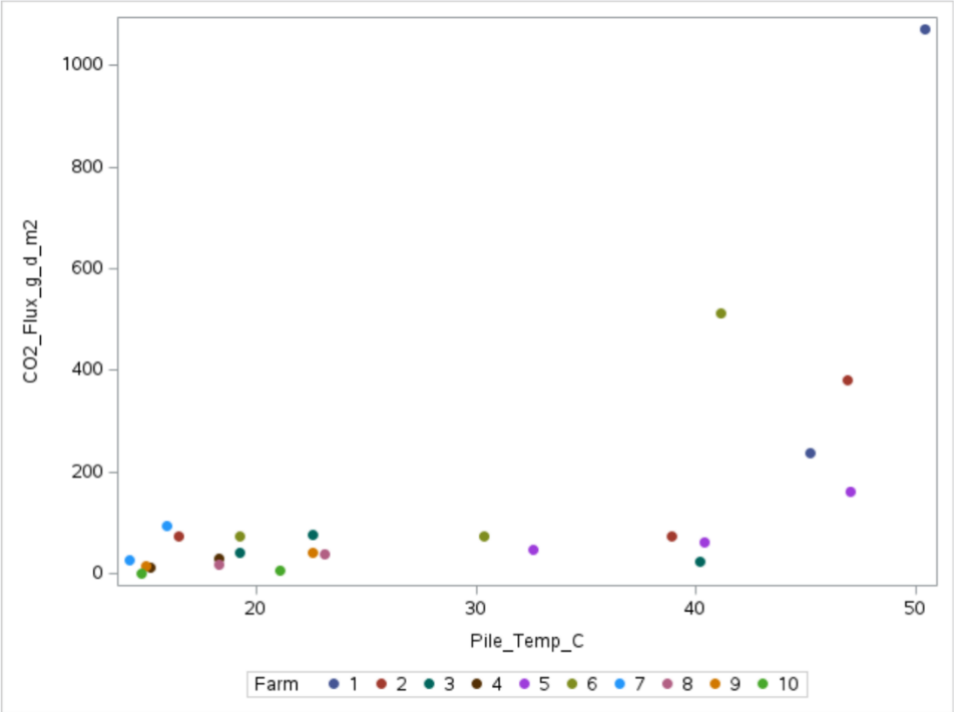
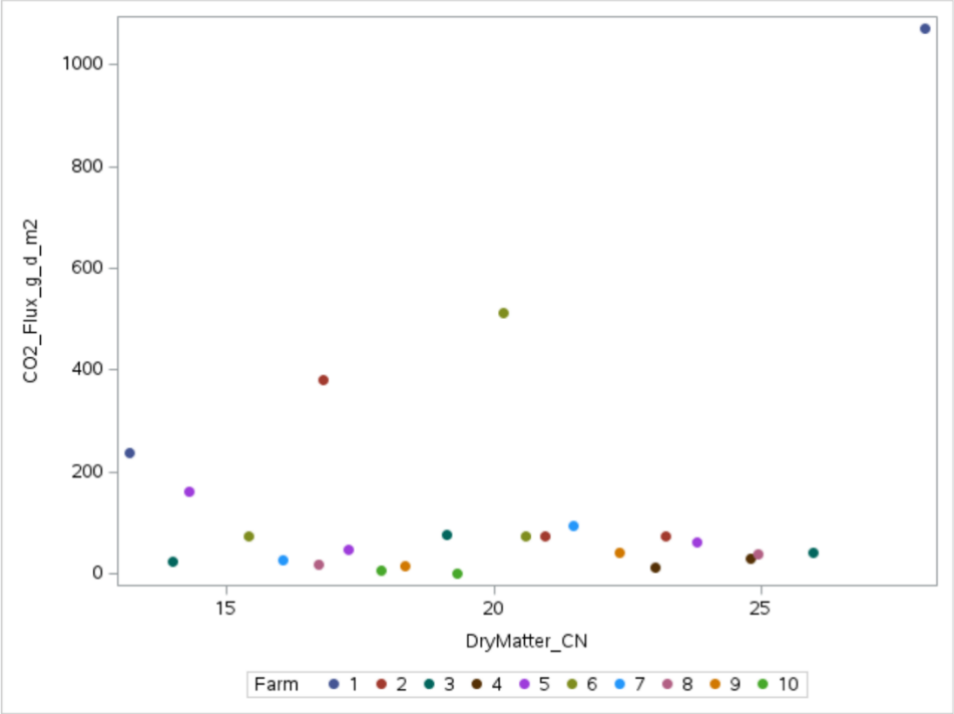
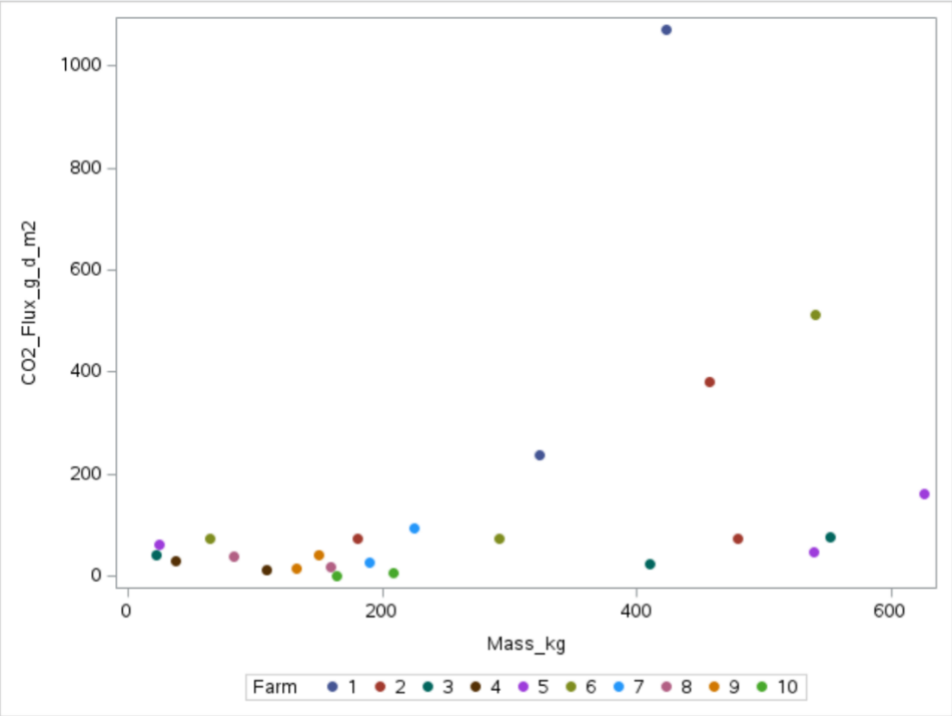
8.0 APPENDIX A



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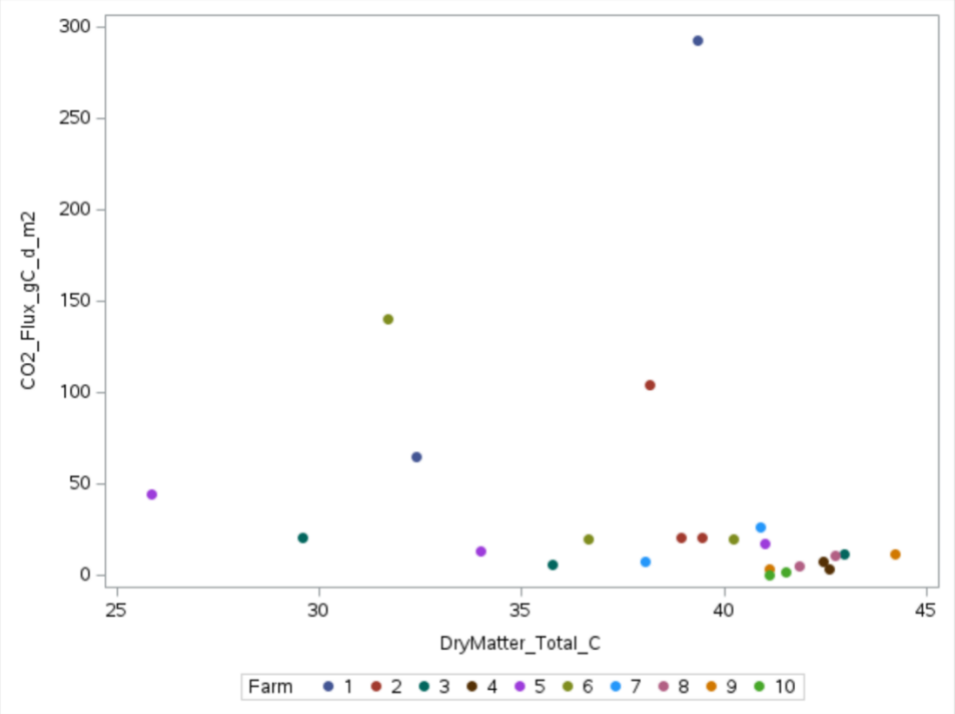
800
600
400
200
0
0
200
400
600
Mass_kg
Farm 1 2 3 4 5 6 7 8 9 10


CO2_Flux_gC_d_m2
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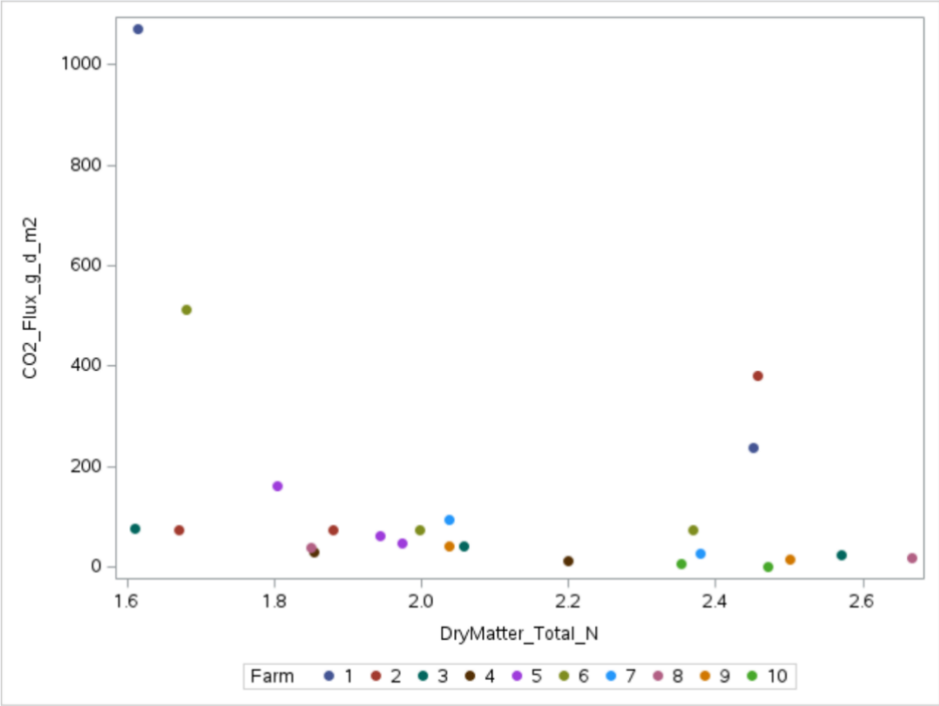
250
200
150
100
50
0
25
30
35
40
45
DryMatter_Total_C
Farm 1 2 3 4 5 6 7 8 9 10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800
600
400
200
0
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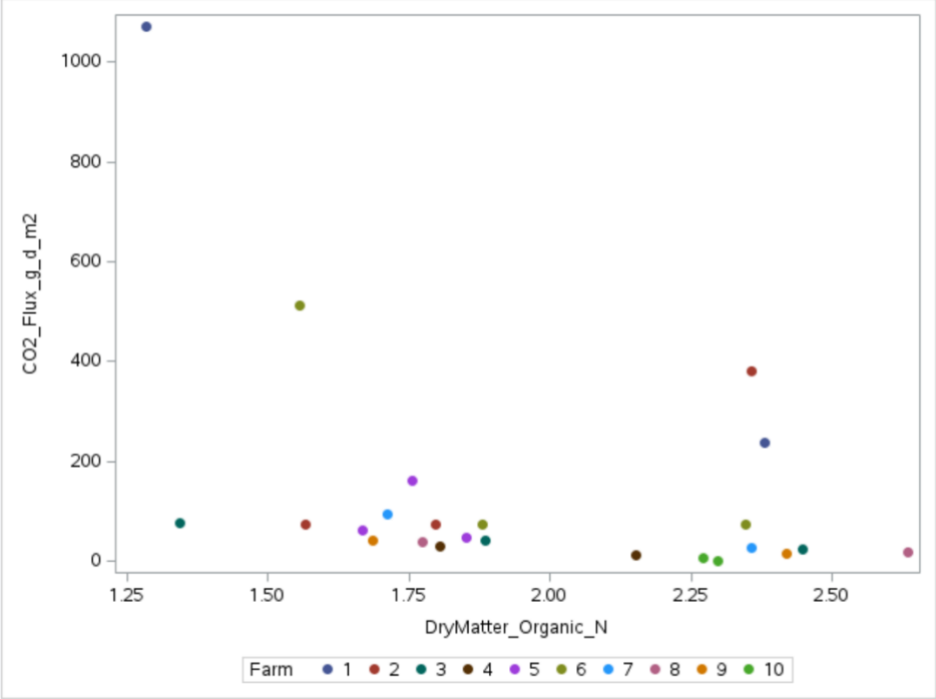
1.8
2.0
2.2
2.4
2.6
DryMatter_Total_N
Farm 1 2 3 4 5 6 7 8 9 10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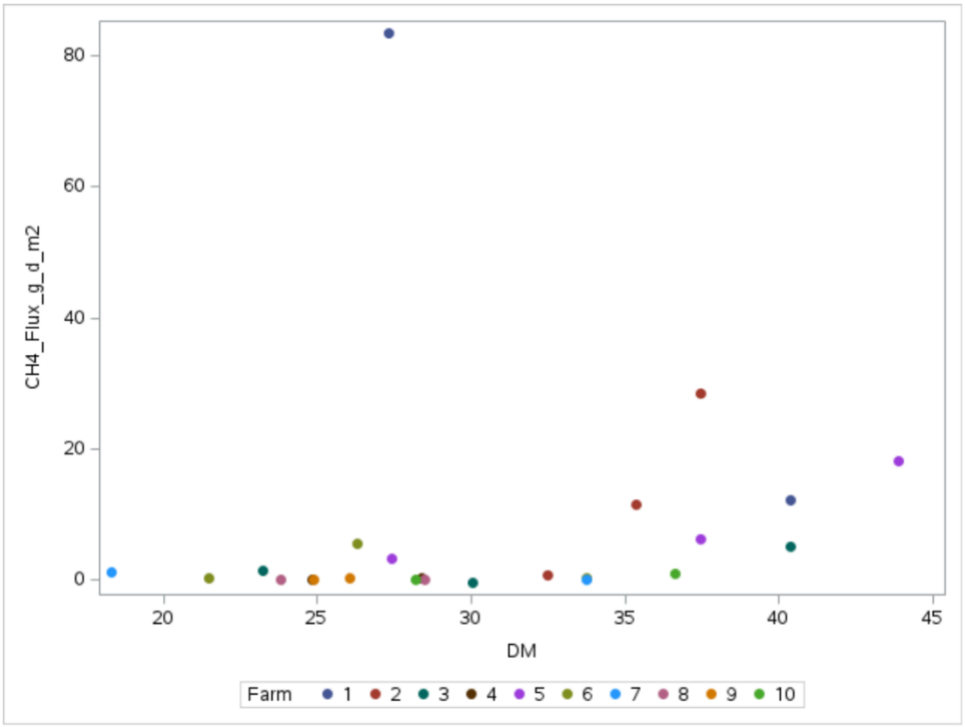
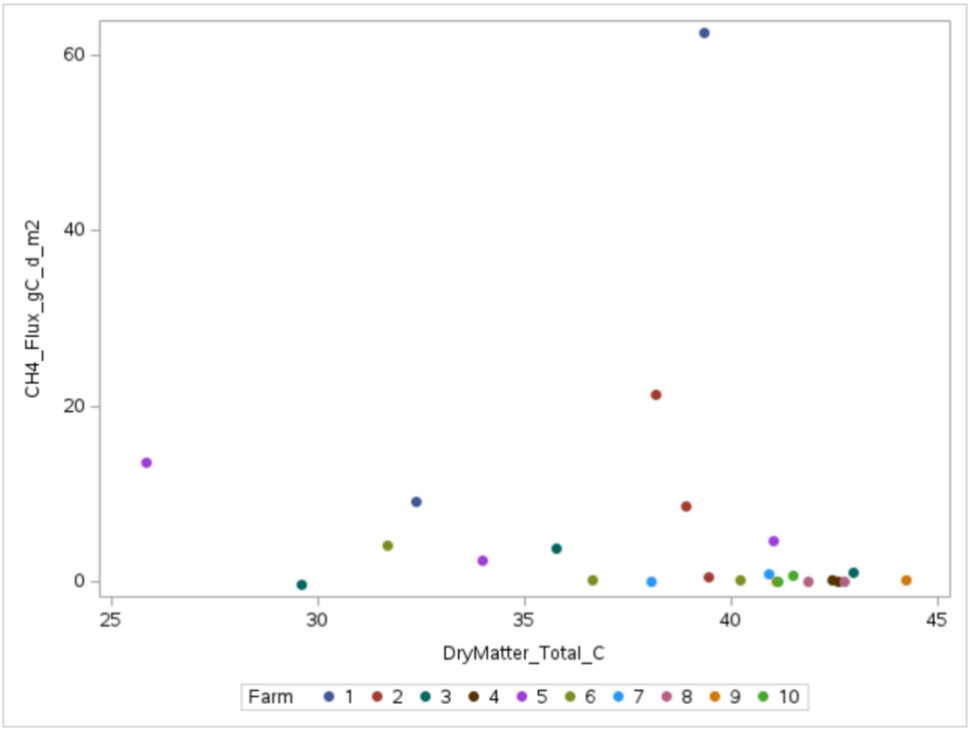
800
600
400
200
0
1.25
1.50
1.75
2.00
2.25
2.50
DryMatter_Organic_N
Farm 1 2 3 4 5 6 7 8 9 10


CH4_Flux_g_d_m2
80
60
40
20
0
20
25
30
35
40
45
DM
Farm 1 2 3 4 5 6 7 8 9 10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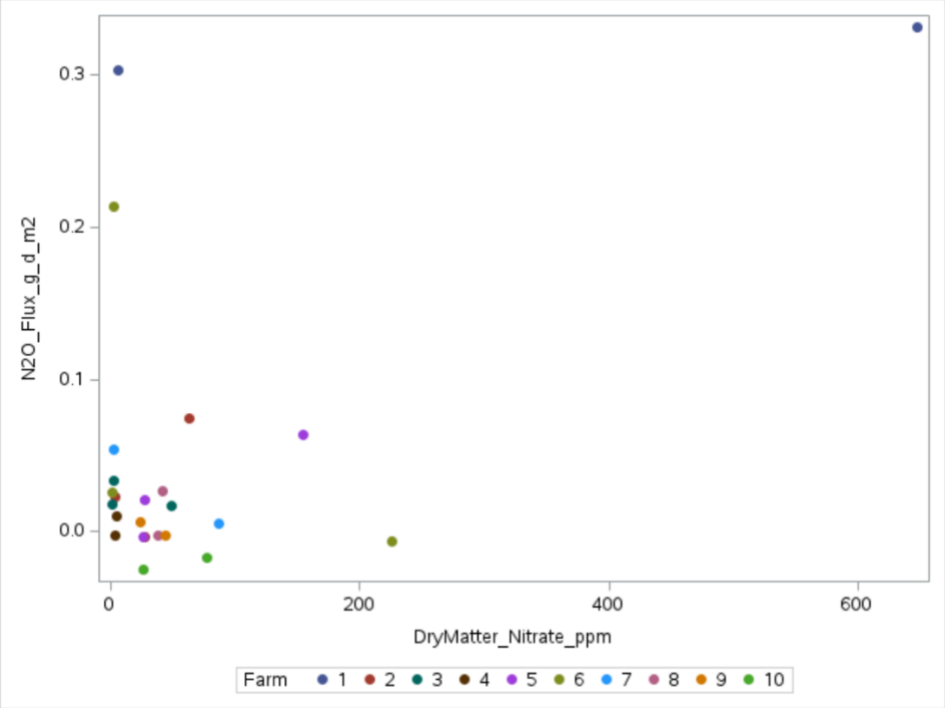
40
20
0
25
30
35
40
45
DryMatter_Total_C
Farm 1 2 3 4 5 6 7 8 9 10


N2O_Flux_g_d_m2
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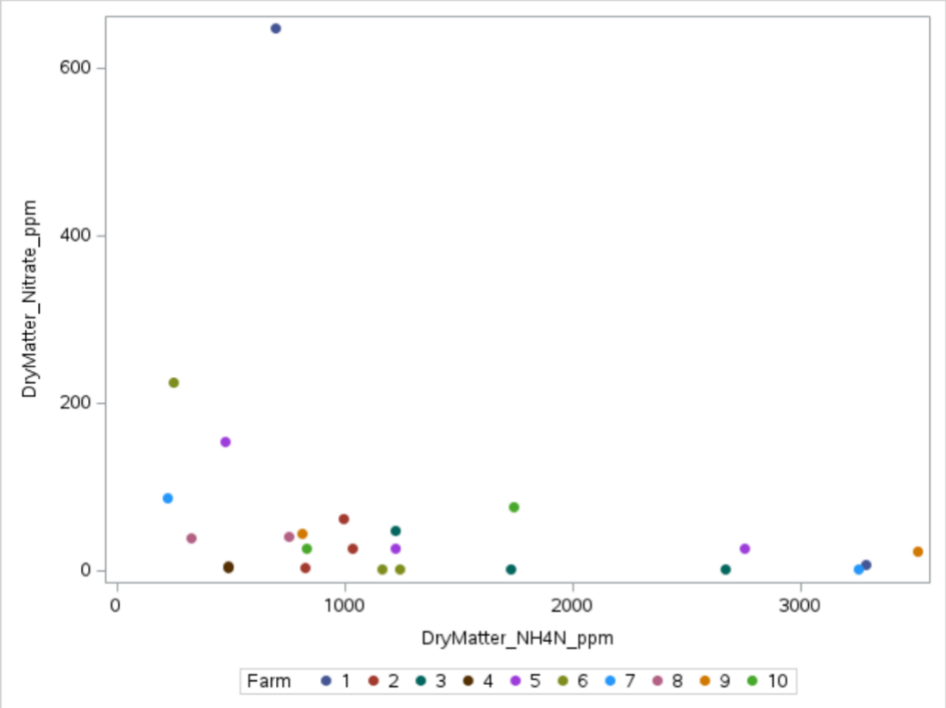
0.2
0.1
0.0
0
200
400
600
DryMatter_Nitrate_ppm
Farm 1 2 3 4 5 6 7 8 9 10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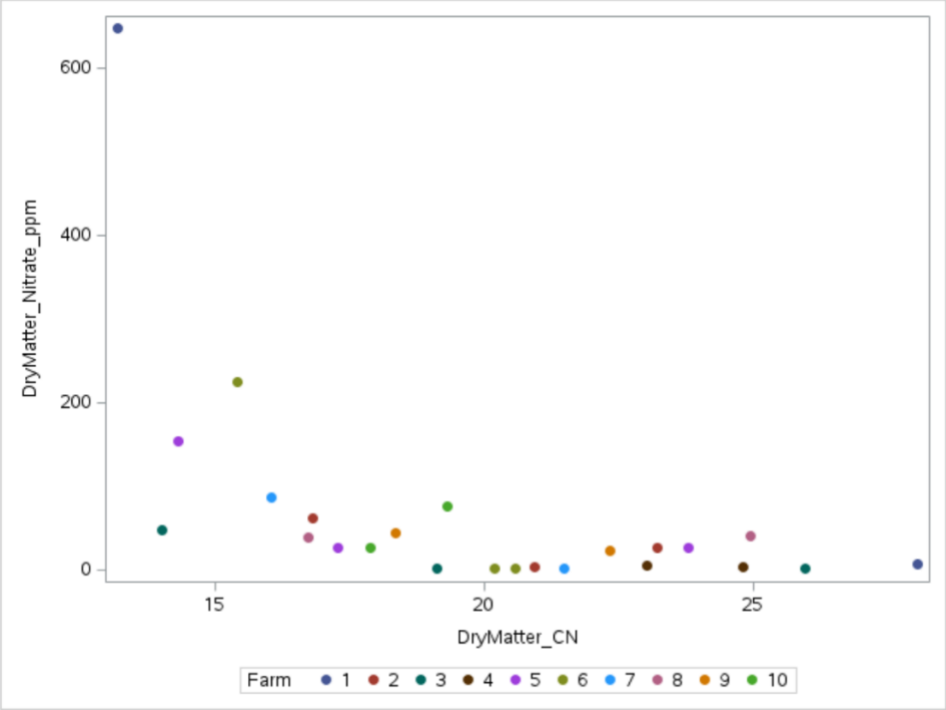
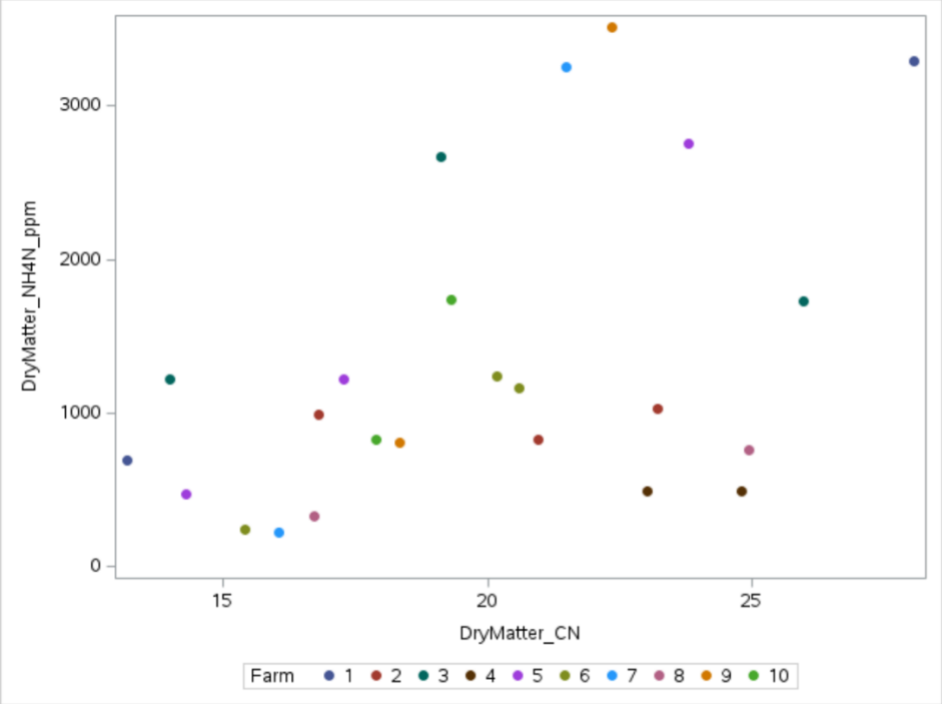
400
200
0
0
1000
2000
3000
DryMatter_NH4N_ppm
Farm 1 2 3 4 5 6 7 8 9 10


600
400
200
0
DryMatter_Nitrate_ppm
15
20
25
DryMatter_CN
Farm 1 2 3 4 5 6 7 8 9 10


3000
2000
1000
0
DryMatter_NH4N_ppm
15
20
25
DryMatter_CN
Farm 1 2 3 4 5 6 7 8 9 10

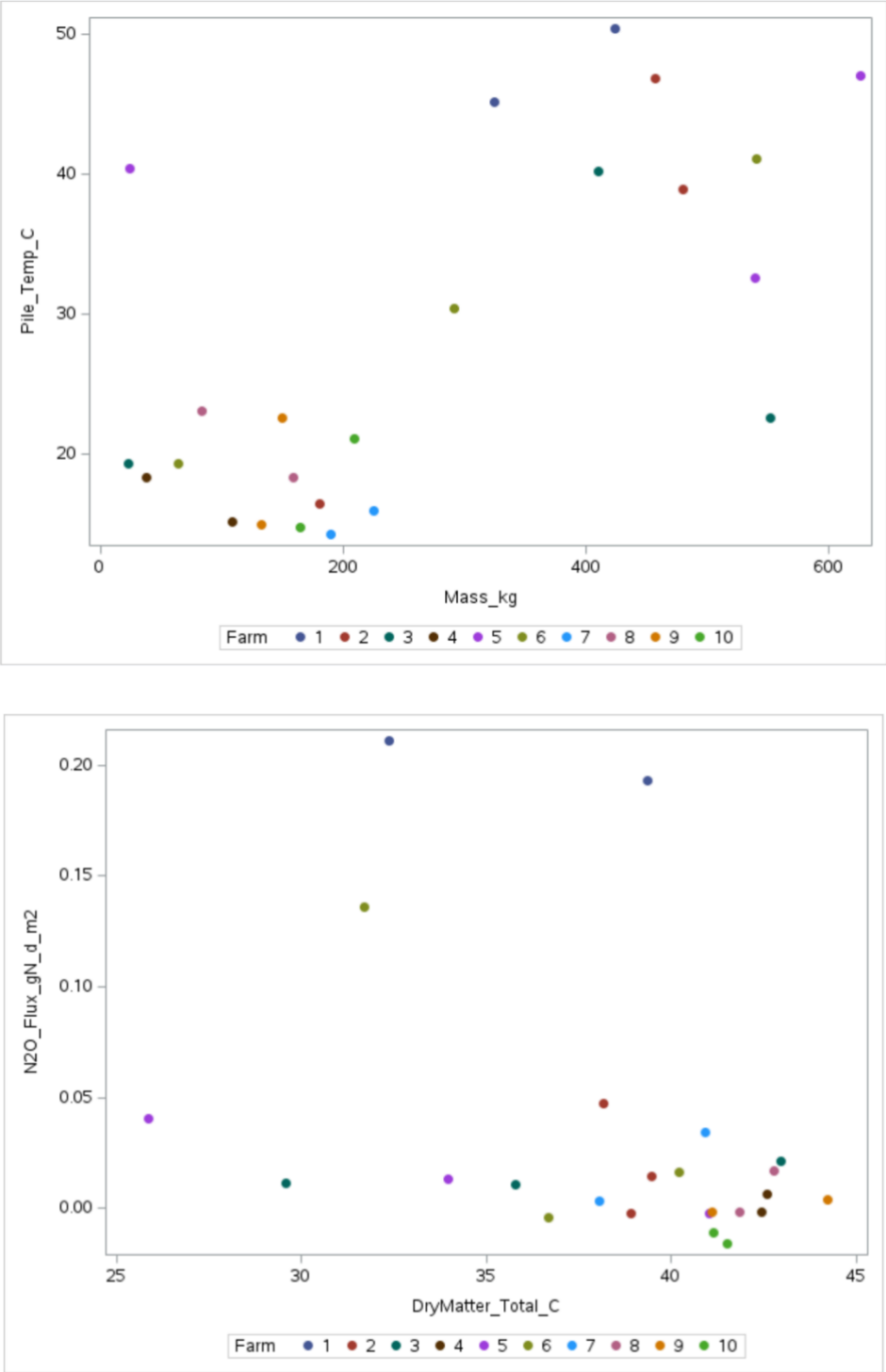


Figure A 1. Select Spearman Rank Correlation scatter plots

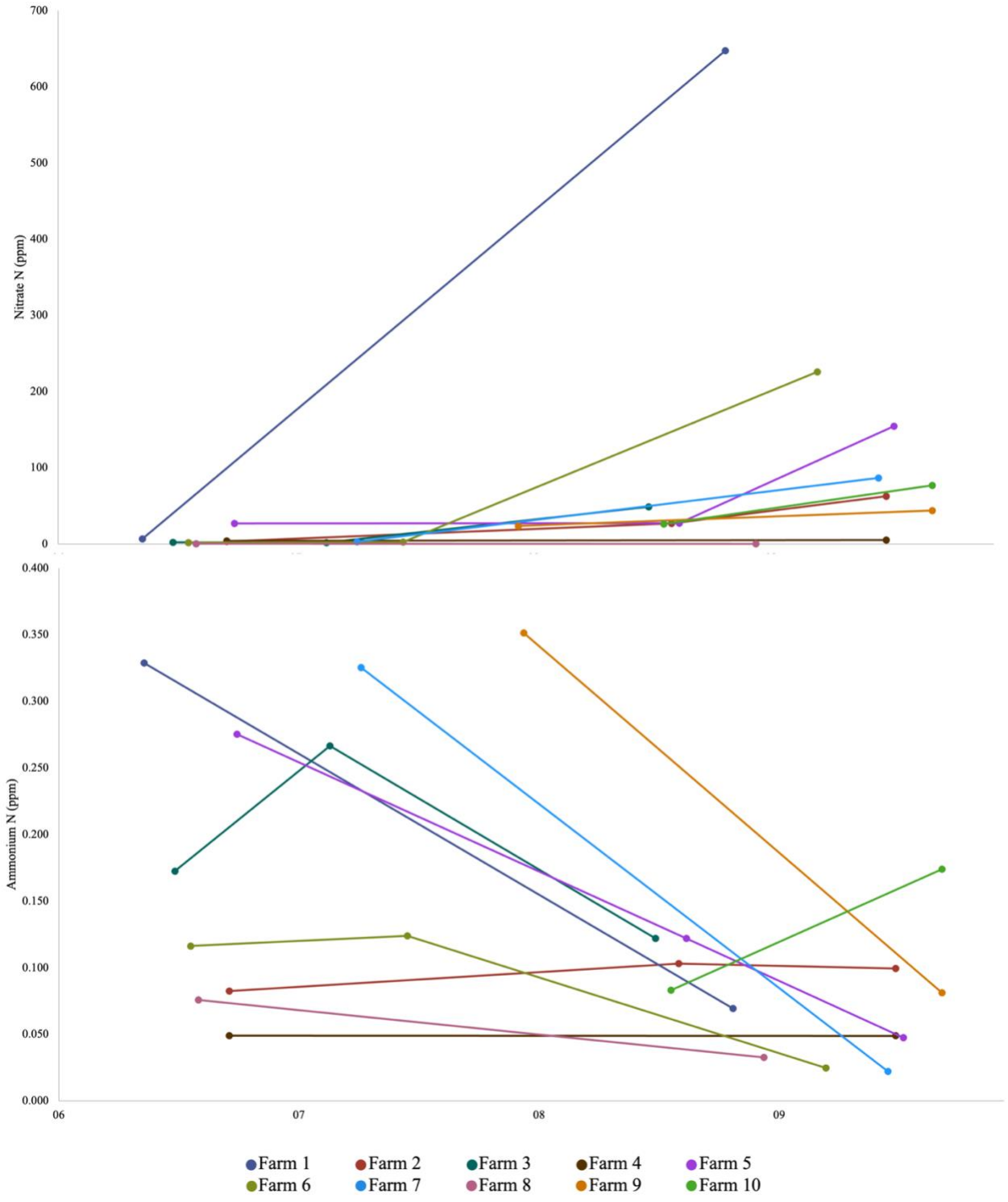


Figure A 2. Ammonium- and nitrate-nitrogen content (ppm, DM basis) of stored solid beef cow manure over 104 d storage period (June – Sept 2020).