Modelling Beneficial Management Practices in Agriculture in Western Canada to Observe Impacts on Greenhouse Gas Emissions and Environmental Sustainability

by

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Abstract

Reducing greenhouse gas (GHG) emissions and other detrimental environmental effects of agriculture is a goal paramount to societal stability and prosperity. Understanding the advantages and constraints of beneficial management practices (BMPs) to the fullest extent in varying conditions is imperative for effectively selecting the right interventions tailored to specific farming scenarios. Modelling agricultural management practices and scenarios enables comprehensive testing of simulation experiments to be conducted efficiently, conveniently and at low cost while yielding accurate, representative results. The objectives of this research include: 1) Identify and review existing BMPs for mitigation of GHG emissions within farming systems relevant to the Canadian Prairies, 2) to implement the Holos model software to run simulations of selected farming scenarios and management practices, and 3) to inform future research recommendations in agricultural sustainability and identify existing knowledge gaps. The scenarios modelled focused on the Canadian Prairies, and hence the modelled replicates were evenly distributed across locations within Alberta, Saskatchewan, and Manitoba. A set of beneficial management practices was modelled using the Holos model software. The greatest reduction in farm GHG emissions occurred when nitrogen and phosphorus fertilizer inputs were reduced. The average reduction in emissions from a regime of high inputs to conservative inputs was 26% Kg CO_2e. Across a variety of soil types and fertilizer regimes, the average reduction by switching to no-till or reduced tillage from intensive tillage was 24.9% Kg CO_2e and 17.6% Kg CO_2e respectively. This great reduction was attributed to increased soil carbon sequestration and reduced fossil fuel emissions from farm equipment operations. Livestock dietary changes also resulted in emissions reductions. A high protein diet for beef cattle caused a reduction of 33% Kg CO_2e when compared with a low protein diet. High protein diets can increase efficiency of feed utilization (EFU). Fat supplementation and use of ionophores were also found to reduce emissions. Earlier studies have shown that both fat and ionophore supplements directly reduce methane emissions from digestion for beef cattle. The GHG emissions estimates from the Holos model suggest that implementation of beneficial management practices can play a large and important role in reducing emissions in agriculture. These results contribute to a comprehensive, valuable synthesis of the current knowledge base in BMPs for agricultural sustainability and provide deployable insights to guide BMPs implementation

Preface

Some of the research conducted for this thesis forms part of a research collaboration, led by Professor Guillermo Hernandez-Ramirez at the University of Alberta and collaborators included the lead scientists and technicians working on the Holos model. These collaborators include Roland Kroebel, Sarah Pogue, Aaron McPherson, and Aklilu Alemu. The model scenarios were designed by me, with the contribution of these collaborators. They assisted in creation of the model farming scenarios and troubleshooting while conducting the modelling. The data analysis in chapter 2 and 3 and concluding analysis in chapter 4 are my original work, as well as the literature review in chapter 1.

Dedication

I dedicate this study to my family, closest friends, my kitty Stella, and Karl Kormos; without their love and support I could not have come this far.

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I would like to acknowledge the funding from Environmental Farm Plan (EFP) and ARECA that made this research possible. I would like to acknowledge the help I received from Roland Kroebel, Sarah Pogue, Aaron McPherson, and Aklilu Alemu in developing and carrying out this project. Finally, I would like to recognize my supervisors Dr. Guillermo Hernandez-Ramirez and Dr. Linda Gorim for the excellent guidance and counsel through this endeavour and time in my life; I appreciate your help, patience, and understanding more than you know.

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Introduction

Agriculture is an extremely important industry as it serves to feed and sustain the human population. The products of agriculture also contribute to fibers, energy, and medicine. Furthermore, agriculture is a key source of employment and income for the global population.

From an environmental perspective, the agriculture industry contributes a considerable amount of greenhouse gas (GHG) emissions; 24% of all anthropogenic emission worldwide are sourced from agriculture (EPA, 2010). In Canada, agriculture accounts for 8% of the emissions (Government of Canada, 2021). These assessments of agricultural emissions do not include fossil fuel use or energy put into creating inputs for farming. When fuels and input energy are included, agricultural emissions increase by almost one third (National Farmers Union, 2022).

The use of beneficial management practices (BMP) is a valuable tool to implement on farms to reduce GHG emissions from agriculture (Yanni et al., 2021). BMPs can work in two ways: they aim to use less or produce more. 'Using less' directly contributes to less emissions. On the other hand, 'produce more' helps to reduce the emissions intensity while also indirectly reducing emissions. BMPs can include but are not limited to strategies such as fertilizer management, crop choice and rotation, livestock feeding and housing strategies, and manure handling.

In Canada, farm numbers are declining, the land available for farming is increasing and corresponding farm sizes are getting bigger (Statistics Canada, 2021b). This means that each producer that decides to implement a beneficial management practice has a larger impact on the environment, emissions reduction, and production.

Emissions within the agriculture sector come in large part from the soil due to cycling of nitrogen and other nutrients. These emissions are greatly increased by the use of synthetic fertilizers and the addition of fertilizers in general. GHG emissions also come from use of fossil fuel to run farming equipment, and largely from ruminant livestock who emit methane when digestion occurs. Modelling scenarios can efficiently help in comparing many different practices quickly while holding other farming variables constant, and hence, this approach enables acquiring data that otherwise would require years of field research. Modelling is also a strategy that requires much less time, energy, and funding relative to carrying out biophysical experiments.

The goals and objectives of this project were to:

- identify existing BMPs aligned with GHG mitigation aims within farming systems relevant to the Canadian Prairies
- to implement the Holos model software to run simulations of farming scenarios and management practices in typical cropping and livestock systems
- identify knowledge gaps of BMP and GHG mitigation as well as future recommendation in agricultural sustainability.

It is hypothesized that both reduced fertilizer application, and reduced tillage will reduce GHG emissions. It is also hypothesized that altering livestock diets with macronutrients and additives and adjusting manure management to reduce anaerobic conditions will reduce GHG emissions. Lastly, it is hypothesized that housing management that allows for manure removal and spread to happen often will result in the least emissions.

CHAPTER 1: Literature Review of BMP’s for GHG Reduction Management and Agricultural Sustainability in the Canadian Prairies

1.1 Introduction

Crop and livestock production accounts for 8% of Canada's greenhouse gas (GHG) emissions. When energy use is accounted for including fossil fuel use consumption in fertilizer manufacturing and livestock production accounts for 10% of national GHG emissions (Government of Canada, 2020). More specifically, agriculture accounts for 31% of CH_4 emissions within the country and 76% of N_2O emissions within the country (Environment and Climate Change Canada, 2018). This information provides a clear notion of the impact of agricultural practices on GHG emissions. The three main greenhouse gases emitted by the agriculture sector include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide(N_2O) with increasing ability to trap heat in the order of: 1, 28, and 265 times, respectively (Intergovernmental Panel on Climate Change IPCC, 2021). CO_2 is mainly attributed to soil cultivation and management, CH_4 associated with ruminant livestock, most prominently cattle, and manure decomposition, and N_2O is attributed to fertilizer and manure use (Government of Canada, 2019).

Beneficial management practices (BMP) are agricultural practices that improve the sustainability of a farm operation while maintaining economic success (Asgedom, & Kebraeb, 2011). The management of greenhouse gases and BMP development are imperative when striving for sustainability in cropping and livestock systems and can make significant impact (Alemu et al., 2016). Beneficial practices vary widely and are always evolving.

The latest census shows that the number of farm operations in Canada continues to decline (Statistics Canada, 2017) despite the increasing demand for farm output such as food and fiber. Demand continues to increase due to the increasing populations of Canada and the world (The World Bank, 2019). Each farming operation has expanded immensely over the years as field equipment for large scale production became available and production practices intensified. As farms continue to grow and intensify, addressing areas of improvement for environmental sustainability and economics can make an increasingly large impact per operation.

Precision agriculture can be discussed in almost every aspect of farming as it refers to the basic objective of enhancing yield of products while decreasing inputs and reducing environmental pollution or externalities (Narmilan & Puvanitha, 2020). This topic will be discussed often indirectly.

When it comes to focusing on BMPs for improved crop production, widely recognized strategies of soil management include nutrient plans and precise application of fertilizer. This is in part because preventing excess N fertilizer application typically contributes to mitigation of GHG emissions. Likewise, the adoption of a zero-till farming strategy in order to enable greater carbon sequestration can make a substantial impact as well. Compaction of soil can increase GHG emissions intensity. Similarly, irrigation as well as soil moisture conditions have a part to play in GHG production and mitigation (Trost et al. (2013). Other aspects of crop management are also important. Choosing an appropriate crop species and variety, rotating crops in a mindful manner and utilizing new technologies for applying inputs variably where needed or mapping harvest yield can be impactful (Koch et al., 2004; Guenette & Hernandez, 2018). Livestock BMPs can include improvements in feeding strategies, manure management, and housing options which can substantially contribute to emissions reduction in the agricultural sector.

Computer modelling has projected that if no action is taken, there will be a significant increase in atmospheric CH_4 and N_2O emissions by 2070 (Frank et al., 2019). Incremental changes in cropping systems can add up and make a substantial difference in this outcome.

Understanding current research, implications of management practices and the barriers to implications or negative side effects is important for GHG emission reduction.

1.2 Cropping System Management Practices for GHG's

1.2.1 Soil Management

Soil management is extremely important when it comes to mitigating farm GHG emissions. CH_4 exchange from croplands is often negligible, whereas CO_2 and N_2O emissions are more profound and important to understand land management (Ellert and Janzen, 2008). The addition of balanced fertilization to soil enables plants to grow better by satisfying nutrient requirements and increases crop yield. However, fertilizer application is a massive contributor to GHG emissions from soils (Snyder et al., 2009). The 4R nutrient stewardship model is a useful framework to describe and discuss field agronomy when focusing on fertilizer application options; this refers to right source, right rate, right time, and right place (Foundation for Agronomic Research, 2017). Each point has a significant effect on how effective the fertilizer application will be (Bruulsema, 2019).

Fertilizer

Generally, the addition of nitrogen fertilizer is used to improve nitrogen availability in the soil and increase crop yield (Rochette et al. 2008). Nitrogen being a highly mobile nutrient is very susceptible to transformations such as mineralization, nitrification, immobilization, leaching, volatilization, and denitrification; there is potential of loss as N_2O emissions (Rochette et al. 2008). Optimization of source, timing, and method of application are therefore of interest in order to minimize losses and increase fertilizer use efficiency, especially nitrogen. Studies have found that nitrogen is often applied in excess and more closely matching its application with the needs of a crop can help reduce emissions and improve profit margins (Ribaudo et al., 2011). When fertilizer is used efficiently, the increase in yield and biomass can reduce the net GHG emissions (Asgedom, & Kebraeb, 2011). However, the decision for farmers on what fertilizer management options to implement is mostly based on economic considerations instead of environmental aspects.

Fertilizer Sources

There are many formulations of nitrogen fertilizer. Inorganic N fertilizer formulations include: urea, anhydrous ammonia, urea ammonium nitrate, ammonium sulphate, potassium nitrate, ammonium nitrate, and monoammonium phosphate. Each formulation has its place when a farmer considers results, cost, and access and every form can have the ability to improve crop yield.

A variety of enhanced efficiency fertilizers have been developed as a way to increase nitrogen efficiency. Environmentally smart nitrogen (ESN) is a controlled release nitrogen fertilizer consisting of urea coated with a polymer. It helps control release of nitrogen to increase fertilizer efficiency and reduce losses as emissions or run-off. The effects of this product on GHG emissions can be inconsistent (Li et al., 2012). One study found that GHG emissions were generally lower when compared to a default value from the IPCC; however, they also observed that the reduction in emissions is dependent on the amount of precipitation which can help to explain some of the inconsistencies (Li et al., 2012). In their study with canola, Li et al. (2012) also observed that the resultant GHG emissions were dependent on N uptake of the canola. A reduced N uptake in canola corresponded with increasing GHG emissions. Controlled release fertilizer has been found to be most effective in conditions where nitrate leaching is likely such as in sandy soils that are irrigated (Liegel, and Walsh L. M., 1976). However, a meta-analysis found that on average general polymer coated fertilizers (PCF) were effective in reducing N_2O emissions by an average of 35% when compared to conventional fertilizer emissions (Akiyama et al., 2010). In this study though results varied over land use and soil type, there was evidence that supported more effectiveness in imperfectly drained soil and less to no effectiveness in well drained areas. It was concluded that more research was needed to evaluate their effectiveness (Akiyama et al., 2010).

Nitrification Inhibitors (NI) are compounds that work to slow bacterial nitrifiers in the soil by slowing down the oxidations of NH_4^+ by soil bacteria (Akiyama et al., 2010). The results of a meta-analysis revealed that NI use significantly helps to reduce N_2O emissions by an average of 38% when compared with conventional fertilizer use (Ruser and Schultz, 2015). Findings also showed that results were fairly consistent when land use and the type of NI varied (Akiyama et al., 2010).

Urease Inhibitors (UI) are compounds that work to slow the hydrolysis of urea and reduce ammonia volatilization (Grant et al., 2014). A meta-analysis found that UI's conversely did not significantly reduce N_2O emissions generally when compared to conventional fertilizer use. One specific type of UI did have some significant effects on N_2O emission reduction and that was hydroquinone by an average of only 5% (Akiyama et al., 2010).

Variable Rate Nutrient Application

Fertilizer application is the largest contributor to GHG emissions from croplands. Application of nitrogen fertilizer in excess would cause more GHG emissions while not contributing to yield increase and detracting a farmer's profits. Too little nitrogen application could also result in economic loss and perhaps soil degradation because of nutrient depletion in the long term. Variable rate nitrogen application (VRNA) can significantly reduce GHG emissions by limiting excess application and potentially reducing overall input cost (Balafoutis et al., 2017).

Timing of Fertilizer Addition

Nutrient uptake for crops is timing dependent, the nutrients have to be available when plants need them. Matching the timing of application of nutrients to a crops' nutrient uptake pattern has been put forth as a BMP to improve nutrient efficiency (Zebarth et al., 2009). If the timing of fertilizer application is not aligned, then N or other nutrients in highly mobile forms may move through the soil and out of reach of the plant. Addition of nutrients to a soil when the plants are not able to utilize them contributes to pollution of the environment in the form of run-off or deep leaching into groundwater that becomes detrimental to the environment. Timing can vary as widely as seasons. Fall and spring fertilizer applications do occur in croplands. However, nitrogen losses can occur over the winter and early spring when fertilizer is applied in the fall (Malhi et al., 2008). This causes the crop to have less nutrients available when the growing season comes and also unnecessary N to pollute the environment (Malhi et al., 2008). Winter nitrogen losses can be reduced if the system employs a no-till strategy and if the fertilizer has been applied by banding (Malhi and Nyborg, 1991). Application of N fertilizer has been found to be most efficient in wheat crops when applied right before the period of most rapid nutrient uptake (Howard et al.; Zebarth et al., 2009). Split application of fertilizer instead of applying the fertilizer necessary for an entire growing season at one time can be useful for certain crops that have a continual uptake over the season. One study found that in season with high soil moisture conditions a split application of N fertilizer on potato crops effectively reduced N_2O emissions (Burton et al., 2008). Split application of fertilizer does not consistently affect crop yield except in scenarios where early high moisture conditions occurs and loss of fertilizers occurs at a higher rate (Zebarth et al., 2009). In addition, a study showed that if the split application is delayed, specifically past stem elongation, there could be detrimental effects on yield (Zebarth et al., 2009). Counterproductive effects on yield are important when considering emissions due to the associated decrease in fertilizer efficiency.

Other Soil Additions

Biochar is an alternative amendment made from heating wood or organic material under anaerobic conditions, which may contribute to reducing GHG emissions (Karhu et al., 2011). One study showed that biochar application to agricultural soils can reduce CH_4 emissions while CO_2 and N_2O emissions remained unchanged (Karhu et al., 2011). Another study demonstrated a reduction in N_2O efflux from the soil, and it is suggested that the differences in results may be due to significant differences in pre-existing organic C and nutrient status across study soils (Zheng, Stewart, and Cotrufo, 2012). More research is needed to confirm biochar effects on GHG emissions and to identify the scenarios in which it could become useful.

Soil Testing

Soil sampling and analyses to assess soil nutrient availability can be a powerful tool when addressing and designing fertilizer application plans. However, one study explored the psychology of the farmers in relation to the tests being carried out and the intent to act based on their results. The results of the study demonstrated that the two are not in fact one and the same. Some farmers were found to still do “what has always been done” regardless of the test results (Daxini et al., 2018).

1.2.2 Tillage

Tillage has a profound effect on soil properties and thus has great influence on soil conditions (Mangalassery et al., 2014). Studies show that overall, zero tillage has the highest cumulative reduction of GHG emissions when one considers each important GHG and their respective greenhouse potency (Mangalassery et al., 2014). When practiced in the long term, reduced tillage lowers GHG emissions compared to conventional tillage, and if any tillage is applied to a field, it is recommended it be done during cold and dry conditions (Krauss, 2017). In one study in Alberta, Canada, zero tillage was shown to have less total N_2O emissions than intensive tillage particularly during spring thaw; it was concluded that zero-till could be an effective strategy in reducing soil emissions (Lemke et al., 1999). During early stages of implementation reduced and zero tillage systems can increase N_2O emissions; however, reductions in CH_4 and CO_2 emissions are enough to compensate in the long term (Kong et al., 2009). One study that took into consideration direct and indirect energy expenses compared no-till to minimum till, and conventional tillage found that the average total energy savings were 11% and 14% for minimum till and no-till respectively (Hernanz et al., 2014). The study also compared average productivity of the crop yields in each category and found no significant differences. When they used the productivity data to create a pooled average energy productivity, they found that no-till and minimum till were 19% and 15% higher respectively than that of the conventional tillage systems. However, there are a few studies that have had contrasting results: a study in Belgium over 7 years showed reduced tillage had CO_2 emissions that were twice as large and N_2O emissions were ten times larger than the emission they measured for conventional tillage (Lognoul et al., 2017); these results were thought to be attributed to increased SOC and total N in the soil, and more soil bacteria presence in the topsoil because of the reduced mixing of soil residues when reduced tillage was employed.

When evaluating GHG mitigation, changes in emissions intensity are important to consider. Some studies have shown that tillage practices can have a significant effect on production and yield. In some geographic regions and under certain conditions where soil water availability is a key driver of yield potential, no-till practices can help reduce evaporation from the soil, conserve water, and increase water storage in the soil, and therefore increase WUE by crops (Baumhardt et al., 2017). Relative to fallow in rotations managed under no-till practices, stubble-mulch tillage, was found to increase available soil water at planting by 20 mm for wheat and 30 mm for sorghum (Baumhardt et al., 2017). Runoff was also measured in this study and was found to be consistently lower in the tilled fields(3.9% of precipitation) than under no-till (6.1% of precipitation), and concurrently drainage was much higher for tilled land (~14 mm yr^{-1}) than no-till (~2 mm yr^{-1}) (Baumhardt et al., 2017). When precipitation was corrected for runoff and drainage, WUE were calculated based on evapotranspiration (ET) measurements and this estimation showed that ET did not largely affect wheat, but for sorghum ET was 20 mm greater (Baumhardt et al., 2017). The results also showed that growth and grain yield for wheat did not differ significantly however, sorghum had significant increases in both measures (Baumhardt et al., 2017). The study concluded that no-till practices could contribute significantly to sustainability in semiarid dryland crop systems.

Lafond et al. (2006) found conservation tillage (zero tillage or minimum tillage) resulted in yield increases of 7%, 12.5% and 7.4% for field pea, flax, and spring wheat grown after a cereal crop, respectively. Interestingly, the study found that tillage type had no effect when the preceding crop was fallow or field peas. This difference in yield effect was found to be due to a lack of difference in spring soil water content for field pea and fallow. Conversely, S. Liu et al., 2022 found that no-till reduced yield of maize by an average of 26% when compared to conventional tillage. Kutcher and Malhi (2010) found that barley and canola yields were most often higher by 11-57% or 9-44% respectively under no-till than conservative tillage. It was noted that the no-till treatment increased yields especially in years where precipitation was below normal and so the practice was thought to help preserve soil moisture and in turn increase yield. Observation of a variety of crop types is important as well and effects can vary; Majrashi et al. (2022) found that on average sorghum grain yield was 6% higher under no-till than under reduced tillage or conventional tillage.

Sharma et al. (2011) also found that conventional tillage resulted in the highest yield for maize but minimum tillage resulted in the highest yields for wheat. In addition, the most economic benefits could be obtained by minimum tillage followed by a raised bed tillage option, then no tillage, and then last was conventional tillage (Sharma et al., 2011). This study also measured soil water content which was found to be higher in no-till especially at planting time and in the fall and especially at the soil surface. Porosity, however, was higher in conventionally tilled soils and lower in no-till.

More research is needed to help define tillage effects on crop yields of varying species and under varying conditions.

Soil Compaction

Soil conditions such as soil temperature, moisture, organic matter and mineral N content have a direct effect on microbial activity (Skiba & Ball, 2002).

Compaction can cause increased N_2O emissions. One study demonstrated that increased N_2O emissions in a compacted soil were due to an increase of denitrification correlated with increased water filled pore space in the soil which creates an anoxic microenvironment (Ruser et al., 1998). As compaction reduces the pore space and can in particular damage large vertical drainage pores, the soil cannot drain as quickly, it stays wet longer and anoxic conditions takes place for longer periods of time (Tullberg et al., 2018). In addition, there is reduced plant uptake of N in areas of soil compaction further contributing to higher N_2O emission rates (Ruser et al., 1998).

Controlled Traffic Farming

Controlled traffic farming (CTF) is one of the most effective methods to alleviate soil compaction directly (Tullberg et al., 2018). Since crop zone and machine tracks are permanently separated the overall compaction of a field is reduced. CTF reduces the trafficked area compared with random traffic farming (RTF) from 80% of the total field if tillage practices are being employed, or from 30-60% with no tillage, down to 10-20% of the total field area (Gasso et al, 2013). Conventional traffic practice is likely to cause a trafficked area up to 80% of the total field with intensive tillage practices, and conservation tillage practices such as reduced and zero tillage practices still caused 30–60% traffic on the field (Gasso et al, 2013).

1.2.3 Soil Moisture Effects

The effects of soil moisture on N_2O production are significant (Lin & Hernandez-Ramirez, 2022). One study showed that N fertilized soils that had higher moisture following N application increased N_2O emissions (Ruser et al. 2006). The examination of many studies showed that the results of field research are inconsistent for the N_2O and CO_2 emission effects. In contrast, there is consensus in CH_4 data from field research indicating that a reduction of the amount of irrigation, and avoiding use of the flood irrigation strategy reduced CH_4 emissions (Sapkota et al., 2020).

Irrigation

The effects of irrigation on GHG emissions are substantial. Irrigation is one of the land management practices that is expanding the most in order to reach food production goals with a growing population in particular in regions where moisture limits production (FAO, 2010).

Irrigation can have a direct impact on crop yield and emissions of CO_2 and N_2O. An important factor in what effects will occur in a given scenario is what the climate, specifically the moisture conditions, are like prior to irrigation implementation. Trost et al. (2013) in a review found that irrigation had the largest impact on land that was in a dry climate and less as the climate was more humid. Irrigation was found to increase soil organic carbon in dry areas dramatically and less so as climate was more humid. In the review by Trost et al. (2013), it was also found that in the majority of cases, irrigation increased reactive nitrogen compounds in the soil and thus led to an increased N_2O emissions, ranging from a 50 – 140% increase.

Variable Rate Irrigation

Variable rate irrigation (VRI) can work to reduce GHG emissions by reducing the amount of water being applied to the land and therefore the amount of energy needed to transport and disperse the water. In addition, scheduling irrigation to occur at the optimum time can help reduce GHG emissions from the soil (Balafoutis et al., 2017). Hedley and Yule (2009) studied the difference between VRI and fixed rate irrigation (FRI) by comparing scenarios on 53ha of maize and 156ha of pasture for three years in New Zealand. On average they found a 23-26% irrigation water saving when using VRI (Hedley and Yule, 2009). Hedley et al, 2009 also compared scenarios of VRI and FRI on pasture, maize, and potato sites and found an average annual water use reduction of 9-19% under VRI.

Fertigation

Fertigation describes the process of applying fertilizer periodically admixed with water using irrigation equipment rather than all at once directly into the soil in the spring. The practice has shown to be helpful in reducing N_2O emissions. In one study 32% overall decrease in emissions during the growing season was observed using fertigation practices on wheat and canola crops in southern Alberta (Chai et al., 2020). There was more of an impact in wheat crops as N_2O EF yield was 56 ± 6 vs. 82 ± 5 g N2O-N Mg−1 DM grain in wheat compared to 49 ± 9 vs. 58 ± 10 g N2O-N Mg−1 DM grain in canola. It is important to note that most of the improvements occurred when a low (60 kg N ha¯1) or intermediate (90 kg N ha^{-1}) rate of N application was used (Chai et al., 2020).

1.2.4 Crop Management

Plant genetics

Historically, genetic advancements have enabled major increases in crop yield potential without increasing the area of land farmed. The green revolution was sparked by such advances when wheat cultivars were altered to be shorter, allowing more energy use to be allocated to head growth and grain yield.

Biological nitrification inhibition (BNI) refers to certain plant's ability to produce and release nitrification inhibitors into the soil system, which suppress the first step in the nitrification process mediated by microorganisms. Some wheat cultivars and other plant varieties inherently have this ability, and hence the idea of breeding a competitive cultivar with this ability is not that far-fetched. As nitrification inhibitors tend to conserve N (Lin et al, 2017), BNI would allow application of less nitrogen fertilizer and would slow the nitrogen cycling processes which lead to less N_2O production. Although this mitigation strategy has not been realized yet, plants bred to have BNI could become very useful in mitigating GHG emissions (Subbarao et al., 2017).

Legumes

Including legumes in crop rotations can help reduce GHG emissions by reducing the use of fertilizers as they are able to fix their own nitrogen from the atmosphere. They reduce use of nitrogen fertilizers in the year they are grown, and in the year after as they also leave residual nitrogen in the soil for the next crop. Reckling et al. (2015) found that fertilizer efficiency was higher in crop rotations that include a legume due to the nitrogen fixed by the legume crop, the legume crop also had the lowest N_2O emissions and nitrate leaching when compared with non-legume crops. Specifically, N_2O emissions were reduced by 16% and nitrate leaching was reduced by 11% in the crop rotations that included a legume crop.

Perennial Crops

Perennial forage crops have shown to be substantially greater carbon sinks than annual crops. In an experiment measuring GHG emissions comparing perennial and annual crops, the perennial was found to be a net sink of 8470 kg CO_2-eq ha^{-1} and the annual was significantly less and was actually a net source of 3760 kg CO_2-eq ha^{-1} emitted to the atmosphere (Maas et al. 2013). These results show the impacts of forage crops with legumes requiring much less nitrogen fertilizer as well as having the ability to store much more carbon below ground (Maas et al. 2013).

Competitive perennial grains are not as of yet a realized concept. However, there are some reasonable arguments that suggest they could be a successful crop. Perennial crops have longer growing seasons and it could be deduced that they would perhaps have a longer period of time to capture nutrients and carbon which could translate into a high yielding grain crop and being larger sinks for carbon (Turner et al., 2018). In addition, as perennials have more robust and deeper root systems, they could fair better in period of drought resulting in less risk for a potential producer. Finally, perennial crops have the potential to be more stress-tolerant, often perennial relatives of crops that are wild are sources of genes for resistance to plant stressors (Turner et al., 2018). A very large study across 4 continents sought to inform perennial grain breeding and their results identified the importance of tillering for productivity, and showed that a primary obstacle is longevity, that after the first-year sterility of hybrids and therefore productivity is a problem (Hayes et al., 2018).

1.2.5 Crop Rotations

Interactions with crop sequences can impact productivity and the environment. Some of these factors include GHG emissions, nutrient availability, nitrogen mineralization, nitrate leaching, prevalence of pests, weeds and diseases, and inevitably crop yield (Reckling et al. 2015; Bachinger & Zander, 2007). In their study which developed a cropping system assessment framework using integrated expert knowledge and a vast amount of accumulated data, they studied combination of crop rotations and basic economic outcomes based on the gross margins and environment, (specifically, nitrous oxide emissions, nitrate leaching). The study found that they were able to reduce nitrate leaching by 7% and reduce nitrous oxide emissions by 4% when compared to current practice even without including legumes in the rotation (Reckling et al. 2015). Unfortunately, the crop rotations that were found to be the best environmentally were not the same as those which were the best economically though economic benefits of legumes were found. Zhang et al. (2019) provide further evidence that crop rotation can have a significant impact on GHG emissions with their study of differing rice crop rotations in China and measuring the emissions over three years. When comparing rotations of only rice, rice-winter wheat, and rice-winter wheat-Chinese milk vetch, results showed lower GHG emissions from the rice-Chinese milk vetch and only rice rotations; CH_4 emissions were lower by 40 and 34%

respectively. Experimenting with different rotations has the potential to contribute to reductions of GHG emissions.

Studies have found that crop rotations with legumes tend to emit less GHG and produce less nitrogen runoff when compared with cereal monocrops (Lötjönen & Ollikainen, 2017). In addition, legume inclusion in a crop rotation can increase profits provided that there is a sufficient market for the legume crop chosen, markets for legumes tend to be sufficient where livestock is produced (Lötjönen & Ollikainen, 2017).

1.2.6 Cover Crops

Cropping systems and crop rotations with cover crops have shown to be helpful in reducing greenhouse gas emissions and nitrate concentrations in the soil (Wang et al., 2022). A correlation between cover crop biomass and a reduction in N_2O emission was found and believed to be due to a reduction of denitrification occurrence resulting in decreased nitrate (Behnke & Villamil, 2019). However, not all studies have found that cover crops reduce N_2O emissions in the short term; to experience a reduction in N_2O emissions, it is recommended to not incorporate the biomass of cover crops into the soil and use a non-leguminous cover crop (Basche et al., 2014). Incorporating the biomass or crop residues causes residue decomposition and N mineralization from pre-existing soil organic matter that in turn results in more nitrate availability and increased denitrification. In addition, incorporation through shallow tillage often increases the temperature of the soil, and therefore, also increases the rate of denitrification. Another important aspect to consider is that the direct reduction in emissions measured is not the only measurement worth noting. Since cover crops have been shown to have a significant effect on reducing nitrate leaching of nitrates which would often then undergo denitrification and contribute to indirect N_2O emissions reducing leaching can have a significant impact on emission reduction (Behnke & Villamil, 2019). One study showed a reduction of 70% of leached nitrates when using a non-legume cover crop and 40% when a legume was grown compared to bare fallow over the winter (Tonitto et al., 2006). Cover crops can be referred to as agro-ecological service crops (ASC). One study involving organic vegetable farming found that cover crop or ASC introduction into a system was an important way to achieve higher crop productivity and did not have any negative impact on soil physical properties (Diacono et al., 2021). In addition, the study found that use of ASC resulted in the system that had the best energy use efficiency and carbon efficiency (Diacono et al., 2021). Some studies have found that the direct GHG emissions increased as a result of cover crop utilization however, the yield of the cash crop increased and the net GHG emissions were unchanged (Acharya et al., 2022)

Reducing Summer Fallow

Avoiding summer fallow, where no crop is planted and the soil stays bare, increases overall crop production. Continuous cropping increases plant growth in the long term and so contributes to C inputs for maintaining or enhancing the soil organic carbon (SOC). Also, the increase in crop productivity and plant residue additions to the soils feedbacks into an increased soil water storage and use by subsequent crops (Desjardins et al., 2005).

1.2.7 Seeding Technology

Variable Rate Seeding

Variable rate seeding (VRS) is a technology that can adjust the rate of seed according to variable conditions across the field terrain. This practice may be able to increase nutrient utilization efficiency and water usage efficiency, as well as possible reducing seed consumption (Sarauskis et al., 2022). Variable rate seeding shows a lower potential for GHG mitigation relative to other variable rate technologies. The likely reduction in seed used could help reduce farm costs and having ideal plant densities distributed across heterogeneous fields could help with GHG management (Balafoutis et al., 2017).

1.2.8 Harvest Technology

Crop Residue

Studies on crop residue consistently demonstrate that removal and use of crop residues for another purpose such as biofuel is detrimental to soils physical properties (Cherubin et al., 2018). In the short term, GHG emissions are reduced because plant residue does not decompose in the fields but rather is removed and processed elsewhere. However, in the long-term, there will gradually be fewer nutrients available in the soil for the next crops and more fertilizer application will likely be required, likely increasing GHG emissions (Wegner et al., 2018). Partial removal of crop residue, when quantities are high or when the parts of the residue that contains the least nutrients are easily removed, could reduce overall GHG emission. Decomposition of crop residue can contribute to CO_2 and N_2O emissions. Both organic carbon and nitrogen availabilities derived from residue decomposition and mineralization contribute to denitrification processes. Further research is needed to establish sustainable quantities of residue removal, and the conditions of crop residue removal if it is to be a viable mitigation tactic (Cherubin et al., 2018).

Yield Mapping

Data can be collected and compiled to create harvest yield maps in order to compare outputs with inputs in the farming enterprise (Pierce & Clay, 2007). This technology allows farmers to analyze the economics of their operation because they can compare how well the inputs are translating into yield across their fields. Based on this information, adjustments can be made as needed in order to increase farm efficiencies.

1.2.9 Transportation/Fuel Efficiency

There are two distinct classifications of energy use in agriculture: direct and indirect. Direct energy includes on-farm use of fossil fuels and electricity. Indirect energy includes the manufacturing of synthetic fertilizer and fabrication of farm equipment.

Controlled Traffic Farming

Controlled traffic farming (CTF) can be described as a management system used to reduce the deterioration of soil structure caused by random or unsystematic traffic of farm vehicles (i.e., RTF). CTF not only contributes to the maintenance of soil health but also helps to increase crop yields while benefiting the environment. The primary benefit of CTF is the increase in crop yields when soil compaction is reduced. A study comparing the benefits of CTF on various crop species showed the benefits from CTF were widespread and showed an increase in yield compared with RTF. This benefit was largest for forage, oats, and barley as they had the largest increases in yield (Smith et al., 2007). Li et al (2007) indicated in their controlled traffic research that mean grain yields increased by 337 kg/ha compared with wheeled plots. The largest observed increase in yield was a mean grain yield increase of 497 kg/ha in controlled traffic with zero tillage, compared with wheeled stubble mulch treatment, which was largely attributed to increased infiltration and plant available water under CTF management (Li et al, 2007). CTF may benefit the environment by reducing soil erosion and runoff because of this increased water infiltration. Due to better soil structure and improved efficiency with precision in farming practices, farmers are using fewer fossil fuels and fertilizer, which also decreases greenhouse gas emissions in the long term (Gasso, 2013). The effects on soil aeration and gas diffusivity have substantial effects on GHG release (Tullberg et al. 2018), higher oxygen diffusivity in CTF soil also increases germination rate. With increased seed germination rate and vitality, farmers are able to reduce the seeding rate which reduces inputs and costs (Gasso, 2013). This system also allows for farmers to utilize inter-row tillage and decrease use of herbicides but decrease the necessity of conventional tillage for soil structure reasons, in fact differences in soil texture across the fields diminish overtime creating more cohesion (Chamen, 2015). A study across 16 crop types over a three-year period using gas chambers to sample the soil emissions found that CTF could reduce soil N_2O and CH_4 emissions by 30-50% (Tullberg et al. 2018). The cost of converting from traditional random traffic system to controlled traffic system is one of the main challenges in adopting this technology. However, changing to CTF can often be achieved with standard equipment, it just takes creativity and strategic planning (Chamen, 2015).

1.3 Livestock Management Practices for GHGs

Livestock production practices and the resulting GHG emissions have received more attention in recent years. Cattle production emits all three of the major biogenic GHGs. Methane accounts for 44%, nitrous oxide for 29% and carbon dioxide for 7% (FAO, 2021). Within livestock systems, fossil fuel use, fertilizer use, energy that goes into pesticide production contribute to feed production and contribute to CO_2 emissions. Enteric fermentation, that occurs in the ruminants' gut and manure decay under anaerobic conditions are the main contributors to livestock CH_4 emissions (Beauchemin et al., 2019). CH_4 emissions can range from 2-12% of energy intake being converted to methane depending on many different factors and generally these methane emissions contribute to approximately 6% of anthropogenic emissions globally

(Beauchemin et al., 2019). N_2O emissions from animal agriculture are mostly from manure and manure management (Zhuang et al., 2019).

Animal productivity is a major topic to consider with respect to GHG emissions because the more efficient the production system, the less energy is wasted in the process and ultimately fewer GHG's are emitted (Capper et al., 2009). Using superior management techniques for improving animal health, nutrition and genetics contribute to lowering the intensity of methane emissions, meaning also fewer emissions per unit produced (Capper et al., 2009). However, the benefit of increasing the productivity of already high-producing livestock is less than increasing the productivity of low-producing livestock (Beauchemin et al., 2019).

1.3.1 Feeding Technology

When developing feeding strategies with a focus on reducing enteric methane emissions two types of strategies can be defined. The strategies can be classified into dietary or rumen manipulation. Dietary manipulation focusses on making the diet more digestible and higher value, while rumen manipulation has a focus on bringing in rumen environment modifiers and direct inhibitors of methanogenesis (Kebreab et al., 2021).

Diet Composition

Changing the diet composition of livestock does not only change the animal nutrition and emissions but it changes the overall farm system. If the GHG emissions are analyzed from an individual animal perspective, they will look different than if analyzed from a farm or supply chain scale (Chianese et al., 2009). Within a farm, land that was used for example for forage or pasture may be changed to production of annual crops resulting in changing emissions (Van Middelaar et al., 2013). Alternatively, the farmer could outsource the new addition to the diet and be left with excess grass biomass to sell. This shift in feed sources would imply the need to account for additional transportation and associated fuel emissions to obtain an accurate, comprehensive analysis of GHG emissions.

Physical Composition

The diet of cattle can have a significant effect on GHG emissions from enteric fermentation during digestion and from the resulting manure. As demand for beef, dairy, and animal products rises expectedly with an increasing population, dietary changes and supplementation have a great potential to lower emissions intensity (Caro et al., 2016). A grazing diet has much more fiber in it and high fiber can contribute to increased emissions, whereas a grain diet with much less fiber can contribute less emissions (Chen et al., 2020).

Grazing

Grazing cattle can help reduce GHG emissions in some scenarios as it can reduce the use of inputs that go into crop production. In addition, direct grazing can help decrease emissions that result from manure handling and storage. Studies have shown that GHG emissions and feed efficiencies also depend on the composition of the diet while in confinement feeding. If a feeding strategy can contribute to increasing productivity of livestock systems while increasing GHG emissions at a lesser rate than typical emissions per unit of production, then GHG emissions intensity decreases. In one study on dairy cows, scenarios that led to increases in milk production though supplemental feeding but also included enough grazing to sufficiently decrease inputs and energy usage had the lowest environmental impact (Aguirre-Villegas et al., 2017).

When focusing on only the enteric emissions as a function of feed intake, methanogenesis increases when dietary forage increases. Forage is high in neutral detergent fiber (NDF), and an increase of NDF in the diet can cause an increase of methane emissions per day. There is some scientific evidence to support the idea that a diet higher in grain can increase enteric methane production per day compared to a high forage diet because the livestock grow bigger and have higher intakes (Boadi et al., 2004). However, if these outcomes were to be converted to associated GHG emissions per gram of product (beef or milk) the results may be different. In another study, extended backgrounding which increased forage feeding more extensively reduced the average daily gain and so this increased the time to get to slaughter weight by 4 months which increased GHG intensity significantly (by 479 tons) (Beauchemin et al. 2011).

Grazing management can be an important tool in managing GHG emissions from pasture and rangelands. A simulation study based on the Holos model, and focused on beef cattle production found that total GHG emissions for light continuous (LC) grazing were 10.2% higher than that of the total GHG emissions for heavy continuous (HC) grazing (Alemu et al., 2017). In addition, it was found that total GHG emissions were 7.5% higher in light continuous for cow-calf pairs and moderate rotational grazing for backgrounded cattle (LCMR) than that of heavy continuous for cow-calf pairs and moderate rotational grazing for backgrounded cattle (HCMR). However, the GHG intensity [kg CO_2 equivalents (CO_2e) kg^{-1} beef] showed that when stocking rate increased the intensity decreased as the HC intensity was 9.2% lower than the LC intensity (Alemu et al., 2017). Another study on adaptive multi-paddock (AMP) grazing, a type of rotation grazing where for short time periods small paddocks are grazed with high densities of livestock and then the paddocks have long recovery periods. It was found that AMP grazing in areas with warmer soils (25°C) could be a viable strategy to increase soil consumption of CH_4 (Bharat et al., 2020). The consumption of CH_4 by soil under an AMP grazing regime was higher in all scenarios compared to continuous grazing however, under cooler conditions the grazing management strategy and temperature of soil seemed to interact to cause CO_2 emissions to differ. Under cooler conditions (5°C) the CO_2 emissions increased outweighing much of the benefit of the increased consumption of CH_4 (Bharat et al., 2020). AMP grazing can aid in increasing animal and forage productivity and has the potential to sequester more soil organic carbon (Stanley et al., 2018). There are also reports suggesting that AMP grazing can improve physical, chemical, and biological soil properties when compared to light or heavy continuous grazing options (Teague et al., 2011).

Deferred rotational grazing (DRF), a system where divided pasture units are alternately rested or "deferred" when the pastures are in critical growth periods (Schmutz, 1973), when compared to continuous grazing can reduce pasture quality and results in reduced animal performance. Conversely, DRF can increase the DM yield and therefore allow for higher stocking rates (Alemu et al., 2019).

Grain Feeding

Grain feeding can be a strategy to reduce GHG emissions intensity as well as it delivers concentrated nutrients with a lower fiber ratio and can contribute to accelerated weight gain. In one study where grain feeding was extended the cattle had less grazing and an aggressive grain finishing program, the GHG emissions intensity was reduced by 2% as the cattle produced less enteric emissions and had a shorter time to market (Beauchemin et al. 2011). Feeding a higher proportion of more digestible components to dairy cattle can also lead to production of manure that is less volatile and lead to less CH_4 emissions however N_2O emissions from the excretions increase (Caro et al., 2015).

Using some maize silage to supplement a diet of grass silage is a strategy for reducing CH_4 emissions produced through animal digestion. One study of dairy cattle showed that when observing only enteric emissions from the diet change including maize silage resulted in 12.8 kg CO_2e reduction in CH_4 emissions per ton of fat-and-protein-corrected-milk (FPCM) produced.

However, when one assesses changes at the farm scale, specifically ploughing grassland into corn production land, the study showed that it would take 44 years until the annual emission reduction would pay off emissions (913 kg CO_2e) that would occur due to the land use change (Van Middelaar et al., 2013). Another study compared dairy cows fed high maize silage (MS) diets to high grass silage (GS) diets and found that the MS diet resulted in higher dry matter intake (DMI), greater milk production and a lower methane yield (g/kg of DMI) than the cow fed the GS diet (Hammond et al., 2015). In the same study they also experimented with NDF additions to the diets, they found that adding NDF to the MS diet increased the methane yield but not for the GS diet, and in both diets, the added NDF caused decreased DMI and milk yield.

Legumes can possibly decrease methane production compared with grass due to their faster digestion; however, there are not many studies comparing legumes with forage and the effects can differ with maturity of the material. There is no conclusive evidence to say that legumes reduce enteric methane emissions (Guyader et al., 2016).

Creep feeding is a feeding strategy for calves that provides feed in a variety of possible forms including hay, silage, pasture, or most often a grain blend to the calves while they are still nursing (Hamilton, 2002). This feed is provided in a way that it is not available to the cows and the aim is to increase the growth rate during this period. Benefits of this strategy include the production of a more uniform group of calves, reduced weaning stress on the calves, young or thin mother cows are allowed more recovery, reduced feed requirements of the cows and performance maintenance or improvement of the nursing calves (Hamilton, 2002). Creep feeding with corn silage was found to help reduce the carbon footprint; the overall CO_2 emissions increased, but the gain in weaning weight was enough to offset those increased emissions (Toro-Mujica, 2021).

Macronutrient Composition

A study that modeled a diet with amended macronutrients for dairy cattle across the globe found the potential emissions reductions of enteric CH_4 was 15.7% (Caro et al., 2015). The amended diet included supplementing fat content to 6%, decreasing the amount of fiber, and keeping the gross energy intake (GEI) the same (Caro et al., 2015).

Protein

Dietary protein intake can have substantial impact on GHG emissions (Caro et al., 2016). The amount of crude protein (CP) in the diet of cattle can affect manure emissions as any excess CP in the diet in excreted as urinary urea which contributes to NH_3 emissions and can contribute to indirect N_2O emissions (Hristov et al. 2011). Reducing crude protein in pigs' diet to the minimum necessary for proper nutrition is an effective strategy in reducing ammonia emissions (Philippe & Nicks, 2015). However, there are conflicting results as to whether reduction of crude protein in the diet helps reduce other GHG emissions (Philippe & Nicks, 2015). Ammonia itself is a major pollutant of air and water, so keeping its emission to a minimum helps the environment even if it does not get converted to GHG emissions (Hristov et al. 2011). In one study, two groups of dairy cattle were fed a low CP diet and a high CP diet and compared to a control group. The low crude protein diet group was able to maintain their milk production. This outcome gave evidence that CP can be reduced without affecting production and that CP requirement may be overestimated sometimes (Lee et al., 2012).

Fats and Oils

Studies have shown that supplementing fat into the diet can reduce methanogenesis. In a meta-analysis it was demonstrated that it is mono and polyunsaturated fatty acids that are most useful for methane reduction and not saturated fatty acids. Use of up to 6% fat of dry matter diet can help increase milk production in dairy cows and decrease methane production by 15% when compared with an average diet that would normally contain 2% fat of dry matter intake. Adding more fat above this proportion tends to decrease milk production and digestion even though methanogenesis continues to decrease substantially (Patra, 2013). Grainger and Beauchemin (2011) also found that supplementing lipids at 5-8% of the dry matter intake in the diet is effective in reducing enteric methane emissions. However, they also outlined that feeding more than 10% lipids in the DMI is detrimental to digestion of fiber because it results in a shift of the rumen microbial population. In another study, canola oilseeds were fed to cattle in different feeding patterns. The cattle fed the oilseeds that backgrounding cattle were found to have reduced GHG emissions intensity by 1% while when fed to finishing cattle the intensity was 2%, and lastly, when fed to a cow-calf herd, the GHG intensity was reduced by the highest amount at 8% (Beauchemin et al., 2011). These emission reductions were found to be attributed to the higher fat content in diet and the reduction of overall dry matter intake due to higher nutrient concentration which decreased enteric CH_4 emissions. There were also lowered emissions from manure as the quantity of manure produced was reduced (Beauchemin et al., 2011). Toro-Mujica (2021) used a simulation model based off scientific literature outcomes to represent the effect of supplementation of canola oil into the diet of cattle in Chile. The variables were evaluated based on their impact on carbon footprint (CF) which considered emissions for all inputs and processes within the production cycle. It was found that a dose of canola oil of 46 g/kg DM resulted in a 2.5% decrease in carbon footprint when carbon sequestration was not considered and 2.4% when it was.

Fiber

Replacing some less digestible fiber such as that which is high in forage feed with more digestible fiber can help to reduce emissions from enteric digestions (Moraes et al., 2015). High forage diets are common in extensively managed production systems. By increasing intensity of the system through gains in efficiency of feed utilization, overall production can be increased and intensity of emissions decreased (Moraes et al., 2015).

Supplements

In general, it has been recognized that strategies which use a substrate that will divert dihydrogen in the rumen from contributing to methanogenesis are the most effective inhibitive interventions to reduce methane production. Chemical inhibitors that can reduce methane emission directly are considered a high priority as it has been seen there is a lot of potential even though the process of development, approval, and production for such supplements can be lengthy and complex (Beauchemin, 2019). One such supplement is **nitrate**, which can divert substrates contributing to methanogenesis in the rumen due to it being an alternative electron sink (Latham et al., 2016). Dietary nitrate being the preferred electron acceptor undergoes microbial reduction to dinitrogen gas or to ammonia using electrons that would contribute normally to the reduction of carbon dioxide to methane (Latham et al., 2016). Unfortunately, there are concerns about the intermediate product nitrite and its toxicity for animals as well as other nitro-compounds, including 3-nitro-1-propionate and 3-nitro-1-propanol. These compounds have been found to accumulate in cattle and cause animal poisoning (Latham et al., 2016). One way to manage this potential poisoning is to gradually adapt the cattle to the higher concentrations in their systems as there are rumen organisms that metabolize nitrite and they would slowly proliferate in response (Latham et al., 2016). Nitrate supplementation can also cause N_2O emissions that can even reduce or eliminate the methane mitigating effects and the cause is not always known (Peterson et al., 2015). An *in vitro* study has now isolated a bacterium called *Paenibacillus* 79R4 that was able to decrease nitrite accumulation and contribute to the main goal of nitrate dietary additions decreasing methane production. As an additional benefit, it was discovered during a study that this bacterium also acts as an antimicrobial agent against pathogens that can occur in the rumen as well which is an added value to its potential use as a probiotic for cattle and other ruminants (Latham et al., 2018). Ideally, researchers will eventually be able to develop supplements that reduce methanogenesis and make fermentation end products that are beneficial to productivity, as the ruminants would be able to absorb and utilize the products. However, a consistent solution like this has not been discovered (Ungerfeld, 2018).

Algae has been identified as having potential to reduce methane emissions when feed to ruminants as a supplement due to naturally occurring anti-methanogenic compounds. *Asparagopsis taxisformis* has bromoform and dibromochloromethane, bioactive compounds that inhibit cobamide-dependent methanogenesis (Kinley et al., 2016). One in vitro research study that supplemented 20g kg^{-1} of forage *Asparagopsis taxisformis* demonstrated an almost complete elimination of methanogenesis and there was zero detectable hindrance to digestion of forage (Kinley et al., 2016). Another study found that feeding this same algae species at a rate of 3% of organic matter intake reduced enteric methane emissions by up to 80% (Li et al., 2018). Another study found that these algae reduced emissions intensity in dairy cows by 67% and reduced emissions of beef cattle by 98% (Kebreab et al., 2021) analysis of the production and transport emissions would have to be conducted and factored in (Kinley et al., 2016). A barrier to the use of this supplement is the challenge of mass production of this specific species.

Phytocompounds from plants have been studied for their effects on methanogenesis and at least 25 have been found to have potential value, but they need further study (Beauchemin, 2019). Tannins as a supplement can have highly variable results depending on many variable characteristics of the product such as the type, source, and molecular weight (Jayanegara et al., 2012). Generally, when considering many experiments on tannin supplementation, the more tannin that is fed, the larger the decrease in enteric methane emission (Jayanegara et al., 2012). However, reliable effects can only be expected when dry matter intake become greater than 20g kg^{-1} and currently when this strategy is used this threshold is not often exceeded. A meta-analysis involving several in vivo studies showed a reduction of 0.109 L CH_4 kg^{-1} of dry matter (r^2= 0.47). Unfortunately, evidence also indicates that some of this reduction is due to a reduction in nutrient digestibility and a concomitant decline in dry matter intake (Jayanegara et al., 2012).

Ionophores are supplements fed to cattle to help production efficiencies, they are described as antimicrobials (Callaway et al., 2013). Monensin is an ionophore that has been found to reduce DMI in cattle from dairy production and beef steer without affecting production in dairy cows. Monensin caused a direct significant reduction in methane emitted by beef steers (19g day^{-1}), but this did not translate into the dairy cows (6g day^{-1}) (Callaway et al., 2013). However, when the dose of monensin is adjusted for DMI and the difference of dose (the doses were often lower in dairy cows) then monensin had similar effects on both groups suggesting that if given at a higher rate to dairy cows to be in proportion with their DMI, it could reduce methane emissions (Callaway et al., 2013). Toro-Mujica (2021)'s study simulated a scenario of feeding monensin at 30 mg/kg DM. The study found that this supplementation resulted in a 1.4% decrease in CF when carbon sequestration changes were not considered and 1.3% when they were.

Future Technology

Vaccines

A vaccine as a strategy for reducing methane emissions is thought to have great potential, but effects on productivity and animal health would have to be considered. The concept of a vaccine for methanogenesis reduction is based on a theory that the active ingredients would cause the immune system to begin producing antibodies in the ruminant's saliva, which would then enter the rumen and suppress the growth methanogens (Subharat et al., 2016). Research on a vaccine targeting methanogenesis production is in relatively early stages and there are various aspects that are being explored. The selection of an antigen is key for the evolution of this strategy. One strategy that has been explored is whole cell additions of different species of *Archaea* that may target methanogens. Wright et al. (2004) derived a mix of three methanogens and seven methanogens that aimed to induce an immune response in sheep which would produce antibodies against methanogens. They found that the 3-methanogen mix resulted in a significant 7.7% reduction in methane produced after being corrected to exclude the effects of DMI (Wright et al., 2004). Another strategy being researched is use of cell components such as proteins rather than whole cells. Subharat et al. (2016) used glycosyl transferase (GT2) in their vaccine and measured the levels of antibody found in the saliva and rumen post vaccination. Their results indicated that though the levels they reached were likely too low, an effective vaccine could theoretically be developed. An effective vaccine would have sufficient levels of antibodies in the saliva and be able to survive in the rumen and target methanogens effectively. Other important aspects being considered are the type of adjuvant used in the vaccine and its effectiveness in carrying the antigens for successful performance (Baca-González et al., 2020). In addition, the timing of the booster shot can be important in achieving effectiveness (Baca-González et al., 2020).

1.3.2 Manure Management

Manure is a valuable resource as it contains nutrients that can be utilized to fertilize crops. Manure also has high potential to emit GHGs. In addition to GHGs, manure can release ammonia (NH_3) and ammonium (NH_4^+) which can be biologically-transformed to GHGs through the nitrogen cycle. Volatilization of NH_4^+ is considered the most substantial mode of N loss (Montes et al., 2013). The link between volatilization of NH_3 and N_2O emissions is complicated by the fact that if emissions of NH_3 are reduced the higher presence of N in the manure may in turn inflate N_2O emissions later (Montes et al., 2013). How management practices impact this trade off between NH_3 volatilization and N_2O emissions in manured fields deserves further investigation.

Land Application of Animal Manure

The most common method of disposal for manure is land application as this enables cycling and distribution of nutrients back to the soil. In fact, 48.4% of Canadian farms spread manure on their land in 2010 according to the Census of Agriculture (Dorff and Beaulieu, 2015). However, land application of manure can cause accumulation of excess of nutrients in the soil, it uses fossil fuels, and the GHG emissions resulting can be significant (Aguirre et al., 2014).

The timing can be important in terms of emissions; if land application is avoided in the fall or winter loss of nitrogen due to wet conditions in the spring can be avoided, as well as potential continuation of denitrification over the winter (He et al., 2020). Furthermore, adding nitrogen to the soil when active nutrient uptake by plants is not occurring leaves potential for loss to the environment in various forms (He et al., 2020). Also avoiding land application during times when the weather conditions are hot and windy or when rain is expected can also reduce N_2O emissions (Rochette et al., 2004; He et al., 2020). After application, incorporating the manure right away increases N_2O emissions, but can decrease NH_3 emissions (Aquirre-Villegas and Larson, 2017).

The size of the farm can affect the GHG emissions that come from land application, smaller farms have a greater proportion of emission coming from land application as they tend to apply more often, and manure spends less time in storage (Aquirre-Villegas and Larson, 2017). Larger farms have a larger proportion of emissions that come from manure storage because they store manure for longer and typically apply only once a year (Aquirre-Villegas and Larson, 2017). Manure storage length and seasonal changes in temperatures have been found to be important considerations, even short periods of storage in summer can cause significant emissions and while under winter conditions emissions are minimal (Cardenas et al., 2021). Cardenas et al. (2021) suggest that focusing on shorter storage time in summer and allowing longer storage in winter could be a beneficial management practice.

Storage of Manure

Aerobic Conditions

Oxygen conditions greatly influence N_2O production, rapid nitrification can occur under aerobic conditions and denitrification occurs under anaerobic conditions (Bremner and Blackmer, 1978). Anaerobic conditions inhibit nitrification, and this prevents NO_3^- formation which limits losses of N_2O by denitrification (Chadwick, 2005). The plentiful oxygen supply in scenarios such as when composting leads to increased GHG emissions (Philippe & Nicks, 2015). Anaerobic conditions during solid storage keep the reaction rates low and help eliminate some sources of emissions; although strong anaerobic conditions can counteract by increasing methane emissions (Philippe & Nicks, 2015). Compacted stored dry manure and covering help to reduce N_2O emissions and nitrogen loss from the manure as NH_3 by reducing aeration and inducing anaerobic conditions (Chadwick, 2005). Anaerobic conditions also favor CH_4 production. High soil moisture can increase CH_4 emissions because it decreases oxygen concentrations as the manure carbon decays, and consequently, the microbes experience a lack of oxygen leading them to produce CH_4 instead of CO_2 (Government of Canada, 2020).

Temperature

In general, higher CH_4 emissions have been reported from manure stored at higher temperatures (Im et al., 2020). Storage in cooler temperature setting can reduce microbial activity (AESA, 2004). In one experiment when CH_4 emissions manure sludge were monitored for a period of 80 days at differing temperatures, the highest amount of emissions (375.1 kg CO_2 eq./ton volatile solids (VS) at the highest temperature tested (35°C) and these emissions more than halved when the temperature was reduced to less than or equal to 20°C (Im et al., 2020). Im et al. (2020) articulated that methanogenic bacteria are inhibited by lower temperature and that the energy required to cool manure could be easily offset by the reduction in emissions. In another study, emissions of methane increase significantly at temperatures 20°C and above, at 20°C CH_4 emissions went from 0.01 to 0.10 g C h^{-1} kg^{-1} VS (Sommer et al., 2007). In addition, an increase in temperature from 10-15°C increased the amount of organic N able to be transformed from very little to 80% (Sommer et al., 2007). In another study of pig manure, emissions in warm climatic conditions were significantly greater than in cold conditions (Amon et al., 2007); the authors found that CH_4 emissions were 30-43% higher and N_2O emissions were 58-80% higher in warm conditions. The difference in NH_3 emissions were less substantial ranging from 0-20% higher in warm conditions (Amon et al., 2007). Cardenas et al., (2021) found that CH_4 emissions were higher under summer temperatures than winter temperatures. In addition, they found that manure stored at winter temperatures did not continue to produce CH_4 after the temperature returned to favourable conditions (20°C). This was an unexpected outcome and may suggest that a cold period of storage could significantly reduce manure storage CH_4 emissions, and hence, this can be a beneficial management practice.

Moisture Content

Moisture in stored manure can increase N_2O emissions (AESA, 2004). Solid manure stored in piles most often can have more aeration that liquid manure which is stored in pits or tanks which leads to anaerobic conditions and this causes an increase in CH_4 emissions (Aquirre-Villegas and Larson, 2017). Cardenas et al., (2021) found that diluting manure with more water and having less dry matter content proportionally caused an increase in CH_4 emissions.

Other Interventions

Coverings

Covering manure slurry tanks has been found to be useful in reducing CH_4 and NH_3 emissions; however, it may cause N_2O emissions to increase but this increase does not outweigh the other reductions, so it can still be a useful management strategy (Clemens et al., 2006). It has also been found that covering of solid manure piles can reduce GHG and NH_3 emissions as well (Hansen et al., 2006). Hansen et al. (2006) found that covering a manure pile with an airtight covering reduced NH_3, N_2O, and CH_4 by 12%, 99%, and 88%, respectively, though this was an unreplicated study.

During storage if a crust develops on the surface on the manure, this has been found to aid in the reduction of CH_4 and NH_3 emissions; however, it increases emissions of N_2O (Aquirre-Villegas and Larson, 2017).

Frequent Manure Removal

Frequent removal of manure from housing has been found to help reduce NH_3 losses (Ivanova-Peneva et al., 2008) and CH_4 and N_2O emissions (Amon et al., 2007; Philippe & Nicks, 2015). Frequent slurry channel flushing also can help reduce CH_4 and N_2O emissions for pig and cattle manure storage; one study showed reductions of 21% for pig slurry and 35% for cattle slurry when compared to only flushing once a month for the cattle and bi-weekly for the pigs. (Sommer et al., 2004). Philippe & Nicks (2015) compiled the results from six different studies and they showed that bedded floors compared to slatted floors also have an increase in emissions, in particular nitrous oxide (Philippe & Nicks, 2015).

Composting

Composting manure involves allowing the manure to decompose at an accelerated rate causing a transition to a more stable form. Use of composting for manure solids can reduce the volume of excrement by up to 50% Therefore, when applying composted manure to land, transportation and application costs can be reduced, and perhaps, fossil fuels usage is also decreased (Manitoba Agriculture, 2008). Composting also has the benefit of reducing the risk of pathogens, and its application instead of synthetic fertilizer improves soil structure (Onwosi et al., 2017). A study also found that composting followed by compost land application instead of using synthetic fertilizer can overall reduce GHG emissions (Yaman, 2020).

Acidification

Acidification of manure play a significant role in GHG emission. The type of acid used has been found to affect the effectiveness of mitigation, organic acids resulted in less of a decrease in emissions than mineral acids and acidic salts (Cao et al., 2020).

Adding acids to manure in order to lower the pH prevents bacteria from producing urease resulting in conservation of NH_4^+, and effectively lowers NH_3 emissions (Fangueiro et al., 2015; Mohankumar Sajeev et al., 2018). The addition of acids can occur during housing or storage, it may even begin as early as feeding the livestock (Mohankumar Sajeev et al., 2018). The effectiveness of acidification on N_2O emissions reduction has been varied (Fangueiro et al., 2015). In a study on acidified manure slurry using sulphuric acid digestion, the emissions of N_2O were halved, the total N lost as N_2O was reduced from 0.10% to 0.5% with an acidification treatment to pH 5.5 (Owusu-Twum et al., 2017). In another study using lactic acid to acidify manure slurry, N_2O emissions were reduced by 90% but conversely, the treatment using nitric acid led to a substantial increase in N_2O emissions (Berg et al., 2006). Wang et al. (2014) found that a pH of 5.5 reduced CH_4 emissions by 80.8%; however, an increase of 11 324% in hydrogen sulphide (H_2S) resulted. When a pH of 6.5 was used, CH_4 emissions were reduced by 31.2% and H_2S emissions were not significantly affected (Wang et al., 2014).

When liquid dairy manure was acidified to a pH of 6-6.5 using sulfuric acid (H_2SO_4) CH_4 and NH_3 emissions were reduced by >87% and >40% respectively (Sokolov et al., 2019). This particular study also put the cost of using the H_2SO_4 as \$6.55-9.60 cow^{-1} (Sokolov et al., 2019). Complete removal of manure in a storage space has been shown to help reduce emissions as it eliminates inoculum being spread to the fresh manure. However, this complete removal is often unattainable on large farms (Ngwabie et al., 2016). Due to infeasibility of complete inoculum removal a study was done to observe the effects of acidifying the inoculum (Sokolov et al., 2020). The storage units in the experiment were all 20% inoculum and 80% fresh manure, there were some that were a control group left untreated, some were acidified 1 year before, and some newly acidified. (Sokolov et al., 2020). When compared to the control, the newly acidified and previously acidified inoculum reduced CH_4 emissions by 77 and 38%, respectively (Sokolov et al., 2020). In addition, NH_3 and N_2O emissions were reduced by 33 and 73% for newly acidified inoculum and 23 and 50% for previously inoculated compared to the control (Sokolov et al., 2020). Excess acidification of manure can be detrimental in that it can cause an increase in N_2O emissions (Cao et al., 2020). In this experiment a pH of 5.0 was found to increase emissions during composting by 18.6% (Cao et al., 2020). However, when the pH was reduced only to 6, then emissions were reduced during composting, N_2O by 17.6%, CH_4 by 20%, and a total reduction of global warming potential reduction was found to be 9.6% (Cao et al., 2020).

The acidified manure can still be used as a fertilizer. When manure is acidified it increases the amount of soluble N and P available in the soil, this is linked to the fact that less nutrients are being released as GHG's, which was initially discussed (Regueiro et al., 2020). Acidification of the manure causes a reduction of NH_3 volatilization and there is more NH_4^+ in the soil that is plant available. In addition, more P is dissolved in the soil water at a higher pH more available P for plant for uptake (Regueiro et al., 2020). When examining acidified manure combined with a nitrification inhibitor, a conclusion was reached that this combination could be used as a starter fertilizer for maize (Regueiro et al., 2020). Available uses for the acidified product supports sustainability of the practice.

Anaerobic digestion

Generating biogas as a product of anaerobic digestion has potential as a GHG mitigation strategy. Anaerobic digestion involves bacteria breaking down the manure when no oxygen is available (Holly et al. 2017). A biogas made up of primarily CH_4 is produced and any other components are filtered out and the methane can be used as an energy source. The more easily the organic matter in the manure can be broken down, the more biogas production occurs. After digestion, solids can be separated and repurposed as livestock bedding or sold for another use and the digested liquid can be used as a fertilizer (EPA, 2020). Studies can be difficult to compare due to differing measurements. A study by Aguirre et al. (2014) compared anaerobic digestion of dairy cattle manure (AD), AD coupled with solid-liquid separation (AD + SLS), and SLS alone to direct land application. Their results showed a decrease of global warming potential in every case, AD had the highest reduction of 48%, AD + SLS at 47%, and SLS at 19%. However, the study also considered depletion of fossil fuels (DFF), ammonia emissions and nutrient balances. For AD, DFF was reduced by 43%, but ammonia emissions increased by 40%. For AD + SLS, DFF reduced by 40%, but ammonia emissions increased by 44%, and lastly SLS reduced DFF by 13%, but ammonia emissions increased by 2%. When focusing on nutrient availability, SLS came out on top as nitrogen availability stays the same and the other two treatment types reduce the nutrient availability although injection of the manure shortly upon application has been proposed as a way to manage this issue (Aguirre et al., 2014). Another study demonstrated that AD was not economically feasible for farms with fewer than 400 cows, and when compared with low prices of natural gas, it can even be an uncompetitive option for farms with 1000 cows (Faulhaber et al. 2012). The price of AD technology is high and there are high maintenance costs as well (Aguirre-Villegas et al., 2017).

Solid Liquid Separation

Solid liquid separation (SLS) is a management practice in which the solids in the manure are separated from the liquids. The solid fraction is then stored separately and often has increased aeration which lowers the potential for CH_4 production (Holly et al., 2017). Separation systems are considered to be an affordable option to mitigate emissions while some other are often considered too expensive to employ. It also is often easily implemented into a farming system being that it is quite simple and has low attention requirements.

1.3.3 Productive and Efficient Herd

There are many factors that can contribute to the efficiency of a herd with ramifications on the GHG emissions intensity of livestock production. Zhuang et al. (2019) suggest that improving herd efficiencies, productivity and structure while limiting livestock population growth could be effective in managing GHG emissions. Increasing the number of calves weaned by taking steps to ensure survival can increase beef production, more animals increase the total GHG emissions, but overall, the emission intensity can be decreased. One study showed this strategy to reduce GHG emission intensity by 4% (Beauchemin et al., 2011). The age of slaughter is an important factor that contribute to the energy efficiency and productiveness of a herd because the muscle to bone and muscle to fat ratios change over time on average, they both increase with time (Marple, 2003). Increasing longevity of cattle has shown to have some impact on emission reduction as well. In one study, increasing longevity by a year allowed for more offspring and reduced GHG emissions intensity by 1% (Beauchemin et al., 2011).

Stocking Rate

Stocking rate is a term used to refer to the number of animals on a specified area of land for a specified period of time and is numerical animal units per unit of land (Oklahoma State University, 2017). Smith et al. (2016) found that the lower stocking rates resulted in the lowest GHG emissions and the highest economic returns. This was due to not increasing fertilizer use in order to increase stocking rate. When fertilizer rates were increased, GHG emissions and economic returns decreased along with GHG efficiency, so there were greater average emissions per cash return on each cow (Smith et al., 2016). One study evaluated variables based on their impact CF which considered emissions for all inputs and processes within the production cycle (Toro-Mujica, 2021). By using this framework of production, the overall impact can be assessed more easily. For example, if the overall CO_2 emissions increased, but the amount of product produced increased more than enough to offset these emissions increases, then this shift is considered by the CF. Similar to Smith et al. (2016), Toro-Mujica (2021) found that an increased stocking rate could increase CF if fertilizer or supplementation was not increased accordingly. This is because the grazing pressure would increase and less material would be available to add to carbon sequestration and emissions mitigation. The same study also modelled scenarios that did not consider soil carbon sequestration and these scenarios output did not show clear trends affecting CF, but rather were just dependent on the initial stocking rates.

Breeding Technology

Mitigating GHG emissions by using selective breeding and genetic selection is a valid strategy. Studies have shown two viable strategies to reduce emissions: selecting and breeding more efficient cows, and specifically selecting for decreased methane production per day (Pickering et al., 2015). A review of many experiments found a decrease of 0.13 g kg^{-1} DMI and 0.29 g day^{-1} as the overall emission measurement for sheep and for cattle 0.19 g kg^{-1} DMI and 0.40 g day^{-1} (Pickering et al., 2015). When it comes to directly selecting for lower CH_4 producing individual cows, there is some controversy on phenotype selection as emissions often are tied to diet composition and further research is needed (González-Recio et al, 2020). Correlation between selecting for lower methane emitting cows and the resulting productivity of the animals could result in productivity suffering, so selection of these traits could cause the benefits to be negated (Capper et al., 2009). One study on sheep found that the animals selected for lower emissions in fact had decreased ability to digest feed and therefore reduced feed efficiency (Løvendahl et al., 2018). Even though these reports provide some initial evidence of how breeding can help to decrease GHG emissions, there is a clear paucity of studies focusing on breeding technology for emissions reduction. Some of the knowledge gaps include aspects of examination and documentation to specify feed intake. Also, most studies, only assess one specific trait, or they only analyze the improvements for one portion of the chain of production (Barwick et al., 2019). Selection of livestock traits can affect GHG emissions differently depending on carbon pricing and the cost of feed (Barwick et al., 2019).

1.3.4 Economics

One study in Europe modelled implementing a tax system on N fertilizer in order to see the effects on increase use efficiency (Meyer-Aurich et al, 2020). The study found that moderate tax on N fertilizer, ranging from 10-100% of the cost of N fertilizer, were effective in reducing emissions and application volume for rye, barley, or canola when costs were at or below 100 €/t CO2eq (Meyer-Aurich et al, 2020). The effect of a tax was not effective for wheat production because of the direct connection of N fertilizer to wheat quality which directly effects wheat prices (Meyer-Aurich et al, 2020).

Conclusion

The BMPs can have substantial impacts on GHG emissions and are vital in the efforts to reduce agriculture environmental impact. There are many BMPs that have been consistent in aiding reduction of GHG emissions. The broader themes surround the aims of increasing fertilizer use efficiency whether that be inorganic or perhaps a manure application. Variable rate fertilizer application, soil testing to prescribe fertilizer addition, ensure nutrient concentrations prior to application, utilization of enhanced efficiency fertilizers, and improving soil health through controlled traffic farming, and reduced tillage are some important strategies. Livestock production employs a set of strategies to reduce emissions as well. Many of the BMPs are aimed at increasing efficiency. This can take the shape of efficiency of feed conversion, of reproduction, or of energy use. Utilizing the best quality feed and supplements can enhance nutrient absorption and production, and therefore, GHG emission intensity. However, there are robust strategies that focus more on dealing with waste management options in livestock production. Manure handling and filtration of gases are evolving strategies to reduce intensity of emissions as well.

Knowledge gaps in the literature include developing full life cycle assessments and considering fuel use and energy used for production of agricultural inputs. It becomes self-evident that when one does not consider every associated emission, the complete view of the impacts cannot be obtained and analyzed. Having different studies using different methodology to analyze emissions with different definitions of what needs to be accounted for as GHG also makes the outcomes of the studies difficult to compare and integrate. Standardization of quantification strategies could be of benefit so that multiple studies could be compared and contrasted more easily. In addition, the social and economic analyses are often left out without integration together with environmental assessments. Future opportunities for new studies are immense. Many further studies to document specific practices in the Canadian prairies would be helpful as climate and soil conditions vary greatly and have significant impact on outcomes. This is a major challenge ripe for scientists to engage and discover.

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CHAPTER 2: Cropping Systems Scenarios and Considerations

2.1 Introduction

As the human population increases, the demands on farmland and the pressure to increase agricultural outputs rises. Ensuring farming production practices are sustainable is an important part of the missions to continue feeding the world. Sustainable farming practices can help to ensure that the land is taken care of and GHG emissions are kept as low as possible. Compiling as much knowledge as possible about sustainable farming practices is very important to help inform producers and aid the process of practice implementation. The more evidence that can be provided to farmers about the outcomes and implementations of BMP's to reduce risk and uncertainty the more likely proper implementation will occur (Trujillo-Barrera, 2016). Many beneficial management practices still require further study. Modeling many land management options and comparing their efficacy on GHG emissions reduction can contribute to the knowledge base surrounding sustainable farming practices.

Fertilizers are added to the soil to supplement the nutrients that plants need to grow. Supplementation of nutrients to the soil has substantially increased production capacity (Melillo, 2012). Nitrogen specifically is often the most limiting nutrient in soil (AAFC, 2008). However, when nutrients are supplemented to the soil, this can also increase the amount of nutrients lost to the atmosphere. Fertilizer application in cropland is one on the largest contributors to GHG emissions (Menegat et al., 2022). Running simulations of differing scenarios of fertilizer applications can help to quantify the differences in emissions across management practices and possibly contribute to development of a cost-benefit analysis.

Tillage has been found to have a significant impact on GHG emissions from the soil for several reasons. A no-till or reduced tillage strategy can result in a reduction in fuel consumption which directly contributes to CO_2 emissions, and crop residue retention can lead to higher stable

C and N in the top soil which prevents these nutrients from cycling through to the atmosphere (Stosic et al., 2021). A conventional tillage regime conversely increases fuel consumption and can encourage volatilization of N and C in the soil (Stosic et al., 2021).

Crop rotation can contribute to the sustainability of farm by affecting the accumulation of soil organic matter and the crop yield (Yang et al., 2023). Crop rotation can also contribute to lowering GHG emissions and increasing yields which reduces emissions intensity (Benke et al., 2018). Usually, the benefits come from diversifying the existing crop rotation by planting different crops from years to year and avoiding planting the same crop year after year (Xiao et al., 2022). Another strategy found often to reduce GHG emissions in the additions of legumes to a crop rotation as it can help to reduce fertilizer application while also providing diversity (Lötjönen & Ollikainen, 2017).

Legumes are commonly used as cover crops as well due to their ability to fix nitrogen and provide nutrients to the following crop (Kandel et al., 2018). Cover crops are crops grown to cover the soil instead of alternatively leaving the soil bare and exposed in the off season or during a fallow period (Morrison and Lawley, 2021). Keeping the soil covered protects the soil from erosion, increases food availability for soil microbes, and the plants fix carbon and collect solar energy that incorporate into the soil which builds soil organic matter (Morrison and Lawley, 2021).

The objectives for this area of focus are to identify existing BMPs aligned with GHG mitigation aims within farming systems relevant to land management on the Canadian Prairies and to identify knowledge gaps of BMP and GHG mitigation as well as future recommendations in agricultural sustainability.

We hypothesize that using less nitrogen fertilizer will lead to a reduction in GHG emissions and that no-till will result in the least GHG emissions when compared to reduced and intensive tillage. We also hypothesize that adding legumes and diversifying crop rotations will lead to a reduction in emissions. Our objectives are to compare GHG emissions data to identify BMP that have that most potential to reduce emissions, and generally to provide more knowledge and insight of the sustainability and the GHG emissions of agricultural land management practices.

2.2 Methods

2.2.1 Holos Model

The modelling software application Holos was employed in this study. The Holos model was developed by Agriculture and Agri-Food Canada (AAFC) with the goal of estimating greenhouse gas emissions that occur as an outcome of Canadian farming systems. Holos is based on individual farms that estimate GHG emissions based on model-defined information and user-defined settings. The model's defined information includes country-specific emission factors and algorithms as well as climate and soil data which varies among defined ecoregions within the model. User-defined inputs are anything the user can define using the capabilities of the model. Possible inputs a user could choose to define include fertilizer rates, tillage intensity, crop species, crop rotations, livestock feed, livestock housing type, manure handling system and storage and others. The output from the Holos model gives GHG emissions output data in different categories. These categories are: enteric CH_4, manure CH_4, direct N_2O, indirect N_2O, energy CO_2, land use change CO_2, upstream CO_2, and a subtotal of all the categories in CO_2e. CO_2e is an abbreviation for carbon dioxide equivalent which means the number of metric tons of CO_2 emissions that would have the same global warming potential as one metric ton of another greenhouse gas; to calculate CO_2e you would multiply the amount in tonnes of the gas you are looking to convert by the GWP of that gas (CFR, 2023). The enteric CH_4 category includes any methane emissions that come from ruminant digestion. Manure CH_4 includes any methane emissions that result from manure handling or storage. Direct N_2O includes the N_2O emissions that come directly from soil at the sites where fertilizers are applied or crops are seeded. (Fu et al., 2018). Indirect N_2O includes N_2O emissions associated with leaching and runoff and which results in emission from places such as ditches and streams and can also include emissions from manure and residue (Fu et al., 2018). The Energy CO_2 reporting figure when referring to livestock scenarios includes the energy required for manure spreading on fields, and any emissions emitted from housing for a group of animals (eg. electricity, heating and gas). The energy CO_2 figure for field scenarios includes energy involved in fuel usage, herbicide usage, fertilizer conversion for N and P, and any energy for irrigation (Holos Algorithm, 2022). Land use change include CO_2 emissions that occur when land is converted from grassland or perennial forage to arable land or vice versa (Kätterer et al., 2008) Upstream CO_2 includes estimates of emissions from the productions of inputs such as fuels, fertilizer and herbicides, however, this figure is not included in the subtotal as they are produced off farm.

2.2.2 Model Scenarios

Holos modelling software was utilized to compare the various scenarios and to generate modelled data for yield and GHG emissions. The emissions are reported in units of kg CO_2e. Some general farm characteristics were set constant across each scenario. A farm size of 1400 acres was used for cropping system scenarios as this is a calculated average grain farm size across the Canadian Prairies including Alberta, Saskatchewan, and Manitoba (Statistics Canada, 2017). The sample area for farm locations included three provinces: Alberta, Saskatchewan, and

Manitoba. Each scenario was carried out in multi-year mode, but this only affects carbon modelling as the emissions provided by the detailed emissions report only summarize the emissions for the latest year in the model run. Currently the model does not allow changing of the year for the detailed emissions output. In summary, our data covers multiple provinces, and soil orders but only one year. We chose soil orders that were available in all three provinces to keep them constant across the provinces and to be able to observe differences, if any.

2.2.3 Fertilizer and Tillage

The locations that the modelling software uses are sites across the Canadian prairies; specifically the provinces of Alberta, Saskatchewan and Manitoba. There are areas designated as ecoregions within the model that have differing soil orders and climate data. Ecoregions were picked based on the criteria for each process being modelled in order to have enough locations modelled that fit all of the defining characteristics being controlled for such as soil order, and province. All regions that fit the necessary characteristics were identified, then the regions to be utilized were selected randomly from the larger group. More specifically the soil types used were: Black Chernozem, Dark Grey Chernozem, Gray Luvisol, Eutric Brunisol, Regosol, and Humic Gleysol. These were chosen after surveying the prairie provinces and finding soil orders that were abundant in ecoregions across all 3 prairie provinces. Choosing the soil orders in this way allows comparison across the different provinces while keeping soil order as a constant.

The Holos model uses emission factors adjusted for variations in climatic and soil conditions across Canada, which are drawn from a database of ecodistricts, with soil information obtained from the Canadian Soil Information System National Ecological Framework (Marshall et al. 1999). The model farm default for many scenarios was located in ecodistrict 727008 (i.e., within the Subhumid Prairies ecozone), and the soil was a dark gray Chernozem of fine soil texture, it was well drained, and managed using reduced tillage practices. The duration of the growing season utilized was May to October which is the typical length across the Canadian prairies.

When modelling scenarios pertaining to fertilizer input, the Alberta Fertilizer guide was consulted and the conservative, moderate, and high input levels were based on the lowest, mid, and highest numbers that define the given ranges of fertilizer recommended for each crop and soil (Alberta Agriculture, Food and Rural Development, 2004). This guide gives recommendations in nutrients per acre (N and P_2O_5) and need to be converted to urea and mono-ammonium phosphate (MAP) which were chosen due to being the most common fertilizer sources on the Canadian Prairies. To calculate the rate for each input the rate had to be cross-multiplied by the N concentration. The fertilizer compositions are: Urea: 46-0-0 and MAP: 11-52-0

The formulas used to calculate urea and MAP rates were as follows:

Urea= [(N*100)/46] – (0.1*MAP)

MAP= (P*100)/52

These values were then converted to kg/ha by multiplying by 1.121.

The fertilizer recommendation was chosen according to the soil classification provided in each region by Holos.

Alberta Farm Fertilizer Information and Recommendation Manager (AFFIRM) (version R) was used to obtain crop yield estimates for differing soil regions and the conservative, moderate, and high fertilizer regime as well and the differing tillage regimes. This program can be found at https://mezbahu.shinyapps.io/AFFIRM_R_version_yield_response_nitrogen/. It is a nitrogen sub-model of AFFIRM v3.0 where you can run scenarios and get an idea of output without requiring very specific input as in the entire AFFIRM v3.0 which requires more details and soil sampling tests. Brown, and Black soil classifications (or Soil Zones in the application) were tested and the program output is a chart that shows the yield for each additional increment of nitrogen fertilizer. Organic matter changed automatically along with the soil order. The other settings included were crop species which was changed to either canola or wheat, the nitrogen fertilizer product used was urea, the fertilizer application time was spring, and placement was banded, others were left as default (i.e., soil texture: medium, spring soil moisture: optimum, soil test nitrogen: 35.7 lb N/ac, estimated nitrogen release from mineralization over the growing season). The crop yield was recorded for each soil order and corresponding fertilizer scenario that was defined by conservative, moderate and high rates. This AFFIRM model did not allow for change of tillage type and assessment of tillage practices on yield.

The crop rotation scenarios were carried out in 15 replicates each of two soil Great Groups: Black, and Brown. The size of the fields used in the crop rotation was 283 ha, two fields equal 567 ha total which is the average farm size in Canada (Statistics Canada, 2017). No tillage was the tillage regime utilized and the fertilizer inputs were not specified.

2.2.4 Crop Rotation

When choosing crop rotations to compare, crop diversity, length of rotation, and use of perennial crops were all focuses. The crop rotations chosen to model are based on realistic rotations commonly used in Canada according to statistics Canada (Statistics Canada, 2021b). In addition, multiple options within each scenario were specifically included to assess model features currently provided by Holos as well as to represent pertinent options to the Canadian Prairies. Some crop options such as Faba Beans may not be available within Holos and so could not be modelled. The possibilities of farming scenarios are nearly infinite, but within the Holos model, only some of these combinations and options can be reasonably represented. For instance, preliminary results of crop rotation scenarios showed that within the Holos model, GHG emissions are unaffected by changes in the order of crops within a rotation. For example, a canola-wheat-field pea rotation and a canola-field pea-wheat rotation would result in the same model GHG output in the same year and ecoregion. Therefore, further evaluation of alternative crop sequences was precluded.

To attain a baseline of the average emissions from each crop species 30 replicates of 283 ha fields for each crop were run with Alberta fertilizer recommendations for Black Chernozem soil types. 283 ha is 700 ac which is half of the most statistically common farm size. Only one soil type was used here as there were not soil specific recommendations available for every crop.

2.2.5 Cover Crops

A recently conducted survey by Morrison and Lawley (2021) strongly influenced the methodology of cover crop scenarios in our study. The most common crops that preceded a cover crop were barley (23%), wheat (22%), oats (21%), field peas (13%), and canola (12%) so these were the crops used to seed a cover crop. The most common cover crops used were clover (57%), oats (52%), peas (41%), hairy vetch (37%), radish (36%) (Morrison and Lawley, 2021).

2.2.6 Output Analysis and Statistics

This modelling experiment was a completely randomized block design. The total CO_2e were used to do an overall comparison of differences in emissions between the three tillage options and three fertilizer rates. The independent variables in the model were fertilizer rate and tillage options. The GHG emissions (total CO_2e) was the dependent variable for this analysis. The soil classification was considered as a blocking factor; however, the province where the ecoregions were found was not included as a blocking factor as we inferred that climate was associated with the different soil classes.

The application R was used to carry out the statistical analysis. First prior to statistical tests a Shapiro-Wilk test was carried out to check for normality. The null hypothesis that the data was considered normally distributed was rejected at alpha critical level of 0.05 (p-value $\leq$ 0.001), therefore a boxplot transformation. Another Shapiro-Wilk test showed that the boxplot-transformed data still did not conform to normal distribution; however, it was much more normally distributes (p-value = 0.003). This was the closest to normal that transformations could get the data to. The non-normal data distributions are common for GHG emissions they can follow a logarithm distribution. Subsequently, we carried on to observe the outcome of a statistical analysis and planned to check the normality of the residual of the statistical model. An analysis of variance (ANOVA) was the test method carried out to observe differences among comparisons in the study ($\alpha = 0.05$). The ANOVA yielded significant results, so a Tukey HSD post-hoc test was carried out. Least square means were also run on the data. A plot of the residuals was made to examine the distribution and if there was any skew to the data. The data looked well distributed as it was equally distributed on both sides of the line and left to right on the plot. A QQ-plot was also produced and the line was adequately straight from the bottom left corner to the top right other than some outliers which would overall indicate most of the data followed normality.

2.3 Results

2.3.1 Fertilizer Rate

The Holos model outputs showed a pattern of GHG emissions increasing as N fertilizer rates increased (Figure 2.1 and Table 7). The same pattern was found when yield was factored in to observe emissions intensity. The high rate of fertilizer has the higher GHG emissions and emissions intensity followed by the moderate rate and the lowest emissions and emissions intensity resulted from the lowest fertilizer rate (Figure 2.1 and 2.2 and Table 7).

2.3.2 Fertilizer Application Timing

At the present, the Holos model does not differentiate between the application of fertilizer in the spring versus in the fall. In other words, when the same amount of fertilizer is applied in the fall as in the spring, the following crops production will be the same and the GHG emissions that occur will also be the same.

2.3.3 Tillage

The Holos model output shows that when tillage is applied, this results in increased GHG emissions. When soils underwent intensive tillage, the emissions were higher at every fertilizer rate than when no tillage was applied (Figure 2.1). A simple average of all outcomes across soil types and fertilizer rates showed that the average emissions for Intensive Tillage were 412926.2 Kg CO_2e, 340207.4 for reduced tillage, and 310333.2 Kg CO_2e for No-Till (Table 7). This shows a 24.85% decrease in emissions when using No Tillage compared to Intensive Tillage (Table 7).

2.3.4 Soil Type

The Black Chernozem was the highest GHG emitter with an average of 404494.7 kg CO_2e, followed closely by Grey Luvisol (400159.4 kg CO_2e), then Regosol (367083.1 kg CO_2e), Dark

Grey Chernozem (345893.3 kg CO_2e), Humic Gleysol (332974.2 kg CO_2e) and lastly Eutric Brunisol (276329 kg CO_2e) (Table 7).

2.3.5 Crop Rotations

The Holos model was able to produce an average emissions for many different crop types. The results show that many pulse crop results in lower GHG emissions than wheat or canola crops Table 2.8. A few other non-pulse crops contribute even less than pulse crops. The average emissions across 30 fields spread across the prairie's provinces showed that the lowest emitting crop were Native Rangeland (28328.30 kg CO_2e) then Tame Legume (45055.95 kg CO_2e), and Tame Mixed Grass emitted (55602.50kg CO_2e). In contrast, the highest emissions came from Canola (239723.61 kg CO_2e), second highest was Potatoes (223509.75 kg CO_2e), and then Wheat (191122.21 kg CO_2e) (Table 2.8). Beans (dry field) was the pulse crop that resulted in the lowest emissions (58772.6 kg CO_2e) when tested against Soybeans (69914.4 kg CO_2e), Field Peas (96517 kg CO_2e), Chickpeas (157081 kg CO_2e), and Lentils (124005 kg CO_2e) (Table 2.8). Within the Holos model, the order of the crop sequence did not result in differing emission as abovementioned. Every time any crop was grown under the same conditions in the same ecoregion, the same emissions resulted no matter which crop species preceded it. This indicates that legacy effects are not being captured in the current version of the Holos model.

2.3.6 Cover Crops

Cover crops were found to have no effect on GHG emissions within the Holos model (Table 2.10). At this point the Holos model has the same response for every cover crop type it gives the same emissions for every cover crop type used in any regular cropping season crop combination.

2.4 Discussion

2.4.1 Fertilizer Rate

Generally, the addition of nitrogen fertilizer is used to improve nitrogen availability in the soil and increase crop yield. Nitrogen being a highly mobile nutrient is very susceptible to transformations such as mineralization, nitrification, immobilization, leaching, volatilization, and denitrification; there is potential of loss as N_2O emissions (Rochette et al. 2008). Optimization of source, timing, and method of application are therefore of interest in order to minimize losses and increase use efficiency. When fertilizer is used well, the increase in yield and biomass can reduce the net GHG emissions (Asgedom, & Kebraeb, 2011). Precision agriculture incorporates knowledge of precise application of nutrients in order to give crops as close to exactly what they need to grow and not limit growth but prevent excess application which can lead to higher GHG emissions and nutrient run off (Balafoutis et al., 2017). The analysis of the Holos GHG emissions output showed that there was a significant increasing trend in the emissions due to the fertilizer rate applied ($p=<0.0001$) (Table 2.4). The high fertilizer rate resulted in the highest emissions, the moderate fertilizer rate was in the middle, and the conservative rate of fertilizer resulted in the lowest emissions (Figure 2.1 and Table 7).

There is a direct correlation between soil type and organic matter. This was observed when utilizing the AFFIRM (version R) model, when the soil type was changed, automatically the OM would change. The AFFIRM model gave an OM of 2.4% and 7.2% for Brown and Black soils, respectively. With the yield data from the AFFIRM model we were able to analyze emissions intensity. The same pattern was found even when yield was factored in. The lowest emissions intensity resulted from

2.4.2 Fertilizer Application Timing

Earlier experimental studies have shown that application of fertilizer in the fall compared to in the spring results in more GHG emissions (Smith et al., 2019). The larger emissions emerging from fall N applications are often thought to be related the lack of active plant uptake, whereas application of fertilizer in the spring enables the plants to take up nutrients immediately leaving less labile N compounds in the soil exposed to potential transformation and losses (Smith et al., 2019). Within the Holos model, emissions are not affected by the timing of fertilizer application. The literature suggests that this is not the case and is a possible area for improvement in the Holos model in the future.

2.4.3 Tillage

Using the Holos model, three types of tillage regimes were evaluated utilizing three different fertilizer regimes (Table 2.2). Within Holos, No-till is defined as no tillage at any point in the rotation except for at the time of seeding. Reduced tillage is defined as one or few tillage passes with most residue retained on the surface. Intensive tillage is defined as complete burial of residue (Holos Algorithm, 2022).

The Holos model produced data that revealed declining GHG emissions as tillage intensity decreased (Figure 2.1 & Table 2.7). This correlates with earlier studies which have shown that reducing tillage can result in less GHG emissions when compared with higher intensity tillage or ploughing (Voltr et al., 2021; Baumhardt, 2017). One of the ways in which emissions were reduces in the Holos modeling was a reduction of Energy CO_2 from reduced use of fuel to run farm equipment to implement tillage. Stošić et al. (2021) demonstrate in their study that the reduction of fuel consumption that is part of a reduced tillage system is also an important factor in the reduced emissions that result in a system with less intense tillage practices.

At the present, the Holos model does not produce changes in crop yield when changes in tillage intensity are applied. However, the literature suggests that decreasing evaporation by reducing tillage in climatic zones where water is a limiting factor for yield can be an important strategy to increase crop production (Baumhardt et al., 2017). Many regions across the Canadian prairies are considered semi-arid (Chepkemoi, 2017); Baumhardt et al, (2017) demonstrate that semi-arid dryland crops can increase their yields by utilising a no-till residue management strategy. This yield increase was deduced to be due to increased soil water availability comes for two main reasons: decreased evaporation because of soil cover as well as increased organic matter and water infiltration (Baumhardt, 2017). Furthermore, DeFelice et al., (2006) found that a no-till regime tended to result in better yields than conventional tillage in well-drained soil regions and but lower yields when the soils were poorly drained. However, it was also discussed that implementing tillage can help to counteract certain aspects that may be growth deterrents, including, poor drainage or cool climate where soil temperature can delay growth in the spring. Soils with these limiting characteristics may not realize the same benefits from reduced tillage (DeFelice et al., 2006). Our study did not isolate and evaluate soil texture alone, but soil classification in general. Many studies focussed on wheat, barley, canola, and peas found increased yield with minimum tillage but many studies on corn found tillage increased yield (Lafond et al., 2006; Kutcher & Malhi, 2010; Sharma et al., 2011; Liu et al., 2022; Majrashi et al., 2022).

A study that took place in Eastern Canada in much more humid conditions where there was significant disease pressure and weed infestation did not see positive effects on wheat yield when utilizing conservation tillage compared to moldboard plow and chisel plow (Munger et al., 2014). This represents how differing conditions can change the effectiveness of a management practice and should always be thoroughly considered. More studies on the effects of tillage on yield are necessary to understand the nuance of the effects.

The Holos model results also show that there is no difference between N_2O emissions between the No-Till and Reduced Tillage treatments. In field experiments you would likely see a persistent difference in emissions with no-till emitting less N_2O in most cases; wet soils could be an exception as waterlogged soils emit more N_2O and tillage can help to dry out the soil (Huang et al., 2015).

The statistical analysis also yielded no significant interaction effect between tillage and fertilizer application rate ($p=0.9907$) (Table 2.4). In field experiments we would likely see an interaction effect as tillage would increase GHG emissions and this effect would be greater as more fertilizer was applied. One study of three different fertilizer application rates and three different tillage regimes showed there was an interaction effect between tillage and fertilizer application rate in term of N and P pools in the soil (Vilakazi et al., 2022). This is not direct evidence, but it could support the idea of GHG emissions interaction effects as well.

Another reason conservative tillage practices help to reduce emissions is the crop residues' role in protecting the soil from erosion, therefore protecting the yield capacity of the soil. Vaidya et al. (2023) found that a non-eroded soil had higher averaged yields than an eroded soil. However, non-eroded soils were found to emit more N_2O so emissions intensity would have to be evaluated. Not only is there evidence that erosion can lead to reduce yields and higher emissions intensity, but the opposite is also true (Liang et al., 2018). Increased topsoil can lead to yield increases and lower emissions intensity (Liang et al., 2018). Soil erosion is important to be prevented to reduce GHG emissions to the atmosphere.

2.4.4 Soil Type

The soil types that had the highest average emissions were also those that had the highest fertilizer application rates. The highest three emitters Black Chernozem, Grey Luvisol, and Regosol are considered Black soils in the Holos model and Alberta Fertilizer Guide and this qualifies them for a higher range of fertilizer application (Table 2.3). The actual names of each soil (Table 2.7) from the Canadian System of Soil Classification are used when the average emissions from each soil type were calculated and when the ecoregions were chosen with these specific names of the soils used as a blocking factor. Additionally, there are soil zones of the Canadian Prairies which include Black, Dark Brown, Brown, Dark Grey, and Grey the names of the zones are based on the major soil type found in the area, Chernozems, and based on the Chernozem Great group names. However, there are soils within the zones that would not be defined as Chernozems, yet they are still considered a Black, Dark Brown, Brown, Dark Grey, or Grey soil as they can be called such as part of the zone vernacular (Willms et al., 2011).

2.4.5 Crop Rotations

In the literature, increasing crop diversity and lengthening rotation have been found to have good potential in reducing GHG emissions and increasing soil structure and microbiota populations and diversity (Singh, 2020; Grover et al., 2009). The Holos model output on crop rotations suggests that diversifying crop rotations in the Canadian Prairies would help reduce emissions as well but we were not able to test this directly. This assumption of decreasing emisions with diversification is in large part because the highest emitting crops were the most common rotation that occurs on the Canadian Prairies: wheat-canola. In fact, these common crops are often grown repeatedly two or more. years in a row creating wheat-wheat or canola-canola rotations (Statistics Canada, 2022 and Gill, 2018).

The average emissions for a wheat crop in Holos is 191 122 kg CO_2e and canola is 239723.61 kg CO_2e. The only other crop with higher emission than wheat is potatoes (22350.75 kg CO_2e) (Table 2.8). Two of the crops in the top three top emitters, canola and wheat, are also the most common crops grown across the Canadian prairies. Most other options that farmers have to diversify their crop rotations on the Canadian Prairies are lower emitting (Table 2.8). Therefore, in most cases diversifying a rotation with more common options would help to reduce emissions according to the Holos model output. The two main ways N_2O emissions are affected within the Holos model are the rate of N applied to a crop, and the amount of N that ends up in the crop residues (Holos Algorithm, 2022).

Crop residues contain both nitrogen (N) and carbon (C), as do all parts of the plants as these are some of the basic building blocks of plant tissue. As mediated by soil microbes, N within the crop residues left in the fields are exposed to decomposition and mineralization and subsequently nitrification and immobilization, while organic C is a medium for microbial growth. (Frimpong and Baggs, 2010, Ferrari Machado et al., 2021). Crop residues are produced on a large scale and always increasing. Cherubin et al, (2018) showed that in 2013, residue production was estimated as 1.5 billion Mg in America.

Excluding forages, our study indicated that the lowest emitting crops were legumes including beans (dry field) (58772.63 kg CO_2e), soybeans (69914.43 kg CO_2e), and field peas (96516.99 kg CO_2e).

Crop residues differ between crop species and can affect the success of different crop sequences. The amount of residue and the value differs between crop species (Alberta Agriculture and Rural Development, 2008). Crop residues left behind in the field inherently have nutrients and these nutrients can be factored in and subtracted from the nutrients that need to be added the next growing season which can help reduce fertilizer related GHG emissions (Janzen & Kucey, 1988; Pal et al., 2016). Choosing a reasonable crop sequence to aid in reducing the amount of fertilizer needed could reduce GHG emissions, legumes are specifically useful for this initiative because of their symbiotic nitrogen fixation ability (W.-X. Liu et al., 2022).
Unless otherwise specified Holos assumes that 100% of the underground residues from roots are left in the field and 100% of other residues are removed.

An important consideration is that crop residues are highly impacted by placement as well as soil nutrient status so the tillage regime will impact the decomposition rate and therefore the nutrient availability, and the previous fertilizer application and soil nutrient levels will be important (Chaves et al., 2021).

Lafond et al. (2006) found that growing crops in a specific rotation order and including certain crops in rotation could affect crop yield. This change in crop yield was despite fertilizer being applied based on recommendations from soil sampling and analyses; therefore, keeping soil nutrient availability equal across assessed rotations. The study found that Spring Wheat always yielded more when grown after field peas than when grown after another cereal, and that winter wheat always yield higher when grown after flax when compared to being grown after spring wheat. Flax yield also increased when grown in rotation with field peas compared to a rotation without field peas (Lafond et al., 2006). This supports that just including field peas in rotation helped to yield more flax even when the flax was planted directly after spring wheat and not the field peas. As the study was conducted over 12 years of varying precipitation, the results further show a positive yield effect from conservation tillage even under a range of conditions.

The crop GHG emissions data showed that the direct and indirect emissions changed when the region the crop was grown in changed and when the crop changed. So the crop type effects these types of emissions as well as all of the factors that change with location (soil type, climate etc.). The data output also showed that the energy CO_2 emissions and the
The average overall GHG emissions data captured can suggest which crops to consider including in a rotation to result in lower emissions. The Holos model does have some interesting capabilities being developed around carbon cycling and this aspect of the model would be a very interesting aspect to study.

2.4.6 Cover Crops

Within the Holos model, all cover crops are modelled similarly. Every different cover crop type has no effect on GHG emissions within the model (Table 2.10). This outcome in general expresses the consensus of the body of knowledge on cover crop implementation. A desired consistent outcome of a decrease of emissions is not represented in all existing studies (Nguyen & Kravchenko, 2021). However, different crop species and regions across the world, as well as other factors, can affect the usefulness of the cover crop. Incorporating a cover crop can enhance soil carbon sequestration, increase aggregation, increase water filtration, and reduce erosion and nutrient leaching (Muhammad et al., 2019). These benefits helps to improve sustainability even if they are not visible in GHG emissions flux monitoring. A meta-analysis of data found that all cover crops resulted in an increase in CO_2 emissions, but a decrease in N_2O emissions, except when a legume was used which also resulted in an increase in N_2O emissions (Muhammad et al., 2019). Some studies have found that the SOC increase that can occur with the inclusion of a cover crop can more than compensate for the increases in CO_2 and N_2O emissions that can occur resulting in lower total GHG emission balance than control treatments (Abdalla et al., 2014). Another study used a more holistic approach and calculated net carbon equivalent (CE) and found multiple cover crop systems all had net lower CE than the systems without cover crops even though they did not consistently result in the lowest GHG emissions (Wang et al., 2022). A survey of farms in the Canadian Prairies found that farmers using cover crops responded saying that they enjoyed benefits such as improved soil health, increased biodiversity, increased OM, less erosion, increased infiltration, less weeds, more earthworms, less need for N fertilizer, reduced compaction, financial gains and more (Morrison, & Lawley, 2021). More studies on cover crops are needed to help define the parameters in which they are useful.

2.5 Conclusion

Reducing fertilizer and tillage application results in reduced emissions. These results are supported by the literature. Timing of fertilizer application and the differences in emissions that result have yet to be reflected in the Holos model output. Crop rotations including a legume can help to reduce GHG emissions due to the resultant data output showing that a season of growing a legume emits less GHG’s than growing a cereal or canola. Cover crops potential for GHG emissions reduction have yet to be consistently defined in the literature and so Holos shows zero change in GHG emissions with implementation of a cover crop.

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Table 2.1 Input variables and options used to model scenarios in Holos and the values used.

Variables	**Value**
Provinces	Alberta, Saskatchewan, Manitoba
Measurement	Metric (kg CO_2e)
Model Type	Advanced
Soil Types	Black Chernozem, Dark Gray Chernozem, Gray Luvisol, Eutric Brunisol, Humic Gleysol, Regosol
Beef Diet Types	Low protein energy, Medium protein energy, High protein energy
Dairy Heifer Diet Types	High Fiber, Low Fiber
Dairy Lactation Diet Types	Legume, Barley, and Corn (all silage)
Sheep Diet Types	Low energy diet, Medium energy diet, High energy diet
Beef Feed Additives	2% Fat, 4% Fat, Ionophore, 2% Fat + Ionophore, 4% Fat + Ionophore
Dairy Cattle Feed Additives	5% Fat, Ionophore, 5% Fat + Ionophore
Housing types for Beef Cattle	Confined no barn, Housed in barn (solid), Housed in barn (slurry)
Housing Types for Dairy Cattle	Tie-Stall (solid litter), Tie Stall (slurry), Free-Stall barn (solid litter), Free-Stall barn (slurry scraping), Free-Stall barn (flushing), Free-Stall barn (milk-parlour – slurry flushing), Drylot
Housing Types for Sheep	Confined, Housed. Pasture
Manure Management for Beef Cattle	Deep bedding, Solid storage, Compost intensive, Compost passive, Anaerobic digester
Manure Management for Dairy Cattle	Solid Storage, Compost Intensive, Compost Passive, Deep Bedding, Liquid w/ natural crust, Liquid no crust, Liquid with solid cover, Daily spread, Anaerobic digester
Manure Management for Sheep	Pasture, Solid Storage, Compost Intensive, Compost passive, Anaerobic digester

Table 2.2 Fertilizer rates (Kg N ha-1) used in Fertilizer rate and tillage scenarios. (Alberta Agriculture, Food and Rural Development, 2004)

	Wheat		**Canola**	
	Urea	Monoammonium phosphate	Urea	Monoammonium phosphate
Brown	48.7	0	48.7	21.6
	85.3	17.2	92.6	28.0
	121.9	32.3	134.0	32.3
Black/ Grey	73.1	32.3	97.5	32.3
	134.0	60.4	170.6	53.9
	195.0	86.2	243.7	75.5

Table 2.3 Yield of crops at the three different fertilizer rates and in two different soils according to AFFIRM.

Soil	**Crop**		**Fertilizer Rate**	
		Conservative	Moderate	High
Brown	Canola	56	62	67
	Wheat	55	61	68
Black	Canola	77	80	80
	Wheat	78	84	88

Table 2.4 Results of the two-way ANOVA of tillage and fertilizer rate HOLOS total GHG emissions output.

Source of Variation	**numDF**	**denDF**	**F-Value**	**p-value**
Intercept	1	796	6624.254	<.0001
Tillage	2	796	75.322	<.0001
Fertilizer Rate	3	796	81.095	<.0001
Tillage:Fertilizer Rate	4	796	0.071	0.9907

Table 2.5 Emissions significance for ANOVA statistical analysis separated by treatment levels of tillage and fertilizer rate.

Province	Soil Type	Treatment	Emissions
All Ecoregions		NT x RT	**
		RT x IT	***
		NT x IT	***
All Ecoregions		C x M	***
		M x H	**
		C x H	***

Tillage treatments: NT= No Tillage, RT= Reduced Tillage, IT= Intensive Tillage
Fertilizer Treatments: C= Conservative, M=Moderate, H=High
*denotes P<0.05, **denotes P<0.01, ***denotes P<0.001, NS denotes no significance.

Table 2.6 Results of the two-way ANOVA of tillage and fertilizer rate HOLOS total GHG emissions intensity output.

Source of Variation	numDF	denDF	F-Value	p-value
Intercept	1	796	785.8087	<.0001
Tillage	2	796	73.7591	<.0001
Fertilizer Rate	3	796	28.7588	<.0001
Tillage:Fertilizer Rate	4	796	0.0916	0.9851

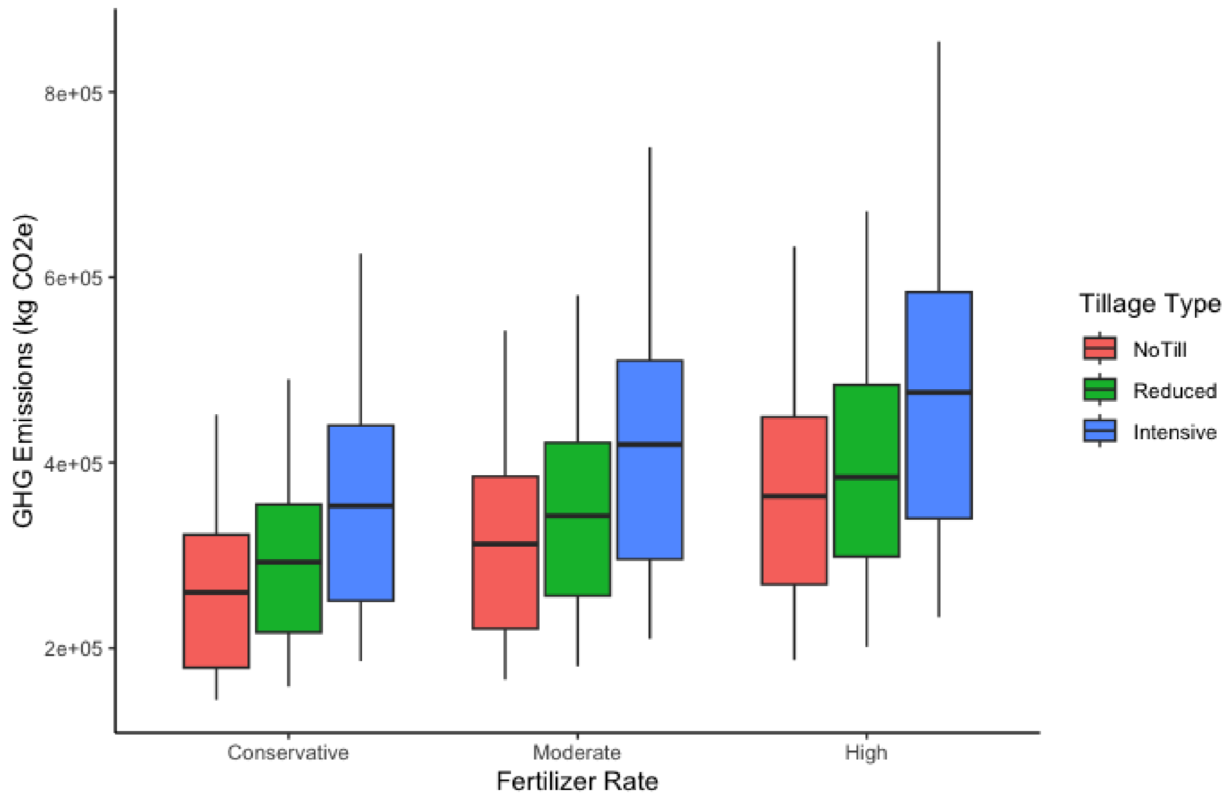

Figure 2.1. A boxplot comparing the GHG emissions (kg CO_2e) for each fertilizer rate (conservative, moderate, and high) and for each tillage type (intensive, no-till, and reduced). The diagram shows that within each fertilizer rate, no-till has the lowest emissions followed by reduced, and intensive tillage has the highest emissions. The high fertilizer rate has the highest GHG emissions in each of the fertilizer ranges and the emissions decrease as the fertilizer rates decrease.

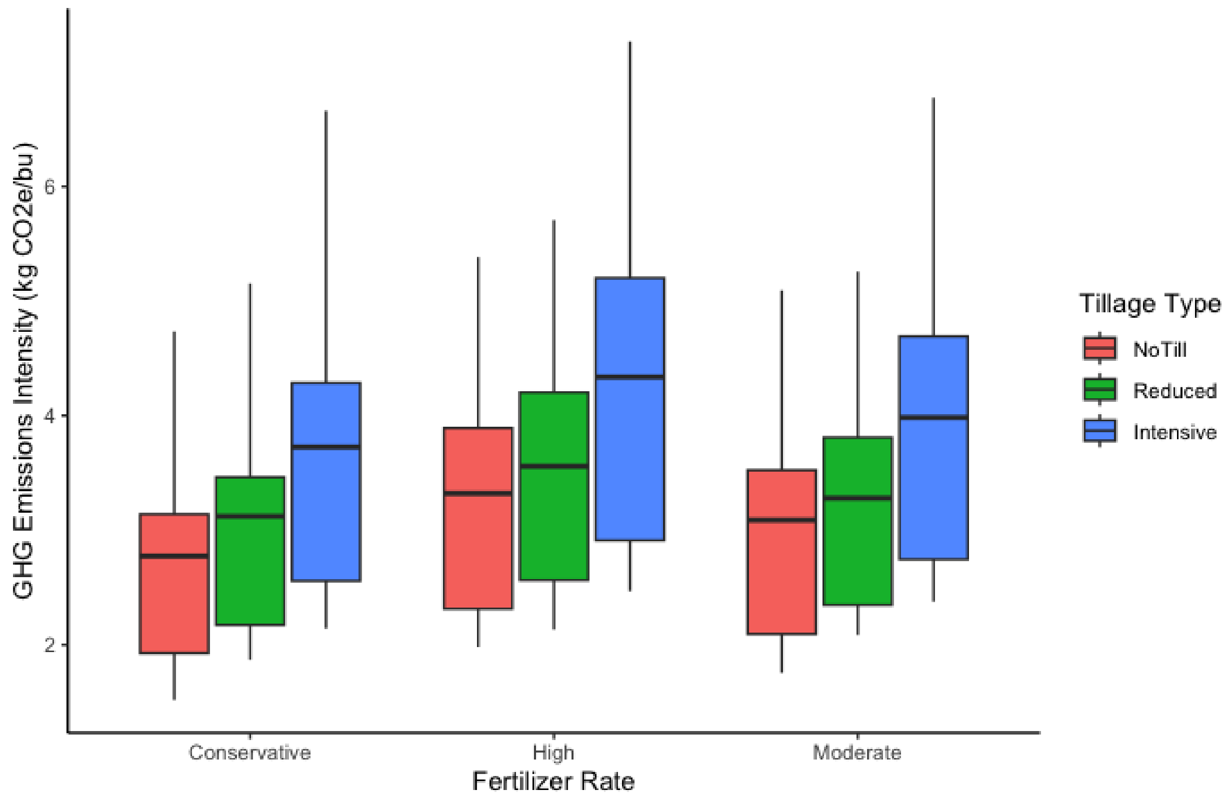

Figure 2.2. A boxplot comparing the GHG emissions intensity (kg CO_2e/bu) for each fertilizer rate (conservative, moderate, and high) and for each tillage type (intensive, no-till, and reduced). The diagram shows that within each fertilizer rate, no-till has the lowest emissions intensity followed by reduced, and intensive tillage has the highest emissions intensity. The high fertilizer rate has the highest GHG emissions intensity in each of the fertilizer ranges and the emissions intensity decreases as the fertilizer rates decrease.

Table 2.7. Average GHG emissions (Kg CO_2e) by multiple factors.

Fertilizer Application	**Average Emissions (Kg CO_2e)**	**Emissions Difference for BMP's (%)**
Conservative	301501.7	-26.01
Moderate	354486.1	-13.01
High	407479.0	-
Tillage Type		
No-till	310333.2	-24.85
Reduced	340207.4	-17.6
Intensive	412926.2	-
Soil Type		
Black Chernozem	404494.7	
Grey Luvisol	400159.4	
Regosol	367083.1	
Dark Grey Chernozem	345893.3	
Humic Gleysol	332974.2	
Eutric Brunisol	276329	
Province		
Alberta	383233.3	
Saskatchewan	393906.9	
Manitoba	286326.6	

Table 2.8. The average emissions from crops across the Canadian Prairies modelled with sample size of 30 replicates each on Black soil zones using the Holos model.

Crop Type	**Average Emissions ($KgCO_2e$)**
Native Rangeland	28328.3
Tame Legume	45055.948
Tame Mixed	55602.502
Beans (dry field)	58772.628
Soybeans	69914.4253
Seeded Grassland	89775.157
Field Peas	96516.9937
Forage for Seed	107906.477
Tame Grass	116519.374
Fall Rye	119186.197
Lentils	124005.749
Barley	124930.818
Triticale	156558.347
Chickpeas	157081.022
Oats	158723.607
Corn	165339.481
Flax	177608.667
Wheat	191122.206
Dry Peas	212983.526
Potatoes	223509.748
Canola	239723.614

Table 2.9. Fertilizer recommendations used for the crop rotation scenarios, based on The Alberta Fertilizer Guide

Crop	**N (Urea) (kg/ha)**	**P (Monoammonium phosphate) (kg/ha)**
Wheat	128.1	59.3
Canola	165.2	53.9
Barley	128.1	59.3
Oats	164.1	64.7
Triticale	144.8	75.5
Field Peas	17.9	64.7
Lentils	20.1	43.1
Chickpeas	17.9	64.7
Dry Peas	17.9	64.7
Soybeans	17.9	64.7
Grain Corn	188.5	64.7
Beans (dry field)	17.9	64.7
Flax	75.4	37.7
Potatoes	203.2	161.7
Fall Rye	122.0	59.3
Seeded Grass	215.0	43.1
Forage Seed	160.2	43.1
Tame Grass	215.0	43.1
Tame Legume	2.5	97.0
Tame Mixed	43.3	53.9
Native Grassland	0.0	0.0

Table 2.10. Two of the ecoregions GHG emissions for cover crop inclusion. All cover crops showed the same emissions. – depicts any cover crop that we tested including Sweet Clover, Hairy Vetch, Oat, Radish, and a control with no cover crop.

Ecoregion	**Cover Crop**	**Cash Crop**	**GHG Emissions (kg CO_2e)**
744002	-	Field Peas	80288.4
744002	-	Oats	149353.7
744002	-	Wheat	179317.6
744002	-	Canola	224347.5
744002	-	Barley	118672.1
750006	-	Field Peas	86252.6
750006	-	Oats	160679.7
750006	-	Wheat	195385.7
750006	-	Canola	245274.2
750006	-	Barley	127218.1

Chapter 3: Livestock Systems Scenarios and Considerations

3.1 Introduction

Agricultural emissions from livestock are a significant contributor to the total emissions from agriculture representing 14.5% of anthropogenic emissions which is 7.1 Gigatonnes CO_2e per year (FAO, 2021). Improving management strategies and focussing on efficiency can significantly reduce GHG emissions (Alemu et al., 2017).

When evaluated on a commodity basis, beef is responsible for the most emissions of all livestock groups at 41% of global emissions (FAO, 2021). Improving management and increasing efficiency of cow-calf production could result in a 31% reduction in emissions intensity (Alemu et al., 2017). As a commodity category, dairy is the second largest emitter of all livestock groups at 20% of global emissions (FAO, 2021). The majority of Canadian dairy cattle are the Holstein breed at 93% of the herd. Genomic evaluation has been important to Canadian farmers and selection of over 60 traits has established Canada's reputation for superior cow genetics (Government of Canada, 2020). Sheep are grouped into a category of small ruminants and their meat and milk production account for 6% of global livestock emissions (FAO, 2021). These three livestock categories can be explored in the Holos model, other categories such as poultry and swine are under development.

Livestock feeding strategies are an important way in which GHG emissions can be reduced. Many different strategies are being experimented with such as increasing concentrates in feed, improving forage quality which both can adjust fiber and protein content, and using feed supplements such as fats, nitrates, or tannins (Lui & Lui, 2018). Feed conversion efficiency is important to consider as well, as the more end product per unit of input the less GHG emissions will be produced to meet production (Wyngaarden et al., 2020).

Manure management strategies can also have an important impact on GHG emissions; the right strategy to handle and store manure can reduce methane emissions (Sajeev et al., 2018). Liquid manure creates more anaerobic conditions and often increases CH_4 emissions, whereas a method of dry handling leads to more aerobic conditions and often reduces CH_4 emissions (EPA, 2022).

Housing strategies use in reducing GHG emissions are linked with energy use, temperature, (Pinto et al., 2020) and manure handling (Pereira et al., 2012).

Nutritional attributes define the diet quality for livestock and associated GHG emissions. It's important to define and understand the components that make up the feed and can be altered to invoke changes in animal health and GHG emissions. Neutral detergent fiber (NDF) refers to the structural components of the plant matter in the feed (Rasby and Martin, 2022). Total digestible nutrients (TDN) is a measurement that accounts for the digestible energy (DE), which accounts for the gross energy of the feed minus that which is lost in excretion of feces, as well as the protein energy in the feed (Oregon State University,2018). Metabolizable energy (ME) is the DE minus what is also lost as gases and urine, this typically is 82% of the DE (Oregon State University, 2018). Crude protein is an estimate of the amount of protein in a food using the nitrogen concentration (Alberta Agriculture and Rural Development, 2006).

The objectives for this area of focus is to identify existing BMPs aligned with GHG mitigation aims within farming systems relevant to livestock management on the Canadian Prairies and to identify knowledge gaps of BMP and GHG mitigation as well as future recommendations in animal husbandry and agricultural sustainability.

3.2 Methods

3.2.1 Holos Scenarios

The 2020 census reported an average dairy farm size in Canada of 139.17 cows (Government of Canada, 2020). This is a large increase from even 2016 when the average was 73 animals per farm (Luby et al., 2020). Holos uses 80 animals with an equal number of heifers, dry, lactating, and calves, 20 each. This number and distribution seemed appropriate. Beef cows average numbers per farm in Canada over the last 5 years was 155 cows and calves on January 1st and 169 cow and calves when reported July 1st (Statistics Canada, 2021). These are numbers of cow and calves reported under the heading of beef and veal, and so does not include dairy which was reported separately. However, when we narrow our focus to the Prairie Provinces the numbers go up. Statistics Canada (2021) numbers for Western provinces average farm size over the last five years are 191 at January 1st and 211 on July 1st when Alberta, Saskatchewan and Manitoba are averaged. Since Holos asks for more detailed numbers for the different types of animals and we lacked these detailed statistics, the default numbers of animals were used in the model since the total of 246 was close to the Statistics Canada number when calves were accounted for. For beef cattle the number of bulls was 4, replacement heifers was 20, cows 120, and calves 102. This number and distribution of animals is also often used in scientific studies (Hünerberg et al., 2014; Alemu et al., 2017). The amount of pasture used for Beef cattle was based on an assumption of 2 ac per cow and 0.5 ac per calf so in total 339 acres. An assumption of 2 acres pre cow was also used for dairy cows and the total pasture was 160 acres (University of Massachusetts, 2022).

For sheep we continued to use the simplified defaults. They used 100 animals for each animal stage/type: Lambs, Rams, and Sheep. The amount of pasture used to house the sheep was 55 acres, with 15 acres per 100 sheep and 10 acres per 150 lambs (Outhouse et al., 2007)

3.2.2 Sampling Population

An important difference that exists between sampling populations in real life and within the Holos is that the model does not have multiple livestock populations you can run scenarios with that vary in terms of genetics, stressors, disease, and the vast array of possible conditions that can ultimately affect the emissions of an animal. For this reason, the emissions output data for livestock scenarios are based on one population and these populations are defined by many average numbers from the industry, expert opinions, and formulas that help to define the latest scientific knowledge. In these scenarios where only one ecoregion was used to obtain outcomes an ecoregion that best defined the average characteristics according to literature and statistics was used (Awada, Lindwall, & Sonntag, 2014, Pennock 2011). This selected ecoregion was: Red Deer Plain, Alberta (737005). This ecoregion, is represented by a medium texture Black Chernozem soil. The model output becomes valuable for comparative studies as it captures principles of scientific literature and represents available scientific data.

3.2.2 Mathematics and Formulae

The Holos model uses a variety of formulas to define enteric emissions from beef cattle. These formulae often include a conversion factor (Y_m) and Additive Reduction factors (AR). A Y_m indicates the proportion of the animal's gross energy intake that will be converted to CH_4 and AR is a percentage that defines the amount that an additive reduces emissions. Each formula was carefully made to reflect the most current scientific knowledge. Formula ‘a’ was made in part by closely studying articles on the prediction of enteric methane production (van Lingen et al., 2019). These are a couple of the formulas that make up the Holos model and that are important to understand in order to create scenarios and understand the model output.

a) $CH_{4enteric}\text{-rate} = GEI * \frac{Y_m}{55.65} * (1 - \frac{AR}{100})$

where

$CH_{4enteric}$-rate	Enteric CH_4 emission rate (kg head^{-1} day^{-1})
GEI	Gross energy intake (MJ head^{-1} day^{-1})
Ym	Methane conversion factor (changes by diet)
55.65	Energy content of CH_4 (MJ kg^{-1} CH_4)
AR	Additive reduction factor (changes by additive)

b) $CH_{4enteric} = CH_{4enteric}\text{-rate} * \#cattle$

where

$CH_{4enteric}$	Enteric CH_4 emission (kg CH_4)
#cattle	Number of beef cattle

3.2.3 Output Analysis

The reduction of emissions is calculated in comparison to a common practice across the Canadian Prairies (Sheppard & Bittman, 2012). The common practice used for manure handling for both beef and dairy cows is solid storage. When reviewing multiple articles, solid storage was a very common practice among both populations of cattle across the Canadian Prairies even though the rates of use vary across different provinces (Sheppard et al., 2011). The GHG emissions amount from each practice are looked at directly as they represent averages from the Canadian Prairies and the culmination of a vast amount of scientific research.

3.4 Results

3.4.1 Beef Cows

The Holos model output showed a pattern of decreased emissions with increased protein in the diet (Table 3.1). Diet additives resulted in a decrease of emissions as well (Table 3.1). Of the five diet additives the combination of 4% fat and ionophore caused the largest emissions decrease of 15.2% with a subtotal of emissions of 545350.92 kg CO2e, the 4% fat additive alone was next (555287.6 kg CO2e), followed by the 2% fat and ionophore combination (589102.14 kg CO2e), next was the ionophore (622916.68 kg CO2e), and last was the 2% fat additive with a subtotal of emissions of 599038.83 kg CO2e (Table 3.1). Overall, a 2% fat additive caused GHG emissions to decrease and a 4% additive caused a larger decrease in emissions than the 2% additive. When the animals were fed the 2% fat additive the cows, bulls, replacement heifers, and calves emission responses were consistent, each group resulted in an emissions decrease.

The housing type for beef cattle that resulted in the lowest GHG emissions was pasture (639277.8 kg CO2e), next lowest was housed in barn (solid) (641961.2 kg CO2e), then housed in barn (slurry) (642552 kg CO2e), and last confined no barn (642790.1 kg CO2e) (Table 3.2).

The manure management type that resulted in the lowest GHG emissions was anaerobic digestion (464672.4 kg CO2e), next lowest was intensive composting (486551.3 kg CO2e), then passive composting (491927.8 kg CO2e), solid storage (509379.32 kg CO2e), and the largest emitter was deep bedding (642790.1 kg CO2e) (Table 3.2).

3.4.2 Dairy Cows

The Holos model outputs showed that when Dairy Heifers were fed a high fiber (6614.1 kg CO2e) diet this reduced emissions when compared to a low fiber (5882.3 kg CO2e) diet. There was a 11.1% decrease in emissions when dairy cattle were fed the low fiber diet (Table 3.1).

When Dairy Heifers were fed feed additives, two of the three additives resulted in a reduction of GHG emissions. The 5% fat additive did not reduced emissions, the ionophore reduced emissions by 14.9%, and the 5% fat and ionophore combination reduce emissions by 7.4% (Table 3.1).

Lactating cows fed a corn silage diet had the lowest GHG emissions (17144.21 kg CO2e) when compared to a legume and forage diet or barley silage diet. In further details, the legume and forage diet ranked intermediate in terms emissions (17847.66 kg CO2e) followed by the barley silage diet that resulted in the highest emissions (18400.85 kg CO2e).

The manure management practice that resulted in the lowest emissions was daily spread (27346.2 kg CO2e), the next lowest was anaerobic digestion (27900.4 kg CO2e), then intensive composting (31923.7 kg CO2e), then passive composting (32533.2 kg CO2e), then solid storage (34910.3 kg CO2e), then liquid with natural crust (42867.2 kg CO2e), then liquid with solid cover (43269 kg CO2e), then liquid no crust (54864.5 kg CO2e), and the most GHG emissions came from deep bedding (55025.7 kg CO2e).

Housing choices resulted in different GHG emissions. Their emissions ranked as tie-stall (solid litter)(28635.5 kg CO2e), Tie-stall (slurry) (28726 kg CO2e), free-stall barn (solid litter) (26017.9 kg CO2e), free-stall barn (slurry scraping) (26209.4 kg CO2e), free-stall (flushing) (26129.6 kg CO2e), free-stall (milk parlour – slurry flushing) (26129.6 kg CO2e), drylot housing (29051.8 kg CO2e) and pasture (22553.8 kg CO2e).

3.4.3 Sheep

The sheep, rams, and lambs and ewes fed the high protein or good quality forage diet emitted the lowest emissions (9615.6 kg CO2e). The medium protein or average quality forage diet was the second lowest (13520.1 kg CO2e), and the low protein or poor quality forage diet the highest emissions.

When comparing types of manure handling and storage within Holos, the solid storage had the lowest emissions (136164.7 kg CO2e). The next lowest emitter was compost passive (226607.49 kg CO2e), then pasture (245682.4 kg CO2e), followed by deep bedding (355206.3 kg CO2e), and the highest emissions came from compost intensive (2022562.9 kg CO2e).

When comparing types of sheep housing within Holos, the pasture had the lowest emissions (5436 kg CO2e), the confined housing had the next lowest emissions (9615.6 kg CO2e), and then housed ewes had the highest emissions (10637.7 kg CO2e).

3.5. Discussion

Attempts to reduce emissions from ruminant animals often focus on digestion and enteric fermentation because methane is an end product emitted from ruminant digestion; methane contributes 70% of livestock emissions (Kebreab, 2021). One way management can work to alter enteric methane emissions is in the form of dietary intake.

Management practices such as feed adjustment and genetic changes have already been proven to help lower GHG emissions and increase production efficiency in the beef cattle sector (Legesse et al., 2016). The intensity (kg CO_2e/kg) of GHG emissions lowered from 1981 to 2014 by 14% in the Canadian beef cattle industry (Legesse et al., 2016). This reduction in emissions was seen by analyzing and comparing differences in reproductive efficiency, average daily gain, slaughter weight, and production yields (Legesse et al., 2016). The newest version of the Holos model has been adjusted to reflect current emissions and uses more current knowledge and emissions factors.

Feed plays a massive role in the main source of emissions from livestock, enteric CH_4 (van Lingen et al, 2019). In the new version of the Holos model diets are created by making a feeding regimen using real components that have had their nutritional compositions defined. This means that the diets are more realistic but they also become more complicated. Diets can no longer be adjusted simply to increase the protein by 1% without also changing other aspects of the nutritional value of the feed. The diets used to demonstrate the effect of protein intake also differ in other ways rather than protein alone. The amount of forage (%) included in the diet, and the NDF (kg kg^{-1}) decrease as protein increases. The amount of TDN (%) and ME (Mcal kg^{-1}) increase as protein increases. These are common relationships between these components and therefore including them as such is reflective of reality (Jayanegara et al., 2019). The output from the Holos model demonstrated this effect as well. The high protein diet was defined by 17.7% crude protein and this was compared to a medium protein diet defined by 12.4% crude protein and a low protein diet with 5.7% crude protein and as the CP went up so did the TDN and ME and the % of forage DM, and NDF went down (Table 3.4). Another noteworthy fact is that Holos does not account for waste feed and the related GHG emissions as it assumes all feed is consumed and there is no waste.

3.5.1. Protein

Feeding strategies including macronutrient profile and feed additive can have different effects on different ruminants as there are differences in feed intake and rumen physiology (Van Gastelen et al., 2019). Increasing protein in the diet of beef cattle up to 18% CP can help to reduce methane emissions. Supplementing protein in the diet of beef cattle can help by increasing the efficiency of feed utilization (EFU) (Shreck et al., 2021). A higher EFU of the feed means the cattle can obtain nutrition more easily and produce more with less feed and therefore the emissions intensity is reduced. Protein is also highly digestible and so it spends less time in the rumen which reduces the time for enteric methane production (Kohlman & Bjurstrom, 2023). In the Holos modelled scenario where feed protein was adjusted the same results were observed; the overall CO_2e emissions of beef cattle were lowered when protein in the diet was higher. If CP content is in surplus it can lead to increased emissions of N_2O due to the amount of N lost in the cows' urine so the slurry types of manure are especially effected. When there is a lot of excess N the C:N ratio is low which enhances N loss and NH_3 emissions increase which are highly susceptible to volatilization (Külling et al., 2001). Higher CP in the diet increases digestibility of the feed and so was found to be negatively correlated with the amount of fibre in the manure which further decreases the C:N ratio and reduces crust formation which limits oxygen contact and N_2O emissions are further increased (Külling et al., 2001). This helps to explain why as the CP content in the diet decrease the manure CH_4 specifically was reduced (Appendix).

For sheep as well, the same pattern emerged, as protein and feed quality increased the resulting GHG emissions decreased (Table 3.3). The sheep high protein diet was defined by 18% CP, the medium protein was 12%, and the low protein was 6%. Similar transformation and soil properties as described for cattle would explain this pattern. Regarding sheep specifically, a unique factor that contributes to decreases emissions and emissions intensity is that feeding higher protein is correlated with ewes being more likely to have twins, and better recovery and maintenance after lambing (Carvalho et al., 2022).

Sometimes when cattle are supplemented with high protein the feed supplement can also inherently be higher in fat and so the addition of fat could also be affecting the emissions changes (Shreck et al., 2021). However, we can rule that out in Holos as the diet charts show the fat level stays the same for all three levels of protein diets.

3.5.2. Fiber

Forage digestibility directly affects CH_4 emissions (Hristov et al., 2013). The effects of forage digestibility of varying types of feed such as legumes, grasses, and corn, has been observed with different farm species and results have varied (Van Gastelen et al., 2019).
The Holos low fiber diet was defined as a diet containing 63% DM forage, 12.63 kg kg^{-1} CP, 0.336 kg kg^{-1} NDF, and 75% TDN. The high fiber diet had 87.6% DM forage, 13.3 kg kg^{-1} CP, 0.45 kg kg^{-1} NDF, and 70% TDN. The lower fiber diet resulted in lower emissions and three different categories of emissions were affected, enteric CH_4, manure CH_4, and indirect N_2O emissions (Appendix).
Increased forage digestibility (lower fiber) can result in increased dry matter intake (DMI) and increased CH_4 emissions for beef and dairy cattle but when production was considered emissions intensity was reduced overall (Van Gastelen et al., 2019). If a feed has a lower DE animal intake will reduce and this leads to less animal growth and the result will be a higher amount of methane produced per unit of production (IPCC, 2019). In some cases, increased digestibility can even lead to decreased methanogenesis for beef and dairy cattle and therefore decreased methane emissions (Van Gastelen et al., 2019). Sometimes the digestibility of the feed is defined by maturity of the crop when harvested and nitrogen content could also change along with fiber and this should be investigated as to its effects on digestion as well (Van Gastelen et al., 2019). The fermentation process of plant fiber produces a higher amount of CH_4 than non-fiber carbohydrate fermentation (Moss et al., 2000).

3.5.3. Feed Composition

Lactating cows were specifically looked at for feed composition. Three types of silage feed were compared one made from barley, one from corn, and one from legume forage.
The difference in the resulting emissions from each of the three diets is likely affected by the macronutrient composition of the diets and those macronutrients effects on rumen digestion and methanogenesis. The legume forage-based silage was defined by (77.8% DM forage, 16.15 kg kg^{-1} CP, 0.353 kg kg^{-1} NDF, and 70% TDN. The barley-based silage was defined by 60.5% DM forage, 16.82 kg kg^{-1} CP, 0.383 kg kg^{-1} NDF, and 71% TDN. Lastly, the corn-based silage had 59.1 % DM forage, 16.44 kg kg^{-1} CP, 0.380 kg kg^{-1} NDF, and 72% TDN.

Corn silage has become an attractive feed due to its high TDN which improves animal performance (Guyader et al., 2017). The corn silage diet resulted in the lowest emissions, followed by legume and then barley. The largest emissions change was in enteric CH_4, but there were marginal differences in manure CH_4 emissions and indirect N_2O emissions as well (appendix). Barley had the lowest indirect N_2O emissions of the tree diets but they highest from manure CH_4 and enteric CH_4. Bencharr et al. (2013) similarly found that including corn silage in the diet of lactating cow resulted in a reduction of methanogenesis when adjusted for DMI but since the DMI tended to increase with use of corn silage the overall methane emissions increased. The amount of feed was kept constant in the Holos model scenario so a decrease in emissions was plainly observed when corn silage was fed without the need to adjust for DMI. Guyader et al. (2017) also found that corn-based silage helped to reduce emissions when compared to barley silage, however, when production was taken into account the emissions intensity of a barley silage feed was less. Since we were not able to obtain production estimates from Holos this would be an aspect of the emissions data that could require more thorough analysis.

It is interesting to note that Weber et al., (2022) found that manure from a corn-based diet resulted in fewer N_2O emissions when applied to certain types of soils when compared to manure from a barley-based diet.

3.5.4. Fat Additive

Supplementing fat into the diets of ruminants has effectively reduced production and emissions of methane (Rasmussen & Harrison, 2011). Another study specifically on cattle found that increasing fats or oils in the diet or increasing feed digestibility helped reduce methane emissions (Kebreab, 2021). Fat additives are only effective in reducing GHG emissions if the cattle feed in inherently lower in fat. Before adding fat it is imperative that the amount of fat already in the feed is known (Williams et al., 2014). The amounts of fat used, 2% and 4% for beef cattle and 5% for dairy cattle, are based on expert opinions sourced within the Holos algorithm. There is literature to support these fat additive amounts as well. Williams et al. (2014) discuss how the upper limit of fat content in the diet to maintain normal functioning of the rumen is 6% dry matter (DM).

Williams et al. (2014) found that adding a fat additive of 10% to a dairy cow diet that contained 22% fat already was able to reduce emissions by almost 3%. The Holos model output also resulted in a decrease of GHG emissions when a fat supplement was added. Formula 'a' describing the enteric CH_4 emissions is used within the model and an *AR* factor is applied. For beef cattle the *AR* factor is 10 for 2% fat and 20 for 4% fat and for dairy cattle the *AR* is (5+ % fat added). We did not see the reduction realized in our data for the dairy cattle even though the

AR factor suggests there should have been a reduction. Since the model is always changing it is possible there was a glitch in the system when the scenario was carried out.

Supplementing dietary fat into the rumen can reduce methane production by reducing the intake of fermentable OM, reducing fiber digestion, inhibiting the activity of methanogens in the rumen and reducing the hydrogen accumulation through fatty acid biohydrogenation. Biohydrogenation converts unsaturated fatty acids to saturated fatty acids so less unsaturated fatty acids are available for uptake into milk, meat or tissues which decreases efficiency feed utilization (Beauchemin et al., 2020). As with increased protein and reduction of fiber, fat supplementation provides highly digestible food that easily converts to yield and spends very little time in the rumen fermenting and so produces little enteric CH_4 (Vargas et al, 2020; Kebreab, 2021).

3.5.5. Ionophore Additive

Ionophore supplementation has also been found to be helpful in reducing GHG emissions from beef steer. Specifically, methane production was reduced by 19g day-1 for each steer in one study (Callaway et al., 2013). In another study the carbon footprint (CF) was measured, and it was found that an ionophore supplement resulted in a 1.4% reduction. The data from the Holos model indicated that ionophore supplementation reduced emissions by 3.1% (Table 3.1). The ionophore was also able to be combined with a fat additive to decrease emissions even further. When the fat and ionophore feed additives were used together the combined effects were less than additive, meaning the outcome was less than if you added each additive reduction on its own together. Ionophores are antimicrobial which causes a shift in the rumen bacterial environment, they reduce the effectiveness of methanogens and may increase the effectiveness of other bacteria that use other fermentation pathways that do not emit CH_4 (Martin et al, 2010). In addition, total fatty acids in the rumen can also contribute to a rumen bacterial environmental shift (Jenkins et al., 2009). Since both ionophore and fat additives are meant to affect the rumen microbiome in similar but different ways it could be that neither can do so to its fullest potential (Jenkins et al., 2009).

It is noteworthy that the effect of ionophores reduces over time and the model also reflects this as the equation used incorporates a denominator that includes the number of days that the ionophore is used. (Holos Algorithm document, 2022). In addition, the dosage of an ionophore is important because studies have shown that dose is imperative to result in emissions reduction (Callaway et al., 2013).

3.5.6. Manure Management

The amount of methane manure emits is based on many different variables. A methane conversion factor defines the amount of potential to produce methane. In order to reach a factor number for each type of manure management many variables are accounted for such as laboratory tests on animal waste and CH_4 production, knowledge of manure storage systems, temperature variation throughout the year, volatile solid retention in a system, and management that affects the amount of volatile solids available for methane conversion (Mangino et al., 2001). Volatile solids can be estimated by feed intake and digestibility (DE). Temperature of manure has a substantial effect on GHG emissions and this is factored in to the management type within Holos. Pereira et al. (2012), found that the highest emissions from excreta resulted when the temperature was 25°C followed by 15°C, then 35°C, and the lowest at 5°C; N_2O emissions were not significantly affected by the temperature difference but CH_4 emissions increased with temperature to 25°C and lowered again at 35°C.

The GHG emissions for the manure manage practices differed in direct N_2O emissions, indirect N_2O emissions, and manure CH_4. The manure management practice that emitted the least GHG emissions for beef cattle and sheep was anaerobic digestion (Table 3.2 and 3.4). The process of anaerobic digestion produces biogas (methane) which is a renewable energy made from the organic residues, the methane is collected and utilized instead of being emitted to the atmosphere as a waste product. Another product of anaerobic digestion is digestate which is a useful organic fertilizer. The process also helps to reduce the volatile solids in the stored manure which helps to reduce CH_4 emissions from the digestate later (Aguirre-Villegas et al., 2022).

The manure management practice with the highest emissions was the same for beef and dairy cattle and sheep and the practice was deep bedding. Deep bedding is when the excrement is mixed with bedding and accumulates on the floors of housing and its left for much longer than other manure management types as it provides bedding for the cattle (Mathot et al., 2016). The decomposition of the OM mixed with the manure also gives off heat which can exacerbate emissions (Webb et al., 2012). The bedding mixed in with the manure provides a source of carbon and freely available C stimulates denitrification and can increase N_2O emissions (Borhan et al., 2012).

The lowest emissions practice for dairy cattle was daily spread (Table 3.2), this was not an option in Holos for beef cattle or sheep. It has been found that the less time manure is stored the less GHG emissions result; there is less time in anaerobic conditions which increase the production of CH_4 (Costa et al., 2012).

3.5.7. Housing Practices

Housing practices varying between different types of livestock, but some commonalities also exist. Holos provides a variety of housing options which were run in scenarios to compare the respective GHG emissions (Table 3.2).

The different housing options differed mostly due to changes in the indirect N_2O emissions, and some small changes in the manure CH_4, all other types of emissions stayed constant. Indirect N_2O emissions refer to losses from ammonia (NH_4^+) volatilization and nitrate (NO_3^-) leaching.

For beef cattle the 'confined (no barn)' describes the housing in a straight-forward manner the cattle are confined in a smaller area, not a large field or pasture and there is no barn, it describes a feedlot. Confined housing assumes solid storage manure with land application that happens later if the manure handling is not otherwise specified. The other types of housing for beef cattle are 'housed in barn (solid)', and 'housed in barn (slurry)' and 'pasture'. The housed options both describe a situation in which all of the cattle are indoors, and they differ by the method of manure storage, either as a solid or a slurry. Pasture describes a confined outdoor area with sufficient forage for feed and minimal energy is required to feed.

Housing temperature is important variable for multiple reasons, one being that if the environment is cold the animal's feed efficiency can decrease as more energy is required to maintain the animal's body heat. Even a windbreak can help reduce heat loss from unhoused animals and can lower the energy requirement (IPCC, 2019). This factor would affect all the housing types for every species.

For beef cattle the confined (no barn) housing had the highest emissions (Table 3.2). Manure from outdoor confinement is collected less often than manure in barns so bacteria that enable transformations thrive and inoculate fresh excrement (Peterson, 2018) and the manure loses more N to volatilization of NH_4^+ compared to stored manure (Wilson et al., 2004). Similarly, scraping of manure off floors is associated with higher emissions than flushing the manure because some residue is left behind with scraping and NH_3 volatilization increases (Ni et al., 1999).

Housing beef cattle on pasture had the lowest emissions (Table 3.2), this is likely because excrement is immediately applied to the land, and there are minimal energy costs with no power needed for lighting, heat or aeration. Chai et al. (2014), found that less GHG emissions resulted from immediate land application than from manure storage. The C:N ratio of the manure environment is likely immediately lowered when deposited on pastureland which helps to inhibit CH_4 and NH_3 emissions (Jiang et al., 2011). Aeration is also higher when manure is directly deposited on pasture rather than being piled or made into a slurry for storage which would create anaerobic conditions which reduce NH_3 and N_2O emissions but CH_4 production is increased under anaerobic conditions (Jiang et al., 2011). Overall, the differences between the GHG emissions from beef cattle housing were minimal with the largest change in emissions being 0.55%.

The dairy cattle housing types included 'tie-stall (solid litter)' and 'tie-stall (slurry)'; tie-stall means the cattle an in a barn and they can stand up and lie down but can turn around or walk around and they are tether with food and water in front of them and they differ by the type of manure management. 'Free-stall barn (solid litter)', 'free-stall barn (slurry scraping)', 'free-stall barn (flushing)', 'free-stall barn (milk-parlour-slurry flushing)'; free-stall means the cows can move around within a barn and go into exercise or resting/comfort stalls as they like. A milk parlour is a room in a barn specifically for milking and then the cows are housed in loose housing where they are free to roam about and there are no stalls. Flushing is when water is used to wash off the excrement, and scraping is when the manure is scraped form the floors. There was also ‘drylot’ which is like a feedlot as the cows are help is open outdoor confined areas but there are also covered sheds for shaded and bedded areas and there is a separate milking parlour, and there was also a pasture housing management practice.

The dairy housing type that emitted the least GHG’s was pasture as well (Table 3.2) and the highest emitter was ‘drylot’ which has the same emissions principles as confined (no barn) in beef cattle. The main reasons for pasture housing having the lowest emissions for dairy cattle would be the same as for beef cattle; related to manure emissions, and feed efficiency, and fuel/energy use. The literature supports this outcome; Pinto et al. (2020), found that dairy cows having access to pasture resulted in significantly lower CH_4 emissions.

Sheep housing types included ‘confined’, ‘housed ewes’, and ‘pasture’, confined was defined as housed in a small area with little energy required to obtain feed, housed ewes is the same as confined but it’s the last 50 days of pregnancy, and pasture is a confined area with sufficient forage. The GHG emissions for the housing types followed a similar pattern to cattle; the confined housing had higher emissions, ‘housed ewes’ had the most, and pasture had the least and the reasons behind these outcomes would be similar (Table 3.2). The housed ewes have higher emissions than confined because as they are pregnant and they would have a higher feed intake and higher output of manure which leads to higher GHG emissions (Borhan et al., 2012).

3.6. Conclusion

The Holos model livestock scenarios have allowed us to observe the GHG emissions output from a variety of BMP’s that use strategies involving diets and feed additive, manure management, and housing (Figure 3.3). The data output has revealed that a high protein diet for beef cattle and sheep can aid in reduction of enteric methane production. Increasing fiber in a dairy cow's diet can have a similar effect in reducing enteric methane emissions. Additionally, feed additives such as fat and ionophores can also be effective in reducing methanogenesis in cattle. Anaerobic digestion may have a promising future in helping to reduce emissions from livestock manure as it is the practice that Holos modelling showed to reduce emissions from manure management the most. Regarding housing, the option of putting cattle out to pasture was associated with the lowest GHG emissions. Identifying the BMP's that result in the lowest GHG emissions in an important step in reducing agricultural GHG emissions.

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Table 3.1. GHG emissions and emission reduction (%) for feed type and feed additives for Beef and Dairy Cattle.

Beef Cattle			Dairy Cattle		
Feed/ Additive	**Emissions (kg CO2e)**	**Emissions Difference (%)**	**Feed/ Additive**	**Emissions (kg CO2e)**	**Emissions Difference (%)**
High Protein	559686.66	-33%	**High Fiber (heifers)**	6614.06	-
Medium Protein	669018.86	-16%	**Low Fiber (heifers)**	5882.32	-11.06%
Low Protein	834711.49	-			
			Legume Silage (lactating)	17847.66	-
			Barley Silage (lactating)	18400.85	+3.1%
			Corn Silage (lactating)	17144.21	3.94%
Default	642790.05		**Default**	28635.53	
Fat 2%	599038.83	-6.81%	**Fat 5%**	28635.53	0.0%
Fat 4%	555287.6	-13.61%	**Ionophore**	24380.87	-14.86%
Ionophore	622916.68	-3.09%	**I + 5%**	26508.2	-7.43%
I + 2% Fat	589102.14	-8.35%			
I + 4% Fat	545350.92	-15.16%			

*Changes for Dairy cattle feed type is for heifers or lactating cows only, feed additives are for all dairy cattle.
*Diet types are compared to each other.
*All feed supplements are compared to the default diets which differ for each season for and cattle type.

Table 3.2. GHG emissions and emissions reduction (%) for housing and manure management options for beef and dairy cattle.

Beef Cattle			Dairy Cattle		
Manure Management	**Emissions (kg CO2e)**	**Emissions Difference (%)**	**Manure Management**	**Emissions (kg CO2e)**	**Emissions Difference (%)**
Solid Storage	509379.32	-	**Solid Storage**	34910.32	-
Compost Intensive	486551.26	-4.48%	**Compost Intensive**	31923.68	-8.56%
Compost Passive	491927.81	-3.43%	**Compost Passive**	32533.23	-6.81%
Deep Bedding	642790.05	+26.19%	**Deep Bedding**	55025.66	+57.62%
Anaerobic Digester	464672.37	-8.78%	**Liquid w/ natural crust**	42867.2	+22.79%
			Liquid no crust	54864.47	+57.16%

			Liquid w/ solid cover	43269	+23.94%
			Daily Spread	27346.18	-21.67
			Anaerobic Digester	27900.41	
Housing Type	**Emissions (kg CO2e)**	**Emissions Difference (%)**	**Housing Type**	**Emissions (kg CO2e)**	**Emissions Difference (%)**
Confined no barn	642790.05	-	**Tie-Stall (solid litter)**	28635.53	-
Housed in Barn (solid)	641961.16	-0.13%	**Tie-stall (slurry)**	28726.01	+0.32%
Housed in Barn (slurry)	642551.97	-0.04%	**Free-stall barn (solid litter)**	26017.87	-9.14%
Pasture	639277.83	-.55%	**Free-stall barn (slurry scraping)**	26209.43	-8.47%
			Free-stall barn (flushing)	26129.61	-8.75%
			Free-stall barn (milk-parlour – slurry flushing)	26129.61	-8.75%
			Drylot	29051.75	+1.45%
			Pasture	22553.82	-21.2%

Table 3.3. GHG emissions and emissions reduction (%) for housing and manure management options for sheep.

Sheep		
Feed Type	**Emissions (kg CO2e)**	**Emissions Difference (%)**
High Protein (Good Quality Forage)	9615.59	-28.88%
Medium Protein (Average Quality Forage)	13520.11	-
Low Protein (Poor Quality Forage)	21200.47	+36.23%
Manure Management	**Emissions (kg CO2e)**	**Emissions Difference (%)**
Solid Storage	9615.59	-
Compost Intensive	8423.41	-12.40%
Compost Passive	8582.01	-10.75%
Deep Bedding	15536.6	+61.58%
Anaerobic Digester	7707.04	-19.85%
Housing Type	**Emissions (kg CO2e)**	**Emissions Difference (%)**
Confined	9615.59	-
Housed Ewes	10637.71	+9.61%
Pasture	5435.95	-39.29%

Table 3.4. Diet coefficients for beef cattle.

Diet Type	Forage (%DM)	CP (kg kg^{-1})	Starch (kg kg^{-1})	NDF (kg kg^{-1})	TDN (%)	ME (Mcal kg^{-1})
Low energy/protein	100	0.057	0.055	0.714	48	1.73
Medium energy/protein	97	0.124	0.071	0.535	55	1.97
High energy/protein	85	0.177	0.099	0.451	60	2.14

Table 3.5. (*Taken from the Holos Algorithm document). Additive reduction factors for beef cattle and dairy cattle.

Beef cattle		*Dairy cattle*[1]	
Additive	*AR* (%)	Additive	*AR* (%)
No additives	0	No additives	0
Ionophore	20*30/#days*	Ionophore	20*30/#days[2]
2%Fat	10	5%Fat	5 * %addedfat[3]
4%Fat	20		
Ionophore + 2%Fat	10 + 0.5 * 20 * 30/ #days	Ionophore + 5%Fat	(5 * %addedfat) + 0.5 * (20 * 30/ #days)
Ionophore + 4%Fat	20 + 0.5 * 20 * 30/ #days		

[1] Values for dairy cattle are based on expert opinion (Darryl Gibb, Karen Beauchemin, Sean McGinn, AAFC).
[2] The effect of ionophores is reduced over time. This calculation prorates the reduction over the time period.
[3] Up to 6% added fat possible.

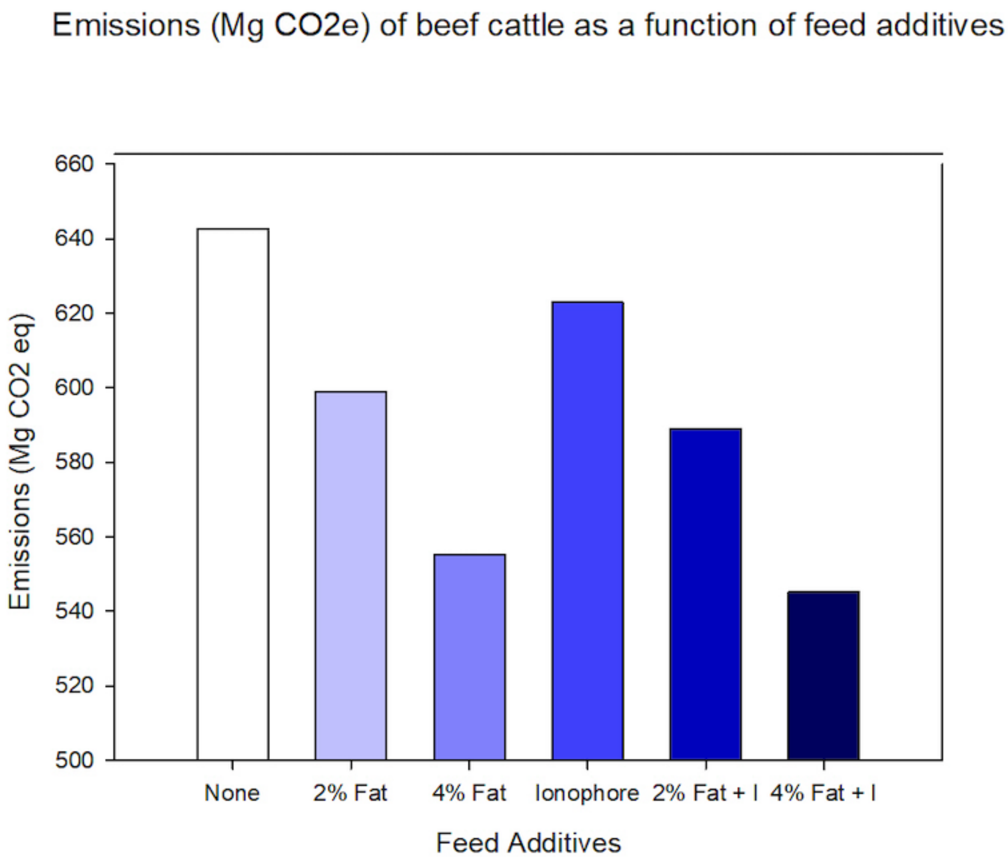

Figure 3.1 Emissions of beef cattle as a function of food additives.

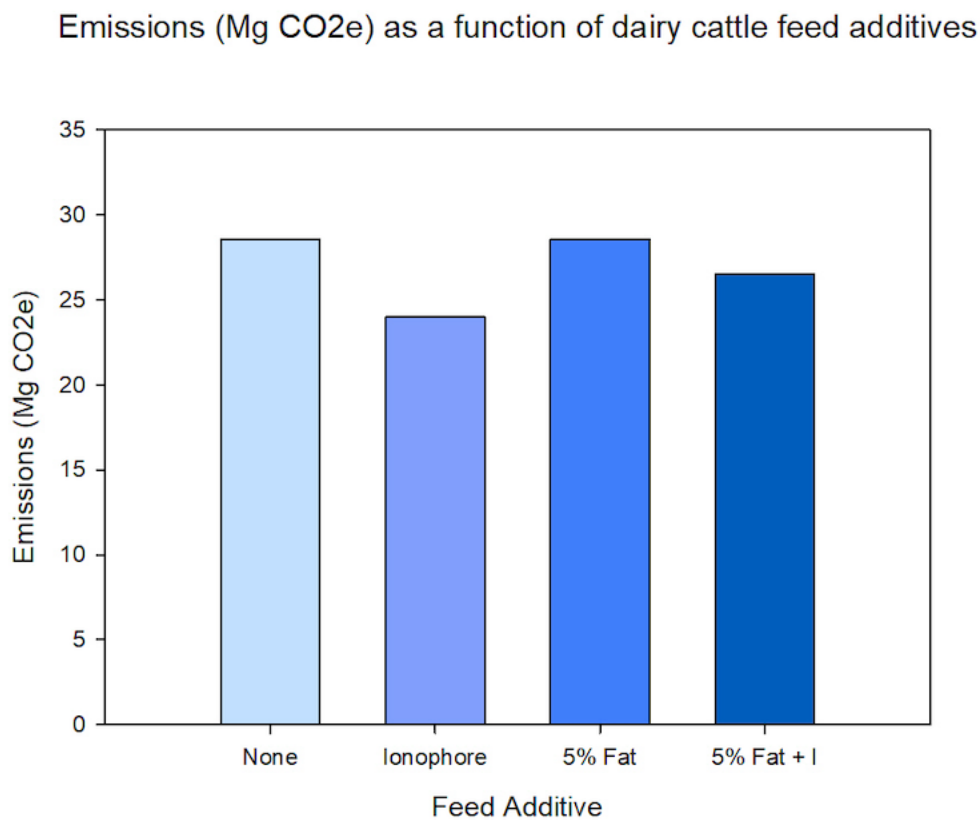

Figure 3.2 Emissions of dairy cattle as a function of food additives.

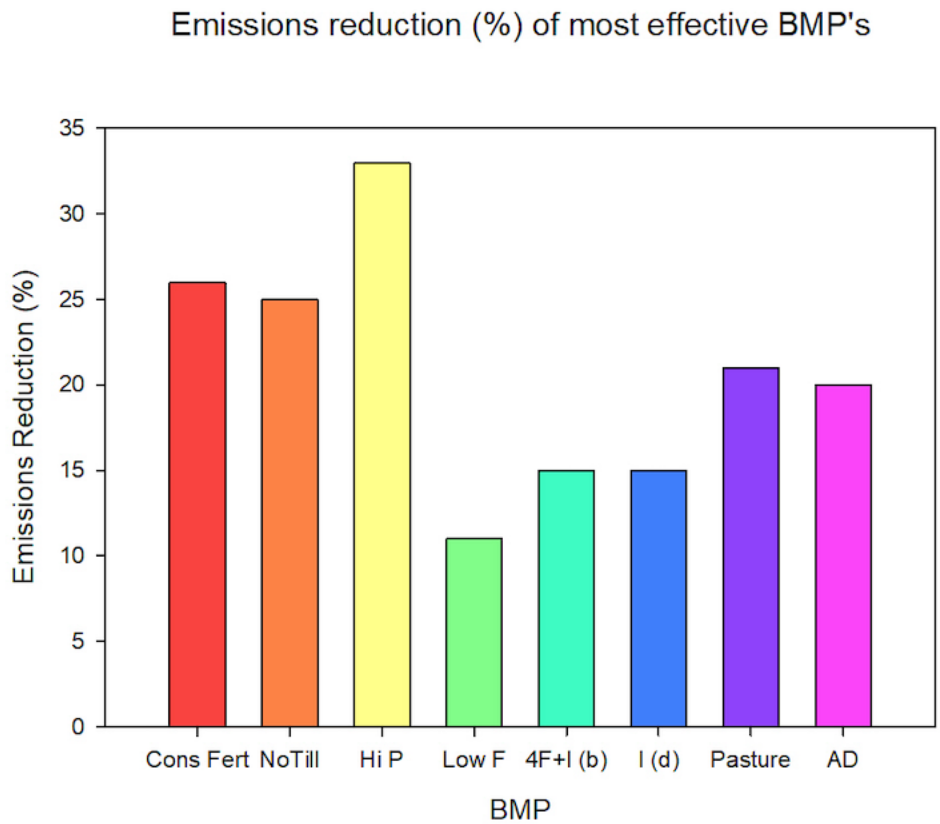

Figure 3.3 GHG emissions as a function of best management practices.

Chapter 4 - Conclusion

Conclusion and Recommendations

Using Holos to model farming scenarios and comparatively analyze GHG emissions data output enabled the integral evaluation of many management options and research questions. In a first stage, the land management practices that were analyzed were tillage options and fertilizer rate. The model output showed that as tillage intensity increased, GHG emissions increased as well. As anticipated the model results also captured that as the fertilizer rate was increased the GHG emissions also increased. Even when relative crop yield was considered, the GHG emissions intensity results showed that per unit of production, emissions were still highest at the highest tillage intensity and the highest fertilizer rate. The general outcome of decreasing emissions with decreasing tillage intensity and decreasing fertilizer application is supported in the scientific literature but this outcome with specific modeling for the Canadian Prairies and the clear pattern and average emissions decrease are good evidence for management practices in this specific region and specific outcomes with emissions reduction numbers and percentages that can help inform producers and researchers. It was also very notable to see that even with specific yields considered emissions intensity also showed the same pattern of reduced emissions for this region.

Assessment of crop rotations showed that order of rotation within Holos has no effect on both the GHG emissions and crop yields. Because the model output showed the GHG emissions from each crop type, this model result could inform which crops to include within a rotation to keep emissions down. In general, inclusion of a lower emitting crop into a rotation would shift the overall farm GHG emissions down. For example, most legumes had lower GHG emissions, so by including a legume in rotation emissions could be reduced. Because this is preliminary evidence, there is a need to further investigate mitigation of GHG emissions when choosing a crop rotation.

The Holos model output showed that use of cover crops in general reduced GHG emissions. However, the model does not currently differentiate between the different cover crop species. Nevertheless, Holos enables gaining insights of the GHG emissions reduction that is possible by utilizing this BMP.

Livestock BMP scenarios also provided valuable information on GHG emissions. Regarding beef cattle, the diet options proved useful. Additives of fat and ionophores effectively resulted in decreases in GHG emissions. The largest mitigation of GHG emissions attained from using feed additives resulted from a combination of 4% fat additive and ionophore. GHG emissions also decreases when protein was increased from 5.7% to 12.4% and to 17.7%. Different types of manure storage were also evaluated, and anaerobic digestion was the intervention with the lowest emissions while intensive composting had the second least emissions. Lastly, housing type that emitted the least emissions was “Housed in Barn (solid)”. When dairy cattle interventions were modelled using Holos feed additive were also experimented with. A low fiber diet was found to result in less emissions than a high fiber diet. An addition of ionophore was found to reduce emissions the most compared to a 5% fat additive and the combination of the fat and ionophore. The manure storage type that resulted in the least GHG emissions was “Intensive Compost”. The housing type with the least emissions for dairy cattle was “Free-stall Barn (solid litter)”.

The initial aim of this work was to identify potentially useful BMPs and provide further evidence of the resultant changes in GHG emissions. This goal was achieved to a certain extent.

The goal was constrained by the capacity of the model and the existing body of subject knowledge. The Holos model is fed by existing research findings as available in the literature. Therefore, the modeling of newer BMPs with limited availability of scientific evidence was unfeasible in the model. Other limitations of the project were time and the ability to have in-depth research on many different topics. To create scenarios specific pieces of the model had to be fully understood as well as the practices and scientific knowledge behind the practices. Some practices like irrigation for example could be another entire thesis project on its own even though it can be considered under the heading of BMP.

The output data from the Holos model became useful as it takes generalized outcomes from scientific studies and allows those outcomes to be applied to a broad variety of locations and conditions to witness if the outcomes hold true and to learn how they are being affected. Modelling experiments in general and their outputs can have its limitations as we are not replicating in real groundwork experiments, but these simulations by model scenarios are still valuable as an addition to the realm of knowledge. Running many scenarios under similar conditions across the prairie provinces and many factors held constant within the model allowed a unique comparison of the chosen BMP's. The BMP's were able to be looked at and compared as to which ones had the greatest impact on reducing GHG emissions.

From this comprehensive analysis, recommendations could be made with some confidence. As the model provides generalizations, there would always be the necessary caveat for the grower to do the research for the specific area, conditions, and economic factors. This is where Holos could be employed widely, this tool can be used to meticulously represent the producers' specific farm conditions and input and hence, the results could be tailored closely to the actual farming system.

Overall, this study leads to overarching recommendations of reducing tillage as it reduces emissions from farm equipment fuel emissions as well as from soil GHG emissions, the majority from nitrogen cycling. The modelling outcomes also support a recommendation to reduce nitrogen fertilizer inputs where possible. Balancing the fertilizer inputs with the yield expectations so that the farm strategy takes into account reducing GHG emissions as well as maximizing profits can benefit the environment in terms of climate change mitigation.

The study outcomes support livestock recommendations of implementing feed additives such as fats, and ionophores to mitigate GHG emissions as well as further evaluating and adjusting feed macronutrients such as protein and fiber to reach the most productive levels. The study also supports use of solid manure storage and perhaps future implementation of anaerobic digestion of manure.

There are many new studies that could be carried out in the future to further contribute to the knowledge base. Field experiments involving BMPs implemented within the model would be insightful. Specifically, GHG studies regarding the order of crop species within crop rotations as well as the influence of anaerobic digestion would be particularly interesting. Carbon sequestration is also an interesting topic that is closely linked with GHG emissions. Holos also has interesting capabilities to predict this aspect, a BMP study with carbon sequestration as the primary measurement would be informative. Next steps can also include the continued evolution of the Holos model into a series of updated versions that represent even more complex farming scenarios and new BMPs within regenerative agriculture. It will be extremely interesting when production and economic aspects of the model become operational, and an entirely new angle of sustainability can be explored and unveiled. For the continued growth of the model to occur, continued high quality research must be performed to inform the model.

Agriculture and soil science are multifaceted encompassing infinite possibilities and factors, and growers and researchers will continually be learning how to produce more, emit less, and become more sustainable. The broad challenge is ripe for joint engagement by industry and academics. The future holds so much knowledge and growth.

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Appendix

Raw Data for Tillage Type and Fertilizer Rate

Alberta

Black Chernozem

ER: 744 002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	227119.33	269911.21	312559.24	227119.33	269911.21	312559.24	311122.37	369741.38	428163.34
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	337230.86	406875.83	475942.56	375662.26	444911.03	513977.76	469174.1	554250	639090.66

Dark Grey Chernozem

ER: 727 008	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	54707.02	65014.44	75287.22	54707.02	65014.44	75287.22	74941.12	89060.88	103133.18
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	165214.74	201979.06	238670.54	203249.94	240014.26	276705.74	232992.85	273569.5	314060.5

Gray Luvisol

ER: 732 001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	341337.71	405649.622	469745.36	341337.71	405649.622	469745.36	467585.9	555684.42	643486.79
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	451845.44	542614.25	633128.69	489880.64	580649.45	671163.89	625637.63	740193.04	854414.12

2AB

ER: 750 006	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	258641.05	307371.98	355939.09	258641.05	307371.98	355939.09	354302.81	421057.5	487587.8
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	369148.78	444336.6	519322.42	407183.98	482371.8	557357.62	512354.54	605566.12	698515.12

ER: 681 005	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	54196.54	64407.79	74584.71	54196.54	64407.79	74584.71	74241.84	88229.85	102170.84
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	164704.27	201372.41	237968.04	202739.47	239407.61	276003.24	232293.57	272738.47	313098.16

ER: 708 001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	226481.24	269152.89	311681.1	226481.24	269152.89	311681.1	310248.28	368702.59	426960.41
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	336988.97	406117.51	475064.43	375024.17	444152.71	513099.63	468300	553211.21	637887.74

3AB

ER: 731002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	227246.95	270062.87	312734.86	227246.95	270062.87	312734.86	311297.19	369949.14	428403.92
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	337754.68	407027.49	476118.19	375789.88	445062.69	514153.39	469348.92	554457.76	639331.25

ER: 586011	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	112518.1	133717.8	154846.23	112518.1	133717.8	154846.23	154134.39	183175.06	212118.12
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	223025.83	270682.42	318229.55	261061.03	308717.62	356264.75	312186.12	367683.69	423045.45

ER: 678 002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	111497.16	132504.49	153441.21	111497.16	132504.49	153441.21	152735.83	181513	210193.44
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	222004.89	269469.11	316824.54	260040.09	307504.31	354859.74	310787.56	366021.63	421120.77

5AB

ER: 727002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	54707.02	65014.44	75287.22	54707.02	65014.44	75287.22	74941.12	89060.88	103133.18
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	165214.74	201979.06	238670.54	203249.94	240014.26	276705.74	232992.85	273569.5	314060.5

ER: 687 011	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	265915.3	316016.77	365949.83	265915.3	316016.77	365949.83	364267.53	432899.68	501301.14
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	376423.02	452981.39	529333.16	414458.22	491016.59	567368.36	522319.26	617408.31	712228.46

ER: 682 009	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	230437.41	273854.44	317125.54	230437.41	273854.44	317125.54	315667.68	375143.07	434418.54
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	340945.14	410819.07	480508.86	378980.34	448854.27	518544.06	473719.41	559651.7	645345.87

4AB

ER: 746 001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	255705.83	303883.73	351899.67	255705.83	303883.73	351899.67	350281.96	416279.08	482054.35
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	366213.56	440848.35	515283	404248.76	478883.55	553318.2	508333.69	600787.7	692981.67

ER: 683 003	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	115836.18	137661.04	159412.53	115836.18	137661.04	159412.53	158679.7	188576.76	218373.33
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	226343.91	274625.66	322795.86	264379.11	312660.86	360831.06	316731.43	373085.38	429300.65

ER: 650 005	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	206189.93	245038.47	283756.41	206189.93	245038.47	283756.41	282451.96	335669.13	388707.42
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	316697.66	382003.09	447139.74	354732.86	420038.29	485174.94	440503.69	520177.76	599634.74

Saskatchewan

ER: 736012	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	175433.92	208487.68	241430.32	175433.92	208487.68	241430.32	240320.44	285599.55	330726.46
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	285941.65	345452.3	404813.64	323976.85	383487.5	442848.84	398372.17	470108.18	541653.79

ER: 733004	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	156629.36	186140.12	215551.67	156629.36	1861400.12	215551.67	214560.77	254986.46	295276.27
Indirect N2O	91829.18	114834.74	137762.97	91829.18	114834.74	137762.97	91829.18	114834.74	137762.97
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	320313.59	385494.66	450112.51	358744.99	423529.86	488147.71	426185.2	501885.01	577381.1

ER: 714001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	212443.23	252469.96	292362.14	212443.23	252469.96	292362.14	291018.12	345849.26	400496.08
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	322950.96	389434.59	455745.46	360986.16	427469.78	493780.66	449069.85	530357.88	611423.4

SK 2

ER: 752003	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	212315.61	252318.29	292186.51	212315.61	252318.29	292186.51	290843.3	345641.5	400255.49
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	328926.15	400177.79	471240.66	366961.35	438212.99	509275.86	454997.85	541045	626853.65

ER: 699001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	141582.95	168258.79	194844.96	141582.95	168258.79	194844.96	193949.24	230491.49	266910.9
Indirect N2O	91829.18	114834.74	137762.97	91829.18	114834.74	137762.97	91829.18	114834.74	137762.97
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	305663.38	367613.34	429405.79	343698.58	405648.54	467440.99	405573.67	477390.04	549015.74

ER: 710008	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	323981.62	385023.45	445860.09	323981.62	385023.45	445860.09	443810.44	527429.39	610767.25
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	434489.35	521988.07	609243.42	472524.55	560023.27	647278.62	601862.17	711938.01	821694.58

SK3

ER: 756006	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	212060.37	252014.97	291835.25	212060.37	252014.97	291835.25	290493.66	345225.98	399774.32
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	328670.92	399874.47	470889.41	366706.12	437909.67	508924.61	454648.21	540629.48	626372.48

ER: 687010	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	175174.94	208179.89	241073.9	175174.94	208179.89	241073.9	239965.67	285177.94	330238.22
Indirect N2O	91829.18	114834.74	137762.97	91829.18	114834.74	137762.97	91829.18	114834.74	137762.97
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	339255.37	407534.44	475634.74	377290.57	445569.64	513699.94	451590.1	532076.48	612343.06

ER: 711001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	274210.48	325874.87	377365.58	274210.48	325874.87	377365.58	375630.8	446403.93	516939.15
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	384718.21	462839.49	540748.91	422753.41	500974.69	578784.11	533682.53	630912.55	727866.48

SK4

ER: 748012	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	201595.67	239578.6	277433.84	201595.67	239578.6	277433.84	276158.46	328189.86	380046.36
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	318206.22	387438.1	456488	356241.42	425473.3	494523.2	440313	523593.36	606644.52

ER: 729010	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	162298.01	192876.8	223352.81	162298.01	192876.8	223352.81	222326.04	264214.8	305962.97
Indirect N2O	91829.18	114834.74	137762.97	91829.18	114834.74	137762.97	91829.18	114834.74	137762.97
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	326378.44	392231.35	457913.64	364413.64	430266.55	495948.84	433950.47	511113.35	588067.59

ER: 714010	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	212443.23	252469.96	292362.14	212443.23	252469.96	292362.14	291018.12	345849.26	400496.08
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	322950.96	389434.58	455745.46	360986.16	427469.78	493780.66	449069.85	530357.88	611423.4

SK5

ER: 733005	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	198277.6	235635.36	272867.54	198277.6	235635.36	272867.54	271613.15	322788.16	373791.16
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	308785.33	372599.98	436250.87	346820.53	410635.18	474286.07	429664.88	507296.78	584718.48

ER: 694004	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	146271.83	173831.11	201297.75	146271.83	173831.11	201297.75	200372.37	238124.81	275750.34
Indirect N2O	97931.99	125729.62	153433.75	97931.99	125729.62	153433.75	97931.99	125729.62	153433.75
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	316455.08	384080.53	451529.41	354490.28	422115.73	489564.61	418809.62	495918.23	573526.01

ER: 704002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	66575.52	79119.1	91620.53	66575.52	79119.1	91620.53	91199.34	108382.33	125507.57
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	177083.25	216083.73	255003.85	215118.45	254118.93	293039.05	249251.07	292890.96	336434.89

Manitoba

ER: 724008	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	59301.27	70474.31	81609.79	59301.27	70474.31	81609.79	81234.62	96540.15	111794.23
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	175911.82	218333.81	260663.94	213947.02	256369.01	298699.14	245389.17	291943.65	338392.39

ER: 841001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	137914.14	163898.74	189795.99	137914.14	163898.74	189795.99	188923.49	224518.82	259994.51
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	254524.69	311758.24	368850.15	292559.89	349793.44	406885.35	353078.03	419922.32	486592.67

ER: 715003	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	160374.96	190591.44	220706.34	160374.96	190591.44	220706.34	219691.73	261084.16	302337.45
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	270882.69	327556.06	384089.66	308917.89	365591.26	422124.86	377743.46	445592.78	513264.77

MB2

ER: 764003	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	141870.31	168600.3	195240.43	141870.31	168600.3	195240.43	194342.89	230959.31	267452.64
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	258480.86	316459.79	374294.58	296516.06	354494.99	412329.78	358497.44	426362.81	494050.8

ER: 718004	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	54196.54	64407.79	74584.71	54196.54	64407.79	74584.71	74241.84	88229.85	102170.84
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	170807.09	212267.29	253638.87	208842.29	250302.49	291674.07	238396.38	283633.35	328768.99

ER: 379001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	97331.53	115669.9	133946.62	97331.53	115669.9	133946.62	133330.86	158451.91	183488.46
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	207839.25	252634.52	297329.95	245874.45	290669.72	335365.15	291382.59	342960.53	394415.85

MB3

ER: 841002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	137914.14	163898.74	189795.99	137914.14	163898.74	189795.99	188923.49	224518.82	259994.51
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	254524.69	311758.24	368850.15	292559.89	349793.44	406885.35	353078.03	419922.32	486592.67

ER: 726001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	54196.54	64407.79	74584.71	54196.54	64407.79	74584.71	74241.84	88229.85	102170.84
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	170807.09	212267.29	253638.87	208842.29	250302.49	291674.07	238396.38	283633.35	328768.99

ER: 724002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	59301.27	70474.31	111794.23	59301.27	70474.31	81609.79	81234.62	96540.15	111794.23
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	169809	207438.93	322721.56	207844.2	245474.13	283028.31	239286.35	281048.77	322721.56

MB4

ER: 846001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	188706.23	224260.63	259695.52	188706.23	224260.63	259695.52	258501.68	307206.34	355747.29
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	305316.77	372120.13	43749.68	343351.97	410155.33	476784.88	422656.22	502609.84	582345.45

ER: 724008	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	59301.27	70474.31	81609.79	59301.27	70474.31	81609.79	81234.62	96540.15	111794.23
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	175911.82	218333.81	260663.94	213947.02	256369.01	298699.14	245389.17	291943.65	338392.39

ER: 714015	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	54196.54	64407.79	74584.71	54196.54	64407.79	74584.71	74241.84	88229.85	102170.84
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	164704.27	201372.41	237968.04	202739.47	239407.61	276003.24	232293.57	272738.47	313098.16

MB5

ER: 753002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	67468.84	80180.74	92849.91	67468.84	80180.74	92849.91	92423.08	109836.64	127191.66
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	184079.39	228040.24	271904.07	222114.59	266075.44	309939.27	256577.62	305240.14	353789.82

ER: 720001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	54196.54	64407.79	74584.71	54196.54	64407.79	74584.71	74241.84	88229.85	102170.84
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	170807.09	212267.29	253638.87	208842.29	250302.49	291674.07	238396.38	283633.35	328768.99

ER: 376001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	54196.54	64407.79	74584.71	54196.54	64407.79	74584.71	74241.84	88229.85	102170.84
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	164704.27	201372.41	237968.04	202739.47	239407.61	276003.24	232293.57	272738.47	313098.16

AB1 **Eutric Brunisol**

ER: 614002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	240551.01	270653.54	299640.17	240551.01	270653.54	299640.17	329521.93	370758.27	410465.98
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	336561.91	382117.91	426442.24	350428.91	396381.11	440705.44	448908.63	505994.65	561040.06

Regosol

ER: 821008	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	126428.5	150249.07	173989.57	126428.5	150249.07	173989.57	173189.72	205820.64	238341.87
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	236936.23	287213.69	337372.89	274971.43	325248.89	375408.09	307073.25	390329.26	449269.2

Humic Gleysol

ER: 592010	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	48468.75	54534.12	60374.65	48468.75	54534.12	60374.65	66395.54	74704.27	82705
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	127901.43
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	144083.45	165998.5	187176.73	158346.65	180261.7	201439.93	185782.24	209940.65	257447.28

AB2

ER: 616001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	48468.75	54534.12	603374.65	48468.75	54534.12	603374.65	66395.54	74704.27	82705
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	144083.45	165998.5	187176.73	158346.65	180261.7	201439.93	185782.24	209940.65	233279.08

ER: 623018	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	116474.27	138419.35	160290.66	116474.27	138419.35	160290.66	159553.8	189615.55	219576.25
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	226982	275383.97	323673.99	265017.2	313419.17	361709.19	317605.52	374124.17	430503.58

ER: 708001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	202545.43	227891.94	252298.86	202545.43	227891.94	252298.86	277459.49	312180.74	345614.88
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	127901.43
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	298160.13	339356.32	379100.94	312423.33	353619.52	393364.14	396846.19	447417.12	496188.96

AB3

ER: 631002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	231306.41	260252.07	288124.72	231306.41	260252.07	288124.72	316858.1	356509.68	394691.39
Indirect N2O	33712.61	44986.77	55843	33712.61	44986.77	55843	33712.61	44986.77	55843
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	330335.92	377977.68	423928.95	344599.12	392240.88	438192.15	439659.6	498007.3	554267.62

ER: 750006	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	258641.05	307371.98	355939.09	258641.05	307371.98	355939.09	354302.81	421057.5	487587.8
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	369148.78	444336.6	519322.42	407183.98	482371.8	557357.62	512354.54	605566.12	698515.12

ER: 798008	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	218067.23	245356.14	271633.45	218067.23	245356.14	271633.45	298722.23	336104.29	372100.62
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	313681.93	356820.51	398435.53	327945.13	371083.71	412698.73	418108.93	471340.67	522674.69

AB4

ER: 687002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	68555.78	77134.84	85395.88	68555.78	77134.84	85395.88	93912.03	105664.17	116980.66
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	164170.48	188599.22	212197.96	178433.68	202862.42	226461.16	213298.73	240900.55	267554.74

ER: 838012	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	79082.11	93982.08	108831.97	79082.11	93982.08	108831.97	108331.66	128742.58	149084.89
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	189589.84	230946.7	272215.29	227625.04	268981.9	310250.49	266383.39	313251.2	360012.21

ER: 771005	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	272165.26	306223.99	339020.17	272165.26	306223.99	339020.17	372829.13	419484.92	464411.2
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	367779.96	417688.37	465822.25	382043.16	431951.57	480085.45	492215.83	554721.3	614985.27

AB5

ER: 650006	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	184398.62	207474.24	229694.46	184398.62	207474.24	229694.46	252600.85	284211.29	314649.94
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	280013.32	318938.62	356496.53	294276.52	333201.82	370759.73	371987.55	419446.67	465224.01

ER: 815003	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	168032.06	199691.22	231243.95	168032.06	199691.22	231243.95	230180.91	273549.61	316772.54
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	278539.79	336655.84	394627.28	316574.99	374691.04	432662.48	388232.64	458058.24	527699.87

ER: 809001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	290654.47	327026.93	362051.08	290654.47	327026.93	362051.08	398156.8	447982.1	495960.38
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	386269.17	438491.31	48853.15	400532.37	452754.51	503116.35	517543.5	583218.47	646534.46

SK1

ER: 691009	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	48468.75	54534.12	60374.65	48468.75	54534.12	60374.65	66395.54	74704.27	82705
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	144083.45	165998.5	187176.73	158346.65	180261.7	201439.93	185782.24	209940.65	233279.08

ER: 694004	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	160502.58	190743.1	220881.96	160502.58	190743.1	220881.96	219866.55	261291.92	302578.03
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	271010.31	327707.72	384265.29	309045.51	365742.92	422300.49	377918.28	445800.54	513505.36

ER: 821003	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	113066.82	127215.99	140840.65	113066.82	127215.99	140840.65	154886.06	174268.48	192932.4
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	208681.52	238680.37	267642.73	222944.72	252943.57	281905.93	274272.76	309504.86	343506.48

SK2

ER: 694002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	143539.77	161502.32	178799	143539.77	161502.32	178799	196629.82	221236.05	244930.13
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	239154.47	272966.69	305601.07	253417.67	287229.89	319864.27	316016.52	356472.43	395504.21

ER: 698002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	185771.01	220772.38	255656.1	185771.01	220772.38	255656.1	254480.83	302427.92	3500213.84
Indirect N2O	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46	38256.48	52444.82	66585.46
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	296278.73	357737	419039.43	334313.93	395772.2	457074.63	412532.56	486936.54	561141.16

ER: 815006	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	150273.49	169078.69	187186.8	150273.49	169078.69	187186.8	205854.09	231614.65	256420.27
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	245888.19	280543.07	313988.87	260151.39	294806.27	328252.07	325240.79	366851.03	406994.35

SK3

ER: 693006	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	147306.09	165739.95	183490.48	147306.09	165739.95	183490.48	201789.16	227041.03	251356.82
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	242920.79	277204.33	310292.55	257183.99	291467.53	324555.75	321175.86	362277.41	401930.9

ER: 715004	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	160374.96	190591.44	220706.34	160374.96	190591.44	220706.34	219691.73	261084.16	302337.45
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	276985.51	338450.94	399760.49	315020.71	376486.14	437795.69	383846.28	456487.66	528935.6

ER: 739003	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	147899.24	166407.33	184229.34	147899.24	166407.33	184229.34	202601.7	227955.25	252368.96
Indirect N2O	69651.19	82317.46	94514.19	69651.19	82317.46	94514.19	69651.19	82317.46	94514.19
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	282867.32	321463.63	358704.75	297130.52	335726.83	372967.95	361341.78	406783.55	450616.37

SK4

ER: 698003	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	166137.68	186928.13	206947.88	166137.68	186928.13	206947.88	227585.86	256065.93	283490.25
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	261752.38	298392.51	333749.96	276015.58	312655.71	348013.16	346972.56	391302.31	434064.33

ER: 709018	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	138297	164353.73	190322.87	138297	164353.73	190322.87	189447.94	225142.1	260716.27
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	254907.54	312213.23	369377.03	292942.74	350248.43	407412.23	353602.49	420545.6	487314.42

ER: 821001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	115004.25	129395.87	143253.99	115004.25	129395.87	143253.99	157540.07	177254.61	196238.34
Indirect N2O	69651.19	82317.46	94514.19	69651.19	82317.46	94514.19	69651.19	82317.46	94514.19
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	249972.33	284452.17	317729.41	264235.53	298715.37	331992.61	316280.15	356082.91	394485.76

SK5

ER: 711001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	245230.38	275918.48	305468.98	245230.38	275918.48	305468.98	335932.02	377970.52	418450.65
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	340845.08	387382.85	432271.05	355108.28	401646.05	446534.25	455328.72	513206.89	569024.73

ER: 822004	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	224822.2	267181.27	309397.95	224822.2	267181.27	309397.95	307975.62	366001.74	423832.81
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	341432.75	415040.77	488452.11	379467.95	435075.97	526487.31	472130.17	561405.24	650430.96

ER: 729006	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	1155939.65	130448.33	144419.17	115939.65	130448.33	144419.17	158821.44	178696.34	197834.48
Indirect N2O	69651.19	82317.46	94514.19	69651.19	82317.46	94514.19	69651.19	82317.46	94514.19
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	250907.73	285504.63	318894.58	265170.93	299767.83	333157.78	317561.52	357524.64	396081.89

MB1

ER: 717002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	68555.78	77134.84	85395.88	68555.78	77134.84	85395.88	93912.03	105664.17	116980.66
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	164170.48	188599.22	212197.96	178433.68	202862.42	226461.16	213298.73	240900.55	267554.74

ER: 669009	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	54196.54	64407.79	74584.71	54196.54	64407.79	74584.71	74241.84	88229.85	102170.84
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	170807.09	212267.29	253638.87	208842.29	250302.49	291674.07	238396.38	283633.35	328768.99

ER: 723011	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	92944.34	104575.38	115775.26	92944.34	104575.38	115775.26	127321.01	143253.95	158596.25
Indirect N2O	73065.99	88578.69	103516.34	73065.99	88578.69	103516.34	73065.99	88578.69	103516.34
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	231327.22	265892.92	299252.84	245590.42	280156.12	313516.04	289475.9	328343.48	365845.82

MB2

ER: 718001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	48468.75	54534.12	60374.65	48468.75	54534.12	60374.65	66395.54	74704.27	82705
Indirect N2O	33712.61	44986.77	55843	33712.61	44986.77	55843	33712.61	44986.77	55843
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	147498.25	172259.74	196178.88	161761.45	186522.94	210442.08	189197.05	216201.89	242281.23

ER: 849007	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	161523.53	191956.4	222286.98	161523.53	191956.4	222286.98	221265.11	262953.98	304502.71
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	278134.07	339815.9	401341.14	316169.27	377851.1	439376.34	385419.65	458357.48	531100.87

ER: 375001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	94230.52	106022.51	117377.38	94230.52	106022.51	117377.38	129082.9	145236.32	160790.93
Indirect N2O	73065.99	88578.69	103516.34	73065.99	88578.69	103516.34	73065.99	88578.69	103516.34
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	232613.4	267340.05	300854.95	246876.6	281603.25	315118.15	291237.79	330325.86	368040.51

MB3

ER: 724002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	53033.98	59670.65	66061.29	53033.98	59670.65	66061.29	72649.29	81740.61	90494.92
Indirect N2O	33712.61	44986.77	55843	33712.61	44986.77	55843	33712.61	44986.77	55843
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	152063.49	177396.26	201865.53	166326.69	191659.46	216128.73	195450.8	223238.23	250071.16

ER: 852005	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	153355.96	182249.97	211046.86	153355.96	182249.97	211046.86	210076.66	249657.49	289105.28
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	269966.5	330109.47	390101.01	308001.7	368144.67	428136.21	374231.2	445060.99	515703.44

ER: 714015	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	92944.34	104575.38	115775.26	92944.34	104575.38	115775.26	127321.01	143253.95	158596.25
Indirect N2O	73065.99	88578.69	103516.34	73065.99	88578.69	103516.34	73065.99	88578.69	103516.34
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	231327.22	265892.92	299252.84	245590.42	280156.12	313516.04	289475.9	328343.48	365845.82

MB4

ER: 723004	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	48468.75	54534.12	60374.65	48468.75	54534.12	60374.65	66395.54	74704.27	82705
Indirect N2O	33712.61	44986.77	55843	33712.61	44986.77	55843	33712.61	44986.77	55843
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	147498.25	172259.74	196178.88	161761.45	186522.94	210442.08	189197.05	216201.89	242281.23

ER: 850003	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	56110.82	66682.73	77219.12	56110.82	66682.73	77219.12	76864.13	91346.21	105779.61
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	172721.36	214542.23	256273.27	210756.56	252577.43	294308.47	241018.68	286749.71	332377.76

ER: 677002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	92944.34	104575.38	115775.26	92944.34	104575.38	115775.26	127321.01	143253.95	158596.25
Indirect N2O	73065.99	88578.69	103516.34	73065.99	88578.69	103516.34	73065.99	88578.69	103516.34
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	231327.22	265892.92	299252.84	245590.42	280156.12	313516.04	289475.9	328343.48	365845.82

MB5

ER: 726003	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	48468.75	54534.12	60374.65	48468.75	54534.12	60374.65	66395.54	74704.27	82705
Indirect N2O	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84	30297.81	38725.53	46840.84
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	144083.45	165998.5	187176.73	158346.65	180261.7	201439.93	185782.24	209940.65	233279.08

ER: 715001	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	160374.96	190591.44	220706.34	160374.96	190591.44	220706.34	219691.73	261084.16	302337.45
Indirect N2O	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29	44359.29	63339.69	82256.29
Energy CO2	72251.25	84519.81	96797.86	110286.45	122555.01	134833.06	119795.25	132063.81	144341.86
CO2	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88	25207.79	45039.16	64885.88
Total CO2e	276985.51	338450.94	399760.49	315020.71	376486.14	437795.69	383846.28	456487.66	528935.6

ER: 846002	No-till			Reduced Tillage			Intensive Tillage		
	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert	Conservative	Moderate Fe	High Fert
Direct N2O	134024.1	150795.86	166945.9	134024.1	150795.86	166945.9	183594.66	206569.67	228693.01
Indirect N2O	73065.99	88578.69	103516.34	73065.99	88578.69	103516.34	73065.99	88578.69	103516.34
Energy CO2	65316.89	72738.84	79961.23	79580.09	87002.04	94224.43	89088.89	96510.84	103733.23
CO2	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93	14639.26	26636.39	38310.93
Total CO2e	272406.99	312113.4	350423.47	286670.19	326376.6	364686.67	345749.55	391659.21	435942.58

Beef Cattle Raw Data

16-Jun		Beef Cow-calf		246 total	737005	number are default

low-protein energy for all

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	15604.72	49640.84	482234.75	49133.62	596613.94
Manure CH4	4801.94	5432.07	147178.69	49711.25	207145.95
Direct N2O	367.05	3201.09	10017.84	2740.63	16326.61
Indirect N2O	214.65	1509.02	5911.83	1092.69	8728.19
Land Use Change CO2					
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	21052.62	60768.52	647270.91	105619.43	834711.49

medium protein energy for all

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	11717.95	34137.69	362121.22	50527.49	458504.34
Manure CH4	3451.15	3575.3	105777.33	48949.48	161753.26
Direct N2O	543.02	4429.28	15417.66	5552.6	25942.56
Indirect N2O	386.89	2572.27	11034.22	2928.52	16921.9
Land Use Change CO2					
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	16163.27	45700.04	496278.22	110877.33	669018.86

high protein energy for all

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	9691.26	26955.35	299490.21	50582.88	386719.69
Manure CH4	2479.27	2452.19	75989.16	42565.16	123485.78
Direct N2O	534.3	4145.12	15150.1	6613.22	26442.75
Indirect N2O	381.02	2423.49	10853.42	3483.71	17141.64
Land Use Change CO2					
Energy CO2	64.26	985.5	2919.24	2919.24	5896.8
Subtotal (kg	13150.11	36961.65	403410.7	106164.2	559686.66

default

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	10642.01	49640.84	326655.55	50573.83	437512.24
Manure CH4	3429.59	5432.07	105066.7	43607.56	157535.92
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	385.51	1509.02	10988.58	3388.11	16271.22
Land Use Change CO2					0
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	15063.57	60768.52	460029.16	106928.79	642790.05

2% fat compared to defaults

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	9577.81	44676.76	293990	45516.45	393761.02
Manure CH4	3429.59	5432.07	105066.7	43607.56	157535.92
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	385.51	1509.02	10988.58	3388.11	16271.22
Land Use Change CO2					
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	13999.37	55804.44	427363.61	101871.41	599038.83

4% fat

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	8513.61	39712.68	261324.44	40459.07	350009.8
Manure CH4	3429.59	5432.07	105066.7	43607.56	157535.92
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	385.51	1509.02	10988.58	3388.11	16271.22
Land Use Change CO2					
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	12935.17	50840.36	394698.05	96814.02	555287.6

Iono

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	10095.04	48824.83	310640.84	48078.16	417638.88
Manure CH4	3429.59	5432.07	105066.7	43607.56	157535.92
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	385.51	1509.02	10988.58	3388.11	16271.22
Land Use Change CO2					
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	14516.6	59952.51	444014.45	104433.12	622916.68

2 + I

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	9304.32	44268.75	285982.64	44268.62	383824.34
Manure CH4	3429.59	5432.07	105066.7	43607.56	157535.92
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	385.51	1509.02	10988.58	3388.11	16271.22
Land Use Change CO2					
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	13725.88	55396.43	419356.25	100623.57	589102.14

4 + I

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	8240.12	39304.67	253317.09	39211.23	340073.11
Manure CH4	3429.59	5432.07	105066.7	43607.56	157535.92
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	385.51	1509.02	10988.58	3388.11	16271.22
Land Use Change CO2					
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	12661.68	50432.35	386690.7	95566.19	545350.92

Housing

Confined no barn

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	10642.01	49640.84	326655.55	50573.83	437512.24
Manure CH4	3429.59	5432.07	105066.7	43607.56	157535.92
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	385.51	1509.02	10988.58	3388.11	16271.22
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	15063.57	60768.52	460029.16	106928.79	642790.05

Housed in barn (solid)

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	10642.01	49640.84	326655.55	50573.83	437512.24
Manure CH4	3429.59	5432.07	105066.7	43607.56	157535.92
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	371.18	1622.15	10619.04	2829.95	15442.33
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	15049.25	60881.66	459659.62	106370.63	641961.16

Housed in barn (slurry)

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	10642.01	49640.84	326655.55	50573.83	437512.24
Manure CH4	3429.59	5432.07	105066.7	43607.56	157535.92
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	383.52	1681.08	10968.63	2999.91	16033.14
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	15061.58	60940.59	460009.21	106540.59	642551.97

Pasture 339 ac 2 ac/cow 0.5/ calf

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	15260.52	64336.87	445329.62	544391.14	579391.14
Manure CH4	177.83	827.23	4791.14	553.93	6350.13
Direct N2O	114.14	253.55	3465.99	363.01	4196.69
Indirect N2O	718.2	1276.77	18313.43	2178.29	22486.7
Energy CO2					
Subtotal (kg	16270.7	66694.41	471900.19	57559.37	612424.66

Manure Management

Deep Bedding

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	10642.01	49640.84	326655.55	50573.83	437512.24
Manure CH4	3429.59	5432.07	105066.7	43607.56	157535.92
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	385.51	1509.02	10988.58	3388.11	16271.22
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	15063.57	60768.52	460029.16	106928.79	642790.05

Solid Storage

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	10642.01	49640.84	326655.55	50573.83	437512.24
Manure CH4	442.2	542.2	13536.58	4714.33	24125.19
Direct N2O	542.2	3201.09	15390.52	6440.05	25573.86
Indirect N2O	385.51	1509.02	10988.58	3388.11	16271.22
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	12076.18	60768.52	368499.04	68035.57	509379.32

Compost Intensive

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	10642.01	49640.84	326655.55	50573.83	437512.24
Manure CH4	170.62	1358.02	5215.66	1178.58	7922.89
Direct N2O	304.73	1600.55	8654.81	3220.02	13780.11
Indirect N2O	485.06	2416.82	13853.55	4659.58	21415.01
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	11666.68	56001.73	356307.37	62551.26	486551.26

Compost Passive

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	10642.01	49640.84	326655.55	50573.83	437512.24
Manure CH4	261.15	2716.04	7989.3	2357.17	13323.65
Direct N2O	304.73	1600.55	8654.81	3220.02	13780.11
Indirect N2O	485.06	2416.82	13853.55	4659.58	21415.01
Energy CO2	64.26	985.5	1927.8	2919.24	58896.8
Subtotal (kg	11757.21	57359.74	359081.01	63729.84	491927.81

Anaerobic digester

	Bulls	Replacemen	Cows	Calves	Subtotal
Enteric CH4	10642.01	49640.84	326655.55	50573.83	437512.24
Manure CH4	170.62	1358.02	5215.66	1178.58	7922.89
Direct N2O	95.76	192.07	2727.38	386.4	3401.6
Indirect N2O	251.8	657.82	7158.38	1870.83	9938.84
Energy CO2	64.26	985.5	1927.8	2919.24	5896.8
Subtotal (kg	11224.45	52834.25	343684.77	56928.89	464672.37

Dairy Cattle Raw Data

16-Jun	default numbers	737005	20 heifers

Dairy Heifers Scenario changes

	High Fiber	Low Fiber
	Heifers	
Enteric CH4	6410.73	5717.97
Manure CH4	78.01	59.98
Direct N2O		
Indirect N2O	125.32	104.37
Energy CO2		
Subtotal	6614.06	5882.32

all default

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH4	6410.73	2733.27		12432.52	21576.52
Manure CH4	78.01	269.38	153.44	173.92	674.75
Direct N2O		553.05	142.42		695.46
Indirect N2O	125.32	255.33	66.91	348.18	795.75
Energy CO2				4893.04	4893.04
Subtotal	6614.06	3811.03	362.77	17847.66	28635.53

Dairy Lactating Diet Changes

Legume Forage based diet

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH4				12432.52	
Manure CH4				173.92	
Direct N2O					
Indirect N2O				348.18	
Energy CO2				4893.04	
Subtotal				17847.66	

Barley Silage based Diet

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH4				13014.08	
Manure CH4				195.34	
Direct N2O					
Indirect N2O				298.39	
Energy CO2				4893.04	
Subtotal				18400.85	

Corn Silage based Diet

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH4				11759.46	
Manure CH4				152.87	
Direct N2O					
Indirect N2O				338.84	
Energy CO2				4893.04	
Subtotal				17144.21	

Housing Scenarios *changed all cattle types

Tie-stall (solid litter)

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	78.01	269.38	153.44	173.92	674.75
Direct N_2O		553.05	142.42		695.46
Indirect N_2O	125.32	255.33	66.91	348.18	795.75
Energy CO_2				4893.04	4893.04
Subtotal	6614.06	3811.03	362.77	17847.66	28635.53

Tie-stall (slurry)

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	78.01	269.38	153.44	173.92	674.75
Direct N_2O		553.05	142.42		695.46
Indirect N_2O	147.43	262.55	66.91	409.33	886.23
Energy CO_2				4893.04	4893.04
Subtotal	6636.17	3818.25	362.77	17908.81	28726.01

Free-stall barn (solid litter)

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6029.07	2336.13		10768.32	19133.52
Manure CH_4	73.36	230.24	153.44	150.64	607.68
Direct N_2O		472.69	142.42		615.11
Indirect N_2O	134.22	223.9	66.91	343.48	768.52
Energy CO_2				4893.04	4893.04
Subtotal	6236.65	3262.96	362.77	16155.48	26017.87

Free-stall barn (slurry scraping)

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6029.07	2336.13		10768.32	19133.52
Manure CH_4	73.36	230.24	153.44	150.64	607.68
Direct N_2O	0	472.69	142.42	0	615.11
Indirect N_2O	184.03	238.71	66.91	470.42	960.08
Energy CO_2				4893.04	4893.04
Subtotal	6286.46	3277.77	362.77	16282.43	26209.43

Free-stall barn (flushing)

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6029.07	2336.13		10768.32	19133.52
Manure CH_4	73.36	230.24	153.44	150.64	607.68
Direct N_2O	0	472.69	142.42	0	615.11
Indirect N_2O	163.28	232.54	66.91	417.53	880.26
Energy CO_2				4893.04	4893.04
Subtotal	6265.71	3271.6	362.77	16229.53	26129.61

Free-stall barn (milk parlour - slurry flushing)

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6029.07	2336.13		10768.32	19133.52
Manure CH_4	73.36	230.24	153.44	150.64	607.68
Direct N_2O	0	472.69	142.42	0	615.11
Indirect N_2O	163.28	232.54	66.91	417.53	880.26
Energy CO_2				4893.04	4893.04
Subtotal	6265.71	3271.6	362.77	16229.53	26129.61

Drylot

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	78.01	269.38	153.44	173.92	674.75
Direct N_2O	0	553.05	142.42	0	695.46
Indirect N_2O	227.04	288.54	66.91	629.48	1211.97
Energy CO_2				4893.04	4893.04
Subtotal	6715.78	3844.24	362.77	18128.96	29051.75

Pasture

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6903.87	2649.17		16677.77	26230.81
Manure CH_4	76.72	347.24	25.06	58.05	507.07
Direct N_2O	194.89	221.93	19.52	30.72	467.06
Indirect N_2O	11.97	2132.36	168.34	276.01	2588.68
Energy CO_2				4893.04	4893.04
Subtotal	7187.45	5350.7	212.92	21935.59	34686.65

Diet Additives for all cattle types

Ionophore

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	5128.59	2186.62		10006.66	17321.86
Manure CH_4	78.01	269.38	153.44	173.92	674.75
Direct N_2O	0	553.05	142.42	0	695.46
Indirect N_2O	125.32	255.33	66.91	348.18	795.75
Energy CO_2				4893.04	4893.04
Subtotal	5331.91	3264.37	362.77	15421.8	24380.87

5% Fat Additive

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	78.01	269.38	153.44	173.92	674.75
Direct N_2O		553.05	142.42		695.46
Indirect N_2O	125.32	255.33	66.91	348.18	795.75
Energy CO_2				4893.04	4893.04
Subtotal	6614.06	3811.03	362.77	17847.66	28635.53

5% Fat Additive and Ionophore

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	5769.66	2459.94		11219.59	19449.19
Manure CH_4	78.01	269.38	153.44	173.92	674.75
Direct N_2O	0	553.05	142.42	0	695.46
Indirect N_2O	125.32	255.33	66.91	348.18	795.75
Energy CO_2				4893.04	4893.04
Subtotal	5972.99	3537.7	362.77	16634.73	26508.2

Manure Management

Solid Storage

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	624.05	269.38	153.44	1391.35	2438.22
Direct N_2O	911.62	553.05	142.42	2550.35	4157.43
Indirect N_2O	401.34	255.33	66.91	1121.52	1845.1
Energy CO_2				4893.04	4893.04
Subtotal	8347.73	3811.03	362.77	22388.79	34910.32

Compost Intensive

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	156.01	67.34	38.36	347.84	609.56
Direct N_2O	455.81	276.52	71.21	1275.18	2078.72
Indirect N_2O	601.21	385.4	102.46	1676.77	2765.84
Energy CO_2				4893.04	4893.04
Subtotal	7623.76	3462.54	212.03	20625.34	31923.68

Compost Passive

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	312.03	134.69	76.72	695.68	1219.11
Direct N_2O	455.81	276.52	71.21	1275.18	2078.72
Indirect N_2O	601.21	385.4	102.46	1676.77	2765.84
Energy CO_2				4893.04	4893.04
Subtotal	7779.77	3529.89	250.39	20973.18	32533.23

Deep Bedding

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	5772.47	2491.76	1419.34	12869.99	22553.56
Direct N_2O	911.62	553.05	142.42	25550.35	4157.43
Indirect N_2O	401.34	255.33	66.91	1121.52	1845.1
Energy CO_2				4893.04	4893.04
Subtotal	13496.15	6033.41	1628.67	33867.43	55025.66

Liquid w/ natural crust

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	4194.37	1810.76	1031.43	9361.08	16397.64
Direct N_2O	0	0	0	0	0
Indirect N_2O	0	0	0	0	0
Energy CO_2				4893.04	4893.04
Subtotal	10605.1	4544.03	1031.43	26686.64	42867.2

Liquid no crust

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	6990.62	3017.93	1719.05	15601.8	27329.39
Direct N_2O	0	0	0	0	0
Indirect N_2O	233.9	147.46	38.15	646	1065.51
Energy CO_2				4893.04	4893.04
Subtotal	13635.25	5898.66	1757.2	33573.36	54864.47

Liquid w/ solid cover

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	3495.31	1508.97	859.52	7800.9	13664.7
Direct N_2O	455.81	276.52	71.21	1275.18	2078.72
Indirect N_2O	231.8	146.12	37.81	640.29	1056.02
Energy CO_2				4893.04	4893.04
Subtotal	10593.65	4664.88	968.54	27041.93	43269

Daily Spread

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	78.01	33.67	19.18	173.92	304.78
Direct N_2O	0	0	0	0	0
Indirect N_2O	125.32	78.19	20.14	348.18	571.84
Energy CO_2					
Subtotal	6614.06	2845.14	39.32	17847.66	27346.18

Anaerobic Digester

	Heifers	Dry	Calves	Lactating	Subtotal
Enteric CH_4	6410.73	2733.27		12432.52	21576.52
Manure CH_4	156.01	67.34	38.36	347.84	609.56
Direct N_2O	54.7	33.18	8.55	153.02	249.45
Indirect N_2O	125.32	78.19	20.14	348.18	571.84
Energy CO_2					0
Subtotal	6746.76	2911.99	67.05	18174.6	27900.41

Sheep Raw Data

Sheep	16-Jun			
Diet changes		default is good forage		

Good Quality Forage

	Sheep	Rams	Lambs & Ew	Subtotals
Enteric CH4	2784.2	2784.2	1724.19	7292.59
Manure CH4	264.53	264.53	163.82	692.89
Direct N2O	558.16	558.16	345.65	1461.98
Indirect N2O	64.19	64.19	39.75	168.13
Energy CO2	0	0	0	0
Subtotal (kg	3671.09	3671.09	2273.41	9615.59

Average Quality Forage

	Sheep	Rams	Lambs & Ew	Subtotals
Enteric CH4	4184.18	4184.18	2602.72	10971.08
Manure CH4	432.39	432.39	268.96	1133.75
Direct N2O	484.09	484.09	301.13	1269.32
Indirect N2O	55.67	55.67	34.63	145.97
Energy CO2				
Subtotal (kg	5156.34	5156.34	3207.44	13520.11

Poor Quality Forage

	Sheep	Rams	Lambs & Ew	Subtotals
Enteric CH4	6876.89	6876.89	4349.9	18103.69
Manure CH4	774.74	774.74	490.05	2039.54
Direct N2O	360.18	360.18	227.83	948.2
Indirect N2O	41.42	41.42	26.2	109.04
Energy CO2				
Subtotal (kg	8053.24	8053.24	5093.99	21200.47

Diet Additives		*no diet additives yet June 16
2% Fat		

Housing	*Good Quality Forage

Confined

	Sheep	Rams	Lambs & Ew	Subtotals
Enteric CH4	2784.2	2784.2	1724.19	7292.59
Manure CH4	264.53	264.53	163.82	692.89
Direct N2O	558.16	558.16	345.65	1461.98
Indirect N2O	64.19	64.19	39.75	168.13
Energy CO2				
Subtotal (kg	3671.09	3671.09	2273.41	9615.59

Housed Ewes

	Sheep	Rams	Lambs & Ew	Subtotals
Enteric CH4	2879.23	2879.23	1777.4	7535.85
Manure CH4	273.56	273.56	168.88	716
Direct N2O	577.21	577.21	356.32	1510.74
Indirect N2O	300.17	300.17	274.77	875.12
Energy CO2				
Subtotal (kg	4030.17	4030.17	2577.37	10637.71

Pasture

	Sheep	Rams	Lambs & Ew	Field	totals
Enteric CH4	2564.67	2564.67	1601.25		6730.59
Manure CH4	28.63	28.63	17.88		75.14
Direct N2O	30.85	30.85	19.26	117.81	198.77
Indirect N2O	289.28	289.28	180.61	508.09	1267.27
Energy CO2				5505.5	5505.5
Subtotal (kg	2913.43	2913.43	1819	6131.4	5435.95

Manure	*default is confined housing

Solid Storage

	Sheep	Rams	Lambs & Ew	Subtotals
Enteric CH4	2784.2	2784.2	1724.19	7292.59
Manure CH4	264.53	264.53	163.82	692.89
Direct N2O	558.16	558.16	345.65	1461.98
Indirect N2O	64.19	64.19	39.75	168.13
Energy CO2				
Subtotal (kg	3671.09	3671.09	2273.41	9615.59

Compost Intensive

Sheep	Rams	Lambs & Ew	Subtotals
2784.2	2784.2	1724.19	729259
66.13	66.13	40.95	173.22
279.08	279.08	172.83	730.99
86.51	86.51	53.58	226.61
3215.93	3215.93	1991.55	8423.41

Compost Passive

	Sheep	Rams	Lambs & Ew	Subtotals
Enteric CH4	2784.2	2784.2	1724.19	7292.59
Manure CH4	132.27	132.27	81.91	346.44
Direct N2O	279.08	279.08	172.83	730.99
Indirect N2O	80.93	80.93	50.12	211.99
Energy CO2				
Subtotal (kg	3276.48	3276.48	2029.04	8582.01

Deep Bedding

	Sheep	Rams	Lambs & Ew	Subtotals
Enteric CH4	2784.59	2784.59	1724.19	7292.59
Manure CH4	2446.95	2446.95	1515.33	6409.22
Direct N2O	558.16	558.16	345.65	1461.98
Indirect N2O	142.33	142.33	88.14	372.8
Energy CO2				
Subtotal (kg	5931.64	5931.64	3673.32	15536.6

Anaerobic Digester

	Sheep	Rams	Lambs & Ew	Subtotals
Enteric CH4	2784.2	2784.2	1724.19	7292.59
Manure CH4	66.13	66.13	40.95	173.22
Direct N2O	33.49	33.49	20.74	87.72
Indirect N2O	58.61	58.61	36.29	153.51
Energy CO2				
Subtotal (kg	2942.43	2942.43	1822.17	7707.04