PERENNIAL LEGUME PHASE AND ANNUAL CROP ROTATION INFLUENCES ON CO_2 AND N_2O FLUXES OVER TWO YEARS IN THE RED RIVER VALLEY, MANITOBA, CANADA

BY

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ABSTRACT

Stewart, Siobhan Elaine. M.Sc., The University of Manitoba, February, 2011. Perennial legume phase and annual crop rotation influences on CO_2 and N_2O fluxes over two years in the Red River Valley, Manitoba, Canada. Major Professor; Mario Tenuta.

Studies have shown that including perennial forages in cropping rotations can increase soil carbon (C) and lower nitrous oxide (N_2O) emissions when compared to continuous annual cropping. Research is needed to evaluate the inclusion of a perennial forage in an annual crop rotation on net carbon dioxide (CO_2) and N_2O fluxes, natural and agronomic drivers of seasonal greenhouse gases (GHGs), and the possibility of using forages as a C sequestration-CO_2 mitigation tool. A long-term field experiment site to determine GHG budgets for Red River Valley cropping systems in Manitoba, Canada was used. The site consisted of four plots with the same annual rotation management history. A perennial legume, alfalfa, was grown in 2008 and 2009 on two plots and spring wheat and industrial oilseed-rapeseed grown on the other two plots in 2008 and 2009, respectively. Nitrous oxide and CO_2 fluxes were measured continuously using the flux gradient micrometeorological method. For the net study period, the perennial phase sequestered twice the atmospheric CO_2 (2070 kg C ha^{-1}) compared to the annual crops. The annual rotation emitted 3.5 times more N_2O than the perennial legume phase. When accounting for harvest C removals and considering GHGs in CO_2-equivalent (eq.), the perennial legume phase was a net sink of 5440 kg CO_2-eq. ha^{-1} and the annual rotation was a net source of 4500 kg CO_2-eq. ha^{-1} for the two year study period. Information gathered will help bridge missing data gaps in national emission trends and enhance development of Canadian GHG mitigation models.

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BNF	biological nitrogen fixation
C	carbon
CH_4	methane
cm	centimetres
CO_2	carbon dioxide
$\sum F_N$	cumulative net N_2O flux
$\sum F_{C\text{-}NEE}$	cumulative net CO_2 ecosystem exchange
$\sum F_{GHG}$	cumulative net greenhouse gas equivalents
°C	degrees Celsius
d	zero plane displacement height
$F_{C\text{-}HARVEST}$	C harvest removal
$F_{C\text{-}STORAGE}$	soil C storage
FUE	fertilizer use efficiency
GDD	growing degree days
GHG	greenhouse gases
GMC	gravimetric moisture content
GWP	global warming potential
ha	hectares
Hz	hertz
IPCC	Intergovernmental Panel on Climate Change
K	turbulent transfer coefficient
km	kilometres
kg	kilograms
LAI	leaf area index
LULUCF	Land Use, Land Use Change and Forestry sector
mm	millimetres
N	nitrogen
N_2	dinitrogen gas
N_2O	nitrous oxide

NH_4^+	ammonium
NO_3^-	nitrate
O_2	oxygen
OM	organic matter
ppb	parts per billion
ppm	parts per million
SOC	soil organic carbon
SOM	soil organic matter
u*	eddy friction velocity
t	tonnes
TGAS-MAN	Trace Gas Manitoba
z	distance above ground/plant canopy

1. INTRODUCTION

1.1 Greenhouse Gases and Climate Change in Canada

Under the recent pressure of complying to the United Nations Kyoto Protocol climate change mitigation policies, there have been demands on the Canadian government to quantify and reduce the amount of greenhouse gases (GHGs) that are emitted by the country every year [Desjardins et al., 2001]. Canada is one of the leading per capita producers of GHGs in the world, responsible for $22x10^3$ kilograms (kg) of emissions per person annually. Approximately $73x10^9$ kg of carbon dioxide equivalents (CO_2-eq.) is emitted by all Canadian sectors, amounting to 1.5% of annual global emissions. In 2008, the agriculture sector was the second largest emitter at 8.5% ($62x10^9$ kg). Only the energy sector, composed of transportation, mining, and combustion sources, emitted more GHGs, at 81% [Environment Canada, 2010]. With the large amount of GHGs supplied by the agriculture sector and the high uncertainty surrounding GHG mitigation estimates and environmental impact reduction, continued research is necessary to improve mitigation inventory planning for the numerous divisions that compose this sector.

Expansion of the cattle industry, changing global crop market demand and subsequent land use change, as well as the continued growth of fertilizer and fuel manufacturing are being blamed for the increase in agricultural emissions. These practices may be looked at for prospective mitigation and inventory planning in Canada's agricultural sector [Environment Canada, 2010]. Animal production and agricultural soils are the two divisions of the agriculture emissions sector, contributing 71% of national nitrous oxide (N_2O) emissions. Nitrous oxide emitted from cropland soil is responsible for 52% of agricultural emissions at $1x10^8$ kg ($32x10^9$ kg CO_2-eq.), mostly due to nitrogen (N) fertilizer addition at seeding. There has been a 29% ($14x10^9$ kg) increase in soil N_2O emissions over the period 1990 to 2008, due to an increase in use of synthetic N fertilizers in the Prairies and the expansion of the beef, poultry and swine industries in Canada [Environment Canada, 2010]. Any CO_2 fluxes from cropland are not included in reported national totals (and therefore, Agriculture sector data), but are accounted for in the Land Use, Land Use Change and Forestry (LULUCF) sector. In the 2009 National Inventory Report, the Cropland subcategory reported that 'cropland remaining as cropland' would contribute an additional $3x10^5$ kg of N_2O ($1x10^8$ kg CO_2-eq.) and $7x10^6$ kg of methane (CH_4, $2x10^8$ kg CO_2-eq.) to the overall emission values from agriculture, while storing $36x10^8$ kg of CO_2 [Environment Canada, 2009]. For the 2010 Report, the LULUCF sector was a net GHG sink of $13x10^9$ kg, the CO_2 atmospheric removal driven primarily by management changes to controlled cropland and forests. If the sink status of this sector were included in the national totals, it would reduce Canada's GHG emissions by 2% [Environment Canada, 2010]. Despite this mitigation possibility, the Intergovernmental Panel on Climate Change (IPCC) anticipates that CO_2 emissions will continue to rise with cropland intensification, although at a slow rate. Nitrous oxide is expected to increase slowly over the 21st century, possibly doubling in some sector divisions [Barker et al., 2007].

Human-controlled systems, such as cropping rotations, allow numerous system management aspects to be considered for mitigation potential; namely the land use, land use change and disturbance trends that increase GHG formation and their ensuing climate warming [Bhatti et al., 2006]. The IPCC Technical Summary states that the main GHG mitigation strategy for agriculture is the change or improvement of cropland management practices. However, this opportunity is highly influenced by the soil type, climate, and farming system in a region. Ninety percent of the management mitigation potential may be feasible by increasing soil carbon (C) sequestration, with the remaining ten percent possible by emission reduction. Limiting emissions may be possible through the minimization of nitrous oxide creation in cropland [Barker et al., 2007]. By understanding which cropping management strategies can reduce atmospheric radiative forcing, steps can be taken to minimize agriculture's atmospheric GHG contribution. Improving agroecosystem CO_2 uptake and decreasing N_2O from cropping systems may lessen atmospheric GHGs [Mosier et al., 2005]. The cycling of C and nitrogen (N) are tightly interconnected and despite increasing C storage, C sequestering cropping practices often creation opposing GHG flux effects [Desjardins et al., 2001; Smith et al., 2007]. Greater amounts of crop available N may result in healthier crops that increase C sequestration. However, the fertilizer application necessary to provide crop health commonly results in N_2O emissions. The amount of soil C and N is known to affect the N gas forms emitted from the soil. Chapin et al. [2002] summarize that high soil nitrate (NO_3^-) concentrations relative to organic C result in the emission of N_2O. Firestone et al. [1980] found that high amounts of dinitrogen gas (N_2) were emitted when NO_3^- was low compared to labile C. Therefore, greater amounts of available soil C decrease N_2O as the dominant N product during denitrification, although high NO_3^- will increase $N_2O:N_2$ by inhibiting the reduction of N_2O to N_2 [Phillips et al., 2007]. This strong nutrient relationship shows the importance of considering GHG impacts together when evaluating the global warming potential (GWP) of agroecosystems. Net GHG emissions will differ depending on whether CO_2 is targeted solely versus looking at CO_2 and N_2O together [Desjardins et al., 2001]. Certain crop management practices can involve trade-offs between gases, whereas other practices will result in benefits for more than one gas, and potentially environmental and economic gains [Smith et al., 2007].

1.2 Carbon and Nitrogen Cycling in Prairie Agriculture

Centuries of grass and leguminous plant growth supplied plant residues that reserved C and N in Canadian Prairie soils [Dumanski et al., 1998; Janzen, 2001]. With the introduction of cultivation to the Prairies over 100 years ago, thousands of hectares were converted to crop production systems [Kucharik et al., 2001]. The annual tillage involved with cultivation released native C and N reserves to the atmosphere through soil organic matter (SOM) decomposition. John Lawes and Joseph Gilbert were British scientists with interest in Prairie OM, and among the first researchers to express concern about C and N fertility loss from Prairie soils [Janzen, 2001]. Long term studies show that OM losses of 20 to 30% were estimated lost in the top 20 cm of soil within 25 years of initial cultivation. However, soil nutrient losses have lessened over time, with soil organic carbon (SOC) losses remaining minimal since 1980 [Janzen et al., 1998; Kucharik et al., 2001]. The soil C losses of the early 1900s are blamed on the wheat-fallow cropping system practices that resulted in a lack of crop residue returned to the soil. The amount of C and N released from native soils combined with the adoption of synthetic N fertilizer application for intensive agriculture has contributed to the increasing atmospheric GHG concentrations [Rochette et al., 2004]. There is potential for sustainable land management practices to transform the Prairies into net C sinks once again, with the possibility of accumulating up to 75% of native SOC concentrations [Smith et al., 2000].

Grant et al. [2004] and Baker and Griffis [2005] agree that the improvement of cropping system management strongly influences the C and N dynamics of a crop rotation, possibly increasing C sequestration and reducing N_2O emissions. Improved cropping practices are being used on the Prairies, such as reduced tillage, the adoption of yield-promoting practices through the addition of nutrient amendments, the elimination of summer fallow, and the diversification of crop rotations. Most current Prairie crop rotations are diverse, including leguminous crops (soybeans, peas), and oilseeds (flax, sunflowers, canola), along with the traditional Prairie cereals (wheat, barley, oats, corn) [Zentner et al., 2002]. Alternating crops in a rotation can result in a healthier soil, due to varying nutrient or water requirements, and can affect residual nutrient concentrations available for subsequent crops. Weed, disease, and insect pressure can be alleviated, as well as the enhancement of future crop yield quality and quantity through improved soil properties. The use of legumes in a cropping sequence can economically support a farmer through creation of natural N by biological nitrogen fixation (BNF) and enhancement of the SOM with C sequestration.

Even in 1910, the return of plant fibre to the soil and the adoption of legumes in a rotation were suggested as a means of reducing soil nutrient loss [Janzen, 2001]. The Century model used to estimate SOC change in work by Smith et al. [2000] predicted that the C source/sink status of the Prairies would reach equilibrium by 2000 with adopted management practices, and become net C sinks by 2005. Agricultural soils becoming atmospheric CO_2 sinks in the early 21st century is also supported by Kucharik et al. [2001] and Boehm et al. [2004], although actual research on C status of soils is lacking. Research by Glenn et al. [2010] has found that a 3-year corn-fababean-wheat rotation in Manitoba is still a significant C source.

Nutrient management, and soil cultivation intensity and frequency impact the C and N cycling and land use changes of a cropping system, such as the crop type grown, or residue and water management [Liebig et al., 2005; Barker et al., 2007]. Because these factors are controlled by anthropogenic preferences, they may be agronomically managed to change the C and N cycling in an agroecosystem. In order to preserve soil fertility and sustain food production, N and C concentrations must be enhanced or maintained near native levels [Kucharik et al., 2001]. Continuous cropping is known to decrease C stored in the soil and release higher N_2O rates due to frequent tillage practices. Soil C is lost through enhanced OM decomposition from greater surface area that is available for microbial decay [Janzen et al., 1998; Kucharik et al., 2001]. Organic matter decomposition results in organic N mineralization, and increased N concentrations available for loss through nitrification and denitrification. Fall tillage had higher N mineralization rates due to warmer soil temperatures the following spring [Liebig et al., 2005]. Less intensive cropping systems can decrease emissions by limiting reliance on nutrient inputs and frequency of field disturbance [Smith et al., 2007]. Over-wintering crops, such as winter wheat, tend to have lower GWPs because they are actively growing in the spring and compete with soil microbes for available soil N. The crop gains access to soil N making less N fertilizer necessary [Mosier et al., 2005]. Crops with high residue inputs of above- or below-ground biomass were found to increase SOC storage

[Liebig et al., 2005; Mosier et al., 2005], particularly perennial crops, such as alfalfa [Janzen et al., 1998], or high residue annual crops, like wheat [Liebig et al., 2005]. Retaining crop residue helps form OM, the main C store in soil [Smith et al., 2007]. Crop varieties with high yields and high residue can help to increase soil C [Janzen et al., 1998; Kucharik et al., 2001; Desjardins et al., 2005]. Low residue crops, like flax, reduce the amount of C that is available for sequestration by the agroecosystem. Modeling has shown that American agricultural cropping systems have regained 10% of their native C concentrations through an increase in the addition of crop residues returned to the soil [Kucharik et al., 2001]. Although increasing residue retained on the field improves SOC storage, Desjardins et al. [2001] found that removing residue from a field may limit N_2O creation by minimizing the C substrate available for nitrification and denitrification. Further research is needed to completely understand the intricate cycling of N and C.

Carbon dioxide is a GHG that may be captured from the atmosphere through crop photosynthesis, with storage as C in the root biomass and SOM of fields. Sequestration is the result of plant biomass deposition on the soil surface with incorporation by organisms, physical disturbance, small amounts of leaching, and plant root exudation and turnover [Ball et al., 2005]. Carbon storage is greatest below the plough layer of the soil profile, due to high root inputs and little tillage disturbance [Gregorich et al., 2005]. Dumanski et al. [1998] found that 50% of organic C is stored below 30 cm, with C below the 15 cm depth subject to less oxidation and the greatest potential of remaining in long-term storage. Enhancement of the SOC pool in soils has positive influences on soil properties: improving soil tilth, water-holding capacity, and microbial biodiversity [Lal and Follett, 2009]. The amount of C sequestered by a cropping system is strongly influenced by the climate, soil and crop type, and disturbance, highlighting the need for regional sequestration assessments.

Although current research is focusing on C storage, it is important to remember that C movement is bi-directional in agroecosystems. Atmospheric CO_2 is converted into soil C, but C forms can also be lost from the system during the growing season, with tillage disturbance, microbial activity, or plant respiration. The agroecosystem undergoes vast changes in a small time period, changing leaf area index quite rapidly during growth and senescence. These agronomic variations can cause rapid sign reversal in CO_2 fluxes [Pattey et al., 2006]. A positive correlation between microbial biomass and soil surface CO_2 flux was seen by Kucharik et al. [2001]. The study documented that the sum of microbial and root uptake and release (CO_2 flux) is one of the most important contributors to the global C cycle, being the largest component, although it is the least understood.

There is the opportunity for the Canadian Prairie to resume its position as a large C sink. To increase C storage in soils, it is integral to increase plant residue on the field, while suppressing decomposition rates [Campbell et al., 2000; Janzen, 2005]. Janzen et al. [1998] have found that labile SOC may accumulate quickly, in under ten years, with the potential for this C pool to become a sink for excess atmospheric CO_2. Labile SOC is considered a mixture of fresh plant material and microbial residue that is available for rapid turnover. However, many research studies have found that it is difficult to accurately detect changes in soil C stocks over small time periods. Several researchers document the need for long-term research trials greater than a decade to understand SOC trends [Kucharik et al., 2001; VandenBygaart and Angers, 2006]. VandenBygaart and Angers [2006] found that short-term C detection was challenging due to comparisons against large background C levels, field spatial variability, and insufficient experimental research. Campbell et al. [2000] used data accumulated over 30 years to determine trends in soil C on the Prairies. Davis et al. [2010] state that although flux measurements are unlikely to detect SOC changes in the short-term, they may be sensitive enough to identify slight changes in ecosystem fluxes between plots or treatments, making them important short-term soil nutrient measuring tools. Regardless of whether Prairie soils are currently C sinks or sources, it is important to realize that the impact of C sequestration will continue only until a new soil equilibrium is reached [Dumanski et al., 1998; Janzen, 2007]. Research shows this equilibrium period is approximately 20 years, or until a new sink-enhancing practice is introduced [Boehm et al., 2004].

Nitrous oxide is a GHG naturally produced by soil bacteria during nitrification and denitrification of mineral N in the soil [Kaiser et al., 1998; Rochette et al., 2004]. This trace gas is the direct product of incomplete denitrification, when high levels of N, C, and soil water exist simultaneously [Hutchinson et al., 2007]. Nitrification is an aerobic process that occurs during wet, but not saturated, soil conditions. Denitrification, however, is favoured by very wet soils that are anaerobic [Phillips et al., 2007]. Both cycling processes are influenced by soil temperature and moisture, oxygen (O_2) availability, SOM content, pH, and N forms in the soil, making N_2O emissions extremely spatially and temporally variable [Voroney and Derry, 2008]. Nitrous oxide is a trace gas of environmental concern, being a GHG that is less abundant than CO_2, but with a GWP

310 times greater than CO_2 [Environment Canada, 2010]. Although small amounts of N_2O are naturally released from plant residue decomposition, mineralization, and leguminous BNF [Rochette et al., 2004], intensive crop production has resulted in greater emission rates of this gas with increased cultivation and use of fertilizers [Environment Canada, 2010]. Direct field emissions are correlated with the volatilization of N from synthetic fertilizer and manure [Kaiser et al., 1998], crop residue decay, and the high SOM decomposition usually associated with increased soil disturbance. Emission rates are strongly dependent on environmental conditions: soil properties, climate, precipitation, freeze/thaw events, but also on farming management practices: quantity and type of N fertilizer, residue management, tillage, and crop type [Desjardins et al., 2001; Gregorich et al., 2005; Hutchinson et al., 2007; Pattey et al., 2007; Dunmola et al., 2010]. The type, rate, placement, and timing of N fertilizer are all factors that will influence the amount of N_2O that is released from a cropping system [Snyder et al., 2009]. Nitrous oxide emissions from agricultural fields are episodic in nature, although occur predominantly in the spring months.

Although synthetic N fertilizer addition for crop production is currently blamed for the increasing Canadian agricultural N_2O emission trends [Moiser et al., 2005; Hutchinson et al., 2007], there is a positive relationship between soil N fertility, biomass and SOC [Gregorich et al., 2005]. The addition of nutrients at seeding typically enhances soil C gains through greater crop residue and root biomass creation, but also results in higher N_2O emissions from a cropping system [Smith et al., 2007; Snyder et al., 2009]. Further research is necessary to improve fertilizer use efficiency (FUE) [Mosier et al., 2005] due to the need for improved yields, particularly in terms of global food sustainability [Lal, 2007]. The use of nitrification inhibitors may lower emission release by slowing the oxidation of ammonium (NH_4^+) to NO_3^-, and limiting the amount of NO_3^- available for denitrification [Liebig et al., 2005]. Synchronizing fertilizer application with plant growth may increase plant-available N uptake [Gregorich et al., 2005], and reduce excess fertilizer. Optimizing plant uptake will result in less N forms available for loss to the atmosphere through microbial activity, lowering environmental impacts [Mosier et al., 2005; Smith et al., 2007]. The use of natural N-producing crops that provide N to soils and subsequent crops through BNF could be an environmentally-friendly and cost-effective substitution for fertilizer use in agroecosystems [Kaiser et al., 1998; Robertson et al., 2000].

Until recent decades, BNF was the main supplier of organic N found in soils. Nodules found on legume roots form symbiotic rhizobium-plant relationships, fixing atmospheric dinitrogen (N_2) that is plant available. Common agricultural crops that exhibit BNF are alfalfa, clover, and peas, therefore reducing the need to apply synthetic N fertilizer to these crops [Russelle, 2008]. Alfalfa, a perennial legume, has been used in crop rotations to provide natural N to the cropping system, to maintain or improve soil structure, and to provide natural control of insects, weeds and disease [Entz et al., 2002]. The perennial nature and extended growing period of this crop sequesters huge amounts of CO_2 from the atmosphere, increasing SOM while improving soil health and microbial biodiversity. Numerous studies over the last 50 years have shown that including alfalfa in cropping systems improved the soil make-up and quality of subsequent crops grown on the field [Spratt, 1966; Kelner et al., 1997; Ball et al., 2005; Su, 2007]. The use of forages may be a management strategy to mitigate atmospheric GHGs, although data gaps exist in actual flux measurements and emission reduction potential from alfalfa rotations [Smith et al., 2007]. Because one agreement of the Kyoto Protocol allows for collecting credits from agricultural nutrient sinks, there is the potential that alfalfa may be a crop that can improve the health of cropping systems, while allowing farmers to achieve monetary C credits [Boehm et al., 2004]. The IPCC suggests the use of incentives to reach Kyoto targets, encouraging the adoption of GHG-reducing technologies [Barker et al., 2007]. Despite the environmentally sustainable benefits of GHG-reducing practices, there are feelings that mitigation choices adopted by Canadian farmers will depend strongly on the price of C storage [Smith et al., 2007].

1.3 Micrometeorological Study of GHG Emissions Using the Trace Gas Manitoba Research Site

Although numerous global and national GHG estimates exist, there are still data gaps for regional GHG fluxes in Prairie agricultural management systems [Liebig et al., 2005]. Because many climate and management factors affect the trace gas fluxes in and out of a system, regional assessments are imperative for complete inventory coverage. However, the temporal and spatial variability in GHG activity from landscapes and the understanding of management practices that affect these emissions makes quantification difficult [Desjardins et al., 2001]. In the past, Canadian GHG work has revolved around the use of gas chambers to monitor emissions from small-scale plots [Rochette et al., 2004; Baron et al., 2006; Dunmola et al., 2010]. Although gas chamber research has supplied much information about CO_2 uptake and N_2O release from agroecosystems, large gaps still exist in the understanding of field-scale C and N cycling from cropping systems. Data are missing in fallow periods (typically October to April) and for net N_2O emissions lost during spring thaw and post-fertilizer application [Kaiser et al., 1998].

Technological advancement has introduced trace gas analyzers [Fried et al., 1993; Edwards et al., 2003] that are capable of measuring high-frequency GHG exchange between the agroecosystem and the atmosphere. Uninterrupted field-scale data are collected throughout the year [Pattey et al., 2006], particularly during periods when accurate chamber studies would be difficult, such as during the winter and spring months. Micrometeorological techniques, unlike chamber methods, allow continuous monitoring of trace gas fluctuations over extended time periods. This monitoring provides insight into environmental flux drivers within an agroecosystem and reduces the spatial and temporal uncertainty typically found in chamber studies. The flux-gradient method is a micrometeorological technique that has been successfully used in agricultural cropping systems. This method also results in very little plot disturbance and allows successive flux measurement from many plots [Wagner-Riddle et al., 1996; Wagner-Riddle et al., 1997; Pattey et al., 2006; Phillips et al., 2007].

Micrometeorological research studies have looked at the various management practices that influence CO_2 and N_2O fluxes from agroecosystems in Eastern Canada [Wagner-Riddle et al., 1996; Wagner-Riddle et al., 1997; Wagner-Riddle et al., 2007], but little micrometeorological work has been done on the fertile Prairie soils of Western Canada. The Prairie ecozone's semiarid to subhumid continental climate makes this region potentially different to Eastern Canada. The Prairies experience cold and dry winters, warm to hot summers, with annual evaporation that typically exceeds the variable spring and summer precipitation. Prairie soils are naturally fertile, with small to medium-texture providing good moisture retention. The Eastern Canadian studies operated under mild winters, a humid maritime climate, with higher annual temperatures and large-textured soil conditions [Wagner-Riddle et al., 1996]. Glenn [2010] and Glenn et al. [2010] have published the first micrometeorological research accounting for agricultural GHG fluxes from annual crops in Prairie clay soils over a three-year period. Because the Prairies encompass 80% of agricultural cropland in Canada [Smith et al., 2000], collecting farm and land management practice information is imperative when undertaking accurate GHG inventory mitigation planning for the country [Huffman et al., 2006].

The Trace Gas Manitoba (TGAS-MAN) research site was established in the fall of 2005 in the Red River Valley of Manitoba, approximately 20 km south of Winnipeg, to monitor GHGs from an annual crop rotation [Glenn, 2010; Glenn et al., 2010]. The net flux of CO_2 and N_2O between the agroecosystem and the atmosphere was monitored continuously using micrometeorological towers and the flux-gradient method on four plots of an agricultural field. Forage alfalfa was planted on half of the plots in the spring of 2008 to begin the perennial phase of the site. These two plots allowed insight into the impacts of perennials on an annual crop rotation. Maintaining half of the plots in annual crops allowed comparisons between the perennial legume phase and the spring wheat-rapeseed rotation. Goals focused on determining the environmental (spring-thaw, precipitation events, air and soil temperature changes, soil mineral N concentrations) and agronomic (N fertilizer addition, forage cutting, harvest biomass removals) drivers of CO_2 and N_2O fluxes, as well as the soil C sequestration potential of the two cropping systems. The objectives of the study were to evaluate (1) the influence of including a perennial legume phase in an annual crop rotation on net CO_2 and N_2O fluxes, (2) natural and agronomic drivers of seasonal N_2O and CO_2 variability between the perennial legume phase and annual rotation, and (3) the possibility of using perennial legumes as a C sequestration-CO_2 mitigation tool. This research will provide valuable insight into the influence of seasonal weather changes and agronomic practices on N_2O emission creation and C sequestration opportunities for different crop types grown on the Canadian Prairies.

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2. CARBON DIOXIDE AND NITROUS OXIDE FLUXES FOLLOWING THE INTRODUCTION OF ALFALFA IN AN ANNUAL CROP ROTATION IN THE RED RIVER VALLEY, MANITOBA, CANADA

2.1 Introduction

Centuries of native grasses and leguminous plants provided large amounts of plant material to Canadian Prairie soils, resulting in the storage of carbon (C) and nitrogen (N) [Dumanski et al., 1998; Janzen, 2001]. With the introduction of cultivation to the Prairies over 100 years ago, approximately $7x10^7$ ha in Western Canada were converted to the growing of crops [Statistics Canada, 1902]. The removal of crop grain and stalks at harvest and use of fallow years decreased the biomass C returned to the soil. As a result, it has been estimated that between 20 and 30% of native soil reserves were lost within 25 years of initial cultivation [Janzen, 2001]. Soil organic C (SOC) losses have slowed over time, remaining minimal since 1980, when a new soil C equilibrium was reached [Janzen et al., 1998].

The increase in crop yields to enhance global food production was accomplished with the use of synthetic N fertilizer application [Lal, 2007]. However, N fertilizers are a source of nitrous oxide (N_2O), a greenhouse gas (GHG) 310 times more powerful than CO_2 [Barker et al., 2007]. Between 1990 and 2008, the national consumption of N fertilizers rose by 46%, mainly in the Prairie provinces, and the amount of N_2O emissions grew by $13x10^6$ kg N [Environment Canada, 2010*a*]. Soil N_2O emissions contributed 52% ($32x10^9$ kg CO_2-equivalent) of GHGs emitted from all agricultural sources, or 4.4% of total anthropogenic emissions for Canada.

Agricultural GHG emissions accounted for $62x10^9$ kg CO_2-eq. or 8.5% of Canadian emissions in 2008 [Environment Canada, 2010*a*]. Only the energy sector, comprised of transportation, mining and combustion sources, produced more GHGs. Canada is one of the highest per capita producers of GHGs in the world, releasing $22x10^3$ kg (CO_2-eq.) of GHGs per person. A total of $73x10^9$ kg of CO_2-eq. is emitted by all Canadian sectors, amounting to 1.5% of annual anthropogenic global emissions [Environment Canada, 2010*a*].

Opportunity exists to lower emissions from the agriculture sector by using soil to remove atmospheric GHGs. Changes or improvements to agricultural management practices, such as diversifying crop rotations or reducing applied fertilizer, may increase soil C sequestration and reduce the CO_2 and N_2O released from cropping systems [Grant et al., 2004; Baker and Griffis, 2005; Barker et al., 2007; Davis et al., 2010]. Soil C can be increased through greater return of crop residues to the soil [Janzen et al., 1998]. It has been suggested that the Canadian Prairies have the potential to restore up to 75% of lost native SOC concentrations through rotation management changes, such as reducing tillage intensity, restoring permanent vegetation, maximizing crop residue return, or using perennial forages in rotation [Janzen, 2005]. The Canadian Prairies were predicted to be C neutral by 2000 with the adoption of improved management practices, such as reduced tillage, reduction of summer fallow, and improved crop rotation selections, becoming net C sinks by 2005 [Smith et al., 2000].

Nitrous oxide emissions can be minimized by limiting N fertilizer use or synchronizing fertilizer application with crop uptake [Kucharik et al., 2001; Desjardins et al., 2005; Janzen, 2005; Mosier et al., 2005; Smith et al., 2007]. However, a recent micrometeorological study found that a three-year corn-faba bean-spring wheat annual crop rotation in Manitoba was still a GHG source [Glenn, 2010; Glenn et al., 2010]. Further inquiries into the effects of crop diversity and varied rotations on C sequestration [Su, 2007] and N_2O emission creation may present prospective opportunities for GHG mitigation.

Perennial forages, such as alfalfa, have been historically used in Prairie crop rotations to provide a biological source of N to agroecosystems [Entz et al., 2002]. Numerous studies over the last 50 years show that including alfalfa in cropping systems improved or maintained soil structure, increased C sequestration, and enhanced the yield and quality of subsequent crops [Spratt, 1966; Kelner et al., 1997; Entz et al., 2002]. Despite the benefits of forage crops, synthetic N fertilizers have largely eliminated the use of legume forages in conventional annual crop rotations [Ball et al., 2005]. Only 5 to 15% of arable cropland in the Red River Valley of Manitoba and the American Dakotas is currently rotated with forages [Entz et al., 2002]. The 2006 Canadian Census of Agriculture showed that in the province of Manitoba, only 6% of the 4, 701, 000 ha planted to agricultural crops were sown to alfalfa or forage crops [Statistics Canada, 2006].

With a deep-rooting system and large above-ground biomass, a perennial forage, alfalfa, can store almost three times more SOC than annual crops [Entz et al., 2002]. The perennial nature of alfalfa eliminates annual soil cultivation disturbance, increasing plant residues and root exudates returned to the soil [Su, 2007]. A nine-year crop rotation with three years of perennial forages had more productive soil than a grain-only system

[Spratt, 1966]. Further benefits of perennial forages include the natural control of insects, weeds and disease, and greater water storage capacity [Entz et al., 2002]. Residual soil N and C benefits of alfalfa can be subtle and the slow SOC accumulation process means that the benefit of the crop in rotations may only be seen after numerous years [Kucharik et al., 2001; Post et al., 2001; VandenBygaart and Angers, 2006].

Micrometeorological monitoring of GHG fluxes may provide rapid determination of improved SOC storage. Monitoring of daily CO_2 and N_2O fluxes throughout the year can show the environmental and agronomic events that drive temporal flux changes within agroecosystems. Precipitation events, spring-thaw, and temperature changes are environmental drivers that contribute to GHG fluxes. Agronomic practices, such as fertilizer application, cutting and harvest of crop material, or the type of crop grown, also contribute to seasonal GHG cycling. Prairie soils have been CO_2 and N_2O sources since the establishment of cultivation in Western Canada, yet since the beginning of the 21st century, soils have become C neutral. Soils are therefore thought to have the potential of becoming a major atmospheric CO_2 sink with the adoption of alternative management practices [Grant et al., 2004; Baker and Griffis, 2005].

In this study, micrometeorological data were collected from the Trace Gas Manitoba (TGAS-MAN) site, a field-scale research site in the Red River Valley of Manitoba, Canada. Trace Gas Manitoba is the only site in Western Canada simultaneously measuring N_2O and CO_2, continuously year-round. From Fall 2005 to Spring 2008, TGAS-MAN measured N_2O and CO_2 from a corn crop in the 2006/2007 crop year and from a faba bean crop in the 2007/2008 crop year [Glenn, 2010]. A perennial legume phase was introduced in May 2008. This study was part of the first long-term research project exploring Red River Valley clays and their impact on the Prairie GHG inventory [Glenn et al., 2010]. The present study focused on field-scale monitoring of CO_2 and N_2O gas fluxes from the perennial legume forage crop in comparison to an annual spring wheat-rapeseed crop rotation for the 2008/2009 and 2009/2010 crop years. Furthermore, year-round weather variables and growing season soil samples were collected to support and explain contrasting gas fluxes from the treatments. The objectives of this research were to determine the environmental and agronomic drivers of C and N fluxes from the perennial legume phase and spring wheat–rapeseed annual rotation, and to identify whether or not the perennial legume forage would enhance C sequestration, while lowering N_2O emissions.

2.2 Material and Methods

2.2.1 Site Description

Flux measurements were carried out from May 1, 2008 to April 30, 2010 at the Trace Gas Manitoba (TGAS-MAN) study site, an experimental field at the University of Manitoba's, National Centre for Livestock and the Environment Glenlea Research Station (49^o 38' N, 97^o 9' W, 234 m a.s.l.), located approximately 20 km south of Winnipeg, MB. The site is within the Red River Valley and the terrain composed of fine-textured soil, predominantly of the Red River and Osborne series [Ehrlich et al., 1953; M.A.F.R.I., 2009], with 60% clay, 35% silt and 5% sand. The area is characterized by a negligible slope ranging from 0 to 2% [MAFRI, 2009], with scattered low areas. The site experienced poor to imperfect drainage due to the clay soil and from slow-draining ditches in the spring and during times of high precipitation. The average bulk density (0-5 cm depth) of the site was 0.97 Mg m^{-3} (n=312) over the two study years. Soil organic C content was 3.4 % and pH was 6.5 at the beginning of the two-year study.

2.2.2 Site Design and Agronomic History

From May 2006 to April 2009, the TGAS-MAN research site examined the influence of three annual crops: corn (2006), faba beans (2007) and spring wheat (2008), on ecosystem N_2O and CO_2 trace gas fluxes using micrometeorological instrumentation [Glenn, 2010; Glenn et al., 2010]. Four annual treatment plots of 4 hectares each (200m by 200m) were monitored within a larger 30 ha field. A perennial legume forage, *Medicago sativa* (alfalfa), and *Phleum pretense* (timothy) mix was introduced into the crop rotation in May 2008 to two of the four site plots. The introduction of the perennial forage began the comparison of GHG emissions between a perennial legume phase and a continuous annual crop rotation (Figure 2.1).

The perennial legume phase, comprised of a custom mixture of 10% timothy grass (L.cv 'Grinstad') and 90% alfalfa (L.cv 'Gala', Proven Seed, pre-inoculated with Nitragin Gold, EMD Crop BioScience, Brookfield, WI) was sown on May 28, 2008 at a seeding rate of 12.5 kg ha^{-1} on plots Perennial 1 (P1) and Perennial 2 (P2; Figure 1). A fungicidal seed treatment of Apron XL LS (1 L 55 L^{-1}water; active ingredient: metalaxyl) was used and no fertilizer was added with the seed. These plots had a Canada thistle (*Cirsium Arvense*, (L.) Scop.) and curled dock (*Rumex crispus* L.) infestation that was sprayed with a mixture of Odyssey (43 g ha^{-1}; a. i.: imazamox, imazethapyr) and Merge (0.5 L 100 L^{-1} water; surfactant) on July 25, 2008. Due to a wet spring, the alfalfa

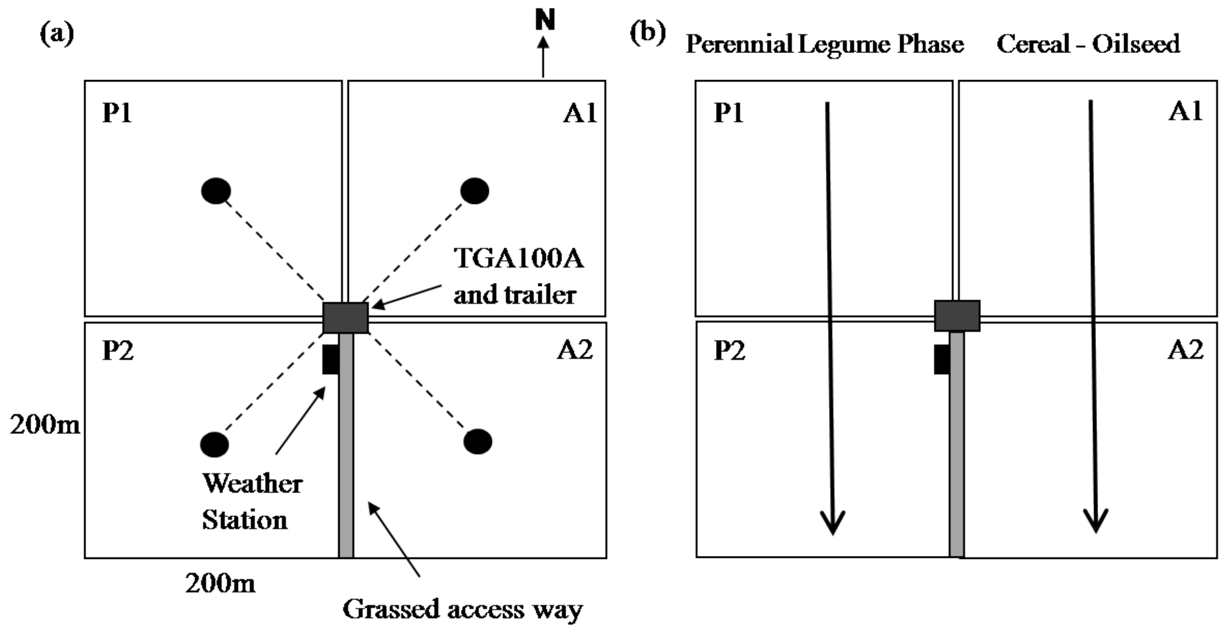

Figure 2.1 (a) Layout of experimental plots at the Trace Gas Manitoba (TGAS MAN) research site used in this study. Towers and intakes are indicated by filled circles in the centre of each plot and (b) the perennial legume phase plots were located on the west side of the site (plots P1 and P2), and the annual rotation plots of the spring wheat–rapeseed rotation were on the east side (plots A1 and A2).

seedlings were slow to establish and the forage was rotary-mowed monthly to encourage crop growth and dampen weed development. The forage was rotary-mowed for the last time on August 20, 2008 before freeze-up. Due to poor stand establishment in the 2008 growing season and crop winter-kill in 2009, plot P1 was spot-seeded with the custom forage mix by press-drill (International 100) on June 15, 2009 to ensure a solid crop canopy for the 2010 growing season. A mixture of timothy and Kentucky bluegrass (*Poa pratensis* L.) dominated this plot for the 2009 growing season. Plot P2 was well-established and no spot-seeding was required. Both plots were swathed for hay on July 6 and November 19, 2009, and baled 4 to 7 days later. Throughout the 2009 growing season, an approximate total of 5098 kg ha^{-1}(1st cut: 3920 kg ha^{-1}, 2nd cut: 1178 kg ha^{-1}) of above-ground biomass in the form of hay bales was removed from the site.

Plots Annual 1 (A1) and Annual 2 (A2) remained in annual crop rotation for the duration of the study and were seeded to a grain-oilseed rotation. Spring wheat (*Triticum aestivum*, L.cv '5602 RS – Hard Red Spring', Viterra (Proven® seed) Inc.) was planted on May 21, 2008 at a seeding rate of 135 kg ha^{-1}. A granular fertilizer blend of 60-10-0 was banded with the seed at a rate of 165 kg ha^{-1} (99 kg N ha^{-1}). A mixture of Axial (0.1 L ha^{-1}; pinoxaden), Curtail M (0.32 L ac^{-1}; clopyralid) and Merge (0.5 L 100 L^{-1} water; surfactant) was applied for weed control on June 23. The wheat was harvested on September 16, 2008, yielding 3070 kg ha^{-1} in the form of grain. Straw was baled and removed from the site for use as livestock bedding, accounting for 2225 kg ha^{-1} of biomass. A total of 5295 kg ha^{-1} biomass was harvested from the plots during the 2008 growing season. The annual plots were tilled on November 3, 2008 with a field cultivator to a depth of 7.5 cm (Summers Superchisel deep tiller). High erucic acid rapeseed (*Brassica napus*, L.cv 'Red River 1826 – Round Up Ready', Syngenta) was sown on May 30, 2009 at a rate of 6.75 kg ha^{-1}. Granular urea (46-0-0) was broadcast at 318 kg ha^{-1} (146 kg ha^{-1} N) on June 7, 2009 prior to a precipitation event. Round-Up Ultra II (0.4 L ha^{-1}; glyphosate) was sprayed as weed control on June 16, 2009. The crop was cut on September 10 and combined on September 22, yielding an average of 1070 kg seed ha^{-1}. Crop stalks were shredded into pieces smaller than 30 cm by the combine and worked into the soil on October 27 and harrowed November 19, 2009 with tine harrows (Bourgault 6000 mid harrows). A brief summary of the agronomic practices carried out during the two-year study can be found in Table 2.1.

Table 2.1 Agronomic management for the annual rotation and the perennial legume phase plots over the two study years.

Rotation	Year	Date	Task	Details
Annual	2008	21 May	Seeding	6502RS Hard Red Spring Wheat at 135 kg ha^{-1}
		21 May	Fertilizer	60-10-0 banded with seed at 165 kg ha^{-1}
		23 June	Herbicide	Axial (a.i. pinoxaden [a]), Curtail M (clopyralid), Merge (surfactant)
		16 September	Grain Harvest	3070 kg ha^{-1}
		22 September	Straw Baling	2225 kg ha^{-1}
		3 November	Tillage	Cultivated to 7.5 cm depth
	2009	31 May	Seeding	RR Helix Xtra Rapeseed at 6.75 kg ha^{-1}
		6 June	Fertilizer	46-0-0 broadcast at 318 kg ha^{-1}
		16 June	Herbicide	Round Up Ultra II (glyphosate)
		10 September	Swathing	
		24 September	Grain Harvest	1070 kg ha^{-1}
		27 October	Tillage	Cultivated to 7.5 cm depth
		19 November	Tillage	Tine harrow
Perennial Legume Phase	2008	28 May	Seeding	90% Gala Alfalfa and 10% Grinstad Timothy at 12.5 kg ha^{-1}
		24 June	Mowing	Residue left on site
		14 July	Mowing	Residue left on site
		25 July	Herbicide	Odyssey (imazamox and imazethapyr), Merge (surfactant)
		14 August	Mowing	Plot Perennial 2
		20 August	Mowing	Plot Perennial 1
	2009	6 July	1st Cutting	
		13 July	Baling	3920 kg ha^{-1}
		19 November	2nd Cutting	
		23 November	Baling	1178 kg ha^{-1}

[a] Herbicides were applied according to label instructions

2.2.3 Micrometeorological Instrumentation and Flux Measurements

A detailed description of the research site, including make and model information of all instruments can be found in Glenn et al. [2010]. Greenhouse gas fluxes were measured from the four research plots using the micrometeorological flux gradient method. A trace gas analyzer (Model TGA100A, Campbell Scientific Inc., Logan, UT) was used to measure atmospheric CO_2 and N_2O gas concentration gradients above the plots year-round. The trace gases were drawn from towers located in the centre of each plot by a rotary vane vacuum pump (Model RS0021, Busch Vacuum Technics, Boisbriand, QC) into the gas analyzer housed in a centrally-located, temperature-controlled, AC-powered modular trailer. A rate of 5 L min^{-1} from each site was continually drawn. Air temperature in the trailer housing the gas analysis system was kept constant at 20°C with air conditioning and electrical heat as the seasonal temperature changed. The gas analyzer operated using a tunable diode laser (Model IR-N_2O/CO_2, Laser Components GmbH., Olching, Germany) and related electronics housed within an insulted fiberglass container. Operated at 84K (-189 $^{\circ}$C) and cooled with liquid nitrogen, the laser measured N_2O and CO_2 concentrations simultaneously at 10 Hz using jump scanning at two absorption wavelengths [Fried et al., 1993; Pattey et al., 2006]. The TGA laser was set to scan a $^{14}N_2O$ absorption line at a frequency of 2243.110 cm^{-1} and a $^{13}CO_2$ line at a 2243.585 cm^{-1} frequency. Ramps were scanned using DC current at 567 mA and 589 mA for the N_2O and CO_2 absorption lines, respectively. A laser beam in the TGA was deflected onto two detectors located in a reference cell and a sample cell using a beam splitter. Atmospheric gas samples were pulled through the sample cell, with gas concentration data recorded using the TGA100A user interface software supplied by the manufacturer. A reference gas with 300,000 ppm $^{14}CO_2$ and 2000 ppm $^{14}N_2O$ concentrations was continually drawn through the reference cell at 10 mL min^{-1}. Edwards et al. [2003] and Pattey et al. [2006] demonstrated the detailed capabilities of the gas analyzer, which has been used in several micrometeorological studies, monitoring trace gas fluxes from agricultural fields [Wagner-Riddle et al., 1996; Wagner-Riddle et al., 1997; Glenn et al., 2010].

The net exchange of CO_2 and N_2O between the atmospheric boundary layer and the agroecosystem was calculated using the aerodynamic flux gradient method [Pattey et al., 2006; Denmead, 2008] over 30-minute periods. The net GHG flux is shown as:

$$F_{GHG} = -K \frac{\Delta [GHG]}{\Delta z}$$

where K is the turbulent transfer coefficient of the gases and $\Delta[GHG]$ is the vertical gas concentration gradient between two points (Δz) above a crop canopy [Edwards et al., 2003; Pattey et al., 2006]. A positive vertical flux is the movement of GHGs into the atmosphere, while a negative vertical flux denotes GHGs moving into the agroecosystem.

The K values for the crop rotations were estimated using 3-D sonic anemometer-thermometers (CSAT-3, Campbell Scientific Inc.) mounted at a 2 m height. Corrections to K for stable and unstable atmospheric conditions were done using the Monin-Obukhov similarity theory [Denmead, 2008; Monteith and Unsworth, 2008]. Crop height and snow depths were measured weekly using a meter stick to estimate the zero-plane displacement height (d) of the crop, a parameter needed for K stability corrections [Monteith and Unsworth, 2008]. Throughout the non-growing season, d was considered to be at the soil or snow cover surface, whereas throughout the growing season it was presumed to be 0.66 of the mean crop height [Monteith and Unsworth, 2008; Glenn et al., 2010].

At the beginning of the study, 3-D sonic anemometers were located only on plots P1 and A2. The anemometer on plot P1 provided the *K* value for both perennial legume phase plots, and that on A2 was used for both annual rotation plots. Two additional anemometers were installed at later dates during the study, October 8, 2009 on plot A1 and September 21, 2009 on plot P2 (Figure 2.1). The two original anemometers were sequentially removed, calibrated, and reinstalled over a period of 6 months. During this calibration period, a minimum of two anemometers remained functioning at all times. During periods when data were only available from one anemometer per treatment, the *K* value was used for both plots. When two anemometers were present within the same treatment, the mean *K* value was used for GHG flux calculations. If no anemometer was installed in either plot of the same treatment, *K* values from the other treatment were used. From June 26 to July 12, 2008 no anemometer data were available from the annual rotation and the *K* value from the perennial legume phase was used. Similarly, during May 2009, no anemometer data from the perennial treatment were available and the *K* values obtained from the annual side were used to calculate fluxes from all plots at the site. Comparisons between the *K* values used for the two treatments indicated an average difference of less than 10% between plots during the growing season and on an annual basis. During the fall and spring periods, however, the large difference in surface roughness characteristics between treatments caused *K* values to differ by approximately 10 to 15%.

To determine Δ*[GHG]*, gas samples were taken at the centrally-located towers using two stainless steel intakes at two heights above the agroecosystem. The upper and lower sample intakes (Δz) were generally distanced vertically by 0.60 m. Intakes were raised and lowered as the crop height or snow-depth fluctuated. Intake height was positioned low enough to ensure the flux footprint remained within the plot of interest, but high enough that surface roughness factors were minimal. The fetch of the plots were kept within 100 m from the central towers to reduce potential cross-contamination of trace gas eddies from adjacent plots.

To measure the trace gas concentration differences between intakes (Δ*[GHG]*) for a plot, gases were sampled at an intake for 12 seconds and then sampled from the other intake for 12 seconds. Switching between upper and lower intakes was managed by one-way solenoid valves that were part of a gradient-valve assembly on the tower. Gases from the intakes moved through a filter and an air dryer at the tower before being pulled by the vacuum pump through approximately 200 m of sample tubing to a solenoid valve assembly manifold in the modular trailer. Within the trailer, four 3-way solenoid valves directed in-coming gas from one of the four sites through another air dryer and into the gas analyzer. Gas samples from the other three plots were discarded using a purge line. The gas samples were brought to a constant temperature in the trailer, and when passed through the air dryers, water vapour was removed. Water vapour flux corrections were therefore unnecessary [Edwards et al., 2003]. The switching of the solenoid valves at the towers and the trailer was controlled by a modified 16-channel DC controller receiving activation signals for the sampling system relay from a datalogger (Model CR1000, Campbell Scientific Inc.). Due to the mixing of gases in the tubing and the lag time from tower to trailer, air from the switch between sampling of the upper and lower intake was omitted from the calculation of the half-hour-average gas concentration. This allowed only pure gas samples from the intakes to be used in the half-hour concentration calculations [Edwards et al., 2003; Pattey et al., 2006].

The raw high-frequency data from the gas analyzer and the anemometers were stored on memory cards in TOB5 format using data loggers and converted to IEEE binary table format with LoggerNet software (Campbell Scientific Inc.). Data were processed using MATLAB (The MathWorks Inc., Natick, MA) and grouped into 30 minute averages. Updating of the communication logistics in July 2009 resulted in the installation of a serial port in the trailer that allowed automatic data downloads every 10 minutes from all plot towers. Prior to this, data loggers stored in protective housing at each tower required weekly, manual downloading of stored data.

Due to the nature of the site design, it was only possible to record gas concentration data from one plot at a time, making it necessary to switch between plots every 30 minutes. A data logger program prevented a “time of day” bias by sampling the midnight half-hour plot twice to advance the plot sampling sequence by 30 minutes each day. An average of 12 half-hour GHG gradients were collected daily from each plot. Data were collected continuously throughout the year, excluding field operations and removal of monitoring instruments, equipment failure, and maintenance. Instrumentation towers were removed for harvest in the fall of 2008, but due to high precipitation, harvest was delayed and no flux monitoring occurred from August 29 to September 22. Local flooding of the Red River Valley in spring 2009 resulted in the loss of spring data from March 27 to May 8, due to emergency flood preparations at the site.

2.2.4 Supporting Environmental and Soil Data

Environmental conditions at the study site were monitored using a weather station that was installed near the centre of the four plots, in close proximity to the modular trailer (Figure 2.1). A tripod stand held most of the weather station instrumentation. Air temperature, incoming solar radiation, photosynthetic photon flux density (PPFD), wind speed and direction, and total daily precipitation were recorded at the site. The precipitation gauge (Model T-200B Series Precipitation Gauge, Geonor, Inc., Milford, PA) was located 3 m from the weather tripod. Soil temperature thermistors were installed at 2, 5, 10, 20, 50, and 100 cm depths within wooden dowels. Soil temperature at 2, 5, 20, and 50 cm depths were also measured at three locations near the towers on each plot. Soil moisture probes (Model EC-10 ECH$_2$O Dielectric Aquameter, Decagon Devices Inc., Pullman, WA) were positioned at 10 and 30 cm depths between the weather station and the precipitation gauge. Model, manufacturing and placement details of all equipment can be found in Glenn et al. [2010]. Weather data were recorded on a CR1000 datalogger (Campbell Scientific Inc.) at 10 second intervals.

Soil samples were taken every three to five weeks between the months of April and November each year. Six sample locations within each plot were randomly selected at the start of the project and repeatedly sampled (±1 m radius) at each sampling period. Six soil samples were taken from the 0 to 30 cm depth and amalgamated into a composite sample for each location. Soil samples were kept cool on ice in an insulated cooler in the field and during transport to the laboratory. Soils were analysed for gravimetric moisture content (GMC) using sub-samples oven-dried at 105°C. The bulk samples were dried at 40°C for three to seven days in a drying room before being passed through 2 mm screens. All soil samples were analyzed for ammonium (NH_4^+) and nitrate (NO_2^- + NO_3^-) using a 2 M KCl extraction at a 5:1 extractant-to-soil ratio and Technicon Autoanalyzer II colorimetry (Pulse Instrumentation Ltd., Saskatoon, SK), and for pH (Orion 8165BNWP ROSS Sure-Flow pH Electrode, Thermo Scientific, Waltham, MA). The mineral N forms within the soil were used to support N_2O emission trends from the agroecosystem.

Soil bulk density was taken to a depth of 5 cm at each sampling location within each plot during every sampling occasion. Soil density samples were taken using a metal ring with a 5cm diameter, 5cm depth. Samples were kept cool on ice during collection and transport. Soil was weighed wet, oven-dried at 105°C, and weighed dry to determine GMC for density calculations.

Harvest biomass removals in the form of wheat and rapeseed grain yields, as well as straw and hay removed in the form of bales, were measured as average weights (kg) per ha. An elevator scale weighed the grain trucks and bales. The harvest biomass was converted to dry weight basis, with moisture content assumed to be 14% for the wheat grain and biomass, 10% for the rapeseed, and 15% for the alfalfa bales [MAFRI, 2010*a*]. A 45% dry weight C was assumed for all crops. When determining N mineralization for the forage crop, crude protein of 18% [MAFRI, 2010*a*], 160 g N kg $protein^{-1}$, and a root-to-shoot ratio of 1.6 [Bolinder et al., 2007] were used.

2.2.5 Data Quality Control

To maintain high quality data, half-hourly gas sample means and anemometer data were discarded during times of site maintenance, field activities (seeding, harvest and tillage), and power disturbances. Low-quality samples collected due to human interference or stable atmospheric conditions were also removed. Site maintenance included pump oil changes and air filter replacements at each tower, liquid nitrogen fills, and various annual instrumentation tests. Bi-weekly liquid nitrogen fills and the subsequent hour were removed from the data set due to possible analyzer vibrations and temperature adjustment affecting gas concentration measurements [Edwards et al., 2003].

To eliminate false trends and maintain quality control when processing data, threshold limits were set to discard fluxes when certain parameters were exceeded or not met. Trace gas concentration data were eliminated if the gas analyzer pressure or temperature left the ±2 kPa or ±5°C range, respectively, or if switching between upper and lower intakes caused a pressure difference greater than 5 Pa. Flux data were rejected if the standard deviations of 30-min averages were greater than 20 ppm for CO_2 concentrations and 20 ppb for N_2O concentrations. Similar filtering methods were used by Glenn [2010]. Any flux data collected when the friction velocity (u*) was below 0.15 m s^{-1} were discarded due to unreliable *K* estimates during periods of low atmospheric mixing. This u* threshold was based on values calculated from the 2008 spring-wheat growing season CO_2 flux data [Glenn et al., 2010]. A total of 60% of the 30-min GHG flux averages collected from both rotations over the two-year study period were removed during data filtering.

Micrometeorological CO_2-C and N_2O-N mass fluxes were calculated by converting gap-filled cumulative net CO_2 ecosystem exchange flux ($\sum F_{C\text{-}NEE}$) and cumulative net N_2O flux ($\sum F_N$) data into net annual kg C and N ha^{-1}. To determine the amount of anthropogenic N_2O lost from the annual rotation, a fertilizer emission factor was established using annual gap-filled F_N data and spring-applied fertilizer rates. The amount of C removed with harvest ($F_{C\text{-}HARVEST}$) was based on the weight of grain yield and crop biomass removals (straw, hay) from the field at harvest. The mean $F_{C\text{-}HARVEST}$ weight was supplied by the field-scale harvesting machinery whereas individual $F_{C\text{-}HARVEST}$ plot values were determined using a weighted-average of biomass sample weights taken at harvest. Biomass samples of 0.5m by 0.5m were taken from six locations in each of the four plots up to 3 days prior to harvest. Plant stalks were harvested 2.5cm from the soil for the alfalfa stand, and 5cm and 7.5cm for the spring wheat and rapeseed plots, respectively. These biomass samples were converted to dry weight, with C and moisture content assumed identical to the biomass that was mechanically harvested. To help explain $F_{C\text{-}NEE}$ and $F_{C\text{-}HARVEST}$ differences among plots, biomass samples collected from the perennial legume phase were separated into alfalfa and grass/weed weight groupings. Differences between the annual treatment plots were simply explained using harvest biomass weights. The soil C storage balance ($F_{C\text{-}STORAGE}$) was calculated by combining $F_{C\text{-}HARVEST}$ with $\sum F_{C\text{-}NEE}$. Both $\sum F_N$ and $F_{C\text{-}STORAGE}$ were converted to CO_2-eq. using a GWP of 310 [Barker et al., 2007] and totaled to determine the net greenhouse gas flux balance ($\sum F_{GHG}$) for the rotations.

2.2.6 Gap Filling

Gap filling was required when certain threshold parameters were not met or during site operations which caused data to be discarded. Carbon dioxide flux gaps less than two hours were filled by linear interpolation. Larger CO_2 data breaks were filled using correlations between air temperature and respiration (nighttime $F_{C\text{-}NEE}$), and light (PPFD) and photosynthesis of a 100-data-point moving-window [Barr et al., 2004; Glenn et al., 2010]. Breaks (one day or less) in meteorological data were filled using linear interpolation of diurnal air temperature and PPFD averages. Parameter averages for larger breaks were estimated using equivalent data from pre- and post-gap days. Little work has been done on establishing meteorological relationships with N_2O fluxes making reliable estimates difficult [Glenn, 2010]. The high temporal and spatial variability of N_2O fluxes resulted in the use of a different gap filling method. Annual N_2O budgets were estimated by linear interpolation of daily fluxes.

2.3 Results

2.3.1 Weather and Soil Conditions

The average daily air temperature at the site was 1.5 and 3.5 °C for the 2008/2009 (May 2008 to April 2009) and 2009/2010 crop years, respectively (Table 2.2). The 2008/2009 crop year was one degree cooler and 2009/2010 was one degree warmer than the 30-year normal of 2.4°C, measured 2 km from the research site at the town of Glenlea, Manitoba [Environment Canada, 2010*b*]. December 2008 and January 2009 were much cooler and several months in the fall and winter of 2009/2010 were much warmer than normal. Soil temperature trends followed air temperature patterns (Figure

2.2). In the 2009/2010 crop year, the 5 and 20 cm soil depths remained almost 5 °C warmer throughout the winter months than during the same period in 2008/2009.

Both years of the study received over 200 mm more precipitation than the normal of 530 mm (Table 2.1). The 2009/2010 crop year experienced 848 mm, with slightly higher precipitation in the early summer and mid-winter months than the 2008/2009 crop year (Figure 2.2), which accumulated 755 mm. The 2009 growing season (seeding to harvest) received 441 mm of precipitation, almost 80 mm more than the same period in 2008.

Concentrations of extractable soil NH_4^+ followed similar patterns for both crop rotations in 2008 (Figure 2.3 a and b); low NH_4^+ concentrations in May, increasing through June and July to approximately 20 mg N kg^{-1} and decreasing as the season progressed. In the annual rotation, soil NO_3^- concentrations were highest in early spring at 17 mg N $kg^{-1}$and declined with crop growth. The perennial legume phase maintained NO_3^- concentrations slightly above 10 mg N kg^{-1}, peaking in August and decreasing into the fall. May 2009 had mineral N concentrations lower than 10 mg N kg^{-1} in both rotations. Mineral N concentrations were highest in June and July of 2009. Ammonium concentration in the perennial rotation peaked at 41 mg N kg^{-1}, and NO_3^- and NH_4^+ reached 50 and 33 mg N kg^{-1}, respectively in the annual rotation, prior to a N_2O emission flux. The remainder of the 2008/2009 season had low N concentrations that elevated slightly in the fall. Although NO_3^- concentrations varied throughout the growing season, no relationship could be found between soil N concentrations and N_2O loss or following precipitation events.

There was little difference between bulk densities of the different rotations. The bulk density (0-5cm depth) ranged from 0.59 to 1.22 Mg m^{-3} for the annual rotation (n=156) and 0.54 to 1.16 Mg m^{-3} for the perennial legume phase (n=156) over the two study years. Mean bulk density was 0.91 Mg m^{-3} for the annual rotation and 0.85 Mg m^{-3} for the perennial legume phase. Standard error was 0.05 Mg m^{-3} for both rotations.

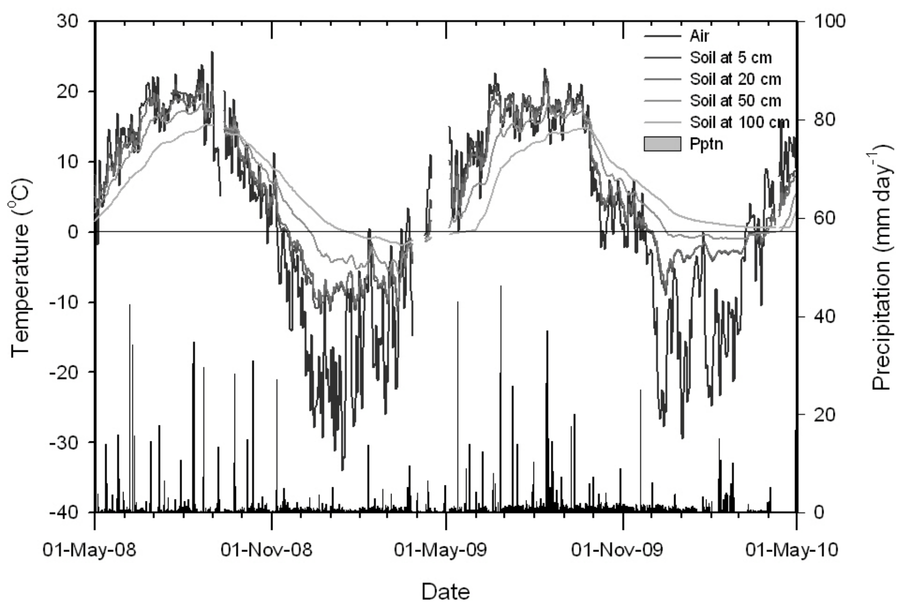

Figure 2.2 Air and soil temperature, and daily precipitation from the on-site weather station for the two study years.

Table 2.2 Air temperature and precipitation over the two study years compared with the 30-year (1971-2000) Canadian Climate Normal for Glenlea, Manitoba, Environment Canada, 2010*b*).

	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Avg
Average Air Temperature (°C)													
2008/2009	9.2	16.0	18.2	18.9	12.4	6.0	-3.5	-19.5	-20.7	-14.4	-7.9[a]	3.1[a]	1.5
2009/2010	8.4[a]	16.5	16.7	16.7	16.9	3.1	0.5	-15.3	-14.2	-14.8	-1.1	8.3	3.5
30 Year Normal	12.4	17.0	19.3	18.4	12.2	5.1	-5.5	-14.8	-18.5	-14.4	-6.6	4.2	2.4
Total Precipitation (mm)													
2008/2009	69	126	56	123	71	73	65	30	25	43	44[a]	30[a]	755
2009/2010	84[a]	124	93	155	76	60	59	42	26	84	13	32	848
30 Year Normal	62	94	80	68	54	41	25	21	19	16	21	29	530

[a] Missing data due to shut-down for flood preparations were gap-filled using data from Winnipeg's James Armstrong Richardson International Airport, approximately 35 km from the site (Environment Canada, 2010*b*)

2.3.2 $F_{C\text{-}NEE}$

Net carbon dioxide fluxes ($F_{C\text{-}NEE}$) were temporally and spatially variable throughout the two-year study. The perennial legume phase was a greater sink of atmospheric CO_2 in the 2009 established year than the 2008 establishment year. Plant uptake began earlier and ended later in the 2009/2010 growing season after alfalfa establishment (Figure 2.3 c). Most cutting events of the alfalfa crop resulted in positive $F_{C\text{-}NEE}$ to the atmosphere with subsequent rapid C draw-down as crop growth rebounded.

During the 2008 growing season, the crop went from being an average 1.4 kg C ha^{-1} d^{-1} sink 5 days prior to first mowing, to a peak 9.9 kg C ha^{-1} d^{-1} source within 4 days of cutting. However, the second and third mowing events did not result in a $F_{C\text{-}NEE}$ change. In the 2009 growing season, the crop went from an average 125 kg C ha^{-1} d^{-1} sink 5 days prior to first cut, to a 25 kg C ha^{-1} d^{-1} source within three days of the cutting event. No data are available for the second cut. A data gap following the second cut was due to data removal for quality control. In the annual rotation, the spring wheat crop of 2008 had a large, rapid C draw-down of atmospheric CO_2, whereas the 2009 rapeseed crop was a small C sink over the growing season (Figure 2.3 d). The rapeseed yield was found to be 50% of the regional average [MASC, 2010]. Once the annual crops reached peak maturity and began senescing, positive $F_{C\text{-}NEE}$ occurred.

Distinctions in $F_{C\text{-}NEE}$ between cropping systems are clear within the first two months of the study. Negative growing season $F_{C\text{-}NEE}$ occurred quickly in the annual rotation because of rapid-maturing annual crops. The perennial legume phase accumulated C at lower rates, although for a longer growing period. Comparisons between crops show the 2008 wheat crop was an equivalent $F_{C\text{-}NEE}$ sink to the 2009 established year of the perennial legume, whereas the 2009 rapeseed crop accumulated only 10% C of the first-year perennial legume phase (Table 2.3). Despite the large C sink seen in the 2008 wheat crop, the longer growing period for the alfalfa crop and the poor 2009 rapeseed yield resulted in a greater $\sum F_{C\text{-}NEE}$ sink for the perennial legume phase over the two-year study period (Figure 2.4 a).

The removal of biomass in the form of grain or bales exported C from the cropping systems. To determine a balance for the C entering and leaving the agroecosystem, it was necessary to include harvest C ($F_{C\text{-}HARVEST}$) in the system C balance calculations (Table 2.3) [Post et al., 2001]. The greatest $F_{C\text{-}HARVEST}$ removal was for the 2008 spring wheat crop at 2030 kg C ha^{-1} (grain and straw), followed by the 2009 established perennial legume phase (1930 kg C ha^{-1}). The 2009 rapeseed crop removed 430 kg C ha^{-1} through grain harvest. When compared to regional yields (Manitoba, Risk Area 12) for the respective years, the wheat crop grain yield (1175 kg C ha^{-1}) was similar to the average yield of 1300 kg C ha^{-1}. When compared to regional canola yields of 860 kg C ha^{-1}, the rapeseed yield (430 kg C ha^{-1}) was 50% lower than the average yield. The ten-year yield average for the province of Manitoba was 1056 kg C ha^{-1} for wheat and 750 kg C ha^{-1} for canola [MASC, 2010]. The provincial ten-yield average for tame hay production was 1700 kg C $ha^{-1}$and the 2008 yield average was 1800 kg C ha^{-1} [MAFRI, 2010*b*]. No alfalfa-hay yield data was available for the 2009 growing season.

Cumulative average C removal (2460 kg C ha^{-1}) was greater for the annual crop rotation than the perennial legume phase due to the fact that the 2008 establishment

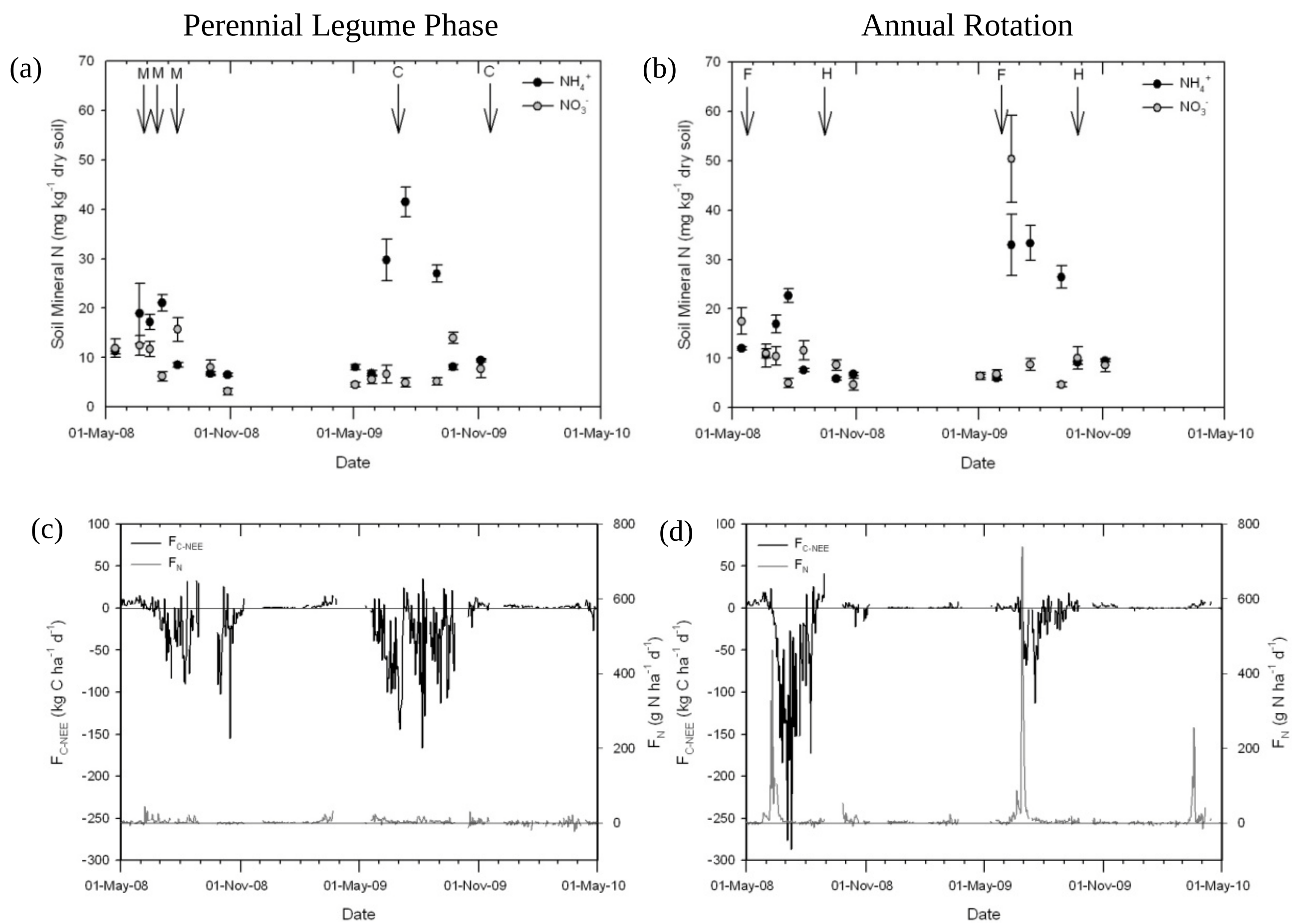

Figure 2.3 Concentrations of NH_4^+ and NO_3^- from the 0 to 0.3 m soil depth (a) the perennial legume phase and (b) the annual crop rotation, with fluxes of nitrous oxide (F_N) and net ecosystem CO_2 exchange ($F_{C\text{-}NEE}$) from (c) the perennial legume phase and (d) the annual crop rotation over the two crop years of the study. Average nitrogen concentrations of six locations in each of the two replicate plots for a treatment (n=12) and ± 1 SE as error bars are shown. Alfalfa mowing (M) and cutting (C), fertilizer application (F), and harvest (H) are denoted by arrows at the top of the figures.

Table 2.3 Ecosystem carbon and nitrogen fluxes: gap-filled cumulative net N_2O flux ($\sum F_N$), gap-filled cumulative net CO_2 ecosystem exchange ($\sum F_{C\text{-}NEE}$), C harvest removal ($F_{C\text{-}HARVEST}$), net soil C storage ($F_{C\text{-}STORAGE}$), and cumulative net greenhouse gas flux equivalents (($\sum F_{GHG}$) from the two crop rotations for the two years of the study (May 1 to April 30). Negative fluxes denote an ecosystem gain; positive fluxes represent an ecosystem loss to the atmosphere. $\sum F_N$ was converted to CO_2-eq. using a global warming potential of 310.

		Crop Years								
		2008/2009			2009/2010			Net Study Period		
Rotation	**Fluctuations**	**Mean**	**Plot 1**	**Plot 2**	**Mean**	**Plot 1**	**Plot 2**	**Mean**	**Plot 1**	**Plot 2**
Annual	$\sum F_N$, kg N ha^{-1}	4.4	5.1	3.7	5.2	5.1	5.3	9.5	10.1	9.0
	$\sum F_{C\text{-}NEE}$, kg C ha^{-1}	-2370	-1730	-3010	-140	-70	-200	-2500	-1790	-3210
	$F_{C\text{-}HARVEST}$, kg C ha^{-1}	2030	2060	1990	430	460	400	2460	2520	2390
	$F_{C\text{-}STORAGE}$, kg C ha^{-1}	-350	330	-1020	300	390	200	-50	730	-820
	$\sum F_{GHG}$, kg CO_2-eq ha^{-1}	850	3700	-1940	3620	3910	3320	4500	7610	1380
Perennial Legume Phase	$\sum F_N$, kg N ha^{-1}	2.0	0.7	3.3	0.9	0.1	1.6	2.7	0.7	4.7
	$\sum F_{C\text{-}NEE}$, kg C ha^{-1}	-1450	-830	-2070	-2350	-1590	-3100	-3800	-2420	-5170
	$F_{C\text{-}HARVEST}$, kg C ha^{-1}	0	0	0	1930	1720	2140	1930	1720	2140
	$F_{C\text{-}STORAGE}$, kg C ha^{-1}	-1450	-830	-2070	-420	130	-960	-1870	-700	-3030
	$\sum F_{GHG}$, kg CO_2-eq ha^{-1}	-4340	-2700	-5980	-1100	530	-2740	-5440	-2170	-8720

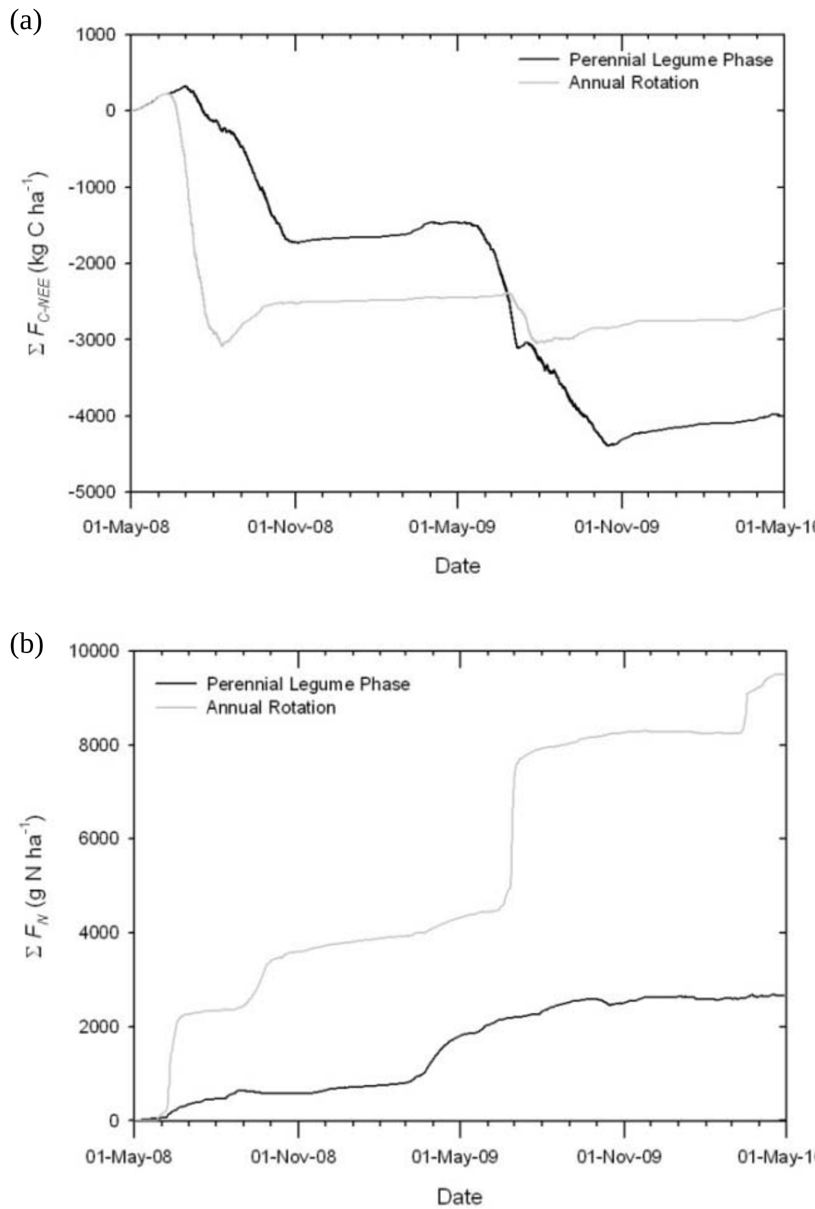

Figure 2.4 Average of cumulative, gap-filled (a) net ecosystem CO_2 exchange ($\sum F_{C\text{-}NEE}$) and (b) nitrous oxide ($\sum F_N$) fluxes of both plots for each crop rotation over the two crop years of the study.

forage was mowed and the cut biomass left on the field. With lower $F_{C\text{-}HARVEST}$ removal rates and greater $F_{C\text{-}NEE}$, the perennial legume phase accumulated greater soil C ($F_{C\text{-}STORAGE}$) than the annual rotation. For the study period, the perennial legume phase sequestered 1870 kg C ha^{-1} after accounting for harvest removals. The annual rotation sequestered 50 kg C ha^{-1} after accounting for harvest removal, remaining C neutral for the study period. The perennial legume phase accumulated almost 40 times more soil C ($F_{C\text{-}STORAGE}$) when compared to the annual rotation over the two-year study.

2.3.3 F_N

The N_2O fluxes (F_N) from the two cropping systems were episodic throughout the two crop years. Average F_N from the perennial legume phase hovered above zero (3.5 g N_2O-N ha^{-1} d^{-1}) for the majority of the study, with slight emissions following major precipitation events and forage cutting (Figure 2.3 c). Following 42 mm of rain on June 7, 2008, 44 g N_2O-N ha^{-1} d^{-1} was emitted from the perennial legume phase. Two days later, the emissions had declined to 2 g N_2O-N ha^{-1} d^{-1}. Emissions over 30 g N_2O-N ha^{-1} d^{-1} were seen throughout the study following heavy precipitation events within prolonged dry periods. Despite, the occasional N_2O flux observed when no precipitation occurred, a relationship was observed between precipitation events and N_2O flux in the perennial legume phase. Nitrous oxide concentrations did not correspond with flux values and therefore, that no relationship existed between N_2O fluxes and soil NO_3^- concentrations. Nitrous oxide fluxes following forage cutting were an average of 8 g N_2O-N ha^{-1} d^{-1} (n=5). Emissions remained high for one to three days following cutting.

Fluxes from the annual rotation were associated with spring-thaw, and precipitation events following N fertilizer application. The average F_N from the annual rotation was 15 g N_2O-N ha^{-1} d^{-1}. Mean daily N_2O emissions were greater in the 2009/2010 than the 2008/2009 growing season. The bulk of N_2O emissions from the annual rotation occurred in late spring, 3 to 4 weeks following fertilizer application and significant rainfall, peaking at 462 g N_2O-N ha^{-1} d^{-1} on June 10, 2008 and at 740 g N_2O-N ha^{-1} d^{-1} on June 29, 2009 (Figure 2.3 d). Two emission peaks were observed, with a small flux preceding the large aforementioned flux in both years. In 2008, the first flux began on May 26, peaked May 28 and lasted until June 2, following a 15 mm precipitation event on May 25. A second flux period began June 6 with emissions lasting to June 23 following a series of major rainfall episodes from June 6 to 11 that contributed 145 mm of rain. In 2009, the smaller flux began on June 18, peaked June 20, and decreased until June 26, when 74 mm of rain caused the second emission episode that subsided July 4. Distinct relationships between precipitation events, N_2O fluxes, and soil N concentrations during the growing season were not observed. Fluxes did not correspond with specific precipitation events during the growing season and soil NO_3^- concentrations did not seem to affect N_2O emission values.

The yearly F_N from the annual rotation was compared to the amount of fertilizer applied at seeding to provide a fertilizer emission factor for the agroecosystem. Background levels of F_N were assumed equal to that emitted from the perennial legume phase and subtracted from the annual rotation treatment. The average emission factor for the spring-applied fertilizer over the two study years was approximately 3% of N fertilizer lost as N_2O. About 2.5% and 2.9% synthetic N was lost from the rotation in the 2008/2009 and 2009/2010 crop years, respectively.

The annual rotation experienced a N_2O flux during the 2010 spring thaw period. Emissions began March 13 when air and 2 cm soil temperatures reached above 0°C, peaked at 255 g N_2O-N ha^{-1} d^{-1} on March 19 and abated March 21, 2010 (Figure 2.5). No thaw emissions were observed during 2009 due to dismantlement of instrumentation for emergency flood preparation. Despite this precaution, no flooding occurred at the research site. A spring-thaw N_2O flux was not observed in the perennial legume phase in the spring of both 2009 and 2010. Negative F_N values were observed in both crop rotations following crop growth spurts, typically upon seedling establishment and a couple weeks following forage cutting, when the crop was actively growing once again. Periods of little rain also seemed to initiate F_N uptake by the agroecosystem.

To provide insight into the amount of N mineralized by the perennial legume phase, N removed by the forage crop was calculated. In the 2008/2009 growing season, the perennial legume phase was estimated to have mineralized 100 kg ha^{-1}, and 240 kg ha^{-1} for the 2009/2010 crop year. These values are noteworthy when compared to the N_2O emissions of 4.3 and 5.2 kg ha^{-1} emitted from the crop rotation over the two study years (Table 2.3).

Cumulative F_N totals ($\sum F_N$) from the two crop years (Figure 2.4 b) showed that the annual rotation contributed 9500 g N_2O-N ha^{-1} to the atmosphere, more than three times greater than the 2670 g N_2O-N ha^{-1} contributed from the perennial legume phase. The $\sum F_N$ in the perennial legume phase increased slowly throughout the 2008/2009 growing season, with emissions typically increasing following the cutting of the alfalfa.

The release of F_N by the forage crop in the late fall of 2009 occurred during an unusual warm period in November that caused renewed alfalfa growth and subsequent death of re-growth with freezing temperatures in early December. The 2008/2009 seedling year had a greater $\sum F_N$ total than the 2009/2010 established crop year. In the annual rotation, large $\sum F_N$ increases were seen in both years during the spring, following the application of N fertilizer and a large precipitation event. The rapeseed fertilizer application contributed almost the same amount of N_2O as that released in the entire 2008/2009 study year.

2.3.4 Variability in Gas Fluxes Within and Between Treatments

There was an obvious distinction in $F_{C\text{-}NEE}$ and $\sum F_N$ from individual treatment plots, most evident during the growing season (Figure 2.6). Patterns in $\sum F_{C\text{-}NEE}$ for individual plots in each rotational treatment began diverging within two months of the beginning of the study (Figure 2.6). Plot P2 sequestered almost three times more C than P1 in 2008 and twice as much in 2009. Plot A2 accumulated almost twice as much C than A1 in 2008. Both annual rotation plots behaved similarly after August 2008, sequestering similar amounts of C in 2009. Over the net study period, plot P2 sequestered twice as much C as P1, and plot A2 accumulated almost two times more C than A1 (Table 2.3).

Differences in F_N from the perennial legume phase plots were noticeable beginning in March 2009, with F_N increasing by 1085 g N ha^{-1} over the month in plot P2 only. This N_2O emission release resulted in a five-fold difference in N_2O flux between plot P1 and P2 for the 2008/2009 crop year. In 2009/2010, P2 experienced F_N emissions sixteen times greater than P1. When averaged over the two study years, plot P2 had $\sum F_N$ almost seven times greater than P1. Differences in $\sum F_N$ between the annual rotation plots occurred following fertilizer application and a precipitation event in both crop years. Plot A1 emitted almost one and half times more N_2O than A2 in 2008, while plot A2 emitted slightly more than A1 in 2009. For the net study period, plot P2 emitted almost seven times more N_2O than P1, and plot A1 emitted only slightly more N_2O than A2.

2.3.5 Net Greenhouse Gas Emissions

To compare and quantify the overall GHG emissions from the agroecosystem over the two-year study, N_2O was converted into CO_2-eq. using a GWP of 310 (Table 2.3, Figure 2.7). Because the annual rotation accumulated less atmospheric CO_2 and emitted more N_2O than the perennial legume phase, the high CO_2-eq.-$\sum F_N$ in the annual rotation offset the $F_{C\text{-}STORAGE}$. Thus, the annual rotation was a source of two and a half times more $\sum F_{GHG}$ than the perennial legume phase. Even after accounting for bale removal of above-ground biomass, the perennial legume phase was a net GHG sink (-5440 kg CO_2-eq. ha^{-1}), whereas the annual rotation was a considerable net GHG source (4500 kg CO_2-eq. ha^{-1}) for the two-year study.

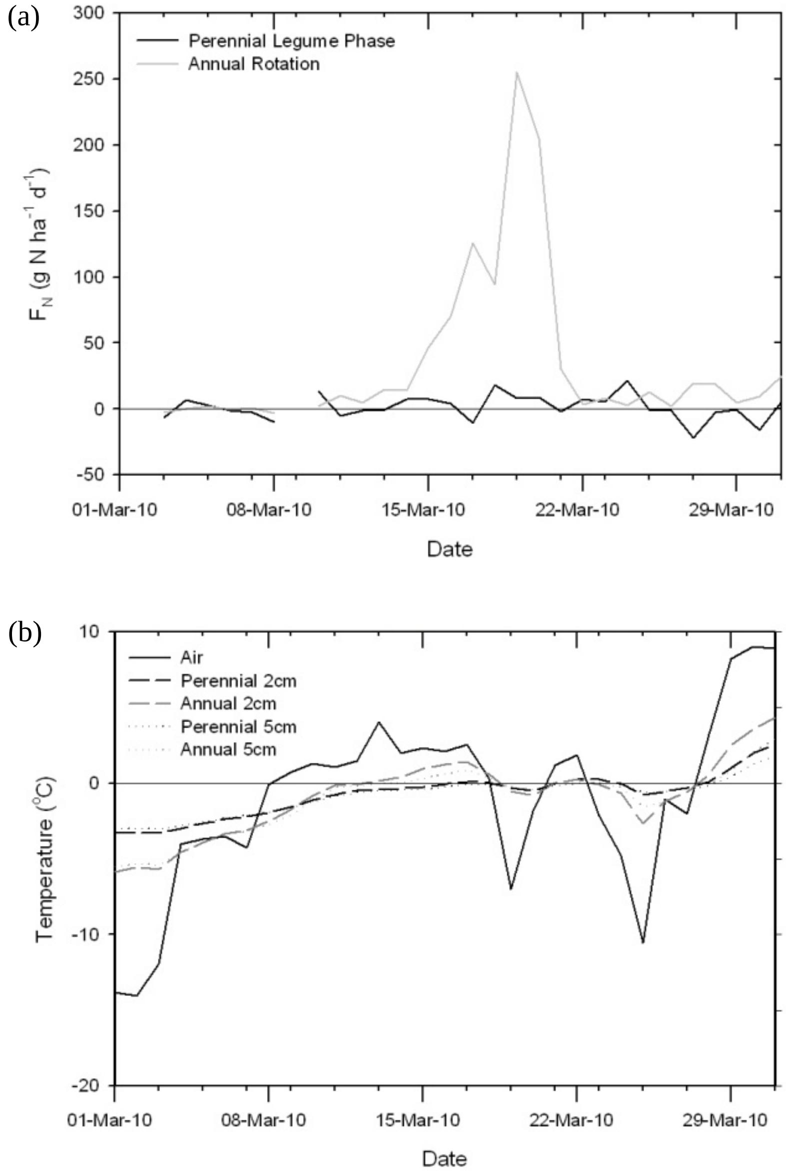

Figure 2.5 (a) Nitrous oxide fluxes from the perennial legume phase and the annual rotation with (b) perennial legume phase and annual rotation plot soil temperatures at 2 and 5 cm depths (n=3) and air temperature (n=1) for March 2010, during the spring-thaw period.

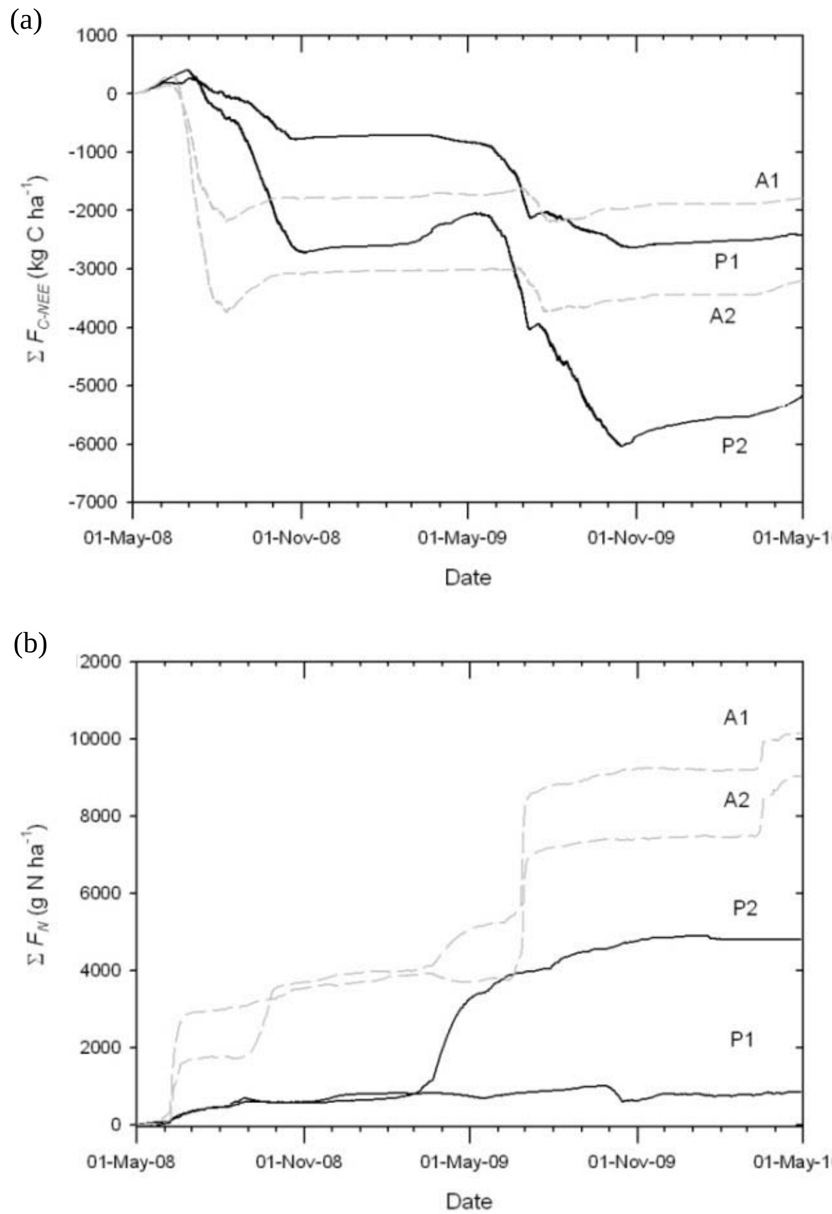

Figure 2.6 Cumulative, gap-filled (a) net CO_2 ecosystem exchange ($\sum F_{C\text{-}NEE}$) and (b) nitrous oxide ($\sum F_N$) fluxes from the perennial legume phase (solid lines) and annual rotation (dashed lines) plots over the two crop years of the study.

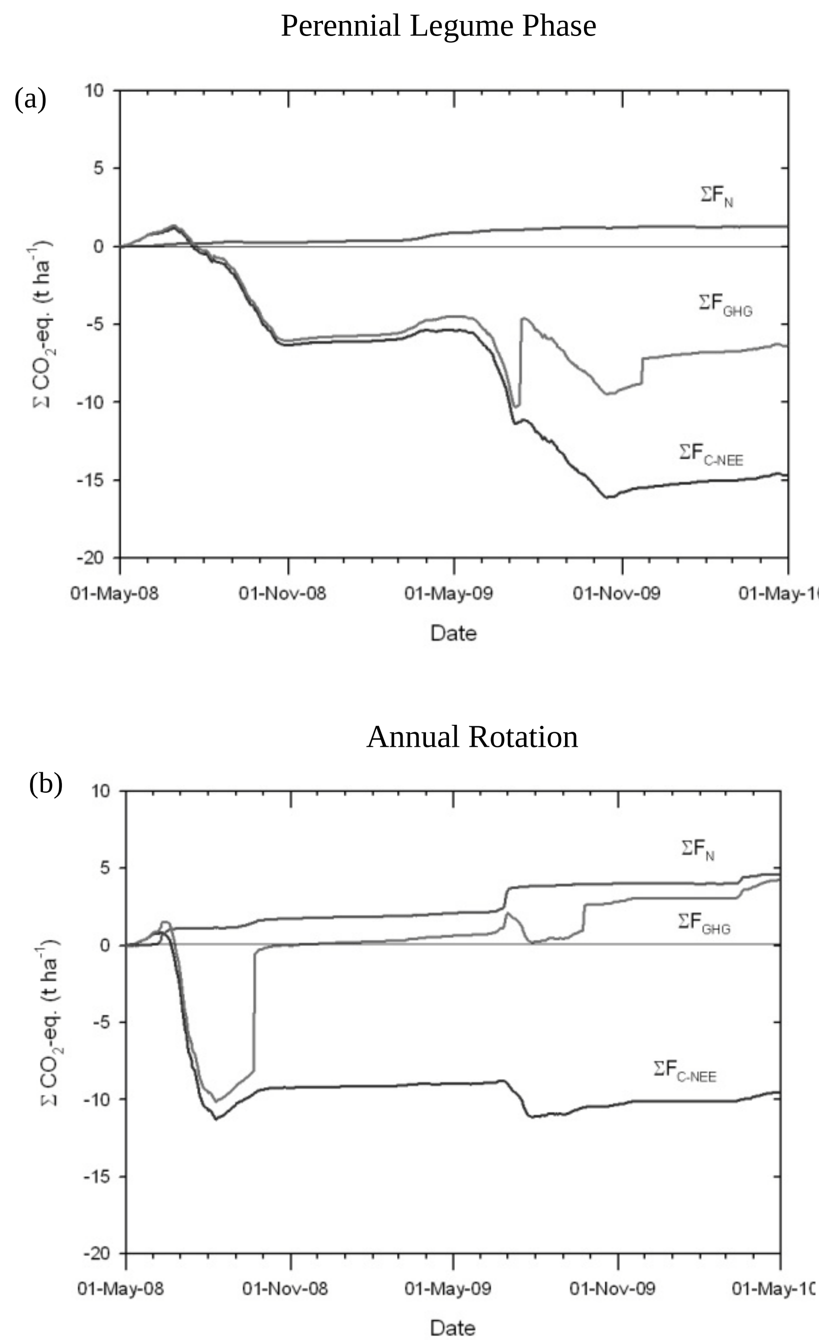

Figure 2.7 Cumulative CO_2-equivalents (CO_2-eq.) carbon and nitrous oxide fluxes from the (a) perennial legume phase and the (b) annual spring wheat-rapeseed rotation: non-gap-filled nitrous oxide ($\sum F_N$), net ecosystem CO_2 exchange ($\sum F_{C\text{-}NEE}$) and net greenhouse gas exchange ($\sum_{GHG}$) over the two-year study. $\sum F_N$ was converted to CO_2-eq. using a global warming potential of 310.

2.4 Discussion

2.4.1 $F_{C\text{-}NEE}$

Although there are naturally variations in gas fluxes by region and crop year depending on soil properties, environmental conditions, and crop stand quality [Mensah et al., 2003; Su, 2007; Davis et al., 2010], the CO_2 fluxes recorded during this two-year study show distinct differences in $F_{C\text{-}NEE}$ between the annual rotation and the perennial legume phase treatments (Figure 2.3). These differences indicate that crop phenology does affect soil C sequestration of an agroecosystem.

During the 2008 growing season, while the perennial legume seedlings were establishing, the spring wheat crop acted as a large atmospheric CO_2 sink (2370 kg C ha^{-1}) in comparison to the perennial legume phase establishment year that collected only 60% of the amount of C (1450 kg C ha^{-1}). In the 2009 established year, however, a longer growing season for the perennial legume phase and a poor rapeseed yield resulted in seventeen times more C sequestered (2350 kg C ha^{-1}) in the perennial than the rapeseed crop (140 kg C ha^{-1}). Furthermore, the late fall of 2009 and early spring of 2010 had warmer air temperatures than normal, possibly extending the growing season for the perennial legume phase, and allowing greater atmospheric CO_2 accumulation than during an average growing season. The 2008 spring wheat was a greater C sink than the 2009 rapeseed crop. When the treatment $\sum F_{C\text{-}NEE}$ were compared for the two-year study period (Figure 2.4), the perennial legume phase accumulated 1300 kg C ha^{-1} more than the annual rotation.

The rapid maturation of the annual crops resulted in the annual rotation performing as a strong C sink during the relatively short three-month growing season, but was a source when plant growth was minimal in the spring, late summer, and early fall of both study years. Davis et al. [2010] observed similar seasonal variations for an annual crop study in Southeastern Ireland. Soil temperatures, above $5^{o}C$, were warm enough for microbial decomposition of soil and residue C during these months [Rabenhorst, 2005]. The perennial legume phase grew for an extended, six-month growing season [Baker and Griffis, 2009], allowing the higher C uptake observed. However, CO_2 emissions were also observed from the perennial legume phase in the two-week period following forage cutting, prior to the forage crop producing new leaves. This is similar to observations in previous forage studies [Sanderson et al., 1997; Baron et al., 2006]. Sanderson et al. [1997] observed that it took alfalfa taproots up to fourteen days after cutting before the plants began sequestering C again.

Although the perennial legume phase $F_{C\text{-}NEE}$ and $F_{C\text{-}HARVEST}$ correspond, this is not the case for the annual rotation. A low-lying area in plot 2 that was used as a drainage ditch may have contributed to the lower plant biomass harvested from this plot for both study years. However, the spring wheat and rapeseed crops tended to be thicker on plot 2, explained by the greater rates of $F_{C\text{-}NEE}$ measured (Table 2.3). Crop physiology and leaf area index variations between crop types are probable explanations for C sequestration differences observed [Baker and Griffis, 2009; Davis et al., 2010] in this study, although actual phenological values were not recorded.

2.4.2 $F_{C\text{-}STORAGE}$

Differences between $\sum F_{C\text{-}NEE}$ and $F_{C\text{-}STORAGE}$ for both rotation treatments suggest that crop biomass removal has a large influence on the C sequestration potential of a cropping system, and must be included in C balance research. Harvest removals reduced the C gains $\sum F_{C\text{-}NEE}$) observed in both rotations, bringing the net annual rotation $F_{C\text{-}STORAGE}$ to approximately neutral at -50 kg C ha^{-1} and the perennial legume phase to a net sink of 1870 kg C ha^{-1} (Table 2.3). Because very little research has looked at CO_2 fluxes from the Canadian Prairies, particularly in perennial forages, it was necessary to compare $F_{C\text{-}STORAGE}$ from this study to global SOM studies. One study in Alberta reported a perennial forage cropping system gained 3000 kg C ha^{-1} more than a wheat-fallow system over a period of six years [Bremer et al., 2002]. A four-year study in China found a similar amount of SOC accumulation, with a 2300 kg C ha^{-1} difference, or 11.5%, observed between alfalfa and annual crop rotations [Su, 2007]. However, our study findings are much different than flux measurements from an Alberta grassland grazing study where the forage crop was a net source in its seedling year and neutral in its established year. When harvest removal was accounted for, the perennial forage system was a small C source for both years of the study at rates much smaller than this study [Baron et al., 2006].

In spite of the large atmospheric CO_2 draw-down observed by the first two years of forage in the present study, past studies have found that the full C sink potential of alfalfa did not occur until it has been established for several years. Typically, alfalfa stand benefits are experienced when the alfalfa stand is five years old or less [Entz et al., 2002]. One Chinese study found that even after four years of alfalfa, the full C sequestration potential of the system was not seen [Su, 2007]. In Wisconsin, Kucharik [2007] found that young forage stands, aged four to five years, sequestered the highest C, with average annual SOC accumulation declining as the perennial forage stand aged.

Optimal sequestration potential therefore, may exist between the second and fifth year of perennial forage stand maturity.

Carbon storage in the annual rotation was highly influenced by the type of annual crop grown each year. The wheat crop had high $F_{C\text{-}HARVEST}$ values that offset the sequestered $\sum F_{C\text{-}NEE}$ in that year, but enough C was accumulated by the annual rotation to create a net C sink in the 2008/2009 crop year. In contrast, the rapeseed crop lost more C through harvest removals than it sequestered, making the 2009/2010 crop year a net CO_2 source. In both crop years, crop phenology and physiology were thought to be major influences on the net C storage by the agroecosystem.

2.4.3 F_N

2.4.3.1 F_N Treatment Differences Both rotations experienced small negative N_2O fluxes (up to -12.8 and -12.4 g N ha^{-1} d^{-1} for the perennial legume phase and the annual rotation, respectively) at different time periods throughout the growing season, which seemed to correspond with lack of precipitation. These emissions do not seem to be affected by crop growth or treatment. As discussed in Wagner-Riddle et al. [1996], the only microbial process that consumes N_2O is denitrification. Due to little precipitation, the sink trend may have been the result of anaerobic microsites below the dry surface layer consuming N_2O during these dry periods.

Nitrous oxide emissions were observed during different time periods for the individual treatments. The annual rotation experienced N_2O fluxes primarily in the spring, following spring thaw and fertilizer application, whereas the perennial legume phase had continuous, albeit small fluxes throughout the growing season. The flux differences between treatments indicate the impact of agronomic practices and environmental conditions on nutrient cycling.

Because there were no synthetic N additions, the limited N_2O fluxes emitted from the perennial legume phase throughout the year were possibly due to the mineralization of organic N from the previous crop [Ellert and Janzen, 2008] or the N mineralization associated with the fast-decomposing legume residues [Rochette et al., 2004]. A study conducted in Southern Ontario found that growing season N_2O emissions were low due to the high availability of C in perennial forage rotations leading to complete denitrification (reduction of N_2O to N_2) [Burton et al., 1997]. The 100 kg N ha^{-1} and 240 kg N ha^{-1} that was estimated fixed by the forage crop for the 2008/2009 and 2009/2010 growing seasons, respectively, limited the soil mineral N concentrations and N_2O capable of being produced from the forage cropping system. Greater below-ground biomass [Rochette et al., 2004] and higher crop yields were associated with high rates of BNF by forages [Schmidtke, 2008], as observed in this study, largely due to the full establishment of the forage in the second study year.

Small N_2O bursts were observed in the perennial legume phase following precipitation events that led to high soil moisture conditions conducive to rapid nitrification-denitrification, particularly during the 2008/2009 establishment year. Although Burton et al. [1997], Kelner et al. [1997], and Wagner-Riddle et al. [1997] related the N_2O bursts from alfalfa to high soil mineral N concentrations (from organic N turnover) prior to precipitation, NO_3^- concentrations in our study were not higher prior to precipitation events than during other periods of the year. Concentrations of soil NO_3^- were low and NH_4^+ concentrations were high during the 2009 growing season. Slow decreases in NH_4^+ over the growing season were assumed to be from nitrification of NH_4^+ into NO_3^-. The soil N forms and concentrations led to the assumption that available NO_3^- was taken up by the forage crop, limiting the amount of N available for N_2O production. Additionally, findings from Kelner et al. [1997] and Rochette et al. [2004] show more N was fixed by established stands. The lower $\sum F_N$ concentrations and greater N fixation (140 kg N ha^{-1}) by the matured crop stand in 2009 support these observations. Soil N concentrations were therefore determined not directly-related to flux values or occurrences, as observed in Rochette et al. [2004].

As in the perennial legume phase, no relationship between N_2O and NO_3^- concentrations prior to precipitation events was observed in the annual rotation during the growing season. This is unlike research conducted by Ruser et al. [2001], which related N_2O bursts from annual crops to high soil mineral N concentrations prior to precipitation. The N_2O emissions observed in the current study were highly episodic and concentrated around times when soil conditions were favourable for denitrification. Denitrification conditions occurred in the spring, during spring thaw and following fertilizer application and precipitation. Only during this time period was a relationship between soil NO_3^- and N_2O found.

None of the above studies, nor the current study, looked specifically at nitrification as a cause of N_2O creation. An incubation study observed that 60% of N_2O emissions were nitrified from the NH_4^+ pool, and 40% denitrified from NO_3^- during unsaturated soil conditions [Mathieu et al., 2006]. When soil was saturated, denitrification was found to contribute up to 90% of N_2O emissions. The N fertilizer addition in the current study was definitely considered the source of NO_3^- that lead to the N_2O emissions observed, and therefore, nitrification can be associated with the N_2O fluxes. However, the N_2O created by both nitrification and denitrification were not considered individually and could therefore not be differentiated in this study. Regardless, both nitrification and denitrification simultaneously contribute to the N_2O flux from an agroecosystem, making further studies mandatory to understand N cycling contributions on emission concentrations.

2.4.3.2 Episodic Events Nitrous oxide emissions from the annual rotation were largely dependent on soil conditions conducive to denitrification: high amounts of NO_3^- and C, water-saturated soil conditions, and low aeration [Voroney and Derry, 2008]. Outbursts occurred predominantly following fertilizer application and a large precipitation event, and during spring-thaw.

A spring-thaw event was observed on the annual rotation in 2010 (Figure 2.5). The 2009 thaw period was missed due to flood preparation and site dismantlement. The soil was frozen to at least 50 cm during the winter (Figure 2.2). Studies have shown that spring-thaw N_2O emissions are associated with the water-saturated soil environment following snow melt, with limited soil aeration, warming air and soil temperatures, and high C substrate from lysed microbial cells, creating conditions conducive to microbial denitrification [Christensen and Tiedje, 1990; Wagner-Riddle et al., 2007; Drury et al., 2008; Dunmola et al., 2010; Tenuta, 2010]. Other research has found that N_2O formed within the soil profile in unfrozen microsites throughout the winter is trapped by the frozen ground and only released with thawing of the soil [Teepe et al., 2001; Greogrich et al., 2005]. Spring-thaw began March 16, 2010 and all snow was melted within two weeks. Nitrous oxide fluxes were observed once air temperature climbed above 0°C, warming the surface of the soil. Emissions increased with the warming of the soil to 2 cm. Because the large outburst of N_2O emissions occurred only with thawing of the surface centimeters of the soil, this result led to the belief that spring-thaw emissions from this study were due to microbial denitrification activity and not trapped N_2O. Pattey et al. [2007] observed that enzyme activity, microbial biomass C, and organic C decreased with soil depth, limiting denitrification and N_2O production. The thaw of the 10 and 20 cm depths therefore, generated the largest emissions. Similar observations were not found in the current study, with greatest emissions observed with the thawing of the top 2 cm of soil. Both a field chamber study [Wagner-Riddle et al., 2008] and laboratory work [Tenuta, 2010] found that denitrification occurred only in the near surface of the soil upon thaw, supporting findings from the current study.

No spring-thaw N_2O emissions were observed in either crop year from the perennial legume phase. The 2009 thaw period was lost due to flood preparation, while in 2010, spring-thaw emissions were not observed. Lack of a spring-thaw burst from the perennial forage could be related to the low soil mineral N concentrations monitored the previous fall. These findings correspond with observations from Wagner-Riddle et al. [1997] and Gregorich et al. [2005] who link low F_N emissions to depleted soil nitrate levels, the slow decomposition of alfalfa residues, and the crop uptake of C.

Furthermore, the perennial legume phase soil temperature did not reach above 0°C until the end of March 2010, with the crop-covered plots requiring a longer time to thaw (Figure 2.5). This slow warming period may have limited microbial activity, reducing the likelihood of N_2O creation. By the end of March, the forage plants were beginning to grow new leaflets and photosynthesize, possibly taking up plant-available soil N, also reducing the denitrification potential. As suggested by Tenuta [2010], the utilization of management strategies, such as the use of cover crops or perennial forages, which restrict denitrification in the soil surface layer by limiting anaerobic soil conditions or reducing excess C substrate, may reduce N_2O thaw emissions.

The largest F_N emission events during the two-year study were observed in the spring following periods of rain after fertilizer application to the annual treatment plots. Similar to soil conditions seen during spring-thaw, a large precipitation event following synthetic N fertilizer application supplied a water-saturated, anaerobic soil environment and available NO_3^- to microbes for denitrification. The large rate of N_2O produced post-fertilizer application was most likely from the conversion of the ammonium-containing urea fertilizer into NH_4^+, resulted in the elevated soil NH_4^+ and NO_3^- concentrations observed, as reported by Bremner [1997] and Pathak and Nedwell [2001].

Soil mineral N samples taken following the spring N_2O emissions showed low NO_3^- and raised NH_4^+ concentrations. It can be deduced therefore, that microbial denitrification consumed the available NO_3^- in the soil, leading to the N_2O burst. Lack of N_2O emissions after other rainfall events in the growing season could be due to limited

NO_3^- (Figure 2.3) or C substrates for microbial denitrification [Wagner-Riddle et al., 1996]. The F_N from the annual rotation throughout the remainder of the study years were low or negative, corresponding with consistently low soil mineral N concentrations. Similar amounts of $\sum F_N$ were emitted from the annual rotation for both crop years, although the rapeseed emitted 0.8 kg N_2O-N ha^{-1} yr^{-1} more, at 5.2 kg N_2O-N ha^{-1} yr^{-1}, possibly due to the larger application of N fertilizer (146 vs 99 kg N ha^{-1} for spring-wheat). This is 1.5 times the amount emitted (3.8 kg N_2O-N ha^{-1} yr^{-1}) from canola (*Brassica napus* L.) in a Southern Ontario study, where 100 kg N ha^{-1} fertilizer was applied [Wagner-Riddle et al., 1997]. The variable, episodic emission events observed throughout this study demonstrate the importance of continuous emission measurement and the temporal variability in N_2O emissions throughout the year [Dunmola et al, 2010].

2.4.4 Within Treatment Variability

Despite relatively uniform field topography, both treatment plots gave varying trace gas flux values throughout the year (Figure 2.6). At the end of the two-year study, greater plot variability was seen between CO_2 fluxes from the perennial legume phase plots than between the two cropping treatments. This variation trend in $F_{C\text{-}NEE}$ was also observed by Glenn et al. [2010]. This observation was due to the large plot differences in the perennial legume phase plant stand density and composition, and helps illustrate the differences that exist in the crop stands of agricultural fields. Fluxes from the micrometeorological study of Davis et al. [2010] observed that plot NEE spatial variability did not exceed that observed between treatments, consistent with a more uniform crop stand. The N_2O flux plot variability did not exceed that observed between treatments. Crop stand can therefore be excluded from impacting N_2O emission creation, which was strongly influenced by soil N cycling and the addition of synthetic fertilizers to the agroecosystem.

2.4.4.1 Crop Stand Differences The perennial legume phase experienced plot variability due to large differences in crop stand density and plant community composition. Weeds and grasses encroached onto plot P1 over the 2008 growing season, adding to plot stand variability in the establishment year. Although both growing seasons were similar in temperature to the 30-year normal of the region (Table 2.2), an early frost in October 2008 and lack of snow cover combined with an atypical rain event in February 2009, resulted in crop damage to the first year alfalfa stand on plot P1. Alfalfa plant crowns throughout the plot were killed, allowing grasses and weeds to take over in the spring of 2009. Despite being reseeded with the alfalfa forage mix in the spring of 2009, 75% of the plot P1 crop stand consisted of timothy grass and a weed mixture, contributing to the perennial legume phase inter-plot variability for the 2009/2010 crop year. Alfalfa accounted for 25% of the plot stand. Plot P2 stand composition was 60% alfalfa and 40% timothy grass and weeds. A 20% difference in biomass weights was observed between the two plots. This plant variability is also demonstrated in terms of C storage differences of 130 and -960 kg C ha^{-1} for plot P1 and P2, respectively (Table 2.3). Higher N_2O emissions observed from plot P2 (1.5 kg N ha^{-1} difference) were possibly due to the natural exudation of N_2O-N from the forage legume roots, and greater CO_2 sequestration potentially due to larger above-ground biomass and a deeper root system, similar to research by Entz et al. [2002].

Excess precipitation interrupted the second cutting of the alfalfa crop in 2009, and combined with lack of manpower and equipment, the second cut did not occur until mid-November. The late cut may have decreased the 2009 perennial legume phase $F_{C\text{-}HARVEST}$ values recorded (Table 2.3), due to movement of C reserves into the crop roots for over-wintering and wilting of the plant above-ground biomass following frost. Carbon in forage biomass may have moved out of the leaves and into the crop roots throughout the fall, providing lower $F_{C\text{-}HARVEST}$ values. Slight visual crop stand differences were observed (aerial photographs, Appendix) between plots of the annual rotation for both crop years, although biomass samples supplied plant weight differences. The 2008 wheat crop stands were similar between plots, with plot A2 having 97% of the A1 biomass weight. Plot A2 had 87% of the A1 biomass weight for the 2009 rapeseed.

2.4.4.2 Soil Properties and Drowned Area Effects The higher-than-average amount of precipitation received at the site throughout the study years (Table 2.2) combined with poor to imperfect site drainage affected the inter-plot stand variability. All plots were affected with the drowning of crops in low areas and the subsequent creation of bare spots. Slow drainage also caused ponding water in the low areas of the field for days at a time, particularly following spring melt and high precipitation events. Using aerial photography, variability between annual rotation plots was observed, and attributed primarily to bare, drowned out areas that existed in the low areas of the plots. Biomass weight differences of up to 20% were seen between the two annual plots. Ponding water on plot P1 may have enhanced the death of alfalfa and growth of weeds and grasses in the 2008 growing season.

2.4.5 Uncertainty

Although numerous CO_2 and N_2O flux gaps existed throughout the study period, the majority of gaps were of short duration (average: 2.3 days, n=31). Nitrous oxide gaps were filled using linear interpolation, whereas CO_2 gaps used the moving-window technique [Barr et al., 2004]. The uncertainty of flux data grew with more missing data points and the use of gap-filling procedures [Davis et al., 2010; Glenn et al., 2010], particularly for N_2O emissions which were episodic and unpredictable. Approximately 10% of CO_2 and N_2O flux data were removed in all plots, making plots equal in comparability. Small amounts of error may have been introduced with the use of K values from an anemometer in another plot of the same treatment, or when mean K values were used for two plots of the same treatment. Uncertainty from u* thresholds and gap filling procedures partially contributed to the $\sum F_N$ plot variability of 6% and 74% of net study fluxes for the annual rotation and perennial legume phase, respectively. Differences in the plot variability for $\sum F_{C\text{-}NEE}$ were similar for both rotations, at 27% and 34% for the annual and perennial treatments, respectively. This uncertainty was based on error estimates performed by Glenn et al. [2010] in the previous 3 years at the same location. Error for Δz was estimated as 0.01 per intake height measured. Random error measured from the study site could be considered similar to approximately 12%, as measured at the same location during the previous triennium by Glenn et al. [2001].

Furthermore, uncertainty existed in $F_{C\text{-}HARVEST}$ that was based on weight measurements from hand-clipped biomass samples (6 samples per plot). The $F_{C\text{-}HARVEST}$ uncertainty combined with that from $F_{C\text{-}NEE}$ would have resulted in accumulated error for $F_{C\text{-}STORAGE}$ and GHG calculations. Glenn et al. [2010] estimated a C storage error of 48% over 3 years of annual cropping.

Uncertainty seen in this study may also have been the result of periods of missing data due to site maintenance and agronomic field activities. The system was not operational in August/September 2008 due to site dismantlement for field operations, and in April 2009 due to emergency flood preparations. Therefore, the late fall of 2008 and the 2009 spring-thaw period are missing for the CO_2 and N_2O budgets of the study site. This missing data may have led to the underestimation of the cumulative GHG budget for the two-year study, although the remaining important measurement periods (growing season, 2009 post-fertilizer application, 2010 spring-thaw and post-fertilizer application) were adequately captured.

2.4.6 Implications for Agriculture System Management

2.4.6.1 Emission Factor Comparison Although the mean N fertilizer emission factor from this two-year study was 2.7% of added N lost as N_2O, this value is higher than the global 0.8% assumed by the Food and Agriculture Organization/International Fertilizer Industry Association [FAO, 2001] and the 1% used by the IPCC. A similarly high emission factor (3.7%) was seen for a corn crop at the TGAS-MAN research site [Glenn, 2010]. A study in Southern Ontario by Wagner-Riddle et al. [1997] measured emission factors of 0.3%, 0.5%, and 0.25% for canola, corn, and barley crops, respectively, using ammonium nitrogen fertilizer. Due to the influence of the Red River clay soil, the fertilizer use efficiency of different fertilizers, and other local factors, a specific explanation for the greater N_2O loss observed from the TGAS-MAN research site cannot be identified.

2.4.6.2 Relative Importance of CO_2 and N_2O to GHG Emissions Because little research has been undertaken in Canada on the GHG flux effects of including alfalfa in cropping systems, this study provides insight into the value of the perennial forage crop on atmospheric GHG mitigation. Conversion of CO_2 and N_2O fluxes from the two-year study into CO_2-eq. provided estimates of net GHG fluxes. In particular, the GHG estimations illustrated when agronomic and environmental events influenced gas emissions, particularly how the control of CO_2 and N_2O gases can be controlled by different means. In the perennial legume phase, C was the driver of the $\sum F_{GHG}$ trends, with crop uptake and harvest removal playing the largest roles. The annual rotation was influenced by both trace gases at different periods of the year, with N emissions during the spring and C uptake/removal throughout the growing season. These flux trends provide specific events for both crop rotations, namely spring-thaw, fertilizer application, and harvest removals, that can be targeted when considering practices to increase GHG mitigation. Because perennial forages have no requirement for synthetic fertilizers and greater C storage potential than annual crops, sequestering C in agricultural soils using perennials may be the most effective strategy to reduce Canada's agricultural emission footprint.

Furthermore, this study demonstrates the need for continuous GHG monitoring throughout the year. Although the majority of trace gas exchange occurred during the growing season (GS, from May 1 to November 1), a sizeable amount of fluxes occurred during the cooler winter and spring months of the non-growing season (NGS). The annual rotation lost 4% and 73% of gained C during the NGS in the 2008/2009 and 2009/2010 crop years, respectively. Ten and 20% of N_2O emissions were emitted during the NGS for the two crop years. The perennial legume phase lost 9% and 11% of gained C in the 2008/2009 and 2009/2010 NGS. The forage also emitted 57% and 25% of N_2O during the NGS for the 2008/2009 and 2009/2010 crop years, respectively. When observing net GHG fluxes, the 2008/2009 annual rotation year experienced a 7% NGS loss when compared to the GS gain. The 2009/2010 crop year lost 7% net GHGs over the GS and an additional 19% over the NGS. The perennial legume phase lost 16% and 12% of net GHGs (gained during the GS) during the NGS, for the 2008/2009 and 2009/2010 crop years. Without year-round emission monitoring, important flux data may be lost, reinforcing the need for constant GHG monitoring.

Flux data obtained from this two-year study illustrated the large GHG sink status (5440 kg C ha^{-1}) achieved by the perennial legume phase, and the net source status (4500 kg C ha^{-1}) of the annual spring wheat-rapeseed rotation on Prairie agricultural soils. This knowledge will enhance the development of climate and GHG mitigation models, which help predict national and global emission trends. An American study conducted in Michigan and Colorado found that alfalfa had a net GWP of -1000 kg CO_2-eq ha^{-1} y^{-1} when taking into account the lack of N fertilizer and CO_2 fuel emissions, and the amount of C sequestration by a perennial rotation [Mosier et al., 2005]. Apart from that study, no research has documented whether the long-term use of perennial forages can mitigate GHGs, but the knowledge gleaned from this study may begin solving this question.

The IPCC predicts that global GHG emissions will continue rising in future decades and may reach 25 to 90% higher than 2000 emission levels, augmenting global temperatures [Barker et al., 2007]. The countries involved with the Kyoto Protocol aim to stabilize or reduce their respective countries' GHG emissions, requiring cooperation from many economic sectors [Desjardins et al., 2005]. Because the agricultural sector is the second largest GHG emitter in Canada [Environment Canada, 2010*a*], it must find mitigation tools to alleviate emission sources.

Canada is working on accumulating and advancing national and regional emission data to improve estimates for Canadian agriculture [Desjardins et al., 2005], but data are lacking for the Western portion of the country and for the sequestration potential of agricultural soils. The wide variability of the country's climate, soil properties, cropping rotations, fertilizer use, and crop management strategies cause inconsistencies in emissions, making accurate predictions hard [Pattey et al., 2007]. Our research findings have implications for both regional and national GHG inventories, providing missing cropping system information for Western Canada, particularly the Red River Valley. In order for a country to efficiently use C sequestration as a tool for GHG mitigation, it is necessary to provide accurate GHG emissions estimates and uncertainty using regional data gathered nation-wide [Hutchinson et al., 2007].

2.4.6.3 Long-Term Soil C Storage and Soil Health The major concern involving C sequestration and storage by perennial forages is the impact of discontinuing this agricultural practice. There is evidence that with the termination of C stocking practices, release of C from shoot and root decomposition will ensue [Bremer et al., 2002]. Also of interest is the large amount of N that may be mineralized from leguminous root systems once a forage crop is killed [Kelner et al., 1997]. The plough-down of alfalfa is known to contribute N to subsequent annual crops, and may reduce the use of synthetic N fertilizers following the use of perennial forages in a crop rotation. Entz et al. [2002] reported that wheat yields across the Prairies have increased up to 50% when sown following perennial forages. Despite the subsequent fertilization opportunity, this freed N may also be lost as N_2O [Kaiser et al., 1998], offsetting the net GHG sink status accumulated by the forage crop. Long-term forage studies will be necessary to obtain net GHG trends from cropping rotations.

2.5 Conclusions

Little is known about the environmental and agronomic drivers surrounding the cycling of CO_2 and N_2O when perennial forages are included in Canadian Prairie cropping systems. Comparing trace gas fluxes from a perennial forage phase and a spring wheat – rapeseed annual rotation over two years provided insight into N and C source and sink differences between the two cropping systems. The perennial legume phase acted as a greater net GHG sink of 5440 kg CO_2-eq ha^{-1} to the agroecosystem over the study period, whereas the annual rotation was a net GHG source of 4500 kg CO_2-eq ha^{-1} to the atmosphere. The strong influence of synthetic N fertilizer application and spring-thaw on annual rotation N_2O fluxes, as well as the effect of harvest biomass removals on net C sequestration from both treatments validates the need for further research on these specific events. Extending the GHG monitoring period of perennial forages to four to five years may improve insight into the potential of this crop to sequester atmospheric CO_2. Collecting micrometeorological F_N and $F_{C\text{-}NEE}$ data from across Western Canada would help enhance GHG inventory that is largely developed from chamber-based studies. Furthermore, the inclusion of additional crop types and agronomic practices, such as residue management, could provide insight into other emission drivers or GHG mitigation practices.

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3. OVERALL SYNTHESIS

3.1 Study Findings and Implications

Little micrometeorological research has been conducted on the Canadian Prairies, leaving large gaps in trace gas flux inventory coverage for the major crop-producing regions of Canada. Part of the first long-term micrometeorological assessment on annual nitrous oxide (N_2O) and carbon dioxide (CO_2) fluxes from crop rotations of the Red River Valley in Manitoba, Canada, this study compared a perennial legume phase and annual spring wheat- rapeseed rotation over two years. Continuous trace gas concentration collection provided insight into seasonal and annual gas emission trends from both cropping systems. Environmental temperature and precipitation drivers and short-term agricultural management practice effects on CO_2 and N_2O emissions throughout the year were observed.

The net soil carbon (C) balance had high inter-annual variability with large sequestration differences between the two cropping systems due to the high uncertainty associated with trace gas micrometeorological monitoring. The perennial legume phase sequestered 1870 kg C ha^{-1} over the two year study period, whereas the annual rotation sequestered 50 kg C ha^{-1}. The 2008 spring wheat took up 95% of the C sequestered by the annual rotation over the net study period. The 2009 rapeseed yield was poor, and therefore, the C sequestration potential was most likely under-represented. After accounting for harvest C biomass removals, the perennial legume phase stored 1870 kg C ha^{-1}, while the annual rotation remained essentially C neutral at -50 kg C ha^{-1}. The annual agroecosystem acted as a C source due to respiration rates exceeding photosynthesis, when vegetation was sparse or absent. Spring and fall were C sources for the annual rotation, whereas the perennial legume phase emitted C primarily following alfalfa cutting.

Nitrous oxide emissions were episodic and emitted predominantly by the annual rotation, following nitrogen (N) fertilizer application and during spring thaw. Emissions from the annual rotation were 3.5 times greater (9.5 kg N ha^{-1}) then the perennial legume phase (2.7 kg N ha^{-1}) due to the addition of synthetic N fertilizer at planting. Spring-thaw emissions from the annual rotation were captured in March 2010 following snow melt, warming of the air temperature, and thawing of the top two cm of soil. Emissions at thaw are therefore thought associated with soil biological denitrification and not due to the physical release of trapped gas by thawing ice. No specific release periods were observed in the perennial legume phase and N_2O emitted from this rotation were assumed from natural nodule excretion and decomposition of dead plant material.

The temporal variability of N_2O seen in this study demonstrates the importance of continuous greenhouse gas (GHG) monitoring, which will limit gap-filling of N_2O data, as is the case in chamber research. Converting N_2O emissions into CO_2-equivalents, allowed comparison between both trace gases for both crop rotations, showing the importance of studying gases simultaneously. When both N_2O and CO_2 emissions, including harvest removals, were considered concurrently, the annual rotation was a significant GHG source (4500 kg CO_2-eq ha^{-1}) and the perennial legume phase was a large GHG sink (5440 kg CO_2-eq ha^{-1}).

Greenhouse gas trends observed in this study will be helpful to filling gaps in the understanding of N_2O emissions post-fertilizer application and during spring thaw, as well as the soil C sequestration potential of various Prairie crops. Previous trace gas data gathered from the Prairies has concentrated on chamber work, supplying important trace gas data to the GHG community, although failing to provide year-round, cumulative data coverage. Approximately 15% and 40% of N_2O emitted, and 40% and 10% of gained CO_2 lost from the annual rotation and perennial legume phase for the 2008/2009 and 2009/2010 crop years, respectively, occurred during the non-growing season (from November 1 to May 1), reinforcing the need for continuous annual GHG monitoring. Meteorological technology provides a more complete analysis of GHG inventory, enhances the understanding of environmental drivers and agronomic events that affect emissions, and limits site disturbance that is associated with issues in chamber research. Insight from this study will promote further research on the use of perennial forages in annual cropping systems and whether this cropping practice may provide atmospheric GHG mitigation, while promoting the reduction of synthetic N fertilizers applied to annual rotations. Even though this study describes the CO_2 and N_2O flux trends occurring in the Red River Valley, this covers only a small region of the variable ecosystems across the Prairies and the country. Specific flux values pertaining to distinct environmental or agronomic factors are unachievable, solely due to the volume of interacting variables in each local region: soil type, typography, climate, agronomic history, cropping management, and soil nutrient concentrations [Janzen, 2007]. However, study findings will provide introductory data for modeling CO_2 and N_2O fluxes from spring wheat, rapeseed, and perennial legume forages.

The forage, grain, and straw harvest material were fed to farm animals. This agroecosystem should be considered an incomplete, open system, since numerous off-field contributions (transportation, baling, fertilizer) and harvest products were not included in the CO_2 and N_2O cumulative budgets. For a complete GHG budget and life cycle analysis from an agroecosystem, all off-field inputs and field outputs would need to be considered alongside the trace gas fluxes.

3.2 Study Recommendations and Improvements

The study objectives of outlining the environmental and agronomic drivers of C and N fluxes from two Red River cropping rotations and to describe agricultural management practices that mitigate CO_2 and N_2O and enhance soil C sequestration were met. Soil mineral N concentrations and climatic conditions were monitored to justify CO_2 and N_2O emission trends observed from the rotations. However, steps could have been taken to improve validation of fluxes or boost the quantity of high quality data retained during quality control elimination.

Measuring leaf area index, root-to-shoot ratios or growing degree days (GDD) could have provided information regarding crop photosynthesis and respiration, improving understanding of conditions influencing C sequestration [Baker and Griffis, 2009]. Monitoring soil organism make-up may have presented insight into microbial activity and soil respiration. Measuring SOC might have led to below-ground understanding of the agroecosystem C dynamics and the use of a control plot could have provided background emission concentrations and soil C and N concentrations throughout the study period. The control plot could have been the annual crop type grown each year without synthetic fertilizer and herbicide additions. Improving data quality could have been accomplished by ensuring flux footprints remained within plot areas, eliminating potential cross-contamination of trace gas eddies from neighbouring plots. Smaller footprints or wider spaces between plots could have helped eliminate contamination of trace gases. More than anything however, the length of the study only provided short-term insight into the agronomic and environmental factors affecting trace gas fluxes. To better describe CO_2 and N_2O flux trends from Prairie agroecosystems, the study would have to be longer in duration or be compiled of numerous research sites over a regional area.

3.3 Future Work

Although this study provided invaluable trace gas information, further understanding of Prairie GHG fluxes and mitigation opportunities could be improved by focusing on supplementary agronomic factors affecting GHG fluxes. Not only does the type of crop grown in a rotation influence GHG fluxes, as seen in this study, the agronomic practices that correspond with the crop grown also affect N and C cycling. The intensity and rate of tillage, fertilizer application rate, type, and timing, or residue management (removal, incorporation, burning) may affect GHGs emitted from an agroecosystem.

Of particular future interest for this study is the impact of discontinuing the perennial forage stand on soil C sequestration and storage. The termination of the crop stand will result in C release with shoot and root decomposition, as well as the mineralization of N from the leguminous root system. However, there is little research on the rate of N_2O and CO_2 emissions upon stand termination. Research has shown that the freed N can act as a natural fertilizer source for subsequent crops, limiting the need for synthetic fertilizer application following a leguminous forage crop. Mineralization of crop and soil N with the resulting N_2O emissions may possibly negate the C accumulated by the agroecosystem prior to stand termination. Stand termination timing (spring, following 1st cut, or 2nd cut) and technique (herbicide, tillage) may also influence the amount of N lost [Malhi et al., 2010].

Also of interest is the issue of increased N fertilizer rates to improve cropping intensity for global food production combined with the need to lower N_2O emissions. The excessive reduction of N fertilizer may reduce soil fertility quality, damaging crop productivity. Nitrogen use efficiency research may help reduce N_2O emissions over time [Boehm et al., 2004]. Adequate soil N supplies are also required to convert C-rich crop biomass into SOM. Therefore, there is the challenge of providing adequate N levels to enhance C sequestration and crop yield, while maintaining low soil N concentrations [Christopher and Lal, 2007]. Further research may be conducted with cover crops to determine proper methodology to balance C:N ratios. Monitoring methane (CH_4) fluxes of the soil would provide better estimates of the true C balance of the site and of the overall net GHG budget. Preliminary research from this site shows that the perennial legume phase acted as a small CH_4 sink [Rutter, 2010].

Information gathered from this research site will help fill missing regional emission gaps in Canada’s national inventory reports. Findings may be used in further modeling efforts to advance understanding of the country’s annual GHG budgets and patterns associated with agronomic practices within the Prairies.

3.4 References

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APPENDIX A

(a) (b)

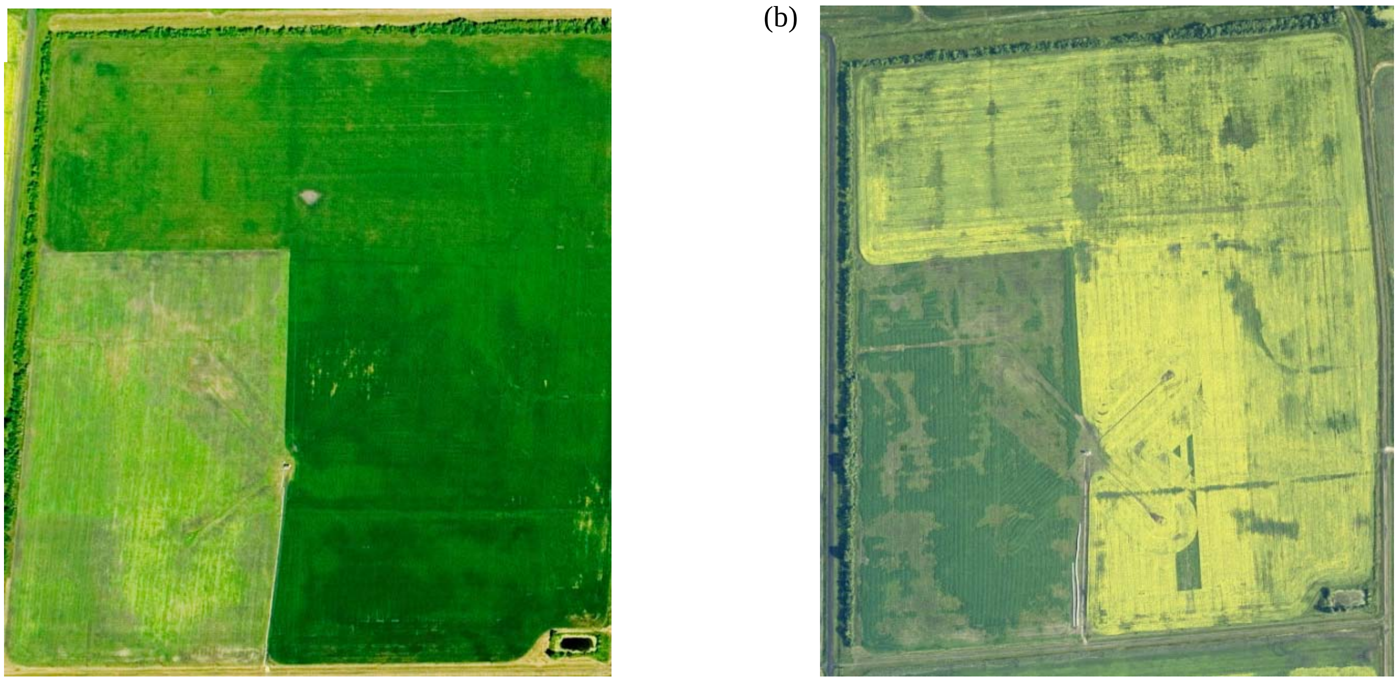

Figure A.1 Aerial photography of the TGAS-MAN research site for the a) 2008/2009 crop year and the b) 2009/2010 crop year.