Greenhouse Gas Emissions from Cranberry Fields under Irrigation and Drainage in Quebec

By:

Angela Grant

Department of Bioresource Engineering

McGill University, Montreal, Quebec

2014

A thesis submitted to McGill University

in partial fulfilment of requirements of the degree of

Master of Science

Abstract

Agricultural management practices influence the fluxes of greenhouse gases by altering the physical, biological and chemical environment of the soil. Cranberry farming is of particular concern because production takes place on soils with high water tables and the fields are flooded at various times of the year. These conditions initiate reductive processes which lead to the production of greenhouse gases. Weekly dark chamber flux measurements of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were taken in two farmed cranberry fields in Quebec over the 2012 and 2013 growing seasons. Findings show that commercial cranberry fields are not significant sources of greenhouse gases throughout most of the growing season. CO_2, CH_4 and N_2O fluxes ranged from 1-142 CO_2-C m^{-2} hr^{-1}, -0.01 to 0.04 mg CH_4-C m^{-2} hr^{-1}, and -0.0013 to 0.0013 mg N_2O-N m^{-2} hr^{-1}, respectively. However, when the fields are flooded during the spring melt and for harvest, they become sources of carbon dioxide and methane. Fields that remain flooded for extended periods of time thus emit significantly more greenhouse gases than those which are flooded and drained quickly.

Résumé

Les pratiques de gestion agricole influencent les flux de gaz à effet de serre (GES) en modifiant l'environnent physique, biologique et chimique du sol. La production de canneberges est particulièrement affectée par ces pratiques puisqu'elle a lieu sur des sols avec une nappe phréatique élevée et dont les champs sont inondés à divers moments de l'année. Ces conditions initient des réactions d'oxydo-réduction qui conduisent à la production de GES. Durant chaque semaine, des mesures du flux de dioxide de carbone (CO_2), de méthane (CH_4) et d'oxyde nitreux (N_2O) ont été prises à l'aide de chambres à air sombres, dans deux champs de canneberges situés près de la ville de Québec, pendant la période de croissance des plantes des saisons 2012 et 2013. Les recherches démontrent que la production commerciale des champs de canneberges n'est pas une source significative de GES. Les flux de CO_2, CH_4 et N_2O varient entre -142 CO_2-C m^{-2} hr^{-1}, -0.01 à 0.04 mg CH_4-C m^{-2} hr^{-1}, et -0.0013 à 0.0013 mg N_2O-N m^{-2} hr^{-1}, respectivement. Cependant, lorsque les champs sont inondés durant le printemps, ainsi que pour la période des récoltes, ils peuvent devenir des sources de dioxide de carbone et de méthane. Les champs qui demeurent inondés pendant de longues périodes de temps émettent alors une plus grande quantité de gaz à effet de serre que ceux qui sont inondés et drainés rapidement.

Acknowledgements

First, I would like to thank my supervisor, Dr. Chandra Madramootoo, for his support and guidance throughout my graduate studies and Agriculture and Agri-Food Canada for funding this project. I would also like to thank Dr. Joann Whalen, Dr. Slava Adamchuk and Eduardo Ganem Cuenca for their expert advice and moral support. Special thanks to Hicham Benslim for carrying out the laboratory components of this project and Ahmed Mat Su for his data processing. My wonderful field assistants, Kaitlin Lloyde, Pernilla Talac and Gianni Montanaro, made my summers collecting data not only productive but fun. I am also grateful to the Bieler family at ATOKA for allowing me to conduct research on their farm and J.F. Peltier for providing me access to all the farm data. Also, a special thanks to Kerri Edwards who was a steady companion to work with during my studies. Finally, I would like to thank my mother, Noreen Stapleton, for all her love and encouragement throughout my life.

Table of Contents

List of Tables

List of Figures

Chapter 1 - Introduction

1.1 Problem Definition

In the atmosphere, greenhouse gases (GHGs) absorb infrared radiation emitted from the Earth and reradiate it back to the Earth`s surface. This “greenhouse gas (GHG) effect” leads to an increased mean annual temperature of the Earth's surface (IPPC, 2007). Besides water vapour, carbon dioxide (CO_2) is the largest of these GHGs, however, substantial contributions to global warming are also made by methane (CH_4) and nitrous oxide (N_2O) because they are more effective at absorbing infrared radiation. One kg of CH_4 has a warming potential 23 times greater than 1 kg of CO_2, over a 100-year period, and N_2O is nearly 300 times greater (Rodhe, 1990).

GHGs in the atmosphere have increased exponentially over the past century. With the use of direct atmospheric measurements and measurements of trapped air in ice cores, researchers have been able to monitor atmospheric CO_2 concentrations dating as far back as 10,000 years. Up until 1750, atmospheric CO_2 concentrations remained around 280 +- 20ppm. Since then, activities such as burning fossil fuels and land conversion to agriculture have led to an increased atmospheric CO_2 concentrations reaching 379ppm in 2005 (IPPC, 2007). Similarly, atmospheric CH_4 has risen from 0.7ppm pre-1750 to 1.778ppm

in 2005 (IPPC, 2007). Major sources of methane are flooded rice paddies, wetlands and livestock production (Le Mer et al., 2001). N_2O has also risen from between 0.180 and 0.260ppm pre-1750 to 0.319ppm in 2005 which is largely a result of nitrogen (N) based fertilizers for agricultural production, biomass burning and some industrial activities (IPPC, 2007).

Continued increases in GHG emissions will have significant impacts on the global climate, ozone depletion and air pollution (IPPC, 2007). In the atmosphere, GHGs interact with other chemicals which results in ozone depletion, N deposition and smog. Higher concentrations of GHGs in the atmosphere will also lead to increases in the Earth's mean annual temperature. This temperature shift will likely trigger many other changes in other environmental systems such as weather systems, hydrological systems, biological and agricultural systems. Consequences include, but are not limited to, increases in the frequency and intensity of droughts, floods and severe storms, reduced crop yields, higher food prices and increased hunger (IPPC, 2007, Parry et al., 2004).

Agriculture is a large source of GHGs, emitting an estimated 10-12% of total global anthropogenic GHG emissions in 2005 (IPCC, 2007) and about 8% of the GHG emissions in Canada in 2006 (Environment Canada, 2008). Agricultural lands can either be sinks or sources of GHGs and the way they are managed

influences their relative fluxes. By altering the biological, physical and chemical environment of the soil, agricultural management practices influence the rate and extent of microbial activities which are responsible for the production and consumption of GHGs and also affect the aeration and diffusion of these gases to the atmosphere (Gregorich et al., 2005). Agroecosystems grown on soils with high water tables are of particular interest because their high soil water content induces reductive processes that lead to the production of GHGs.

The impacts of various water management practices, associated with agricultural systems, on GHG emissions are not well understood in the temperate humid regions of Eastern Canada. The bulk of studies carried out in this region focus on a limited variety of agricultural systems: mainly maize, soybean and wheat (Gregorich et al., 2005). Commercial cranberry production thrives in the temperate humid regions of Eastern Canada. It is traditionally and economically important to Canadian agriculture, particularly Quebec where 40% of Canadian cranberries are produced (Agriculture Canada, 2009). Cranberry production is of particular interest when it comes to GHGs because the fields are flooded at various times of the year, the production takes place on soils with high water tables and they receive small amounts of fertilizers. Such conditions initiate biogeochemical processes which lead to the production of GHGs.

1.2 Objectives

i. Investigate how GHG fluxes vary from two cranberry fields under different soil-water scenarios.

ii. Ascertain how various climatic conditions and management practices influence the fluxes of CO_2, CH_4 and N_2O from commercially farmed cranberry fields.

iii. Quantify the emissions of GHGs from Eastern Canadian cranberry production systems relative to other agroecosystems.

1.3 Scope

Approximately once a week, dark chamber flux measurements of CO_2, CH_4 and N_2O were conducted in two commercially farmed cranberry fields in St-Louis-de-Blandford in the 2012 and 2013 growing seasons. Although the findings of this study are limited to one research site, they are representative of the agricultural management practices and climatic conditions where cranberries are cultivated in Eastern Canada. Farming practices at the site followed normal farming routines, including irrigation, flooding, drainage and fertilization. The two fields selected were under two varying soil-water scenarios: Soil-water scenario 1 (SWS1) is a field with a relatively high water table, high soil moisture content and is flooded more often and for longer periods of time than the field under the soil-

water scenario 2 (SWS2). SWS2, on the other hand, has a relatively low water table, low soil moisture, is flooded less often and is drained more quickly than SWS1.

Chapter 2 – Literature Review

2.1 Carbon Dioxide

2.1.1 Plant Photosynthesis and Respiration

When light is available, plants remove CO_2 from the atmosphere and convert it carbohydrates by photosynthesis as:

$$6CO_2 + 12H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O\,. \quad (2.1)$$

Plants use carbohydrates to create structural components or respire them to release energy. Plant respiration, which can occur through the plant leaves or roots, releases CO_2 to the atmosphere through:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}. \quad (2.2)$$

Rates of plant photosynthesis and respiration are controlled by various soil-water properties such as soil temperature and moisture content (Smith et al., 2003). When temperature increases, photosynthesis and respiration rates increase until they have reached maximum capacity, as long as a sufficient amount of water is available. In a hot-dry year, when the water table becomes exceptionally low, photosynthesis by sphagnum moss in peat bogs has been shown to stop completely (Lafleur et al. 2003). Similarly, high bush blueberry (*Vaccinium*

corybosm) had decreased CO_2 assimilation rates when under water stress (Roh et al., 2012).

2.1.2 Soil Microbial Respiration

Carbon (C) is added to the soil *via* organic matter such as plant residues, roots and organic fertilizers. Once in the soil, C is utilized by a variety of aerobic decomposing organisms which release CO_2 to the atmosphere. The rate of C decomposition depends on the type and amount of C present in the soil. If there is not a sufficient amount of C available in the soil, decomposition rates will be limited and thus CO_2 production will be low. Similarly, CO_2 production will be limited if the type of C is resistant to decomposition, for example lignin (Mitsch and Gosselink, 2007).

Soil moisture influences microbial respiration through its effects on the oxygen supply. Oxygen is necessary for the decomposition of the soil organic matter to CO_2 (Moore et al., 1989). Generally, soils with high soil moisture have restricted aeration because most of the soil pores are filled with water. As a result, soil C respiration is restricted and CO_2 production is limited (Kasimir – Klemedtsson et al., 1997 and Moore et al., 1989). For this reason, flooded ecosystems such as wetlands and lakes tend to have low C decomposition rates and tend to sequester C (Mitsch and Gosselink, 2007).

However, upland soils that have been recently flooded, for the creation of a hydroelectric reservoir, for example, are sources of CO_2 to the atmosphere (Tremblay et al. 2007). Following the flooding of an upland soil, the amount of degradable material in the ecosystem generally increases. This is due to the additions of 1) labile C to the water column from the recently submerged decomposing vegetation and plant litter and 2) dissolved organic carbon (DOC) to the water column imported into the system along with the water used for flooding (Tadonleke et al., 2005). The additions of this labile C, which readily decomposes (within 5 to 10 years), are responsible for the high CO_2 fluxes observed from newer hydroelectric reservoirs (less than 5 years old) when compared to older hydroelectric reservoirs and natural lakes (Tremblay et al., 2007). The C that remains in these more mature flooded systems is mostly lignin C which is resistant to decomposition and thus limits the production of CO_2.

In the presence of a good O_2 supply and suitable C substrate, microbial metabolism and thus CO_2 production is strongly influenced by temperature (Smith et al., 2003). Both seasonal and daily variations in soil microbial respiration reflect a strong correlation with temperature. Highest rates generally occur during the summer months and peak at mid day, while lowest rates typically occur during the winter and drop at night (Lafleur et al., 2003). Soil temperature alone was able to explain 63% of the seasonal variability in CO_2

emission from both well drained and poorly drained soils in Quebec forests (Ullah and Moore, 2011).

2.2 Methane

2.2.1 Methanogenesis

Soils can be either sinks or sources of CH_4 which is determined by one of two opposing microbial processes, methanogenesis and methanotrophy. Methanogenesis is the production of methane by the microbial breakdown of organic compounds in soils under anaerobic conditions. Methanogens, the microbes responsible for the production of CH_4, belong to the kingdom Euryarchacota in the domain Archaea (Lai et al., 2009). There are two main ways by which methane is generated by methanogens as a metabolite in energy production: 1. Acetotrophic methanogens use acetate as a substrate to produce CH_4 and CO_2 gases; 2. hydrogenotrophic methanogens reduce CO_2 using H_2 gas as an electron donor to produce CH_4 (Mitsch and Gosselink, 2007).

CH_4 production does not begin until the reduction of molecular oxygen (O_2), nitrate (NO_3), iron (III) (Fe_3+), manganese (IV) (Mn_2+) and sulphate (SO_4), all of which have higher potential, is complete (Le Mer et al., 2001). As organic substrates are oxidized (donate electrons), the redox potential drops as a sequence of reductions (electron gains) takes place. Since organic matter is one of the most reduced of substances, it can be oxidized when any number of

terminal electron acceptors is available, including O_2, NO_3-, Mn_2+, Fe_3+, or SO_4. Rates of organic decomposition are most rapid in the presence of oxygen and slower for electron acceptors such as nitrates and sulfates (Mitsch and Gosselink, 2007).These chemical and biological transformations take place as a coupled oxidization-reduction reactions and occur in a predictable sequence.

The first and most common transformation is through the oxidization of organic substrate as an electron donor,

$$[C\ H_2O]n + n\ H_2O \rightarrow n\ CO_2 + 4n\ e^- + 4n\ H^+ \quad (2.3)$$

coupled with the following reaction when oxygen is the terminal electron acceptor at a redox potential of 400-600 mV:

$$O_2 + 4e^- + 4H^+ \rightarrow 2\ H_2O. \quad (2.4)$$

One of the first reactions that occur after a soil becomes anaerobic and the oxygen supply becomes depleted is the reduction of NO_3 first to NO_2- (nitrite) and ultimately to N_2O or atmospheric nitrogen (N_2). Nitrate becomes an electron acceptor at a redox potential of 250mV:

$$2NO_3 + 10e^- + 12H^+ \rightarrow N2 + 6H_2O. \quad (2.5)$$

As the redox potential continues to decrease, manganese is transformed from maganic to manganous compounds at about 225mV:

$MnO_2 + 2e^- + 4H^+ \rightarrow Mn2^+ + 2H_2O.$ (2.6)

Iron is transformed from ferric to ferrous form at +100 to -100 mV while sulfates are reduced to sulfides at -100 to -200mV:

$Fe(OH)_3 + e^- + 3H^+ \rightarrow Fe^{2+} + 3H_2O$ (2.7)

$SO_4 + 8e^- + 9H^+ \rightarrow HS^- + 4H_2O.$ (2.8)

Finally under the most reduced conditions the organic matter itself or CO_2 becomes the terminal electron acceptor below -200mV producing low molecular weight compounds and CH_4:

$CO_2 + 8e^- + 8H^+ \rightarrow CH_4 + 5H_2O.$ (2.9)

Such low redox conditions (lower than -200mV) usually require prolonged soil saturation and is therefore common in flooded ecosystems such as wetlands and flooded rice paddies (Mitsch and Gosselink, 2007 and Le Mer et al., 2001).

CH_4 in anaerobic soils can migrate to the atmosphere by one of three different pathways (Figure 2.1). First, diffusion can take place between the soil and the atmosphere. Diffusion is the slow process of methane transport to the surface along a CH_4 concentration gradient between the soil and the atmosphere. Second, is the process of ebullition where methane bubbles produced in the soil solution make their way to the surface. Often, these methane

bubbles are suddenly released to the atmosphere due to mechanical disturbances within the soil profile or a drop in atmospheric pressure, for example (Mitsch and Gosselink, 2007). Because these bubbles are formed for some length of time deep within the soil column, they, generally, contain large concentrations of CH_4 and are thus responsible for large and sudden fluxes of CH_4 to the atmosphere. The third methane transport mechanism is by the continuous air spaces (arenchyma) of specialized plants including rice plants and many wetland species, which are adapted to life in flooded environments. The arenchyma of these specialized plants have evolved to transport O_2 needed for root respiration and cell division from the atmosphere to the root zone when the soil becomes anaerobic. However, they equally serve well as channels for the transport of CH_4 from the root environment to the atmosphere (Le Mer et al., 2001).

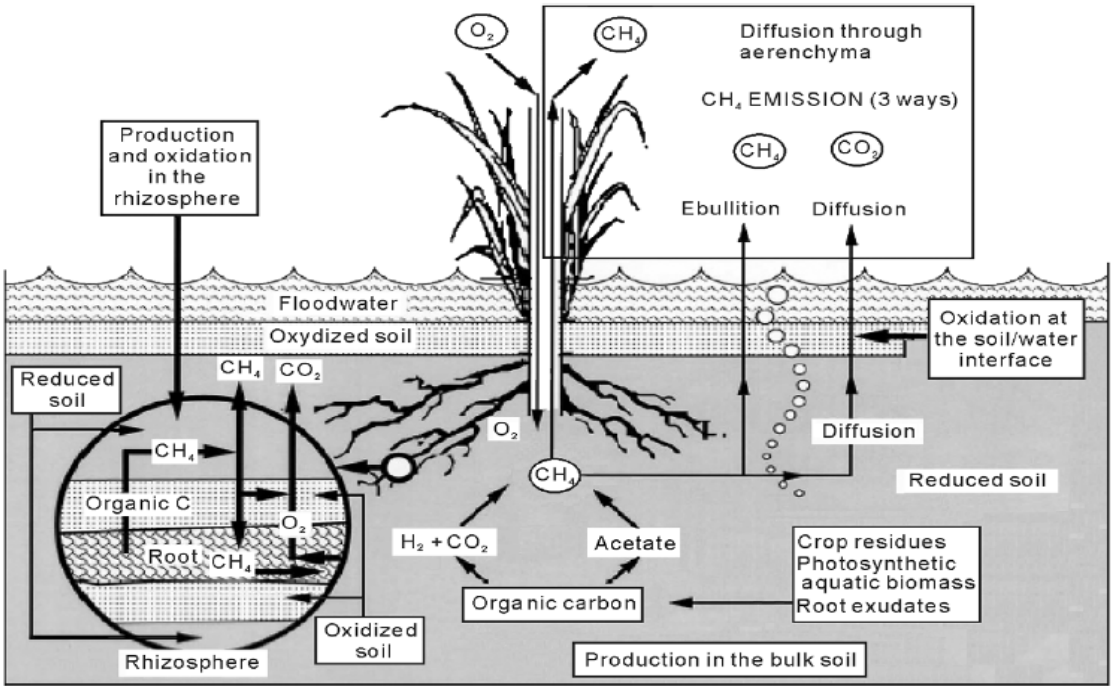


Figure 2.1: Methane production, consomption and transport (Le Mer et al., 2001).

2.2.2 Methanotrophy

Menthanotrophy is the aerobic microbial process in which atmospheric CH_4 and CH_4 produced *in situ* is oxidized by methanotrophic bacteria (methanotrophs). The methanotrophs responsible for this process oxidize CH_4 sequentially to methanol, formaldehyde, formate and eventually CO_2 (Whalen, 2005). All methanotrophs possess the enzyme methane monooxygenase which catalyses the bacterial methane oxidization. The enzyme breaks the O-O bonds of O_2 reducing one atom to H_2O and the other to CH_3OH by incorporating CH_4 (Lai, 2009).

CH_4 -> CH_3OH -> HCHO -> HCOOH -> CO_2 (2.10)

This process requires O_2 and thus occurs in the aerobic zones of soils. Agricultural lands, forests and grasslands are generally considered the major biological sink of CH_4 due to the fact that their soils are well aerated. Even soils that have high water tables, like wetlands, may have a thin aerobic soil layer at the soil-atmosphere interface. Thus CH_4 produced in the deeper anaerobic soil layers may be intercepted by methanotrophs and oxidized to CO_2 in the aerobic soil zones above the water table before making its way to the atmosphere (Le Mer et al., 2001). However, a rise in the water table reduces methanotrophic activity by reducing the size of the aerobic soil zone. Methanotrophs are able to tolerate temporary periods of flooding and can resume CH_4 oxidization within an hour of re-exposure to oxygen (Whalen, 2005).

In addition to methanotrophs, the autotrophic nitrifier communities are also able to carry out CH_4 oxidization. Because methane and ammonium molecules are approximately the same size and structure, the ammonium molecule can inhibit the methanotrophs from oxidizing CH_4 and CH_4 can replace NH_4 for nitrifiers and be co-oxidized (Mitsch and Gosselink, 2007).

2.3 Nitrous Oxide

2.3.1 Soil Nitrogen Inputs

Nitrogen (N) is an important nutrient requirement for crop production and can enter the soil by multiple pathways. The additions of plant and animal matter, including crop residues and organic fertilizers, or synthetic fertilizers, such as ammonium nitrate (NH_4NO_3) or urea ($CO(NH_2)_2$), increases the soil N content. Similarly, N fixation, the biological reaction catalyzed by the enzyme nitrogenise which converts atmospheric N, N_2, to ammonia, also adds to the soil N pool. It is accomplished via lightening strikes, bacteria, Achaea, cyanobacteria, and specialized plants that have a symbiotic relationship with N fixing microbes. (Brady and Weil, 2007)

2.3.2 Mineralization

Nitrogen mineralization refers to a series of biological transformations that convert organic N from the degradation of proteins, amino acids and nucleic acids to the mineral form (NH_4^+). This can occur under both anaerobic and aerobic conditions. Often called ammonification, it refers to the breaks down organic N compounds to NH_4^+ (Baggs et al., 2011). The typical formula for the mineralization of a simple soluble organic nitrogen (SON) such as urea,

$$NH_2CONH_2 + H_2O \rightarrow 2\ NH_3 + CO_2 \qquad (2.11)$$

$NH_3 + H_2O \rightarrow NH_4 + OH^-$. (2.12)

2.3.3 Nitrification

The next step in the sequence of biological transformation of N is nitrification. This is the oxidization of ammonium ions (NH_4^+) to nitrites (NO_2^-) and subsequently to nitrates (NO_3^-) carried out by two microbial communities:

Nitrosomonas sp.:

$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H_2O + 4H^+ + energy$ (2.13)

and Nitrobacter sp.:

$2\ NO_2^- + O_2 \rightarrow 2\ NO_3^- + energy$ (2.14)

This process requires oxygen and nitrification thus occurs in the aerobic zones of soils. N_2O is one of the by-products of ammonium oxidization by ammonium oxidizing bacteria; see Figure 2.2. (Wrage et al., 2001).

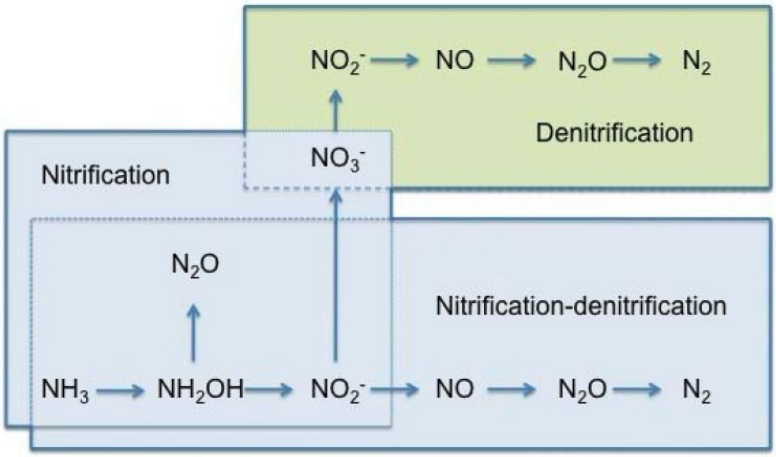


Figure 2.2: Nitrification, denitrification and nitrification-denitrification processes (Wrage et al., 2001).

2.3.4 Immobilization

Immobilization is the opposite process of mineralization, in which soil microbes transform mineral forms of N (NO_2^- and NO_3^-) into an organic form. When microorganisms require more nitrogen than is contained in carbonaceous organic residues, they incorporate mineral nitrogen ions from the soil into their cellular components. When the organisms die, some of the organic nitrogen in their cells may be released. Thus, mineralization and immobilization occur simultaneously in the soil. (Brady and Weil, 2007)

2.3.5 Plant Uptake

Nitrate and exchangeable NH_4+ are the only plant available N forms in the soil. Plants utilize these for the production of chlorophyll, DNA, RNA molecules, carbohydrate synthesis, stimulate root development and to enhance the uptake

of other nutrients. Nitrate enters more easily through the root cell wall, where as NH_4^+ may be attached to negatively charged soil particles (Brady and Weil, 2007).

2.3.6 Leaching

Nitrate (NO_3^-) is a negatively charged ion as opposed to the positive ammonium ion (NH_4^+). For this reason, NO_3^- is not subjected to immobilization by negatively charged soil particles and is thus more mobile in solution. If it is not assimilated immediately by plants or microbes, it may be lost through groundwater seepage or undergo denitrification (Brady & Weil, 2007).

2.3.7 Denitrification

Denitrification is the reduction of NO_3^- or NO_2^- to gaseous oxides, NO or N_2O, which may then be further reduced to atmospheric nitrogen (N_2), typically occurring under anaerobic conditions (Figure 2.2) (Wrage et al., 2001). The microorganisms responsible for this process, also known as denitrifers, include bacteria, archaea, fungi and other eukaryotes (Baggs, 2011). Denitrification is generally an anaerobic process, however, ammonia oxidization (the first step in the nitrification process) carried out by ammonia oxidizing bacteria can reduce NO_3 to N_2O under aerobic conditions. This process is commonly known as nitrifier denitrification (Baggs et al., 2011).

Soil water content controls the dominant pathway of denitrification. In soils with soil moisture greater than 90%, conventional anaerobic denitrification represents 98% of N_2O emission. However, when soil moisture is reduced to 50%, aerobic nitrifier denitification represents 20% of N_2O emission while ammonium oxidization, which was previously thought to be the dominant process responsible for N_2O production in aerobic soils, represents only 25% of the total N_2O produced (Kool et al., 2011).

2.3.8 N_2O Production

As long as suitable reactants are available, N_2O is generally a maximum when soil moisture is between 50-80% (Figure 3.2) (Davidson et al., 2000). When soil moisture is high, the denitrification processes generally converts N_2O all the way to N_2, which is not a GHG. This is typical of many wetland systems, where N_2O fluxes are generally considered to be negligible (Mitsch and Gosselink, 2007). On the other hand, when soil moisture is low, denirification no longer takes place and the nitrification process produces more NO than N_2O. Therefore, when wetland soils are drained for agricultural production, N_2O emissions tend to increase (Kasimir-Klemedtsson et al., 1997).

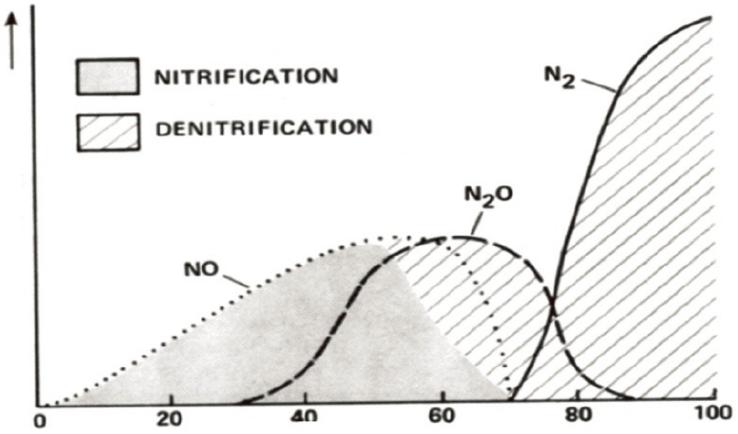


Figure 2.3 Relative contributions of nitrification and denitrification to emissions of NO, N_2O and N2 as a function of soil moisture (from Davidson et al., 2000).

2.4 Cranberry Production

2.4.1 Cranberry Botany

The North American Cranberry *(Vaccininium macrocarpon)* is a perennial evergreen woody vine species native to northern temperate climates. The plant thrives in waterlogged peatlands with slightly acidic soils and is commercially farmed in fields constructed with sandy soils designed for good drainage (Roper et al., 1997). The vines spread by producing runners, horizontal shoots, usually 0.3-0.6m long, that form a dense mat on the soil surface. These runners send out uprights (vertical shoots about 0.15-0.5m high) that will eventually bear small fruits. At the beginning of the growing season (April and May), the small waxy

leaves on the plant turn from a dull red to a dark glossy green colour. By June, flowers bloom from the vertical shoots, open, and pollination is required for fertilization (Eck, 1990). Shortly after pollination small globular fruits begin to grow from the flower buds. The fruit develops rapidly growing to approximately 1cm in diameter and changes colour from green to red. Within 75-100 days of pollination the fruit is ripe and ready for harvest (Murray, 1997).

2.4.2 Canadian Cranberry Production Statistics

North American cranberry farming began in the early 19th century with early agricultural management practices including site preparation, water management and pest control (Peterson et al., 1968). Canada is the second largest producer of cranberries in the world after United States (Agriculture Canada, 2009). The province of British Columbia has the largest area under cranberry cultivation (2350 ha) and contributes to 45% of Canada's cranberry production. However, the province of Quebec is able to produce 49% of Canadian cranberries on only 1650 ha (Agriculture Canada, 2009). From 1998 to 2008, Quebec cranberry production value rose from 9.1 million (Vandenberg et al., 1999) to 66.2 million CAD; see Table 2.1. Not only is this attributed to the increased area under cranberry cultivation, but also the fact that cranberries have become a high value crop (Agriculture Canada, 2009).

Table 2.1: Quebec and Canadian Cranberry Production Statistics (Agriculture Canada, 2009)

Marketed Value (millions CAD)					
	2004	**2005**	**2006**	**2007**	**2008**
Quebec	22.1	19.7	37.2	36.4	66.2
Canada	61.9	52.9	79.7	78.2	133.8
Marketed Volume (tons)					
	2004	**2005**	**2006**	**2007**	**2008**
Quebec	24, 586	24,945	39, 168	29, 132	36, 185
Canada	66, 789	67, 871	77, 086	70, 690	74, 469
Cultivated Area (ha)					
	2004	**2005**	**2006**	**2007**	**2008**
Quebec	1, 114	1, 178	1, 332	1, 510	1, 672
Canada	2, 867	3, 116	3, 310	3, 944	4, 373

2.4.3 Cranberry Agricultural Management Practices

2.4.3.1 Constructed Fields

Although cranberries are native wetland species, they require good drainage during most of the growing season. To achieve this, cranberry growers typically construct their fields with a sandy soil (with a pH between 4 and 5.5) and good drainage characteristics (Roper et al., 1997). The individual fields, which are typically rectangular in shape, are made by first levelling the soil to ensure flatness. Next, dykes, capable of holding the water necessary for flooding, are constructed around each field. Then, to facilitate drainage, ditches are built around the field. Finally, culverts and canals connecting reservoirs to the fields are built in order to control the movement of water around the farm.

Planting involves spreading vine cuttings taken from previously established beds or greenhouses over the newly constructed field and knifed into the soil with a planting disk. The fields generally take 3-5 years before being able to produce commercially viable quantities of fruit (Eck, 1990). Once a field is established, replanting does not occur until it is no longer productive. Since only the berries are harvested, the cranberry vines can remain in the field for up to 25 years.

2.4.4.2 Fertilizers

Farmed cranberry fields receive modest amounts of fertilizers throughout the growing season. N requirements are in the range of 23-68 kg ha^{-1} and are applied during the early part of the growing season (DeMoranville, 2006). Too little N results in low yields whereas too much causes vine overgrowth and also reduces yields. Like most ericaeous species, cranberries prefer ammonium N. They can utilize limited quantities of NO_3-, however, nitrification rates are typically low in cranberry soils due to their high acidity (Davenport and DeMoranville, 2004). Phosphorous (P) and potassium (K) are also crucial for cranberry growth. A single application (at a rate of 22kg ha^{-1}) of both P and K is recommended at the beginning of the growing season (Roper et al., 2004). Depending on the soil, micro nutrients including sulphur (S), iron (Fe), manganese (Mn), zinc (Zn) and boron (B) may also be added to provide sufficient amounts required by the plants.

2.4.4.3 Irrigation and Drainage

Cranberry growers make use of a variety of water management practices to improve the quality and quantity of their fruits. Cranberry farms are water intensive and can use between 15,000 and 25,000 L ha^{-1} $year^{-1}$ (Eck, 1976). However, if part of the water is recycled, it can be as low as 4,000 L ha^{-1} $year^{-1}$

(Robinson et al., 1997). A shallow water table (0.15-1.0m) and a moist but well oxidized root zone are necessary for cranberry production (Roper et al., 1997). Sprinkler irrigation is often used to meet these requirements. Sprinklers are ideal because they are also used to protect the plant against frost damage in the early spring and late fall. When liquid water on the plant freezes, heat is released and is sufficient to protect the plant when air temperatures are near or below 0° C (Roper et al., 1997). During the winter, when the cranberry plant is dormant, the fields remain flooded and are typically covered with a sheet of ice and layer of snow. Drainage is used to lower the water table during the spring snow melt and after harvest. It is often accomplished with subsurface drains and surface ditches that border each field (Roper et al., 1997).

2.4.4.4 Harvesting of Cranberries

2.4.4.4.1 Dry Harvest

Although some small scale farmers still rely on hand held rakes for harvesting cranberries, most dry harvesting is done by a machine resembling a lawn mower with rows of vertically rotating blades. The machine, also used for harvesting blueberries, is pushed up and down the fields while its rotating blades scoop the berries off the vines and dump them into a container. Although this harvesting technique is time consuming compared to wet harvesting, dry

harvested cranberries have a longer shelf life and are typically sold fresh (DeMoranville, 2000). Difficulties with fields under dry harvest include issues with pests, weeds and fungi (DeMoranville, 2000).

2.4.4.4.2 Wet Harvest

Flooding is essential for large scale cranberry production and fields that cannot be flooded are not considered profitable (DeMoranville et al., 1997). Temporary periods of flooding are used to reduce weeds, pests and fungi, but also facilitate harvest (DeMoranville, 2000). Many cranberry farms have their own water reservoirs located on site. These reservoirs, which serve to store the water required for flooding and irrigating the fields, are connected to the cranberry fields by series of canals and culverts which can be opened or closed. Cranberry fields are typically designed with a gently sloping elevation gradient (less than 2%) to allow the water to flow from one field the next field with minimal runoff and erosion (Vandenberg et al., 1999). To facilitate harvesting, many cranberry growers flood their fields with up to 0.5m of standing water. A mechanical beater is then driven up and down the fields knocking the berries off the vines. The berries float to the surface and are then gathered to one end of the field where they are removed by a pump or conveyor belt and loaded into large trucks waiting to transport them to storage or processing facilities (Eck, 1990). Flooding

can last for days or weeks depending on climate, harvest schedule, farm layout, water management infrastructure and the harvesting techniques used.

2.5 Cranberry Fields as Potential Sources of GHGs

Although the influences of water management on GHG emissions from a variety of ecosystems have been studied, there have been no studies conducted on GHG emissions from farmed cranberry fields. Cranberry fields are potential sources of GHGs to the atmosphere because production takes place on soils with high water tables; they are periodically flooded and receive small amounts of fertilizer. How the highly specialized agricultural management practices of cranberry production influence GHG emissions from their fields is unknown. However, one can draw on the results of other studies conducted in ecosystems with similar environmental and soil-water conditions.

2.5.1 Carbon Dioxide

Both plant and soil microbial respiration are strongly correlated with temperature (Lafleur et al., 2003; Smith et al., 2003 and Ullah and Moore, 2011). One would expect respiration rates from cranberry fields to behave in a similar fashion as other biological systems: highest in the summer and at mid day and lowest during winter and at night.

Soils with high water tables generally have low CO_2 fluxes compared to well aerated soils (Moore et al., 1989; Mitsch and Gosselink, 2007 and Ullah and Moore, 2011). The high water table of cranberry fields will likely lead to low O_2 availability. This inhibits aerobic decomposition and thus CO_2 production (More et al., 1989). However, during times of the year when the water table is lowered, the aerobic zone of the soil increases and the rate of aerobic decomposition and CO_2 production will likely increase (Kasimir-Klemedtsson et al., 1997).

The action of flooding an upland ecosystem, for example during the construction of a hydroelectric reservoir (Trembley et al., 2007) or the flood pulse of riverine ecosystem (McClain et al., 2003), can lead to a rapid increase in CO_2 emission. In Quebec, the higher CO_2 emissions from newer hydro dams (less than 5 years old) compared to older hydro dams and natural lakes are due to the additions of liable C to the system (Tremblay et al., 2007). This C originates from the recently submerged decomposing vegetation and the DOC in the water used to flood the land. Similarly, the temporary flooding of cranberry fields may initiate high fluxes of CO_2 due to the bacterial decomposition of the recently submerged vegetation and DOC added to the system.

2.5.2 Methane

Generally, agricultural soils are considered a sink of CH_4 due the fact that most crops are produced on well aerated soils and thus have high methanotrophic activity (Gregorich et al., 2005). Methanogenesis would only occur if the soils become submerged with water long enough to have highly reducing conditions (less than -300mV) (Le Mer et al., 2001). Most research relating the flooding of agricultural soils to GHG emissions is conducted in flooded rice fields (Cai et al., 1997 and Sass et al., 1992) likely because rice paddies account for about half of the global CH_4 emission to the atmosphere (IPPC, 2007). The amount of methane emitted varies greatly with water management practices. For example, in Texas rice fields, average CH_4 emission was 106 mg CH_4 m^{-2} d^{-1} for fields under continuous irrigation, 56 mg CH_4 m^{-2} d^{-1} when the field was drained in the middle of the crop cycle and 13 mg CH_4 m^{-2} d^{-1} when the field was drained 3 times (Sass et al., 1992). Short periods of drainage induce the formation of sulphate and ferric iron, which allows the development of competition between methanogens and sulphate and ferric iron reducers. This competition inhibits CH_4 production and persists after re-flooding the soil (Sass et al., 1992).

Cranberry fields experience temporary periods of flooding throughout the growing season which could initiate the reductive processes that lead to CH_4

production. CH_4 fluxes from these fields are likely to be lower than fluxes from other flooded ecosystems such as peatlands, marshes and rice paddies. This is because the timing of flooding in cranberry production is typically short and usually occurs in the colder parts of the growing season when temperatures are low thus limiting microbial activity. Unlike wetlands, the sandy soils of cranberry farms have a low C content (<10 g kg^{-1}) which will likely limit CH_4 production when the water table is raised.

2.5.3 Nitrous Oxide

The application of N fertilizers on agricultural soils increases N_2O emissions. A peak in N_2O emission is generally observed immediately following fertilization and can remain high for up to 4 weeks (Hellebrand et al.. 2008; Burger et al., 2005 and Bouwman et al., 2002). The abundance of N in the soil after fertilization gives way to biogeochemical processes that lead to the production of N_2O. The use of N fertilizers in cranberry production may contribute to relatively high N_2O fluxes during the early part of the growing season. However, fertilizer applications are typically applied in low amounts (23-68 kg ha^{-1}) compared to other conventional agricultural systems (DeMoranville, 2006) and thus N_2O emissions from cranberry fields are likely to be relatively low. Similarly, nitrification rates are low in the soils of cranberry fields due to their high acidity (Danvenport and DeMoranville, 2004) which is also likely to limit N_2O emission.

N_2O production in soils is higher when soil moisture is between 50-80% (Davidson et al., 2000). When rapidly raising the water table of peatland cores, (Dinsmore et al., 2009) measured pulses of N_2O up to 100 times the seasonal average within one to two days following the water table change. Similar pulses are observed in other ecosystems following heavy precipitation and during the spring thaw (Ullah and Moore, 2011). Ultimately the production of N_2O will depend on the availability of suitable substrates (such as NH_4 and NO_3) for nitrification and denitrification. The sandy soils of cranberry farms have a low N content (<10 g kg^{-1}) compared to wetlands which will likely limit N_2O emission even if conditions are favourable.

Chapter 3 – Materials and Methods

3.1 Site Description

Research was conducted on two commercial cranberry fields located in St.-Louis-de-Blandford, Quebec, a small town approximately 85km southwest of Quebec City (see Figure 3.1). It is an ideal place for growing cranberries due to its availability of clean water (it borders the Becancour River), suitable climate and ideal soil conditions. Based on 1981-2012 measurements from Environment Canada weather stations, the mean annual daily temperature for this region is 5°C and it has approximately 145 frost free days in the year. Mean total annual rainfall in the region is 900mm, half of which is received from May to November.

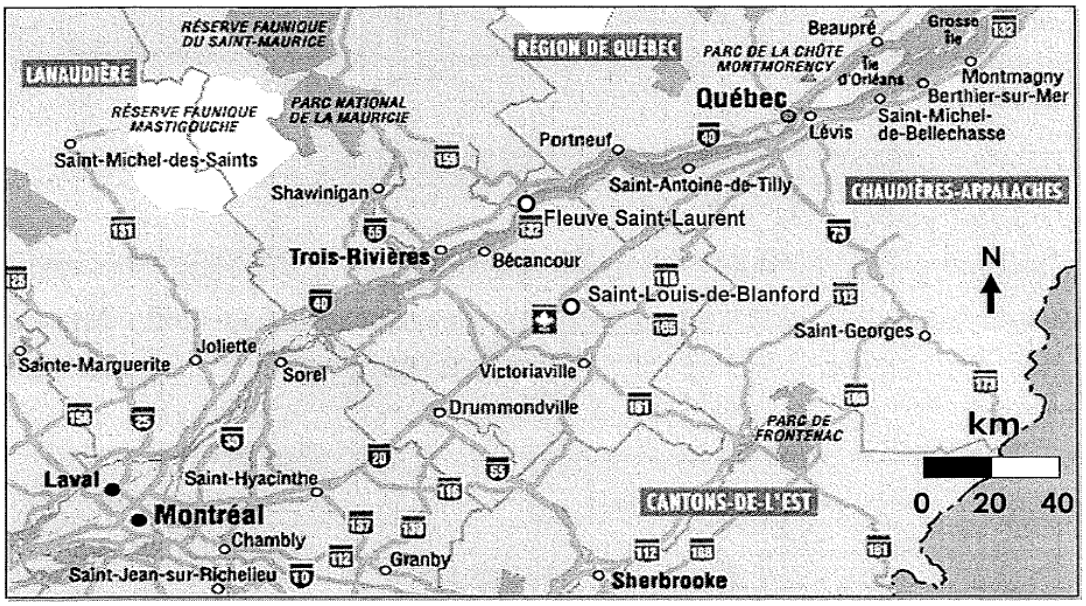


Figure 3.1: St.-Louis-de-Blandford (Tourism Quebec, 2000)

3.2 Sampling Strategy

The sampling and field measurements for this project were undertaken in two of Atoka's commercial cranberry fields under different soil water scenarios: Soil-water scenario 1 (SWS1) has a relatively high water table, high soil moisture and is flooded often and for relatively long periods of time. SWS2, on the other hand, has a relatively low water table, low soil moisture, is flooded less frequent and for shorter periods of time than SWS1. Figure 3.2 shows the locations of both fields. They are rectangular basins (50x500x1m) that have been excavated from their original soils and replaced with sandy soils designed for better drainage. There were no significant differences in the physical and chemical soil properties between each field (Table 3.1). Irrigation and drainage are essential for producing good yields, and a high quality fruit (Roper et al., 1997). In both fields, sprinkler irrigation is used to fulfill the plants water requirements during the summer and is also used to protect the plant from frost during the late fall and early spring. Drainage is achieved *via* surface ditches (0.5m deep) dug at each edge of the cranberry fields and *via* subsurface tile drains (installed 26-36 inches below the surface).

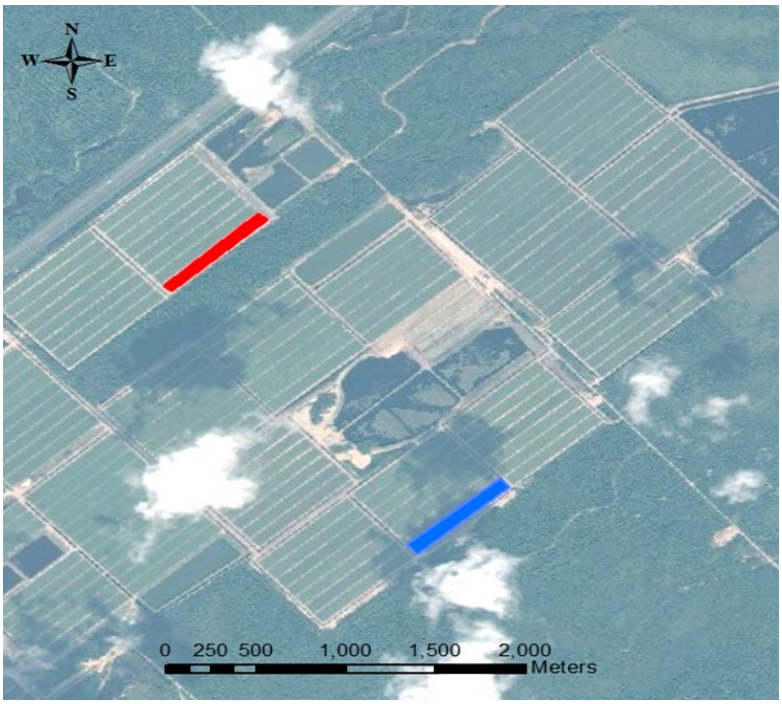


Figure 3.2: Locations of the fields under SWS1 (in blue) and SWS2 (in red).

Table 3.1: Field Soil Properties

Soil Properties	SWS1	SWS2
Type	95% Sand	96% Sand
Bulk density (g cm^{-3})	1.42	1.43
Hydraulic Conductivity (m s^{-1})	10^{-3}	10^{-3}
Organic C (g kg^{-1})	10.7 ± 4.4	4.0 ±1.6
Organic N (g kg^{-1})	1.18 ± 0.8	0.17 ± 0.57
NO_3 (mg kg^{-1})	10.6 ± 2.1	13.7 ± 7.2
P (mg kg^{-1})	516.3 ± 226.4	202 ± 173.6
K (mg kg^{-1})	61.8 ± 5.0	36.8 ± 7.6
Ph	4.6 ± 0.2	5.0 ± 0.2

3.3 Data Collection

3.3.1 GHG Fluxes

CO_2, CH_4 and N_2O fluxes were measured at ten locations (five locations in SWS1 and five in SWS2). The five locations are spread out along the length of each field, which follows a soil moisture/water table gradient. Both soil moisture and water table depth increase from West to East in each field. The ten locations therefore capture a large variation in soil moisture and water table depth on any given day: between the five chambers within each field and also between the two fields under the different SWSs.

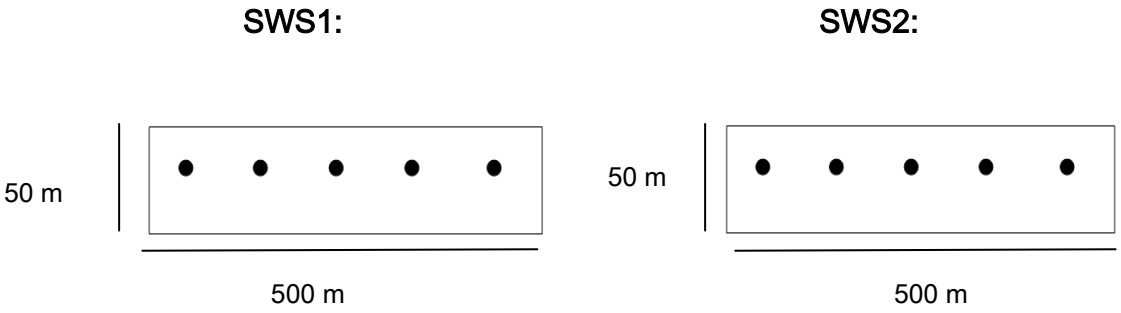
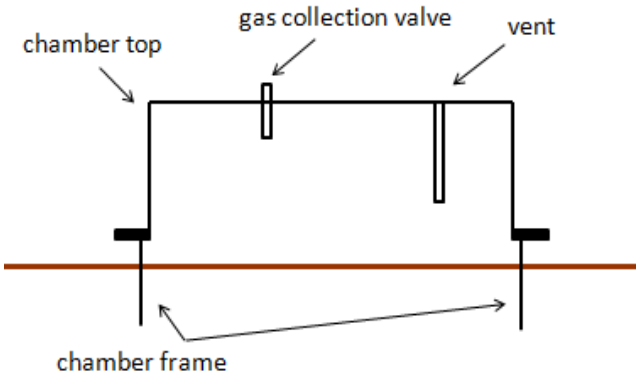


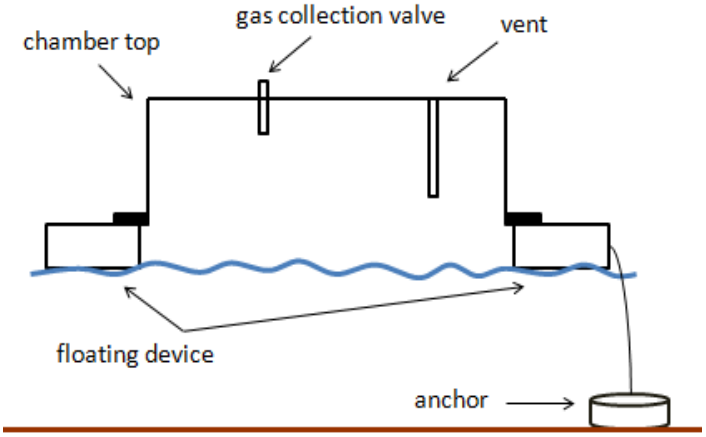
Figure 3.3: GHG sampling locations in both fields.

The static chamber method (Ullah and Moore, 2011 and Moore et al., 2011) was used to measure GHG fluxes at each sampling location on an approximately weekly basis from May 30th to November 4th, in 2012 and April

22nd to October 24th, in 2013. Ten permanent chamber frames made of 1.4" thick acrylic plastic measuring 55.6x55.6x14 cm were inserted 10cm into the soil, leaving 4cm above the soil. When measurements were made (lasting one hour), a chamber top (also made out of 1.4"thick acrylic plastic, 55.6x55.6x14 cm, which was vented to prevent pressure from building up in the chamber and covered in reflective material to prevent temperature build up) was placed on top of each of the chamber frames; see Figure 3.4 a). A five pound weight was then placed on the chamber top to ensure that both the chamber top and frame made an air tight seal. When the fields were flooded, the floating chamber method (Trembley et al., 2007) was used instead. It consists of the same reflective, vented closed chamber (55.6x55.6x14cm) placed on top of a (65x65cm) square block of 5cm-thick styrofoam (with a 55.6x55.6x5 cm square cut out from the center); see Figure 3.4 b). This allows the chamber top to float on top of the water thus measures the gas exchange between the water column and the atmosphere. A five pound weight was tied onto each floating chamber in order to anchor it over a particular location in the field during measurements, without submerging it.



a)



b)

Figure 3.4: a) Static chamber and b) floating chamber design

Over an hour, five gas samples (20 ml) were taken at fifteen minute intervals from the gas collection valve on the top of the chamber with a gas-tight syringe and stored in pre-evacuated 12 ml exetainers (Labco, Wycombe, UK) with an extra 60 ml Teflon-silicone septa (National Scientific, Rockwood, TN). Approximately 15 mg of magnesium perchlorate was placed in the exetainers before sampling to absorb any water vapour. The samples were then brought to

the lab and analyzed for CO_2, CH_4 and N_2O gas concentrations with a gas chromatograph 450-GC System (Bruker crop., Bremen, Germany).

A flame ionization detector (FID), set at 300 °C, was used for CO_2 and CH_4 measurements and an electron capture detector (ECD) set at 350 °C was used for N_2O measurements. Helium was used as the carrier gas for the FID with the flow rate of 30 ml min^{-1}, and argon was used as the carrier gas for the ECD with the flow rate of 10 ml min^{-1}. The GC is equipped with two 30 m packed column, 250 µm diameter. The first column which is installed with ECD is Hayesep D, 80/100, 2m x 1/8 SS''. The second one installed with FID is Hayesep A D, 80/100 Mesh, 3.6m x 1/8 SS'', CP99960 (both are made by Bruker crop., Bremen, Germany). The oven temperature was set constantly at 80 ^oC for a run time of 4.5 min. The data were recorded and analyzed using the integrated Bruker software Compas CDS (Version 3.0.0.68).

The daily fluxes of each gas at each sampling location were calculated using a method developed in matlab (Mat Su et al., 2013). First, in order to remove outliers from the dataset, gas samples that have a N_2O concentration less than 0.29ppm and CO_2 concentrations less than 300ppm (which are below ambient atmospheric concentration) are removed. The rejection rate in 2012 was 2% and 5% in 2013. Once the outliers have been removed, the data (in ppm)

were converted to concentrations (mg CO_2-C m^{-3}, mg CH_4-C m^{-3} and mg N_2O -N m^{-3}) using the constant gas law:

$$Cg= P*n*G(ppm) / (R*T), \quad (3.1)$$

where Cg is the concentration of gas in mg m-3, P is atmospheric pressure, V is volume of headspace, n is molar mass of the GHG, R is the ideal gas constant and T is the temperature at the time of GC analysis. Next, the concentrations (mg CO_2-C m^{-3}, mg CH_4-C m^{-3} and mg N_2O-N m^{-3}) of the 5 samples taken at 15 min intervals over an hour at each sampling location were used to calculate fluxes (mg CO_2-C m^{-2} h^{-1} , mg CH_4-C m^{-2} $h^{-1}$and mg N_2O-N m^{-2} h^{-1}) using the equation:

$$\text{Flux (mg } m^{-2} h^{-1}) = dCg / dt * (V/A), \quad (3.2)$$

where *dCg/dt* is the slope of the linear regression between any two gas concentrations over time (t), V is volume of the chamber headspace and A is the surface area of the chamber. Using this method, there are ten possible ways to calculate the flux between five gas concentrations taken over an hour (Mat Su et al., 2013). They are derived from the ten slopes made between the ten possible combinations of any two of the five samples in a given hour. The median of these ten possible fluxes is recorded as the flux for that chamber location on each gas sampling date.

3.3.2 Meteorological Data

Meteorological data was acquired through an Environment Canada weather station in Quebec City, located ~80km North-East of the research site. Daily mean air temperature (°C) and total daily precipitation (mm) were obtained from May 30th to November 4th in 2012 and April 22nd to October 24th in 2013.

3.3.3 Soil Data

Soil chemical sampling was completed on June 4th, 2012. In both fields, a composite soil sample was taken at each of its five chamber locations. Each sample was a composite of five sub-soil samples collected at a depth of 0-15 cm around a given chamber location. Once collected the samples were stored in a cooler and brought to our lab where pH, C, N, Al, K and P properties were determined.

Soil physical sampling was completed on August 10th, 2012. In the center of both fields a 60 cm deep hole was dug out and then three cores with a height of 7.7 cm and a radius of 8.5 cm were taken at depths between 0-20, 20-40 and 40-60 cm below ground. Samples were undisturbed and returned to the lab where bulk density, particle size distribution and hydraulic conductivity were determined.

3.3.4 Water Table Depth Measurements

Water table depth was measured at each chamber location every time gas flux measurements were made. When the water table was below the surface, measurements were made using observation wells constructed of perforated PVC pipes 1.30 m long and 0.04m in diameter. Each tube was inserted to a depth of 1.30m (flush with the surface) at each gas sampling location. A measuring rod with a sensor attached to the bottom wired to a buzzer at the top was used to take measurements. When the bottom of the rod comes in contact with water, the buzzer makes a sound. The researcher taking the measurement records how deep the measuring rod was below the ground. When the water table was above the soil surface, a measuring stick was used to measure its height above the ground.

3.3.5 Soil Moisture Measurements

Soil moisture (%) was also measured at each chamber location every time flux measurements were made. Measurements were taken with a hand held Theta Probe soil moisture sensor inserted 5 cm into the soil. The median of three soil moisture readings taken in three locations around each chamber was recorded on each gas sampling date.

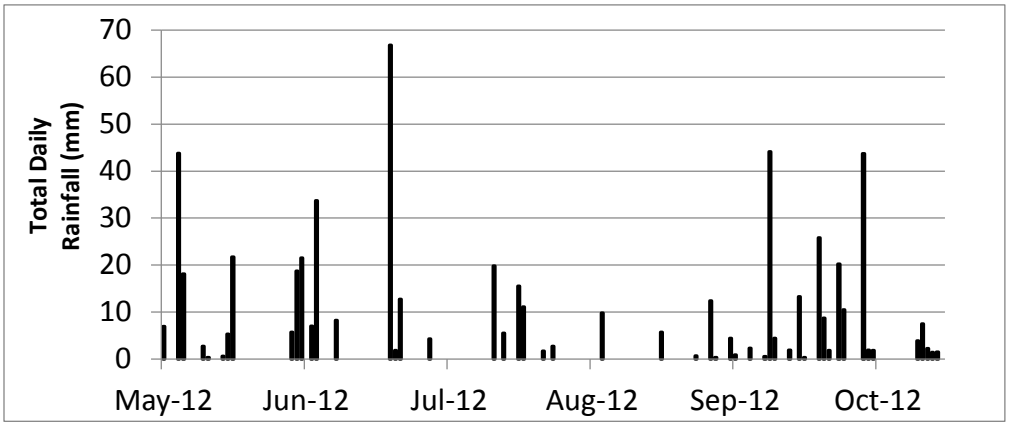
Chapter 4 - Results and Discussion

4.1 Climactic Data

4.1.1 Rainfall

Total daily rainfall (mm) in the 2012 and 2013 growing seasons are displayed in Figure 4.1 a and b, respectively. Rainfall patterns differed greatly between the two years. In 2012, rainfall events were particularly scarce, amounting to only 48 days of rain, compared to 77 days in 2013. The total amount of rain received during the 2012 growing season was 568 mm, well below that received in 2013, 710mm.

a)



b)

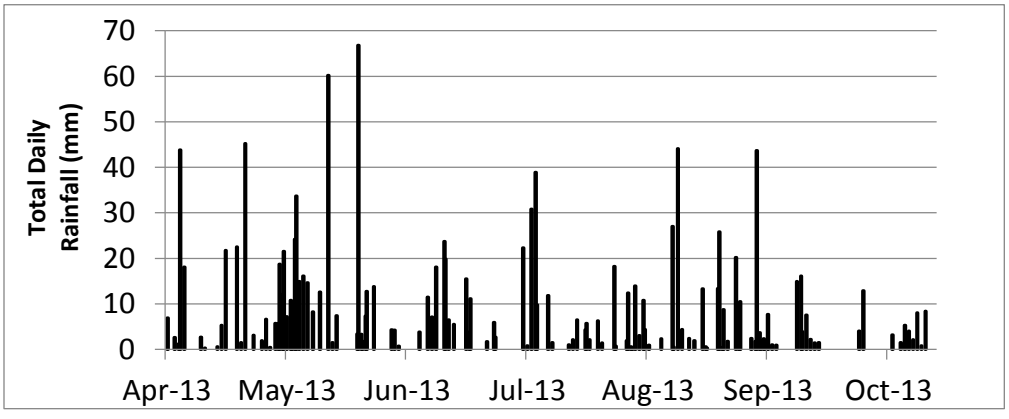
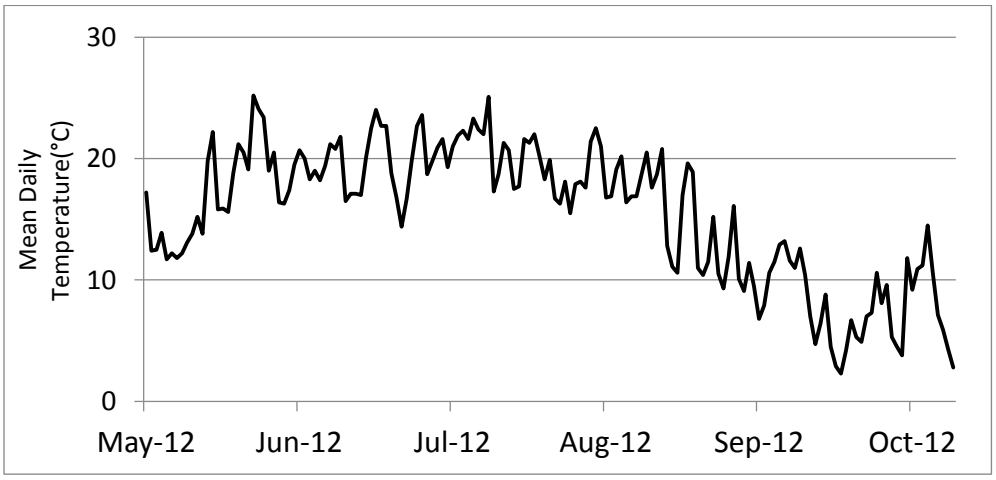


Figure 4.1: Total daily rainfall in a) 2012 and b) 2013

4.1.2 Air Temperature

Average daily mean temperature ranged from 2.8 °C to 25.2°C in 2012 and 3.0°C and 25.3°C in 2013, as shown in Figure 4.2 a) and b), respectively. Temperatures fluctuate depending on season; spring and fall being the coldest and summer being the warmest. However, higher mean daily temperatures were observed in the summer months of 2012 than in 2013 with June, July and August averaging 19.0°C in 2012 and 17.5°C in 2013.

a)



b)

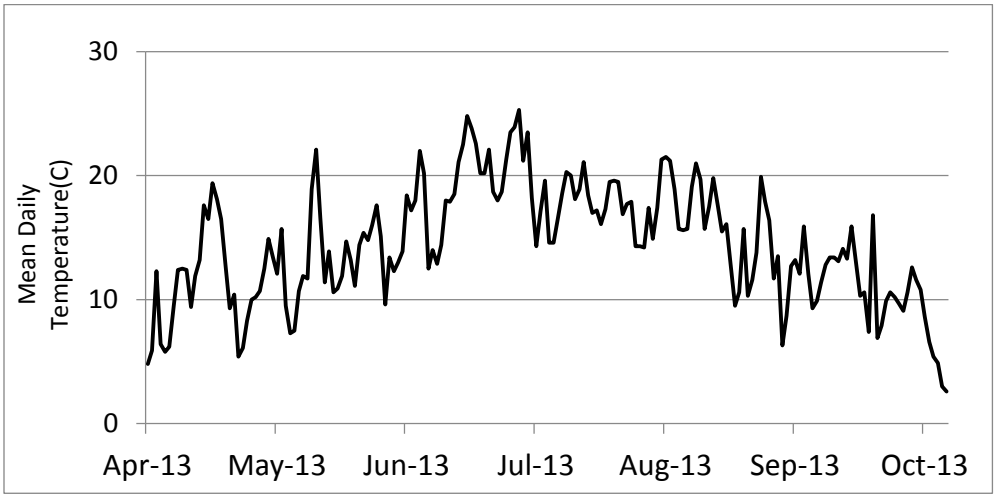


Figure 4.2 Mean daily air temperature in a) 2012 and b) 2013.

4.2 Agricultural Management Practices

4.2.1 Fertilizer Application Rates

Fertilizer was applied by the farmer in accordance with his own routine and practices. The rates and dates of applications in SWS1 and the SWS2 are displayed in Table 4.1 a) and b), respectively. The application rates and dates for both fields varied. In 2012, SWS1 and SWS2 received a total of 43.2 and 46.8 kg of N ha^{-1}, respectively, and in 2013, received 45.8 and 48.9 kg of N ha^{-1}.

Table 4.1: Fertilizer application rates (kg ha^{-1}) in a) SWS1 and b) SWS2.

a) SWS1

Date	N	P_2O_5	K_20	Mg	Cu	S	Ca	B	Zn
June 6, 2012			19.6	9.6		19.9		0.5	1
June 20, 2012	5.3	10.7	32.2			14.5			
June 28, 2012	13.2	8.3	14.7			18.1			
July 3, 2012	13.2	8.3	14.7			18.1			
July 9, 2012	7.9	5	8.8			10.9			
July 16, 2012	0.9	0	0			0			
July 20, 2012	2.7	5.4	16.1			7.3			
September 12, 2012	0	0	90			0			
May 22, 2013	0	0	19.7	9.7	2	20.3			
June 4, 2013	0	0	0			13.5			

June 10, 2013	0	0	25			8.5			
July 1, 2013	5.3	10.7	32.2			14.5			
July 3, 2013	9.2	5.8	10.3			12.7			
July 12, 2013	13.2	8.3	14.7			18.1			
July 17, 2013	0.9	0	0			0			
July 18, 2013	11.9	7.5	13.2			16.3			
July 25, 2013	5.3	10.7	32.2			14.5			
September 4, 2013	0	0	75			0			

b) SWS2

Date	**N**	**P_2O_5**	**K_20**	**Mg**	**Cu**	**S**	**Ca**	**B**	**Zn**
May 25, 2012	0	0	0	0		112.5		0.4	1
May 28, 2012	5.3	10.7	32.2	8.9		14.5			
May 31, 2012	0	21.8	18.2			18.4			
June 19, 2012	5.3	10.7	32.2			14.5			
June 26, 2012	13.2	8.3	14.7			18.1			
July 3, 2012	13.2	8.3	14.7			18.1			
July 9, 2012	5.3	3.3	5.9			7.2			
July 12, 2012	0.9	0	0			0			
July 19, 2012	2.7	5.4	16.1			7.3			
July 20, 2012	0.9	0	0			0			
September 4, 2012	0	0	90			0			
May 30, 2013	0	23.1	19.5	9.5	1.6	23.2			

Date	N	P_2O_5	K_20	Mg	Cu	S	Ca	B	Zn
June 3, 2013	0	0	0			135			
June 19, 2013	0	0	25			8.5			
June 26, 2013	5.3	10.7	32.2			14.5			
July 4, 2013	13.2	8.3	14.7			18.1			
July 9, 2013	13.2	8.3	14.7			18.1			
July 16, 2013	9.9	6.2	11			13.6			
July 19, 2013	0.9	0	0			0			
July 24, 2013	6.4	12.8	38.6			17.4			
September 5, 2013	0	0	75			0			

4.2.2 Water Table Depth

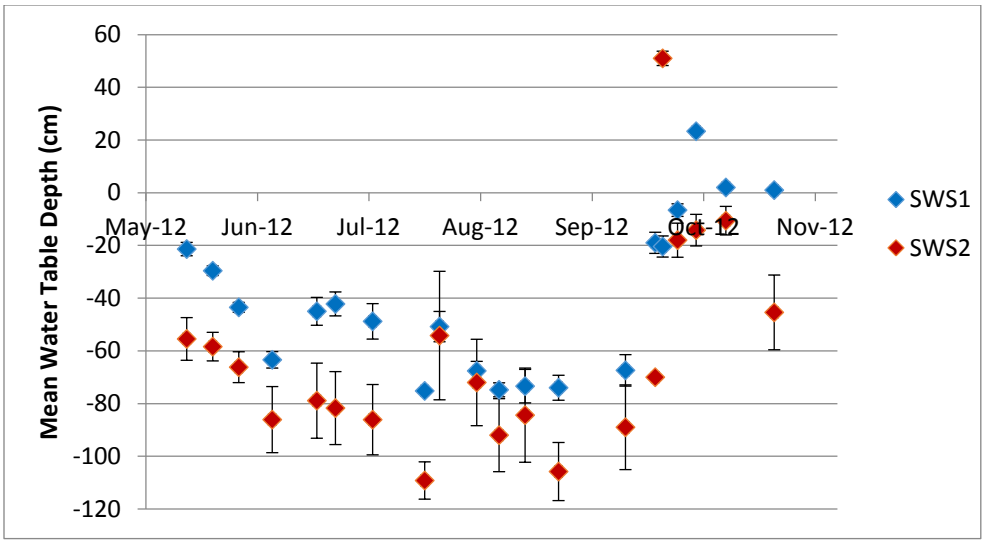
The average water table depths (n=5) on each gas sampling date for each field in 2012 and 2013 are displayed in Figures 4.3 a) and b), respectively. The five chambers in each field are set up along a water table gradient. On each sampling date there is therefore a large variation in water table depth; along the 5 sampling locations within each field and between both fields SWS1 and SWS2.

In 2012, the average water table depth at SWS1 and SWS2 ranged from -75 to 23 cm and -109 to 51 cm, respectively. At the beginning of the season the water table at both fields starts off high, -21cm in the SWS1 and -55cm in the SWS2. Due to the combination of high temperatures and a lack of rainfall, the

water table continuously dropped off into the summer months reaching a maximum depth of -75 cm in SWS1 and -109 cm in SWS2 by the end of August. When the berries were ready to be harvested in October, the water table at both fields increased rapidly, flooding SWS2 from October 4th to October 6th and SWS1 from October 14th to October 28th.

In 2013, the average water table depth in SWS1 and SWS2 ranged from -60 to 37cm and -94 to 22cm, respectively. Sampling in 2013 started on April 22nd, a month earlier than 2012, in order to capture the effects of the spring snow melt on GHG fluxes. For this reason, both fields are flooded at the beginning of the 2013 growing season. The water table began to drop by mid-May and reached a maximum depth of -60 cm in SWS1 and -94 cm in SWS2 in the summer. In the fall, when the berries were ready to be harvested, SWS2 was flooded and drained rapidly from October 5th to October 6th. SWS1, on the other hand, was flooded and drained slowly. This field was originally flooded on September 14th with approximately 5 cm of standing water. The water table remained near the soil surface until October 17th when the field was flooded, yet again with up to 37cm of standing water which lasted until October 27th.

a)



b)

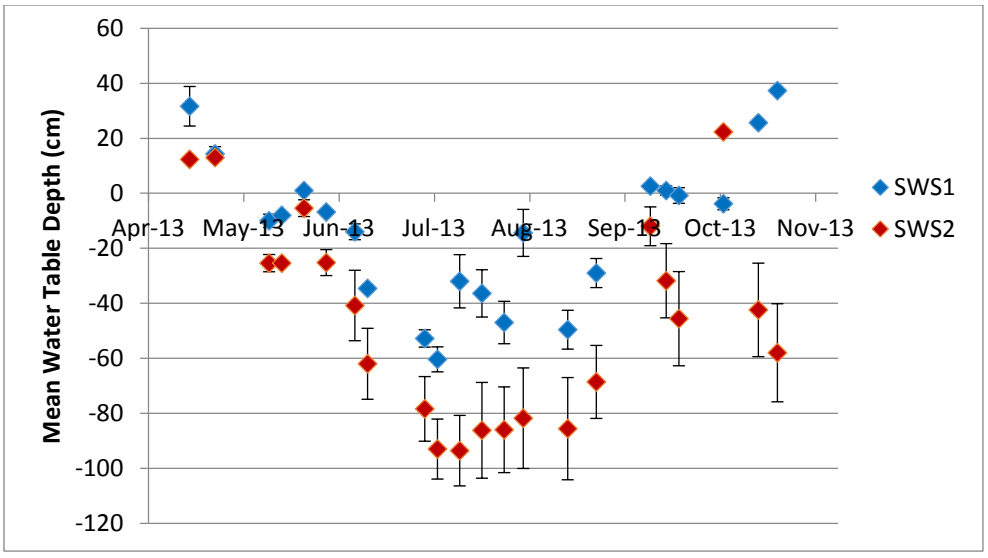


Figure 4.3: Mean water table depth and standard error at SWS1 (in blue) and SWS2 (in red) in a) 2012 and b) 2013.

4.2.3 Soil Moisture

The average soil moisture (n=5) on each gas sampling date for each field in 2012 and 2013 are displayed in Figures 4.4 a) and b), respectively. As with the water table depth, the chambers in each field are set up along a soil moisture gradient. On each sampling date there is therefore a large variation in soil moisture; among the five sampling locations within each field and also between both fields under the different soil-water scenarios.

In 2013, soil moisture was higher than in 2012, and ranged from 29% to 100% and 19% to 100% in SWS1 and SWS2, respectively. In both fields, the soil was saturated at the beginning of the 2013 growing season, because sampling began a month earlier than 2012 in order to capture the effect of the spring snow melt on GHG fluxes. Soil moisture begins to decrease in mid-May and reached a minimum in the summer, 29% and 19% in SWS1 and SWS2, respectively. In the fall, soil moisture increased and SWS1 remained saturated from September 14th to October 24th while SWS2 remained saturated from October 5th to October 6th.

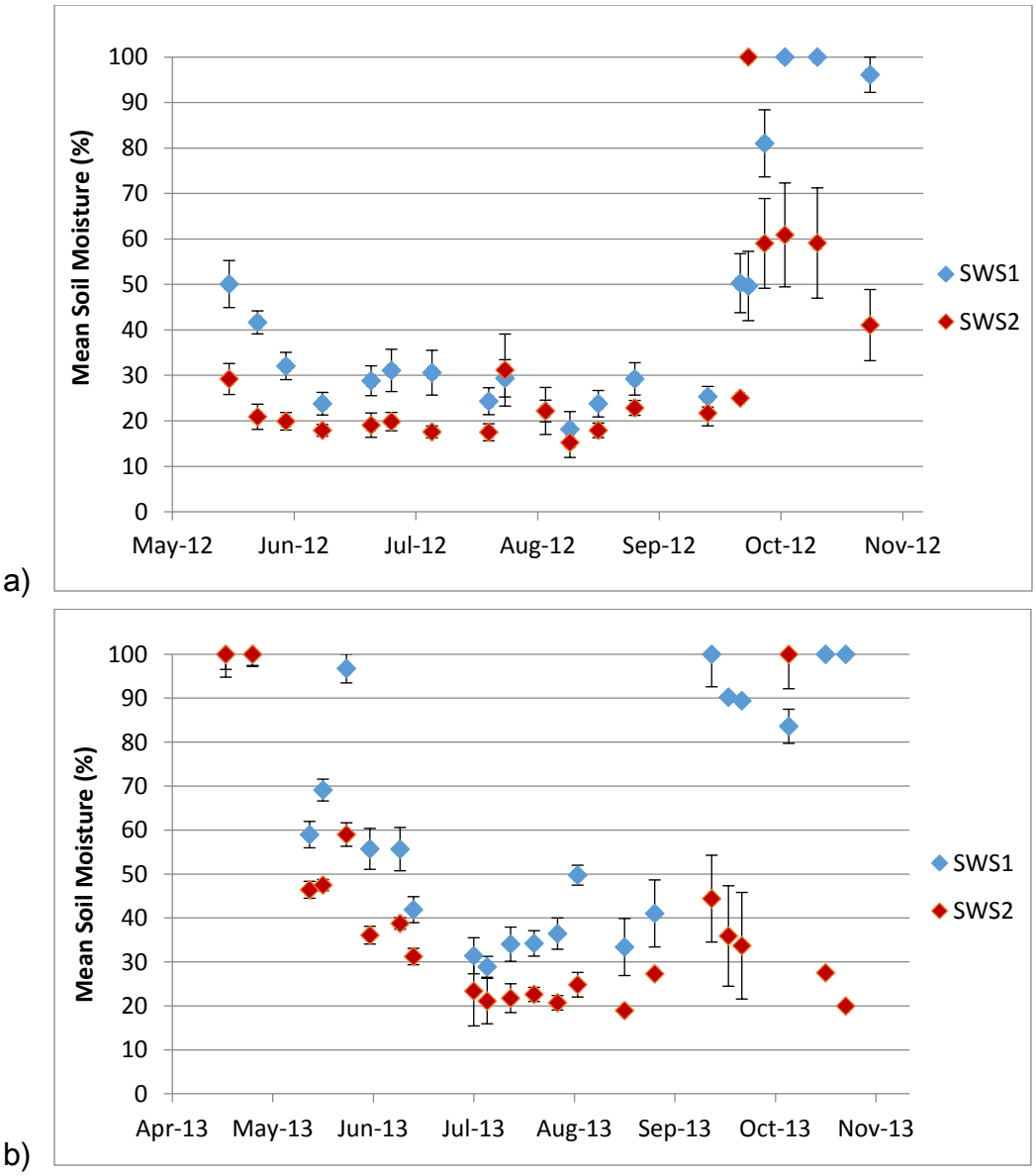


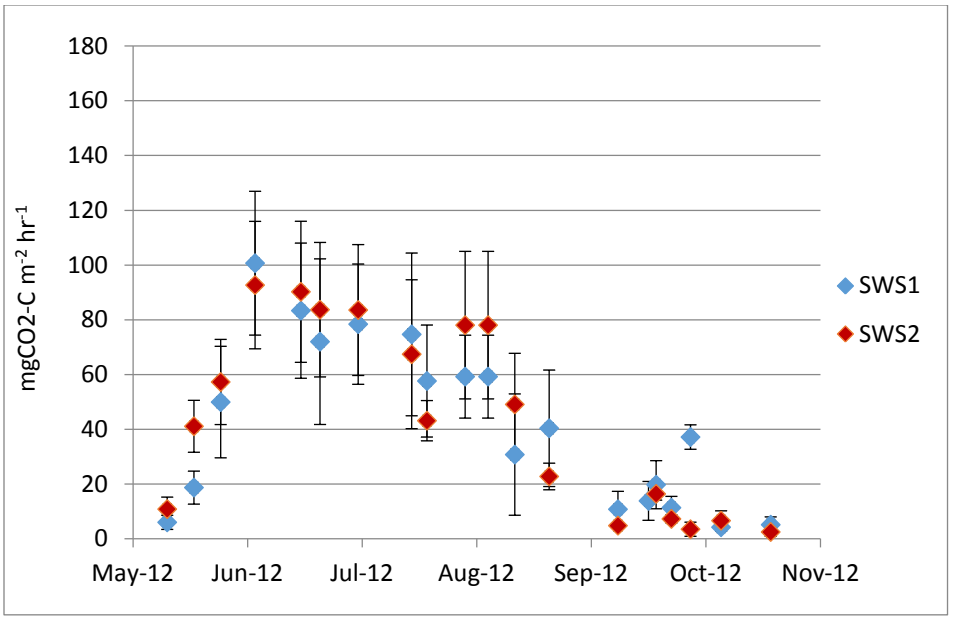
Figure 4.4: Mean soil moisture and standard error at SWS1 (in blue) and SWS2 (in red) in a) 2012 and b) 2013.

4.3 Greenhouse Gas

4.3.1 Carbon Dioxide

Mean CO_2 fluxes (n=5) for both fields in the 2012 and 2013 growing seasons are displayed in Figure 4.5 a) and b), respectively. In 2012, mean CO_2 fluxes ranged from 4 to 93 mg CO_2-C m^{-2} hr^{-1} in SWS1 and from 4 to 101 mg CO_2-C m^{-2} hr^{-1} in SWS2. In 2013, rates ranged from 4 to 142 mg CO_2-C m^{-2} hr^{-1} in SWS1 and from 1 to142 mg CO_2-C m^{-2} hr^{-1} in SWS2. On any given sampling date there was a large variation in respiration rates, reflecting the differences in soil moisture, depth to water table, crop density and soil properties between the ten chambers locations. Fluxes at the beginning of the growing season were near 0 mg CO_2-C m^{-2} hr^{-1} and steadily increased to a maximum in the summer months. By September, CO2 fluxes were, once again, low but nearly doubled when flooded for harvest.

a)



b)

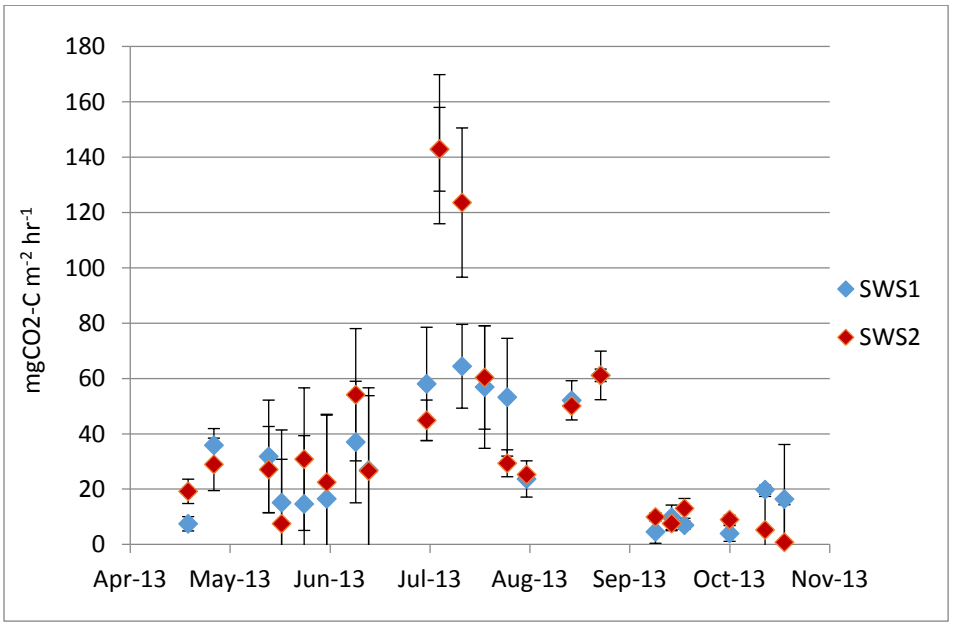


Figure 4.5: Mean CO_2 fluxes and standard error at SWS1 (in blue) and SWS2 (in red) in a) 2012 and b) 2013.

There are clear seasonal trends observed over both years. As expected, average daily CO_2 fluxes are strongly influenced by temperature and soil moisture. 45% of the variation in mean daily fluxes was explained by temperature alone; see Table 4.2. Figure 4.6 shows all 420 CO_2 flux measurements *vs.* temperature from each of the ten chambers during the entire study. An increase in temperature increases plant, root and soil microbial respiration and thus CO_2 production (Smith et al., 2003). Soil moisture also influences mean daily CO_2 fluxes and explains 14% of its variation throughout the season; see Table 4.2. Consistent with the findings of other studies (Ullah and Moore, 2011; Smith et al., 2003 and Moore et al., 1989), CO_2 fluxes generally increase with decreasing soil moisture due to increased O_2 availability for soil microbial respiration. However, when a sufficient amount of standing water was present, CO_2 fluxes were high (averaging 20mg CO_2-C m^{-2} hr^{-1}) given such low temperatures (averaging 5°C). This peak in CO_2 fluxes is apparent in Figure 4.7 displaying all 420 CO_2 fluxes *vs.* soil moisture from all chambers during the entire study. Similar to the creation of a hydroelectric reservoir, the action of flooding adds liable C to the system, originating from 1) the DOC in the reservoir water used to flood the fields and 2) the recently submerged vegetation and plant litter (Tremblay et al., 2007 and Taldonleke et al., 2005). Results of the flood water chemical analysis, which were collected from the fields during the 2013 harvest, are displayed in Table 4.3.

Table 4.2 Stepwise regression model for CO_2 fluxes

	R^2	P value
Temperature	45%	0.0001
Soil moisture	14%	0.005

Table 4.3: Flood water chemical properties

pH	DOC (mg/l)	TN (mg/l)
7.24 +- 0.01	14.35 +- 0.25	0.44 +- 0.06

Throughout most of the study CO_2 fluxes were not significantly different between the two fields under different soil-water scenarios. Only 4 sampling dates showed significant differences ($p < 0.05$) between CO_2 fluxes from SWS1 and SWS2, all of which occurred when one field was flooded for harvest (with more than 20 cm of standing water) while the other was not. CO_2 fluxes were significantly higher in the flooded field which is likely a result of the added DOC and submerged vegetation (Tremblay et al., 2007 and Taldonleke et al., 2005).

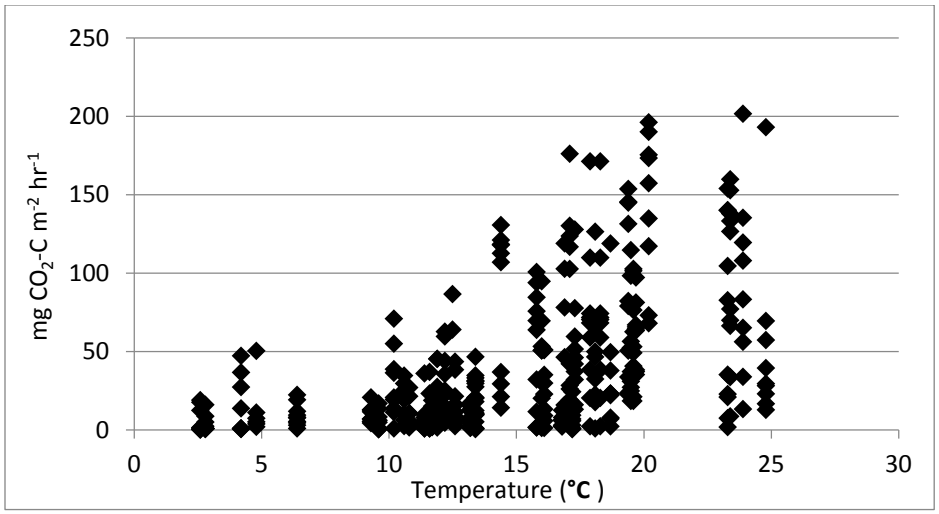


Figure 4.6: Correlation between CO_2 fluxes and mean daily air temperature from all chambers during the entire study.

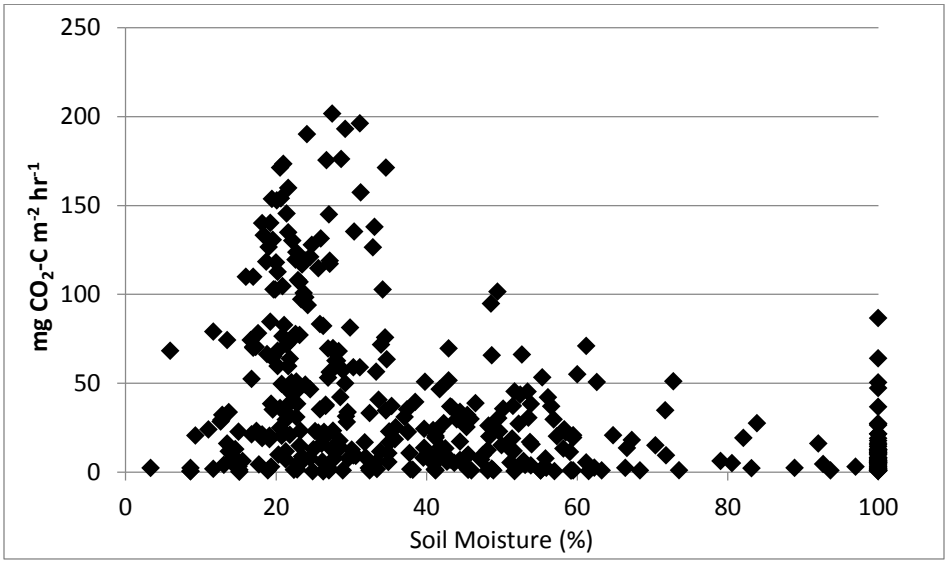


Figure 4.7: Correlation between CO_2 fluxes and soil moisture from all chambers during the entire study.

When compared to other conventional agricultural systems in Eastern Canada, cranberries fields are not major sources of CO_2. Unlike other crops (including wheat, maize and soybean), cranberries are a perennial crop. The plants can remain in the field for up to 25 years and the soils in which they are produced are not disturbed. This lack of soil disturbance lowers soil aeration, increases soil aggregates, and allows the formation of a thin organic layer on the surface which creates a wind barrier, all of which reduce soil microbial respiration. In addition, the sandy soils of cranberry fields have a low C content (<10 g kg^{-1}) which limits decomposition and thus CO_2

4.3.2 CH_4 Fluxes

Average daily CH_4 fluxes from both fields in 2012 and 2013 are displayed in Figure 4.8 a) and b), respectfully. For most of the growing season, the water table and soil moisture are low and the cranberry fields are sinks of CH_4. In both years, from May to September average CH_4 fluxes were -0.001 mg CH_4-C m^{-2} hr^{-1}. However, at times of the year when the soils became saturated, the fields became sources of CH_4 and fluxes averaged 0.2mg CH_4-C m^{-2} hr^{-1}. This occurred during the spring snow melt, the fall harvest and a period of over irrigation in SWS1 in June of 2013. Figure 4.9 and 4.10 illustrate the relationship between all 420 CH_4 flux measurements taken throughout the entire study from

all chambers and soil moisture and water table depth, respectively. When the soil moisture is low, CH_4 fluxes are generally negative and become positive when the soil becomes saturated. Soil moisture explains 55% of the variation in daily CH4 fluxes while temperature explains only 12%.

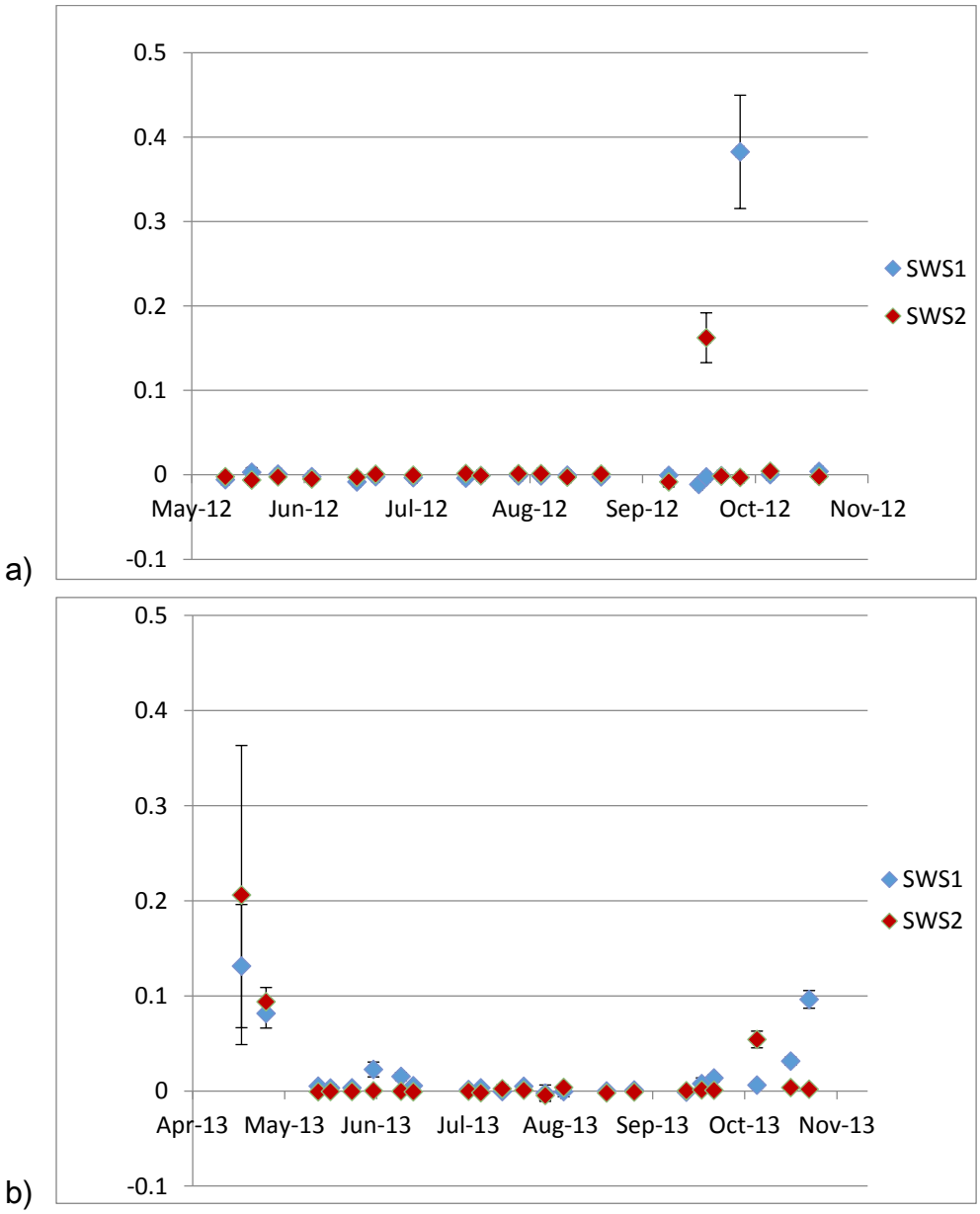


Figure 4.8: Mean CH_4 fluxes and standard error from SWS1 (in blue) and SWS2 (in red) in a) 2012 and b) 2013.

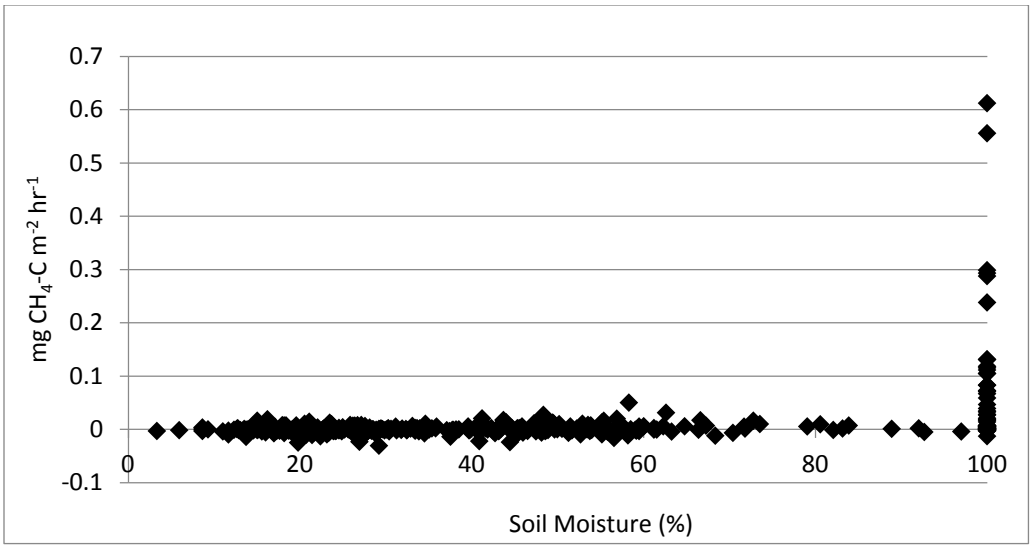


Figure 4.9: Correlation between CH_4 fluxes and soil moisture (%) from all chambers throughout the entire study.

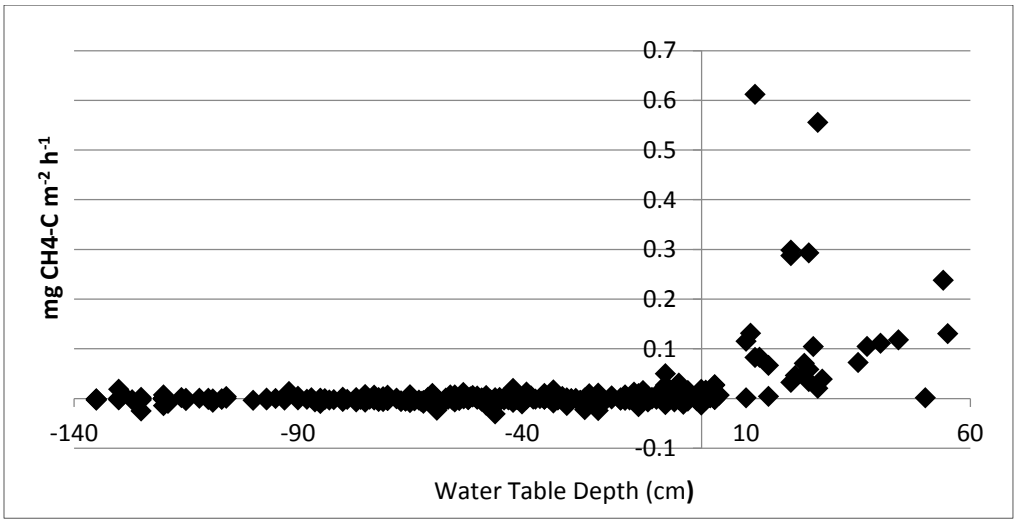


Figure 4.10: Correlation between CH_4 fluxes and water table depth (cm) from all chambers throughout the entire study.

Table 4.4 Step wise regression model for CH_4 fluxes

	R^2	P value
Temperature	12%	0.009
Soil Moisture	55%	0.006

During the study, CH_4 fluxes between the two fields under different soil-water scenarios were significantly different on 10 sampling dates. In 2012, only two dates (October 5th and October 14th) had significant difference between CH_4 fluxes and correspond to when one field was flooded for harvest and while the other was not. As hypothesised, the flooded field emitted significantly more CH_4 than the non flooded field. In 2013, on four consecutive sampling days from May 28th to June 17th SWS1 had significantly higher CH_4 fluxes than SWS2. During this time the mean water table depth in SWS1 was less than 10cm below the soil surface, causing the soil to become saturated in sections of the field, thus favouring CH_4 production. In the fall of 2013, significant difference between CH_4 fluxes from both fields occurred on four consecutive sampling dates from September 23rd to October 24th. Similar to 2012, these dates correspond to when one field was flooded for harvest while the other was not.

Unlike most agricultural fields, cranberry fields are subjected to temporary periods of flooding and are thus a source of CH_4. CH_4 fluxes from cranberry fields are still low (<0.06mg CH_4-C m^{-2} hr^{-1}) when compared to other flooded ecosystems such as rice paddies and wetlands, which can emit up to 1g CH_4-C m^{-2} in a given day (Le Mer et al., 2001). Methane production is likely low in cranberry fields because their soils become saturated for only short periods of time and this generally occurs in early spring and late fall when temperatures are low and thus limit microbial activities. Additionally, the sandy soils of cranberry fields have a low C content (<10 g kg^{-1}) compared to the soils of rice paddies and wetlands (which, in some cases, can be near 100% C) (Mitsch and Gosselink, 2007).This lack of suitable substrate limits decomposition and thus CH_4 fluxes from soils under cranberry production are in comparison low.

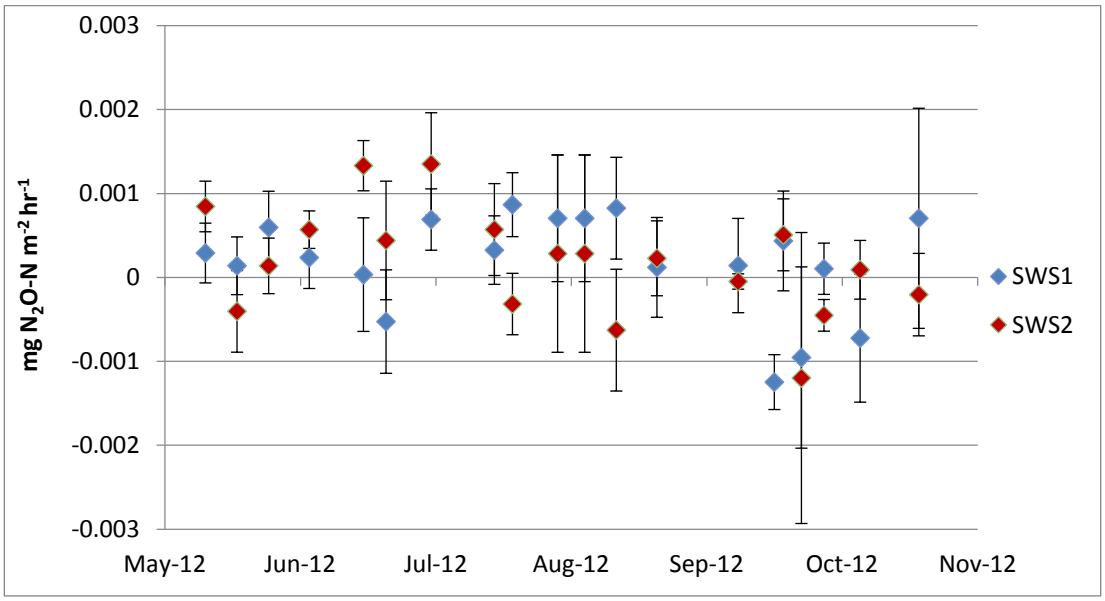
4.3.3 N_2O Fluxes

Mean daily N_2O fluxes during the entire study were negligible (ranging from -0.0013 to 0.0013 mg N_2O-N m^{-2} hr^{-1}). No seasonal trends were observed in N_2O fluxes during the study. Figure 4.12 and 4.11 illustrate the lack of correlation between all 420 N_2O fluxes from all chambers during the entire study and temperature and soil moisture, respectively. This lack of correlation is likely due to the fact that N fertilizers were applied in moderate amounts (less than 50 kg ha-1 during the entire growing season) and the soil lacks the necessary substrates (i.e. C and N) for N_2O production. Commercial cranberries are produced on acidic soils with a pH between 4.0 - 5.5. As a result, nitrification rates in cranberry fields are low (Danvenport and DeMoranville, 2004), which further limits N_2O production.

N_2O emission from cranberry fields are low compared to emissions from other conventional agricultural systems, such as corn or wheat, which can emit up to 2g of N_2O in a given year (Gregorich et al., 2005). The sandy soils of cranberry fields have low N contents (<5%) and receive low amounts of N fertilizer (23-68 kg ha^{-1}) compared to other agricultural systems (DeMoranville, 2006). Similar to bogs, cranberries are produced on acidic soils and thus have

low N2O fluxes. These agricultural management practices unique to cranberry production are likely responsible for the lack of N_2O fluxes.

a)



b)

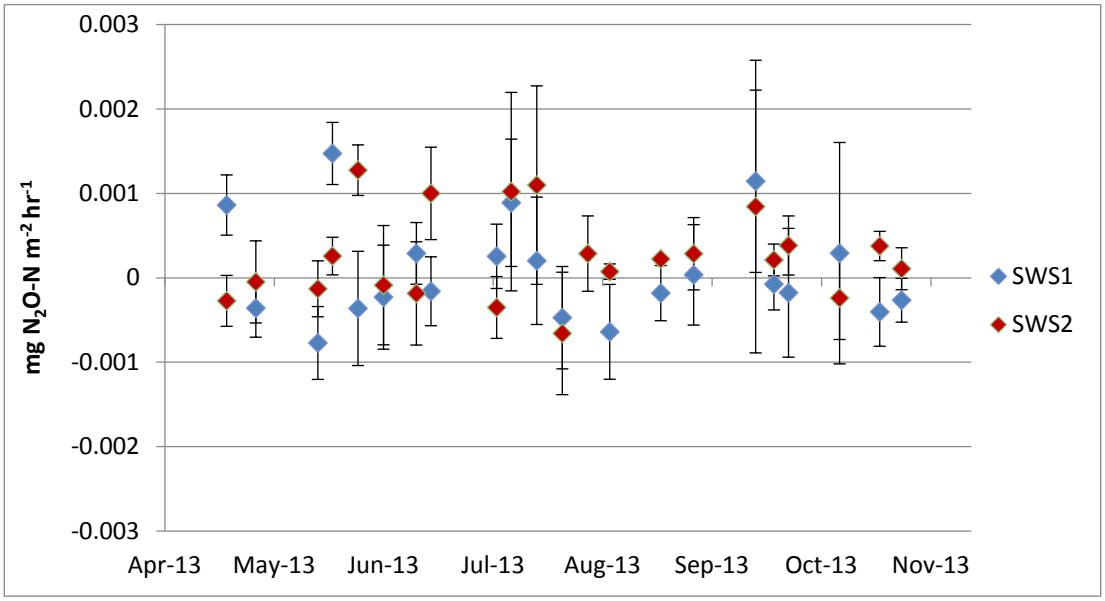


Figure 4.11: Mean N_2O fluxes and standard error in SWS1 (n blue) and SWS2 (in red) in a) 2012 and b) 2013.

There were significant differences in N_2O fluxes between the two fields on four sampling dates, but only in 2013. SWS1 had significantly ($p<0.05$) lower N_2O fluxes than SWS2 on May 28th when SWS1 was over irrigated and became briefly flooded. Similarly, on three consecutive days of sampling (October 7th, 18th and 24th) there were significant differences between N_2O fluxes from the fields. These dates correspond to when one field was flooded while the other was not. The flooded field emitted significantly less N_2O than the non flooded field. When soils become saturated, denitrification converts most of the N_2O into N_2, which is not a GHG (Davidson et al., 2000).

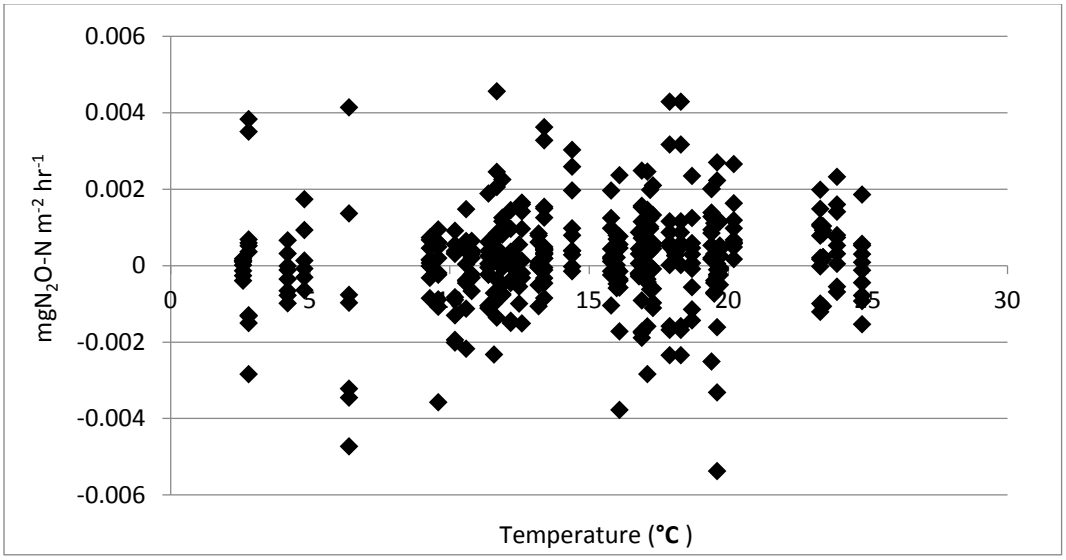


Figure 4.12: Correlation between N_2O fluxes and mean daily air temperature from all chambers during the entire study.

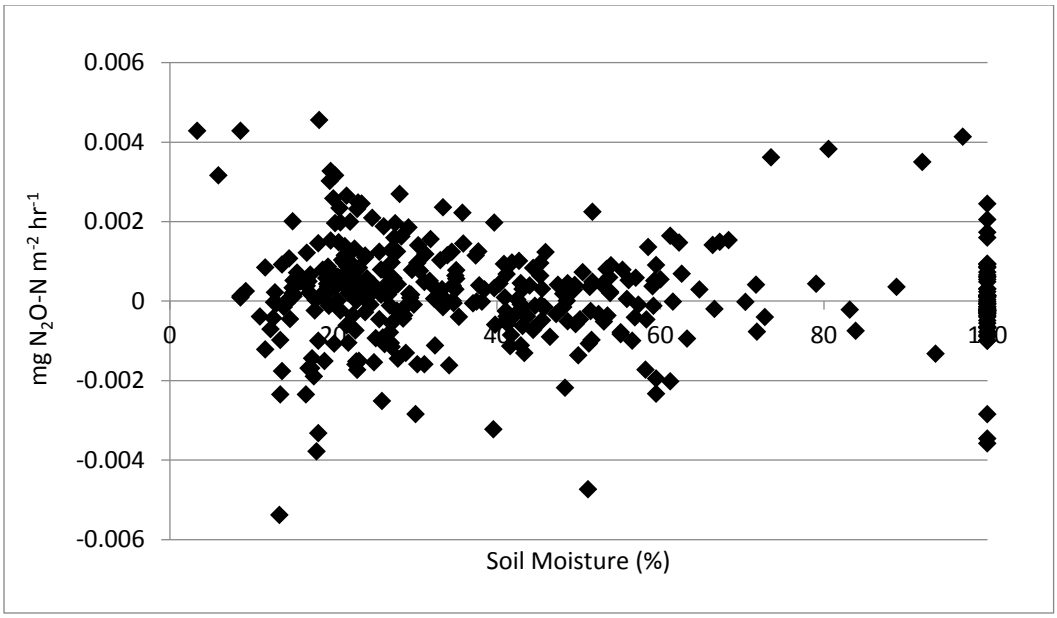


Figure 4.13: Correlation between N_2O fluxes and soil moisture from all chambers during the entire study.

Chapter 5 - Summary and Conclusions

5.1 Summary

This study was the first to quantify the emissions of CO_2, CH_4 and N_2O from farmed cranberry fields. Dark chamber flux measurements were made in two commercially farmed cranberry fields, under different soil-water scenarios, in St.-Louis-de-Blandford, Quebec, over two growing seasons, from May to November in 2012 and April to October in 2013. A total of 20 and 22 days of gas sampling were carried out on an approximately weekly basis in 2012 and 2013, respectively. Soil moisture, depth to water table, temperature and precipitation data was also collected and used to explain the fluxes of GHGs. Although the findings of this experiment were limited to one research site located in southern Quebec it is a region where cranberry production thrives and management practices are representative of commercial cranberry production. All farm practices were completed by the farmer in regards to his normal farming routines, including irrigation, flooding, drainage and fertilization. Additionally, the experiment was conducted over two growing seasons with varying climatic conditions, 2012 being hot and dry while 2013 was relatively warm and wet.

5.2 Conclusions

With regards to the first objective, to investigate how fluxes vary in fields under different soil-water scenarios, there were no significant differences between GHG fluxes from the two fields under different soil water scenarios throughout most of the growing season. Significant differences only occurred on a few sampling dates and were due to flooding/non flooding. On 4 sampling dates, CO_2 fluxes were significantly different between the two fields, all of which occurred when one field was flooded for harvest while the other was not. On 10 sampling dates, CH_4 fluxes were significantly different between the two fields. On these dates, the field with a saturated soil emitted significantly more CH_4 than the field with a lower soil moisture content. N_2O fluxes from both fields, much like CO_2, were only significantly different on 4 dates, all of which occurred when one field was flooded and the other not.

The second objective was to understand how environmental conditions and management practices influence GHG fluxes from commercially farmed cranberry fields. Fluxes of CO_2 generally increased under high temperatures, low water tables and during periods of flooding. For the most part of the growing season the fields were a sink of CH_4, however, when the fields were flooded, due to over irrigation, during harvest and the sprint snow melt, they became a source. N_2O fluxes were negligible throughout the entire study, with fluxes averaging

0.0001 mg N_2O-N m^{-2} hr^{-1} and thus not significantly influenced by fertilizer applications, soil moisture or temperature.

The third objective was to quantify GHG emissions from fields under cranberry production relative to other agroecosystems. When compared to other conventional agricultural systems, cranberries are not major sources of CO_2 or N_2O. Unlike other conventional agricultural systems, cranberries are a perennial crop, their soils are not disturbed and they have a low C content. These conditions reduce the potential for CO_2 production and thus emission is relatively low. Similarly, N_2O emission from cranberry fields are low compared to other conventional agricultural systems, such as corn or wheat, which can emit up to 2g of N_2O in a given year (Gregorich et al., 2005). Unlike these fields, the sandy soils of cranberry fields have a low N content, are acidic and receive low amounts of N fertilizers (22-68 kg ha^{-1}) (DeMoranville, 2006) all of which limits N_2O emission. Agricultural soils are generally considered the major biological sink of CH4 due to the fact that their soils are well aerated. Cranberry fields are subjected to temporary periods of flooding and are thus a source of CH_4. CH_4 fluxes from cranberry fields are still low (<0.06mg CH_4-C m^{-2} hr^{-1}) when compared to other flooded ecosystems such as rice paddies and wetlands, which can emit up to 1g CH_4-C m^{-2} in a given day (Le Mer et al., 2001). This is likely due to the fact that their soils become saturated for only short periods of time

which generally occurs in early spring and late fall when temperatures are low and thus limit microbial activities. Additionally, the sandy soils of cranberry fields have a low C content (<10 g kg^{-1}) compared to the soils of rice paddies and wetlands (which, in some cases, can be 100% (Mitsch and Gosselink, 2007).This lack of suitable substrate limits decomposition and thus CH_4 fluxes from soils under cranberry production are in comparison low.

Chapter 6 – Recommendations for Future Research

i. Flux measurements made using the static dark chamber method inherently have challenges. First, the data collected is limited temporally. For this project, flux measurements were made on a weekly basis during the growing season and were always taken at mid day. Secondly, the data collected is limited spatially. Measurements were limited to ten locations (each only half a squared meter in area) within two individual fields. Third, the dark chambers do not allow the plants to photosynthesize and thus only measure CO_2 respiration rates. Continuous micrometeorological flux measurements of CO_2 and CH_4 would help create a detailed GHG budget from fields under cranberry production. It would allow measurements to be made much on a much smaller time scale, i.e. hourly, and larger spatial scale, i.e. at the farm level. In addition to measuring CO_2 respiration, continuous micrometeorological flux measurements would also measure the CO_2 that is sequestered via plant photosynthesis.

ii. The distribution of cranberry production in North America is wide spread, ranging as far west as British Columbia, east as Newfoundland and as far south as New Jersey. The results of this experiment are limited to southern Quebec. GHG fluxes from fields under cranberry production in other geographical areas would likely vary from this study. For example, fields under cranberry production in climates with short and warmer winters (including United States, the largest producer of cranberries in the world) often do not completely freeze over during the winter. These fields may therefore remain flooded for extended periods of time and thus be significant sources of CO_2 and CH_4 during that time of year. Yearlong flux measurements made in cranberry fields in warmer climates will help determine they are significant sources of GHGs in these regions during the winter.

Chapter 7 - References

Agriculture and Agri-Foods Canada. 2009. Statistical overview of Canadian horticulture. Ottawa, Canada. ISBN 978-1-100-14230-2

Baggs, E. M. 2011. Soil microbial sources of nitrous oxide: recent advances in knowledge, emerging challenges and future direction. Current Opinion in Environmental Sustainability, 321:327.

Bouwman, A. F., and Bourmand, L. J. M., and Batjes, N. H. 2002. Emissions of N_2O and NO from fertilized fields: summary of available measurement data. Global Biogeochemical Cycles, 16: 1058-1072.

Brady, R. R., and Weil, N. 2007. The Nature and Properties of Soils. 14th edition. ISBN: 013227938X.

Burger, M., Jackson, L.E., Lundquist, E.J., Louie, D. T., Miller, R.L., Rolston, D.E., and Scow, K. M. 2005. Microbial responses and nitrous oxide emissions during wetting and drying of organically and conventionally managed soil under tomatoes. Biological Fertility of Soils, 42:109-118.

Davidson, E. A. 2000. Sources of nitric oxide and nitrous oxide following wetting of dry soil. Soil Science Society of America Journal, 56: 95-102.

Davenport, J.R. and DeMoranville, C.J. 2004. Temperature influences nitrogen release rates in cranberry soils. Horticultural Science, 39:80-83.

Demoranville, C. 2006. Cranberry best management practice adoption and conservation farming in Massachusetts. HortiTechnology: 394-397.

DeMoranville, C. and Sandler, H. A. 2000. Harvest and post-harvest management. Cranberry Station Best Management Practices Guide - 2000 Edition.

DeMoranville, C., Sanddler, H., and Bicki, T. 1996. Best management practice guide for Massachusetts cranberry production. University of Massachusetts Press, MA.

Dinsmore, K. J., Skiba, U. M., Billett, M. F., and Ress, R. M. 2009. Effect of water table on greenhouse gas emissions from peatland mesocosms. Plant Soil, 318:229-242.

Eck, P. 1990. The American Cranberry. Rutgers University Press, New Brunswick, United States.

Eck, P. 1976. Cranberry growth and production in relation to water table depth. Journal of the American Society of Horticultural Science, 241: 28-294.

Gregorich, E. G., Rochette, P., VandenBygaart, A. J. And Angers, D. A. 2005. Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. Soil and Tillage Research, 83: 53-72.

Hellebrand, H. J., Scholz, V., and Kern, J. 2008. Fertilizer induced nitrous oxide emissions during energy crop cultivation on loamy sand soils. Atmospheric Environment, 42: 8403-8311.

Intergovernmental Panel on Climate Change (IPPC). 2007. Climate Change 2007: The Physical Science Bais. Contribution of Working Group 1 to the Fourth Assessment Report of the IPCC, edited by S. Solomonet al., Cambridge Univ. Press, New York.

Kasimir-Klemedtsson, A., Klemedtsson, L., Berglund, K., Martikainen, P.., Silvola, J., and Oenema, O. 1997. Greenhouse gas emissions from farmed organic soils: a review. Soil Use and Management, 13: 245-250.

Kool, D. M., Dolfing, J., Wrage, N. And Van Groenigen, J. W. 2011. Nitrifier denitrification as a distinct and significant source of nitrous oxide from soil. Soil Biology and Biochemistry, 43: 174-178.

Lafleur, P., Roulet, N. T., Bubier, J. L., Frolking, S., and Moore, T. 2003. Inter-annual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog. Global Biogeochemical Cycles, 15, 1036.

Lai, D.Y.F. 2009. Methane dynamics in northern peatlands: a review. Pedosphere, 19: 409-421.

Le Mer, J., and Roger, P. 2001. Production, oxidization, emission and consumption of methane by soils: a review. European Journal of Soil Biology, 37: 25-50.

Mat Su, A., Adamchuck, S. Madramootoo, C. and Whalen, J. 2013. Estimating greenhouse gas emissions using experimental data. An oral presentation given at the Canadian Soil Science Society Annual Meeting, Winnipeg.

McClain, M. E., et al. 2003. Biogeochmical hot spots and hot moments at the interface of terrestrial and aquatic ecosystem. Ecosystems, 6: 301-312.

Mitsch, W. J., and Gosselink, J. G. 2007. Wetlands. Fourth edition. John Wiley and Sons, Inc. Hoboken, New Jersey.

Moore, T. R., De Young, A., Bubier, J. L., Humphreys, E. R., Lafleur, P. M., and Roulet, N. T. 2011. A multi-year record of methane flux at the Mer Bleue Bog, southern Canada. Ecosystems, 14: 646-657.

Moore, T. R., and Knowles, R. 1989. The influence of water table levels on methane and carbon dioxide emissions from peatland soils. Canadian Journal of Soil Science, 69: 33-38.

Murray, R. C. 1997. Cranberry facts and pointers. Nova Scotia Department of Agriculture. About Production Technology Branch Bulletin.

Paulstian, K., Six, J., Elliott, E. T., and Hunt, H. W. 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemsitry, 48: 147-163.

Peterson, S. S., Cross, C. E. 1968. The cranberry industry in Massachusetts. Massachusetts Department of Agriculture Bulletin 201.

Rho, H., Jun Yu, D., Jin Kim, Su and Jae Lee, H. 2012. Limitation factors for photosynthesis in 'Bluecrop' highbush blueberry (Vaccinium corymbosum) leaves in response to moderate water stress. Journal of Plant Biology, 55: 450-457.

Robinson, D., and Hanson, E. 1997. The key to successful cranberry production. Horticultural Branch of the Michigan Department of Agriculture Technical Bulletin.

Roper, T. R., and Vorsa, N. 1997. Cranberry: botany and horticulture. Horticultural Reviews, 21: 215-249.

Sass, R.L., Fisher F.M., Wang, Y.B. Turner F.T., and Jund, M.F. 1992 Methane emission from rice fields: The effect of floodwater management. Global Biogeochemical Cycles, 8:135-140.

Smith, K. A., Ball, T., Conen, F., Dobbie, K. A., Massheder, J., and Rey. R. 2003. Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. European Journal of Soil Science, 54: 779-791.

Taldonleke, R. D., Planas, D., and Paquet, S. 2005. Bacterial activity in the water column and its impact on the CO_2 efflux.

Tremblay, A., Lambert, M., and Gagnon, L. 2007. Do hydroelectric reservoirs emit greenhouse gases? Environmental Management, 33, 509-517.

Ullah, S., and Moore, T. R. 2011. Biogeochemical controls on methane, nitrous oxide and carbon dioxide fluxes from deciduous forest soils in eastern Canada. Journal of Geophysical Research, 116: doi:10.1029/2010JG001525.

Vandenberg, J., and Parent, G. 1999. Profile of the Canadian Cranberry Industry. Agriculture and Agri-Food Canada, Horticultural Special Crops Division, Market Industry and Services Branch Special Publication.

Whalen, S.C. 2005. Biogeochemistry of methane exchange between natural wetlands and the atmosphere. Environmental Engineering Science, 22: 73-94.

Wrage, N., Velthof, G. L.; van Beusichem, M.L., and Oenema, O. 2001. Role of nitrifier denitrification in the production of nitrous oxide. Soil Biology and Biochemistry 33: 1723-1732.