A COMPARISON OF THE CARBON DIOXIDE FLUXES OF TWO ANNUAL CROPPING SYSTEMS AND A PERENNIAL HAY FIELD IN SOUTHERN MANITOBA OVER 30 MONTHS

by

AMANDA M. TAYLOR

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Department of Soil Science
University of Manitoba
Winnipeg Manitoba Canada

ABSTRACT

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The eddy-covariance method was used to measure net ecosystem productivity over three adjacent fields from 2009 to 2011: two annual cropping systems (oat-canola-oat and hay-oat-fallow) recently converted from perennial cropping, and a perennial hay/pasture. We compared the management practises, determined the net carbon budget, and examined the effects of inter-annual variability. Carbon accumulation began earlier in the spring and continued later in the fall at the perennial site, compared with the annual crop sites, due to a longer growing season and continual plant cover. Cumulative cropping season net ecosystem productivity at the perennial site ranged from 40 to 240 g C m^{-2} because of variable weather. Including harvest removals and manure additions, the perennial site gained 120 g carbon m^{-2} and the annual sites lost 240 and 415 g carbon m^{-2}, respectively, over the 30-month period. This indicates that the annual cropping systems would decrease soil carbon at this location.

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1. INTRODUCTION

1.1 Overview

Global atmospheric concentrations of carbon dioxide (CO_2) have risen at an unprecedented rate over the last 50 years, increasing by more than 20% (Tans 2011). Strong evidence links the changes in the Earth's atmosphere to the influence of human activities. Agriculture has the potential to both sequester and emit CO_2, making croplands important in terrestrial carbon cycles where they dominate the landscape. Changes in management strategies influence the carbon within agroecosystems by affecting the above- and below-ground biomass, litter, and soil organic matter. Cultivated lands also impact the surrounding climate and affect albedo, surface roughness, hydrological cycling, and long-wave radiation components (Bonan 2002). Expanding the understanding of CO_2 cycling within agroecosystems is integral to quantifying their response to man-made disturbances (Law et al. 2002).

1.2 Carbon in Canadian soils and agriculture transitions

The western prairies account for 80% of the arable land in Canada, with 55 million hectares present in Manitoba, Saskatchewan, and Alberta (Janzen et al. 1998; Curtin et al. 2000). Agroecosystems are heavily influenced by human activities and modify carbon fluxes, in particular when management practises change. Land converted to cropland is disturbance-dominated and will affect CO_2 flux and soil organic carbon as a result. Policy generally views agricultural soils as carbon neutral (Baker and Griffis 2005) when evaluating their impact on carbon balances.

Soil contains 2400 Pg of carbon globally; more than double the amount in the atmosphere (Brady and Weil 2008). One of the primary methods of CO_2 evolution from soils is the decomposition of organic matter and subsequent respiration. Decomposition on prairie agricultural fields in western Canada accounts for 30-50% of the soil organic carbon lost through clearing, tillage, fallow, and cropping of former grasslands (Janzen 2005). Conversion of perennial to annual cropping usually shifts carbon from the soil and vegetation into the atmospheric pool. Tillage alters soil structure, breaks up aggregates and residues, rearranges pore space and moisture, increases soil faunal respiration rates, and stimulates CO_2 production. Even one till per year can cause significant soil organic carbon losses (Curtin et al. 2000). CO_2 fluxes depend on agricultural practice, soil type, and climatic conditions, and their measurement contributes to the field-scale understanding of the processes involved.

1.3 Flux measurement techniques

Chamber techniques are often used to measure soil surface CO_2 flux or soil respiration (Curtin et al. 2000; McGinn and Akinremi 2001; Brye et al. 2002). Chamber measurements are low frequency and rely heavily upon interpolation between point samples, increasing the difficulty of using them for continuous, long-term measurements, or having enough replicates for the averaging to be reliable (Baldocchi et al. 1988). Chambers can affect CO_2 flux measurements by altering the heating gradients and pressure differentials between the atmosphere and the soil.

The eddy covariance technique evolved in combination with the understanding of fluid dynamics, micrometeorology, and instrumentation. It samples the air to provide an instant vertical mass flux density when coupled with Reynold’s rules of averaging (Baldocchi 2003). Short-term studies measuring CO_2 exchange in the 1950-60s relied on the flux-gradient method (Baldocchi 2003). Other techniques for computing eddy flux are the Bowen-ratio energy balance and the aerodynamic method (Baldocchi et al. 1988).

Eddy covariance is now widely used for measuring ecosystem fluxes because of the advantages it offers (Baldocchi et al. 1988; Eugster and Sigrist 2000). It allows for integrated, landscape-scale measurements of net CO_2 flux between the ground and the atmosphere. It is a non-destructive and non-invasive method, with a flux footprint ranging from hundreds of meters to several kilometres, depending on the height of the tower (Baldocchi 2003). It measures a wide temporal range, from hours to years, and the measurements are possible in nearly all weather conditions.

The calculation of mean CO_2 flux density (measured in μmol m^{-2} s^{-1}) is the time-averaged covariance of instantaneous vertical wind velocity fluctuations and fluctuations in the CO_2 mixing ratio. This calculation is the average CO_2 flux, assuming the mean vertical velocity over a homogeneous, horizontal surface is zero (Desjardins and Lemon 1974; Baldocchi et al. 1988). It is commonly expressed as net ecosystem exchange (NEE) and is a net measurement of the inward and outward CO_2 vertical flows for an ecosystem. It is calculated as

$$NEE = \overline{\rho_a}\overline{w'c'}$$

where *NEE* is the mean flux density of CO_2, ρ_a is the air density, *w* is the vertical wind velocity, and *c* is the CO_2 mixing ratio. Primes (‘) denote fluctuations from the mean, and overbars represent mean values. In our study, values are reported as net ecosystem productivity (NEP)

$$NEP = -NEE - DC$$

where DC is dissolved carbon fluxes and assumed to be negligible for our ecosystem. With NEP, positive values are a net transfer of CO_2 towards the ground, whereas negative values indicate a net transfer of CO_2 to the atmosphere.

Prior to the development of fast-responding, stable, and accurate anemometers, eddy covariance studies of any length were difficult, because of the inability to properly measure turbulent transport via vertical wind (Desjardins and Lemon 1974). Sensor performance and data acquisition systems limited the length of eddy covariance studies until the early 1990s (Baldocchi 2003). To accurately sample the slower motions that contribute to CO_2 fluctuations, sampling periods should be between 30 and 60 minutes during the day, and longer at night due to thermal stratification (Baldocchi 2003). Night-time stratification can prevent CO_2 emitted from the soil from reaching the instrumentation. Eddy covariance measurements may also be limited by uneven terrain and non-steady environmental conditions.

1.4 CO_2 flux measurements over agroecosystems

Detailed measurements that account for spatial variation are needed to assess how shifts in agricultural management impact productivity and carbon budgets (Davis et al. 2010). Eddy covariance can measure NEP at the field and farm scales, where farmers' decisions (e.g., crop varieties, sowing, irrigation, fertilization, tillage) affect the carbon budget. Traditional sampling methods have shown a variety of impacts dependent on soil type and climate: that increasing tillage reduces carbon inputs, and annual crops reduce soil carbon more than perennials (VandenBygaart et al. 2008), that summer fallow can reduce soil organic carbon, whereas hay grasses can increase it (Bremer et al. 2002), or that sites may not be affected by fallow or tillage at all within the top 15 cm of soil (Campbell et al. 1996). The current database of direct, continuous measurements needs to be expanded to determine the impact of management decisions on a wide range of climatic and soil conditions. Relatively few experiments continuously measure cropland carbon changes, making it difficult to monitor how persistent or changing agricultural practises affect it (VandenBygaart et al. 2008).

The eddy covariance micrometeorology technique was first used to measure cropland CO_2 fluxes over corn during the summer of 1969 (Desjardins and Lemon 1974). Baldocchi et al. (1981) measured the CO_2 fluxes above irrigated and non-irrigated alfalfa fields in three studies during the summer of 1978. Anderson et al. (1984) measured CO_2 flux over a soybean crop with a drag anemometer and rapid response analyser for a period of ten days in 1981. Measurements taken over a corn crop between July 11 and August 5, 1983 by Desjardins et al. (1984) was one of the first studies to calculate CO_2 flux over a longer period. They acknowledged that the amount of collectable data was limited by sensor response time. Eddy covariance measurements over a perennial tall grass prairie for seven days in 1986 allowed Verma et al. (1989) to conclude that CO_2 exchange was limited by incoming photosynthetically active radiation (PAR). By the late 1980’s, it was still considered impractical to apply micrometeorological methods for extended periods of time (Baldocchi et al. 1988), because of the uncertainties in measurement and lacking technology fast enough to measure and record the data.

Measuring CO_2 flux via eddy covariance expanded into longer studies over forests and peatlands (e.g., Amiro et al. 2006; Glenn et al. 2006), and now includes a global network of micrometeorological towers measuring gas and energy exchange on a long-term basis, FLUXNET (http://fluxnet.ornl.gov/). Annual carbon budgeting through this method is most reliable from sites with extensive, homogeneous canopies on flat landscapes where advection is minimized, making agroecosystems in southern Manitoba well suited to the application. Non-ideal sites can experience uncertainties ranging from 100 to 200 g C m^{-2} $year^{-1}$, compared with the ideal, which are often < 50 g C m^{-2} $year^{-1}$ (Baldocchi 2003).

A compilation of peer- reviewed studies conducted over agricultural land in northern, mid-latitude, temperate zones during the past fifteen years is presented in Table 1.1. Articles compiling FLUXNET sites throughout Europe (Ceschia et al. 2010; Kutsch et al. 2010) were not included. The table includes the yearly carbon flux (NEP), the harvest removals where applicable, as well as the crop rotations and management practises applied in each study. Soil textures ranged from sandy loams to clays. Only a small subset of the current research has been conducted in Canada. Studies with mean annual temperature values comparable to our own were within both in southern Manitoba, Canada (Glenn et al. 2010; Stewart 2011); Glenn et al. (2010) and Stewart (2011) measured CO_2 with the flux-gradient technique. No studies compared the fluxes of crops on land recently converted for annual cropping to that of an adjacent, persistent pasture.

Maize was present in the crop rotations of almost half the studies. When biomass was harvested, it usually resulted in the site becoming carbon neutral or a source. Stewart (2011) found an alfalfa forage site was a carbon sink at the end of its second cropping season after establishment, once harvest removals were accounted for. The flux research conducted over agroecosystems acknowledged that comparisons between rotations are challenging, because different climates, soils, and management practises will produce different results with large amounts of variability (Hollinger et al. 2005; Moureaux et al. 2006; Aubinet et al. 2009; Béziat et al. 2009; Glenn et al. 2010; Prescher et al. 2010).

Table 1.1 The main characteristics, net ecosystem productivity (NEP), and harvest removals of agroecosystem carbon flux studies. Ecosystem C-gains are positive, while C-losses are negative.

Location	Date	Mean annual air temp (°C)	Mean annual precip. (mm)	Crop	Management	NEP ($g\ C\ m^{-2}\ yr^{-1}$)	Harvest ($g\ C\ m^{-2}\ yr^{-}$)	Source
Nebraska, USA	2001	11.8	570	maize	NT - irrigated	517	-521	Verma et al. (2005)
	2001	11.9		maize	NT - irrigated	529	-518	
	2001	12.1		maize	NT	510	-335	
	2002	10.6	566	maize	NT - irrigated	424	-503	
	2002	10.6		soybean	NT - irrigated	48	-183	
	2002	10.7		soybean	NT	-18	-153	
	2003	10.7	589	maize	NT - irrigated	381	-470	
	2003	10.4	589	maize	NT - irrigated	572	-538	
	2003	10.7	589	maize	NT	397	-297	
Toulouse, France	2005	13.0	693	rapeseed	RT	-286 ±23	-213 ±61	Béziat et al. (2009)
	2006			winter wheat	RT	-324 ±20	-279 ±42	
	2007			sunflower	RT	28 ±18	-104 ±36	
	2005	12.9	639	wheat (triticale)	RT	-335 ±42	-505 ±39	
	2006			maize	RT - irrigated	-186 ±42	-806 ±57	
	2007			winter wheat	RT	-369 ±33	-386 ±47	
Thuringia, Germany	2001	9.7	505	winter wheat	RT	-185 to 245	-290	Anthoni et al. (2004)
Illinois, USA	1997	N/A *	N/A *	maize	NT	532.2	-339.5	Hollinger et al. (2006),
	1998			soybean	NT	-103.7	-150.0	Hollinger et al. (2005)
	1999			maize	NT	691.8	-436.9	
	2000			soybean	NT	-9.2	-161.4	
	2001			maize	NT	505.1	-399.4	
	2002			soybean	NT	210.4	-158.2	
Lonzée, Belgium	2004	10.7	800	sugar beet	Cultivated	-800 ±40	-630	Moureaux et al. (2006),
	2005	11.0		winter wheat	Cultivated	-630 ±30	-580	Moureaux et al. (2008),
	2006	11.4		seed potato	Cultivated	-310 ±20	-290 ±30	Aubinet et al. (2009)
	2007	11.5		wheat straw	Cultivated	-800 ±40	-450	
	all	10.0	800	inter-cropping		-880 ±60	N/A	

Table 1.1 (continued)

Location	Date	Mean annual air temp (°C)	Mean annual precip. (mm)	Crop	Management	NEP (g C m^{-2} yr^{-1})	Harvest (g C m^{-2} yr^{-1})	Source
Carlow, SE Ireland	2003	9.3	823	spring barley	CT	205 ±98	-328.5 †	Davis et al. (2010)
	2003			spring barley	NIT	205 ±134	-328.5 †	
	2004			spring barley	CT	88 ±97	-226.5 †	
	2004			spring barley	NIT	152 ±168	-268.5 †	
	2005			spring barley	CT	203 ±80	-236.5 †	
	2005			spring barley	NIT	176 ±162	-234 †	
North China Plain	2002-2003	13.1	528	winter wheat	CT	77.6	-203.6	Li et al. (2006)
	2002-2003			summer maize	CT	120.1	-334.6	
	2003-2004			winter wheat	CT	152.2	-210.1	
	2003-2004			summer maize	CT	165.6	-215.3	
NE Italy	2007	N/A *	N/A *	maize	CT	473	-484 ±25	Alberti et al. (2010)
	2007			maize	CT	616	-793 ±45	
	2008			maize		343	-428 ±26	
	2008			alfalfa forage		481	-658 ±38	
Grillenburg, Germany	2003	7.9	824	managed grassland	2-3 hay cuts/year	295	None	Hussain et al. (2011)
	2004					260	-147	
Manitoba, Canada	2006	4.7	292	maize	RT/CT combined	72±17 †	-123 ±9 †	Glenn et al. (2010) ‡
	2007	2.9	559	faba bean	RT/CT combined	-7±3 †	-307 ±9 †	
	2008	1.4	727	spring wheat	RT/CT combined	240±43 †	-192 ±25 †	
	2009-2010	3.5	848	rapeseed		140	-43 †	Stewart (2011) ‡
	2009-2010	3.5	848	alfalfa forage		235	-193 †	

NT = No-till, RT = Reduced tillage, CT = Conventional tillage, NIT = non-inversion tillage.

*No values given by source.

† Values converted from original document to facilitate comparison.

‡ Measurements obtained through the flux gradient method.

Glenn et al. (2010) recommended that more multi-year micrometeorological studies on CO_2 flux in different systems are required to help identify practises that affect agroecosystem carbon storage.

1.5 Thesis objectives

A gap exists in the current state of knowledge regarding the impact that annual and perennial systems have on the carbon balance of agroecosystems. This thesis is comprised of one manuscript that seeks to address this gap through the placement of three eddy covariance towers on adjacent fields near Woodlands, Manitoba, Canada. The main objectives of this project are: (1) to determine the NEP for three adjacent sites, two with annual crops and one a perennial hay/pasture, over three consecutive growing seasons, (2) establish the relative carbon balance of different crops and rotations in relation to management and climate, and (3) analyze how year-to-year climatic variability impacts fluxes at the perennial hay/pasture.

This project was conducted in collaboration with a variety of partners during its establishment and data collection. The site design and set-up of the eddy covariance towers and inclusive equipment was determined by Trevor Fraser and Brian Amiro in 2009. The data, sampling, lab work, and site upkeep was maintained by a handful of other collaborators prior to my joining the project in September 2010. Fraser (2012) compared the perennial hay/pasture to one of the adjacent sites during its conversion year in 2009, and examined the impacts that conversion from perennial to annual cropping had on the CO_2 flux during the summer of 2009. He found that the converted site lost carbon while the hay field did not; conversion effects were related to fallow and cropping season length affecting gross primary productivity. This project focuses on the differences among the management practices and the effects of inter-annual variability and weather for the duration of the study period from the initial site set-up in 2009 through to fall 2011, and does not include an analysis of the impact that conversion would have on the annual sites presented.

Results are presented by examining the impacts of each rotation's management on cumulative NEP, cumulative gross ecosystem productivity, and the cumulative ecosystem respiration of each site over the 30-month study period. Impacts of biomass removals and additions are included to calculate the carbon budget, while inter-annual variability is demonstrated through a cropping season comparison of the perennial hay/pasture from 2009 to 2011. These topics are further investigated in the discussion, in the context of our uncertainties and quality assurance given the techniques used.

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2. COMPARING THE CARBON FLUXES OF THREE CROPPING SYSTEMS IN SOUTHERN MANITOBA, CANADA

2.1 Abstract

From June 2009 through November 2011, eddy covariance flux towers were placed over two annual cropping systems and one perennial hay/pasture in Southern Manitoba, Canada to measure carbon dioxide exchange. We sought to evaluate how management practises chosen by an independent producer affected the carbon budget and ecosystem processes, and how the sites were affected by inter-annual variability. One field was converted from perennial hay in 2008, and had an oat-canola-oat rotation. Another field was converted from hay in 2009, had oats planted in 2010, but was left fallow in 2011 due to excess moisture in the spring. A perennial hay/pasture was harvested annually and grazed by cow-calf pairs for one month each fall. Prior to harvest removals or manure additions, the cumulative net ecosystem productivity of the oat-canola-oat field showed a loss of 100 g C m^{-2}, the hay-oat-fallow field lost 500 g C m^{-2}, and the hay site gained 550 g C m^{-2} by the end of the 30-month study period. The hay/pasture site had the highest cumulative gross ecosystem productivity of 2525 g C m^{-2}, whereas the oat-canola-oat site and hay-oat-fallow were more than 1000 g C m^{-2} lower. The hay-oat-fallow and the hay site had comparable cumulative ecosystem respiration (1400 g C m^{-2}). Manure additions contributed 300 g C m^{-2} at each annual crop site. Each site lost carbon through harvest removals, but a persistent crop cover allowed the hay site to accumulate carbon in the spring and fall while respiration dominated at both annual crop sites. With exports and amendments included, the oat-canola-oat site was a carbon source of 240 g C m^{-2}, the hay-oat-fallow was a source of 415 g C m^{-2}, and the hay/pasture site was a sink of 120 g C m^{-2} over the 30-month period. Rain during the

cropping season was near-normal in 2009, >100 mm wetter in 2010, and 2011 experienced drought conditions after spring flooding. The drought stunted the oat crop, but may have lessened fallow respiration losses.

2.2 Introduction

Agricultural management practises affect the uptake and release of greenhouse gases into the atmosphere. Measuring the energy, water, and gas fluxes over managed ecosystems allows for the evaluation of the processes impacting them at a field- or ecosystem-scale. Net carbon fluxes are influenced by human activity, particularly over croplands, whose canopies change seasonally due to disturbances like tillage, planting, and harvesting. Few experiments continuously measure changes in carbon fluxes, making it difficult to monitor the impact of the variable management practices applied (VandenBygaart et al. 2008). Cropland fluxes are less understood than those of natural ecosystems, such as forests or grasslands (Prescher et al. 2010).

Producers make decisions based on economic drivers; grain prices may encourage them to focus on crop production instead of animal production, or to convert hay and pasturelands for growing annual crops. The conversion from perennial forages to annual cropping may shift carbon from the soil and vegetation into the atmosphere. How much carbon is lost depends on how much is in the soil (Mudge et al. 2011), with soils high in carbon having the potential to lose more as a result (Kutsch et al. 2010).

Field variability, as well as the cost, time, and soil sampling depths can make it difficult to accurately and continuously monitor changes in soil organic carbon. Eddy covariance can be a way to solve temporal resolution issues (Baker and Griffis 2005), and is better suited to measuring changes in carbon after land use conversion than soil organic carbon inventory changes (Alberti et al. 2010). It allows CO_2 to be measured at the field scale in a non-destructive manner over the long term. Gross ecosystem productivity (GEP) and ecosystem respiration (ER) can be calculated from net ecosystem productivity (NEP), and the net ecosystem carbon budget can be determined when combined with lateral flux measurements. NEP is highly variable and dependent on climate, soil, and vegetation. This spatial variability can make site-by-site comparisons difficult, but carbon flux measurements allow for the quantification of the processes that affect NEP (Davis et al. 2010).

Previous tower-based micrometeorological studies of agroecosystem CO_2 flux have been conducted over winter wheat (Antoni et al. 2004; Moureaux et al. 2008), no-till maize (Verma et al. 2005), no-till maize-soybean (Hollinger et al. 2005), corn-soybean (Baker and Griffis 2005), sugar beets (Moureaux et al. 2006), winter wheat-maize (Li et al. 2006), winter wheat-sunflower (Béziat et al. 2009), spring barley-fallow (Davis et al. 2010), a managed grassland (Hussain et al. 2011), an intensively grazed pasture (Mudge et al. 2011), maize-faba-spring wheat (Glenn et al. 2010), and alfalfa (Stewart 2011).

Few studies were conducted where mean annual air temperatures were below 10˚C (Glenn et al. 2010; Stewart 2011; Fraser 2012), and those were from the same region as this study. Glenn et al. (2010) monitored a maize-faba-spring wheat rotation, and Stewart (2011) examined the impact of perennial legumes within annual crop rotations; both studies utilized the flux-gradient technique. Fraser (2012) evaluated the impact of converting to annual cropping from a perennial system on carbon fluxes at the same site as the current study.

Through the placement of three eddy covariance towers on a producer’s field in Woodlands, MB, Canada, the main objectives of this project are: (1) to determine the

NEP for three adjacent sites, two with annual crops and one a perennial hay/pasture, over three consecutive growing seasons, (2) to establish the relative carbon balance of different crops in relation to management, and (3) to analyze the seasonal dynamics and inter-annual variability.

2.3 Methods

2.3.1 Site description

The sites are located on a privately-owned farm (50°10'1.20"N 97°52'21.60"W; 261 m.a.s.l.) approximately 23 km west of Woodlands, MB Canada. They are in the southern extent of the Interlake Plain, which is part of the greater Interior Plains geographic region. It has a land slope of 2-5% and is Class 4, viable lower-class agricultural land (Land Resource Unit 1999). The soil is of the Isafold Association, shallow, highly calcareous Rendzina, developed under grasses and aspen, with limestone or dolomite parent material. It is a well-drained, Rego Black Chernozem (UdicBoroll) (Ehrlich et al. 1953). Climate data are from the Winnipeg Richardson International Airport (WRIA), MB (49°55'00"N 97°14’00"W; 238.7 m.a.s.l.), approximately 75 km south-east of the research site. Mean annual temperature of the region is 2.6°C and mean annual precipitation is 514 mm (Environment Canada 2012).

Figure 2.1 shows the relative location of the fields, the placement of the instrument towers, and the area of each field. Field area was calculated from GPS polygons of each site. The OatCanOat field was tilled in 2008, prior to which it was a tame pasture for more than 20 years, and during the study period the rotation was oat-

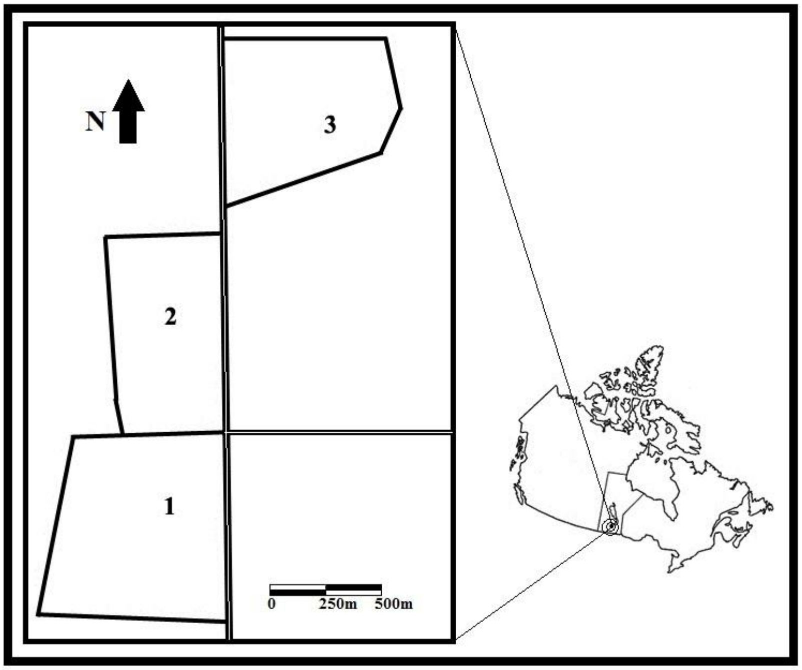

Figure 2.1 The location and size of the research sites. The position of each number shows the location of each instrument tower. Area as calculated by the polygons indicated: OatCanOat site (1) 59.9 ha, HayOatFal site (2) 38.7 ha, Hay Site (3) 39.5 ha.

canola-oat. Cattle grazed the oat stubble from September 21 to October 3, 2011. The HayOatFal field was tilled in 2009, prior to which it was a tame pasture for more than 20 years. During the study period, the rotation was hay-oat-fallow. No crop was planted by the producer in 2011 due to excess moisture in the spring and early summer, and subsequently had large weed growth. Cattle grazed the weed cover from June 24 to July 14, 2011. In order of dominance by visual observation: the weeds were foxtail barley (*Hordeum junatum*), sow thistle (*Sonchus spp*.), *Carduus spp*., plantain (*Plantago major*), timothy grass (*Phleum pratense*), shepherd's-purse (*Capsella bursa-pastoris*), wild mustard (*Sinapis arvensis*), alsike clover (*Trifolium hybridium*), and fescue (*Festuca spp*.). In low lying areas, yellow sweet clover (*Melilotus officinalis*), smartweed (*Persicaria spp*.), and curly dock (*Rumex crispus*) were also prevalent. Other species present included pygmy-flower rock-jasmine (*Androsace septentrionalis*), wild mint (*Mentha arvensis*), Kentucky bluegrass (*Poa pratensis*), lambsquarters (*Chenopodium berlandieri*), and Philadelphia fleabane (*Erigeron philadelphicus*). No cover estimation scales were used to assess the species dominance or abundance. Approximately 50-75% of the field had weed cover until mid-July.

The Hay site had been tame pasture for more than 20 years. It was usually cut by the producer once or twice a year, allowing for cattle to graze in the fall. The Braun-Blanquet cover estimate scale (Table 2.1) was used on July 15, 2011 to determine the species composition of the Hay site (Table 2.2) (Braun-Blanquet 1965). Identification was done within a 0.5 m^2 square quadrat, thrown from the locations of the same transects where soil and biomass samples were collected.

Table 2.1 Braun-Blanquet cover-abundance scale and mid-point cover range.

Class	Cover range (%)	Midpoint of cover range (%)
5	75 - 100	87.5
4	50 - 75	62.5
3	25 - 50	37.5
2	5 - 25	15
1	1 - 5	2.5
<1	<1	0.1
<<1	<<1	*

* Assumed to be insignificant, seldom occurring.
(Adapted from Mueller-Dombois and Ellenberg 1974)

Table 2.2 Species cover-abundance on July 15, 2011.

Species	Mean class	Midpoint cover range (%)
Timothy Grass *(Phleum pratense)*	3	37.5
Rough Fescue *(Festuca campestris)*	3	37.5
Smooth Brome *(Bromus inermis)*	2	15
Sowthistle *(Sonchus arvensis)*	1	2.5
Unknown forbes	1	2.5
Alfalfa *(Medicago sativa)*	1	2.5
Common Dandelion *(Taraxacum officinale)*	1	2.5
Yarrow *(Achillea millefolium)*	<1	0.1
Bed Straw *(Gallium boreale)*	<1	0.1
Wheat Grass *(Agropyron spp.)*	<1	0.1
Trifolium spp.	<<1	*
Rosa acicularis	<<1	*
Vicia americana	<<1	*
Erysimum cheiranthoides	<<1	*

2.3.2 Agronomic management practices

The OatCanOat site was a perennial grass pasture that was tilled for annual cropping in 2008, and its agronomic practises during the study period are in Table 2.3. In 2009, the site was disk-tilled and fertilized with urea in late May. Potassium chloride (KCl), monoammonium phosphate (MAP), and sulphur (S) fertilizers were added with the oat seed and planted by air seeder between May 27 and June 1, 2009. An unspecified broadleaf herbicide was applied on June 25, 2009. The oats were cut at the end of September, and the crop was combined and the straw baled in late October 2009. In 2010, canola was seeded with urea, KCl, MAP, and S fertilizers, after which the field was tine-harrowed, and packer-rollered in mid-May. Glyphosate was applied in mid-June, and the canola was cut mid-August 2010. The field was cultivated at the beginning of October 2010, after which a custom application of solid beef-straw manure was spread. Planting was delayed in 2011 because of a wet spring. A custom application of glyphosate and disk-tillage preceded the oats being broadcast with urea, KCl, MAP, and S fertilizers at the beginning of June 2011. An in-crop herbicide was applied at the beginning of July 2010. The oats were cut at the beginning of September 2011. Cattle grazed the stubble and stunted oats that could not be harvested for a few weeks at the end of September 2011. It was disk-tilled afterwards.

Table 2.3 OatCanOat site management practices.

2009	Date	Event	Quantity
	May 27	Disk tillage & broadcast granular urea	89.7 kg ha^{-1}
	June 1	KCl, MAP, S with seed	22.4, 33.6, 3.2 kg ha^{-1}
	June 1	Oats seeded with air seeder	112 kg ha^{-1}
	June 25	Broadleaf herbicide (unspecified)	
	Sept 25	Oats cut	
	Oct 27	Oats combined	4509 kg ha^{-1} (148 bu/ac)†
	Oct 27	Oat straw, baled, small square	480 bales †
2010			
	May 17	Canola seeded, then tine-harrowed	5.6 kg ha^{-1} DK 3465
	May 17	Field tilled, harrowed, packer/roller, & broadcast urea	78.5 kg ha^{-1}
	May 17	KCl, MAP, S with seed	22.4, 33.6, 9 kg ha^{-1}
	June 20	Custom application glyphosate (Round-Up™)	2.47 L ha^{-1}
	Aug 18	Canola cut	
	Aug 25 to Sept 8	Canola combined	2117 kg ha^{-1} (38 bu ac^{-1})†
	Sept 8	Canola straw left on field	
	Oct 1	Field cultivated (3-4")	
	Oct 21 to 25	Custom manure application (solid beef cattle)	28 tonnes/ha ‡
2011			
	June 1	Custom application glyphosate (Round-Up™)	2.47 L ha^{-1}
	June 9	Disk tillage	
	June 9 to 14	Oats broadcast	123.3 kg ha^{-1} Triactor
	June 9 to 14	Broadcast granular urea	70 kg ha^{-1}
	June 9 to 14	KCl, MAP, S with seed	33.6, 39.2, 5.6 kg ha^{-1}
	July 6	In crop herbicide (unspecified)	
	Sept 7 to 15	Oats cut	
	Sept 15 to 21	Oats combined	709 kg ha^{-1} (20 bu/acre)†
	Sept 21 to Oct 3	Grazing stubble	35 cow-calf pairs
	Oct 3	Disk tillage	

* Prior to flux measurements.

† Yields reported by the producer.

‡ Rate unknown, custom application. Used same rate that was applied to HayOatFal Site in 2009. 7.4 tonne ha^{-1} dry, as per the Tri-Provincial Manure Application & Use Guidelines (PPCLDMM, 2004) average beef manure dry matter of 26.4%.

A summary of the management practises for the HayOatFal site are provided in Table 2.4. The HayOatFal site was perennial pasture that was fertilized with urea, KCl, MAP, and S before measurements began in early June 2009. Glyphosate was applied at the end of July and the site was swathed at the beginning of August 2009. The hay was baled and solid beef-straw manure was applied mid-August, prior to the pasture being tilled for annual cropping. The field was disk-tilled three times through the late

Table 2.4 HayOatFal site management practises.

2009	Date	Event	Quantity
	June 1 *	Broadcast granular urea, KCl	67.5, 11 kg ha^{-1}
	June 1 *	Broadcast MAP, S	17, 1-2 kg ha^{-1}
	July 30	Custom application glyphosate (Round-Up™)	2.47 L ha^{-1}
	Aug 6	Swathed to 10cm height	
	Aug 10 to Aug 18	Baled, square and removed from field	360 (340 kg each)
	Aug 10 to Aug 18	Manuring (beef with straw)	28 tonnes ha^{-1} ‡
	Aug 28 to Aug 29	Disk tillage, very rough	
	Oct 1 to Oct 7	Disk tillage	
	Oct 20	Disk tillage, smooth	
2010			
	May 15	Disk tillage	
	May 19	Broadcast granular urea prior to seeding	50.4 kg ha^{-1}
	May 19	KCl, MAP, S with seed	22.4, 33.6, 4.5 kg ha^{-1}
	May 19	Oats air seeded, harrowed & packer/roller	123.3 kg ha^{-1} Leggett
	June 20	Custom glyphosate and 2,4 D application	
	Aug 25	Oats 25% lodged	
	Sept 8	Perimeter swathed, too lodged/wet to cut	
	Oct 15 to Oct 20	Oats swathed and combined	1597 kg ha^{-1} (45 bu ac $^{-1}$)^{II}
	Oct 15 to Oct 20	Straw and remaining oats baled, round	45 (590 kg each)
	Oct 25	Cultivated	
2011			
	June 9 to June 14	Strip of field (~5%) disk tilled	
	June 24 to July 14	Grazing (on weeds)	35 cow-calf pairs
	July 15 to July 25	Custom application glyphosate (Round-Up™)	2.47 L ha^{-1}
	Aug 5	Disk tillage	
	Aug 24 to Sept 2	Disk tillage	
	Sept 15	Harrowed	

* Date is an approximation.

† Prior to flux measurements.

‡ 7.4 tonne ha^{-1} dry, as per the Tri-Provincial Manure Application & Use Guidelines (PPCLDMM, 2004) average beef manure dry matter of 26.4%.

^{II} Yields reported by the producer.

summer and fall of 2009. In 2010, the field was disk-tilled prior to oats being air-seeded along with urea, KCl, MAP, and S fertilizers in mid-May. Glyphosate and 2,4-D were applied in mid-June. The oats were badly lodged during the summer and were not swathed and removed from the field until the middle of October 2010. This allowed some weeds to grow in the interim. In 2011, the field was too wet to be planted and weeds were allowed to grow. Cattle grazed on the weeds from the end of June until mid-July 2011, after which glyphosate was applied to kill the remainder. The field was disk-tilled twice in August, and harrowed in September 2011.

The Hay site was grass-dominated perennial pasture for more than 20 years, and the management events during the study period are presented in Table 2.5. Prior to measurements beginning, urea, KCl, MAP, and S were broadcast at the beginning of June

Table 2.5 Hay site management practices.

2009	**Date**	**Event**	**Quantity**
	June 1*	Broadcast Urea, KCl	67.5, 11 kg ha^{-1}
	June 1*	Broadcast MAP, S	17 1-2 kg ha^{-1}
	Aug 2 to Aug 14	Swathed to 10cm height	
	Aug 18 to Sept 4	Baled, round and removed from field.	180 (612 kg each)
	Oct 20 to Nov 20‡	Grazing	100 cow/calf pairs
2010			
	Aug 4	Swathed to 25cm height	
	Aug 18 to Aug 25	Baled, round	217 (612 kg each)[II]
	Oct 20	Broadcast urea	50 lb N/ac
	Oct 20	KCl, MAP, S with seed	22.4, 33.6, 4.5 kg ha^{-1}
	Oct 13 to Oct 19	Bales removed from field	
	Oct 20 to Nov 25	Grazing	120 cow-calf pairs[¶]
2011			
	July 26	Swathed to 15cm height	
	Aug 2	Baled, round	269 (612 kg each)[II]
	Aug 9	Bales removed from field	
	Oct 5 to Nov 24	Grazing	120 cow-calf pairs[¶]

*Date is an approximation.
† Prior to flux measurements.
‡ Entire period was gap filled due to power and EC method limitations.
II Yields reported by the producer.
¶ Producer indicated 120 cow-calf pairs grazed 1.5 tonnes ha^{-1} during this period

2009. At the beginning of August 2009, the field was swathed and the bales were removed at the end of the month. For one month in the late fall of 2009, cow-calf pairs grazed. The Hay site was swathed at the beginning of August 2010, and the bales were collected at month's end. The same fertilizers were applied in October 2010 as were in the spring of 2009. Cow-calf pairs grazed the field for one month in late fall of 2010. The field was swathed at the end of July 2011 and bales were collected at the beginning of August 2011. Cow-calf pairs grazed the site for almost two months in the fall of 2011.

2.3.3 Soil measurements

Soil sampling was conducted in October 2009 and May 2011. Samples were taken every 20 m to a maximum of 100 m in three wind directions: north-west, south-west, and south-east. No samples were taken from the north-east transect because winds from this direction are less frequent and have a lesser impact on the average measured carbon fluxes. Incremental samples were taken every 15 cm up to a depth of 1 m on October 27, 2009, with bulk-density samples taken at the same increments from the surface to a minimum depth of 75 cm. Deep samples were taken using a tractor-mounted hydraulic corer, whereas bulk-density samples were taken with a tulip bulb planter. For a more in-depth description of 2009 sampling methods, consult Fraser (2012).

In 2011, samples were taken from the HayOatFal and OatCanOat fields on May 15 and from the Hay field on May 25, 2011. Samples were taken with a 3.8-cm diameter Dutch auger at depths of 0-15 cm and 15-30 cm at the same five sampling distances and the three transects as measured in 2009. Three cores were sampled at each location and combined into one bag. Bulk-density samples were taken with a 7-cm diameter tulip bulb planter to the same depths at the 40 m and 80 m locations. This resulted in 42 samples from each field site. Sampling was complicated by the fields being water-logged below 5-10 cm and riddled with stones. Bulk-density calculations were adjusted for the depth of the sample taken, as the physical sampling of the full second depth (15-30 cm) could not always reach 30 cm, due to an inability to get the corer into the ground. Samples were air dried for at least one week prior to being weighed, milled, and ground using a 2-mm sieve.

Composite subsamples from each plot were sent to ALS Laboratory Group (Winnipeg, MB) to be analyzed for texture, nitrate-N (NO_3-N), phosphate-P (PO_4-P), K, sulphate-S (SO_4-S), pH, and electro-conductivity for soil characterization. Bulk-density samples were weighed and oven dried at 105°C for at least 24 hours, before a second weighting allowed bulk-density to be calculated. Composite samples of each transect and depths were sent to ALS Laboratory Group (Winnipeg, MB), where total carbon, total organic carbon, total inorganic carbon, and the calcium carbonate ($CaCO_3$) equivalent were determined. Total carbon was determined through combustion (Nelson and Sommers 1996), whereas inorganic and organic carbon tests were done by open system acid decomposition (Loeppert and Suarez 1996). Statistical analysis of the bulk density and carbon measurements were done with SAS 9.2 TS (SAS Institute Inc., Cary, NC, USA), and utilized a type 3 ANOVA (mixed procedure). Where significance was found when comparing carbon measurements, Tukey’s test was used in conjunction with an ANOVA to find significance between means at sites and the two measured depths.

2.3.4 Biomass collection and accounting, manure sampling

Biomass samples were collected every year from each of the three sites, except from the HayOatFal site in 2011, because no crop was present on the field (Table 2.6).

Unless otherwise specified, 0.5 m by 0.5 m quadrats were cut by hand at ground level every 20 m of each transect (NW, SW, SE) from 20 to 100 m, with each sample placed in the same burlap bag. In 2010, the Hay had already been cut by the farmer when samples were taken; swaths were 5 m wide, so the sample area was 5 m by 0.5 m. The canola was also swathed at the time of sampling in 2010, with a mean distance between swaths of 7.4 m; each plot taken represented an area of 7.4 m by 0.5 m. 2010 oats biomass was cut from a 1 m by 1 m swath.

Table 2.6 Biomass samples collected by site and date.

Site	Date	Sample area (m^2)	Notes
Hay	July 27 to 30, 2009	0.25	Not all samples collected, as hay already harvested by producer.
HayOatFal	July 27 to 30, 2009	0.25	
OatCanOat	July 27 to 30, 2009	0.25	
Hay	August 4, 2010	2.5	Samples taken from cut swaths at 20, 50, 80m at SE & NW, and 80m at SW.
HayOatFal	August 25, 2010	1	Samples taken at 30, 60m at NW, SW, SW.
OatCanOat	August 25, 2010	3.7	Samples taken from cut swaths at 50m at NW, SW, SE.
Hay	July 8, 2011	0.25	
OatCanOat	August 19, 2011	0.25	

Grain was removed, weighed, and dried separately from the bulk biomass. The samples were air-dried for several weeks, after which grain and subsamples were oven dried at 80°C for at least 24 hours to determine the moisture content. Moisture content values were used to adjust producer yields reported. The area of each field was calculated from GPS coordinate generated polygons. Yields reported by the producer were used to determine how much carbon was removed from each site, assuming 44.5% carbon in the oven-dried organic matter. Wet mass test weights from the Canadian Grain Commission (2011) used to convert bushel weights of grain for carbon calculation were 584 kg wet biomass m^{-3} for canola, 358 kg wet biomass m^{-3} for oats.

A custom application of solid beef manure mixed with straw was applied to both annual sites during the study period; the HayOatFal in 2009, and the OatCanOat site in 2010. The 2010 application was not measured when it was applied in the fall due to late notification of application and freeze-up before samples could be obtained. Samples were taken in early spring after the snowmelt and spring runoff had occurred, which could have resulted in dissolved carbon losses. The amount of manure applied was unknown by the producer. Average application rates range from 20 to 40 Mg wet ha^{-1} (Timmerman, M.D., MAFRI, personal communication, March 5, 2012), and the rate in 2009 was 28 Mg wet ha^{-1}; this value was used in accounting for the 2010 application as well. A single, composite manure sample was collected from various ground locations after the application on the HayOatFal site in August, 2009. The sample was dried at 40°C for several days, before being ground and submitted to ALS Canada Ltd. (Winnipeg, MB) for N, P, K, S and total carbon analysis; this sample was not used in our analysis, as it only provided one value that likely under-estimated the expected manure carbon content. Five random samples of the solid beef manure and straw mixture applied in the fall of 2010 were gathered from the OatCanOat site on April 26, 2011. Sampling was delayed due to snow cover and belated notification of application. Samples were freeze-dried and ground, before being submitted to A&L Canada Laboratories Inc. (London, ON) to determine total carbon, total organic carbon, total inorganic carbon, and total nitrogen. Total inorganic carbon was determined by gravimetric measurement with a detection limit of 0.10%, and total carbon, total organic carbon, and total nitrogen were measured by combustion with a detection limit of 0.10%. Carbon content from the 2011 sampling date and subsequent analysis were used to determine the amount of carbon applied through the two custom manure applications. The manure had 406±84 g kg^{-1}mean total carbon, 401±90 g kg^{-1} mean total organic carbon, and 6±7 g kg^{-1} mean total inorganic carbon (where variation is standard deviation), 20 g kg^{-1} mean total nitrogen, and a mean C/N ratio of 21:1. Total carbon was used in conjunction with an application rate of 28 tonnes ha^{-1} wet manure (7.4 tonnes ha^{-1} dry) as per the Tri-Provincial Manure Application & Use Guidelines (PPCLDMM 2004) to calculate that 300 g C m^{-2} was applied to the HayOatFal field in 2009 and the OatCanOat field in 2011 through manure application.

2.3.5 Environmental measurements

Table 2.7 indicates the instrumentation present at each site. Instrumentation and configuration were established by Fraser (2012).

Table 2.7 Instrumentation present at each research site.

Instrument	OatCan Oat Site	HayOatFal Site	Hay Site
Closed-path differential infrared gas analyser(LI-7000 CO2/H2O analyzer)	1	1	1
CR1000 Measurement & Control datalogger	2	2	2
3-D sonic-anemometer-temperature sensor (CSAT3)	1	1	1
HMP45C temperature & relative humidity probe & associated passively ventilated radiation shielding	1	1	---
Tipping-bucket rain gauge	1	1	---
Soil temperature thermocouples at 5 (as of 2011), 10 & 20cm	1	1	1
Outgoing PAR	1	1	1
Incoming PAR	---	1	---
Net radiometer (CNR1)	---	1	1
Soil heat flux plates	2	2	2
Volumetric water content	2	2	2

Air temperature and relative humidity were measured using an HMP45C probe (Vaisala Inc., Woburn, MA, USA) inside a passively ventilated radiation shield (Model 41003-5 10-Plate Gill Solar Radiation Shielding, R.M. Young Company, Traverse City, MI, USA) situated about 1.2 m above the field surface. Wind velocity and temperature were measured by a 3-D sonic-anemometer-temperature sensor (CSAT3, Campbell

Scientific Inc., Logan, UT, USA). A tipping-bucket gauge (TE525M, Texas Electronics Inc., Dallas, TX, USA) measured rainfall. A wooden dowel with Chromel-Constantan thermocouples (24-gauge) situated at 10-cm and 20-cm depths measured soil temperature for all three years, and in April 2011 a 5-cm thermocouple was added. Soil moisture was measured from 0 to 30 cm by water content reflectometers (CS616, Campbell Scientific) inserted vertically in the soil surface. Soil heat flux plates (HFT3 REBS Soil Heat Flux Plate, Radiation and Energy Balance Systems Inc., Bellevue, WA, USA) were installed approximately 1-cm beneath the soil surface.

Incoming and outgoing photosynthetically active radiation (PAR) (LI-190 Quantum Sensor, LI-COR Biosciences, Lincoln, NE, USA) were measured 3 m above the field surface, while shortwave and longwave radiation were measured by a net radiometer (CNR1, Kipp & Zonen, Delft, The Netherlands). In-field measurements were collected at each site by CR1000 data loggers (Campbell Scientific Inc.), at 1 Hz with values averaged every half-hour period.

2.3.6 Carbon dioxide flux measurements and processing

Flux measurements were collected by CR1000 data loggers (Campbell Scientific Inc.) and subsequently downloaded to a laptop or PalmPilot computer during weekly site visits. Dataloggers and sensors were powered by 12-V, 98 amp-per-hour battery banks, charged by four 85-W solar panels (Kyocera Solar, Inc., Scottsdale, AZ) at each site, and by a 400-W wind generator (Air Industrial: Southwest Windpower, Inc., Flagstaff, AZ) at the HayOatFal and Hay sites.

The CSAT3 was mounted on triangular delhi towers 3 m above the soil surface and orientated into the prevailing winds (west). A closed-path differential infrared gas analyser (IRGA) (LI-7000 CO_2/H_2O Analyzer, LI-COR Biosciences) protected within temperature-control housing (TCH, University of British Columbia, Biometeorology Group) and radiation shielding measured CO_2 and water vapour. Intake for the gas analyser was 30 cm from the midpoint and set back towards the tower from the CSAT3 transducers. Samples were drawn through a 3 μm filter (Pall Corporation, Ann Arbor, MI, USA) and down 4 to 5 m of Bev-A-Line IV 3.18-mm I.D. tubing (Cole-Parmer, Vernon Hills, IL, USA). A pump at each site (Model UN815KNDC; KNF Neuberger Inc., Trenton, NJ, USA) drew the sample at a flow rate of 8 to 10 L min^{-1}. Gas sampling was done at 10 Hz and raw data were saved. The flux measurements were calibrated daily using a cylinder of compressed air with zero CO_2, and one calibrated as a secondary standard by the Meteorological Services of Canada (Downsview, ON), with a known CO_2 concentration that varied by site and year, ranging from 330 to 400 ppm.

The flux dataset began June 3, 2009 and terminated November 25, 2011. Flux measurements were not taken from October 13, 2010 through April 7, 2011 over the HayOatFal and Hay sites, and from October 13, 2010 to April 15, 2011 at the OatCanOat site, because the CSAT3, IRGA, and TCH were removed from the site for calibration, cleaning, and repair.

Raw data were saved to flash memory storage through an NL 115 card reader (Campbell Scientific Inc.) by the CR1000. After collection, data were processed and analyzed using MATLAB (Mathworks Inc., Natick, MA, USA). Raw high-frequency data were split into 30-minute file-sizes, and the calibration offset and slope were applied based on the daily measured calibration. From this dataset, half-hourly cross-products were generated and low frequency meteorological data were integrated. A third processing step applied coordinate rotation to the wind vectors (Tanner and Thurtell 1969).

2.3.7 Gap-filling and quality control

Known interruptions that may have affected instrumentation, such as periods of calibration, electrical malfunction, program errors, field operations or interruption during site visits, were removed from the half-hourly data post-processing. A friction velocity threshold (u*) of 0.19 m s^{-1} was set to filter nocturnal fluxes, which may be underestimated by lack of turbulent mixing in the boundary layer (Goulden et al. 1996; Falge et al. 2001) and prevent transfer of CO_2 out of the plant canopy (Baldocchi 2003). The u* was chosen from a regression plotting night-time NEE versus u*, as the point which accounted for 80% of the maximum night-time CO_2 fluxes (Mkhabela et al. 2009). Manual thresholds were set to include data with the following quality-control conditions, where: IRGA pressure was >50 and < 90 kPa, standard deviation of mean [CO_2] < 1 μmol m^{-3}, mean [CO_2] was >11 and <20 μmol m^{-3}, the standard deviation of vertical wind velocity (w) $\neq 0$, -0.5 m $s^{-1} < w < 0.5$ m s^{-1}, and a valid numerical value count of CSAT3 data > 95%. The Webb-Pearman-Leuning correction (Webb et al. 1980) was applied to correct for density effects caused by water vapour fluctuations. Water vapour fluxes from the OatCanOat site were substituted at the Hay Site from September 29, 2009 through April 23, 2010, and at the HayOatFal site in 2009 from May 20 to October 3, due to a poor water vapour calibration at these sites. After flux calculation of the covariance, net ecosystem exchange (NEE) was filtered for unreasonable data spikes, whose values were set by site: -30 and +10 μmol m^{-2} s^{-1} for the OatCanOat site, -30 and +20 μmol m^{-2} s^{-1} for the HayOatFal site, and -23 and +15 μmol m^{-2} s^{-1} for the Hay site, based on experience with the range of measured fluxes.

Gaps less than or equal to two hours in length were filled via linear interpolation. Larger gaps were filled using a 100-point moving-window method described in Amiro et al. (2006). Gap-filling used the relationship between modelled ER, GEP, and measured air temperature from the HayOatFal site. GEP was set to zero at night and when air temperature < 0°C, when photosynthesis was not possible; during these periods, ER equalled negative NEP. Daytime ER was modelled through an empirical relationship with air temperature. GEP was then estimated as GEP = NEP + ER (when it was not set as zero). With GEP and ER modelled, NEP gaps were filled using NEP = GEP – ER. Where incoming PAR was missing and could not be gap-filled, data were filled with values from adjacent days or with a value obtained through a regression equation of incoming shortwave radiation (K_{in}) (PAR(μmol m^{-2} s^{-1}) = K_{in}(W m^{-2})*2.246 + 0.02342). In one instance, accounting for ~0.13% of the study period, the application of the gap-filling algorithm was not possible, so values of PAR were taken from a time period of the same size after the gap.

Loss of high-frequency flux signals can occur when air is drawn through a sampling tube in closed-path analysers (Sukyer and Verma 1992). This is examined in greater depth in Appendix A of Fraser (2012). Anthoni et al. (2004) found that a high-frequency signal loss of 20% only accounted for a change in annual NEE of 5 g C m^{-2} at their site. Fraser (2012) found that our system only lost a maximum of 5% of the high-frequency signal for both LE and NEE. A correction factor of 1.05 was applied to the calculation of NEE at all sites to account for this attenuation.

2.4 Results

2.4.1 Site characterization

2.4.1.1 Soil characteristics

A characterization of each site was done from samples taken in May 2011 (Table 2.8). There was no significant difference in the bulk density among sites, but the 15-30 cm depth had significantly higher bulk density than the shallower depth. Statistics could not be calculated on the nutrient analyses because testing was conducted on a single composite sample from each depth at each site. The OatCanOat tended to have more N and S than the other sites, while the HayOatFal had more P and K, although they were not tested for significance.

Table 2.8 Soil characteristics.

	B.D. (Mg m^{-3})†			NO$_3$-N (mg kg^{-1})*			SO$_4$-S (mg kg^{-1})*			PO$_4$-P (mg kg^{-1})*			K (mg kg^{-1})*		
Depth (cm)	OCO	HOF	H	OCO	HOF	H	OCO	HOF	H	OCO	HOF	H	OCO	HOF	H
0-15	0.91	0.91	1.08	23	14	7	20	17	8	33	47	20	170	209	206
15-30	1.10	1.22	1.21	16	10	3	20	13	7	20	22	7	129	134	122

OCO = OatCanOat site & HOF= HayOatFal site sampled May 19, 2012. H = Hay site sampled May 25, 2012.

* Detection limits: N = 2.0, S = 3.0, P = 2.0, K=10.0. Nutrients reported as mg kg^{-1} based on dry weight of sample.

† $p < 0.01$ Statistical analysis of bulk-density (B.D.) only (n = 18). Could not be done on nutrient testing (n = 1).

Table 2.9 shows the carbon analysis of each site from the same samples. There was no significant difference between the total carbon values at each of the sites or at either of the depths. There was no significant difference in organic carbon among sites, but there was between sampling depth at each site. Inorganic carbon values were significantly different between sampling depths, and varied between sites.

Table 2.9 Carbon analysis of soil samples from May 2011 (g kg^{-1}).

	Total Carbon*			Organic Carbon †			Inorganic Carbon ‡		
Depth (cm)	OCO	HOF	H	OCO	HOF	H	OCO	HOF	H
0-15	74.0	83.7	70.0	56.5	63.7	57.2	17.5cd	20.0bc	12.8d
15-30	73.7	68.7	54.3	45.0	42.8	28.9	28.7a	25.9ab	25.4ab

OCO = OatCanOat site & HOF= HayOatFal site sampled May 19, 2012. H = Hay site sampled May 25, 2012.
* No significant difference between depth or site (n=18).
† Organic carbon was significantly higher at 0-15 cm than at 15-30 cm at all sites (ANOVA, n=18, p-value < 0.005).
‡ ANOVA Tukey's test, p-value <0.05, n=18. Similar letters mean no significant difference.

2.4.1.3 Temperature and rain

Examining the rainfall distribution and temperature variation at a site helps to understanding the seasonal trends that influences CO_2 fluxes (Figure 2.2). A large storm in July 2010 contributed to higher rainfall that summer. The summer and fall of 2011 had visibly less rainfall than previous years. When these larger trends are compared with

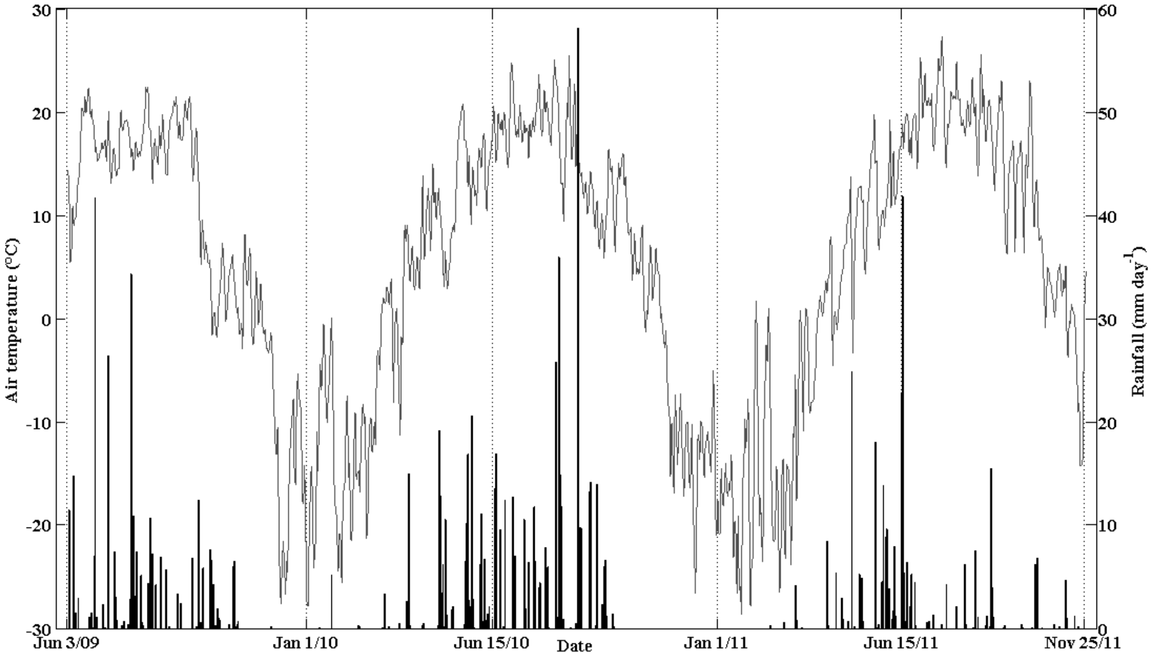

Figure 2.2 Mean daily air temperatures (line) and daily total rainfall (bars) from June 3, 2009 to November 25, 2012 as measured at the HayOatFal site. Frozen precipitation is unaccounted for.

measurements taken at the closest major centre where 30-year climatic data are available (Table 2.10A and 2.10B), we see that the 2009 and 2011 annual mean daily temperatures were within ±0.5°C of the climatic norms, whereas in 2010 the mean annual temperature was 3.8°C higher. Annual precipitation values were closest in 2010, and most disparate in 2011. During the cropping season, the mean daily temperature was within the standard deviation of the climatic norms. Precipitation values in the cropping season show 2009 to be 89%, 2010 to 137% and 2011 to be 54% of the climatic rainfall norms.

Table 2.10 Regional climate averages and HayOatFal site cropping season averages.

A. Annual regional values from Winnipeg Richardson International Airport*

	2009	2010	2011	30-year norms
Mean Daily Temp (°C)	2.1	6.4	3	2.6 ±1.3
Precipitation (mm)	406.5	479.5	352.5	513.7

B. Cropping season as measured at the HayOatFal (June 1 - October 1)

	2009†	2010	2011	30-year norms
Mean Daily Temp (°C)	16.8	16.5	18.1	16.8 ±1.6
Precipitation (mm)	252.3	394.2	156	287.1

* Located at 49°55'00, 97°14'00, 238.7 m.a.s.l.

† Measurements began June 3, 2009.

Temperature error reported as standard deviation.

2.4.2 Comparing the impacts of management on cumulative net ecosystem production

Converted from tame perennial pasture to annual cropping in 2008, the OatCanOat site exhibited spring carbon losses (50 to 100 g C m^{-2}) each year prior to the yearly crop establishing and gaining carbon (Figure 2.3). In 2009 and 2010, the field gained carbon as the crop matured over the summer (225 and 175 g C m^{-2}) before it senesced and ceased taking up carbon. In 2011, carbon uptake was much less (<50 g C m^{-2}). Winter measurements through 2009-2010 show carbon losses, as does the gap-filled period during the winter of 2010-2011 (<50 g C m^{-2}). Herbicide applications corresponded with crop establishment each year when the site began to accumulate carbon for the summer. Without including harvest removals or manure applications, the OatCanOat site was a carbon source of 100 g C m^{-2} at the end of the study period.

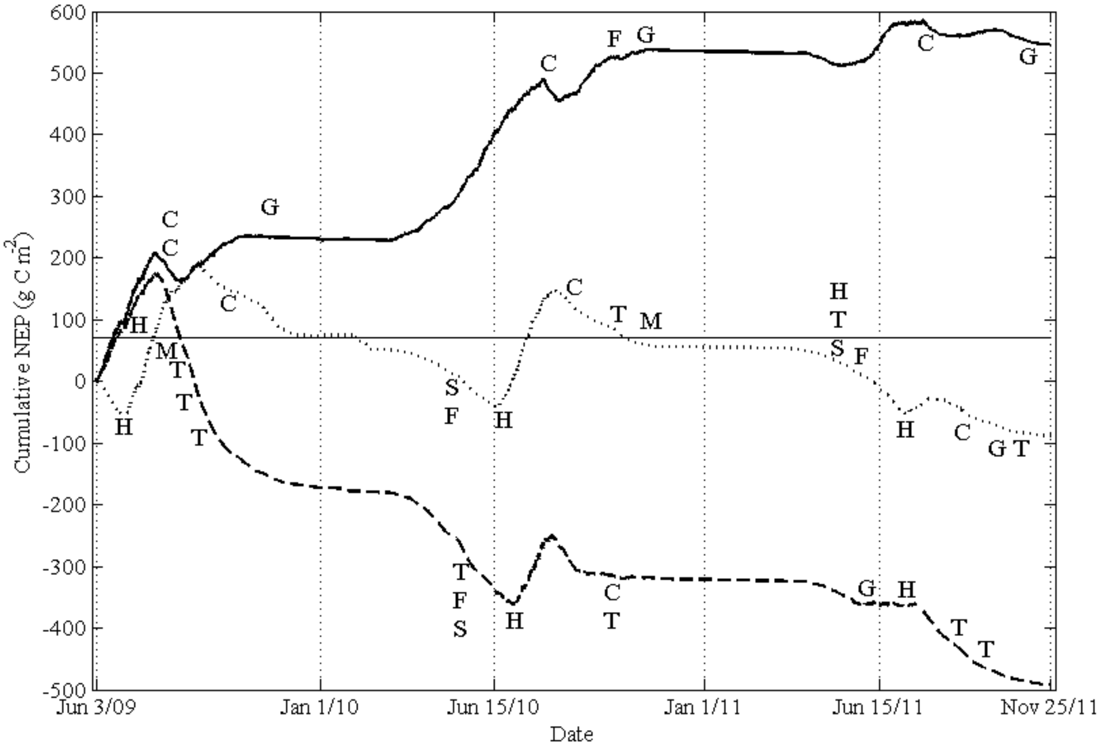

Figure 2.3 Cumulative net ecosystem productivity (NEP) for all three sites from June 3, 2009 to November 25, 2011. OatCanOat site (dots), HayOatFal (dash), Hay (solid line) are shown. Managements shown are herbicide application (H), crop cut (C), manure application (M), tillage (T), grazing (G), fertilizer application (F), and seeding (S). Biomass removals and additions are not included.

The HayOatFal site gained carbon (175 g C m^{-2}) through the summer of 2009, prior to glyphosate application, the hay being cut, baled, and the field tilled for annual cropping for the following year. The field was disk-tilled three times through the late summer and fall of 2009, corresponding with a carbon loss of 350 g C m^{-2} from hay cut to freeze-up. Winter losses both years were minimal (<25 g C m^{-2}). Spring carbon losses in 2010 (175 g C m^{-2}) were greater on this field than the OatFalOat site. During this period, tillage, fertilization application, and planting of the oat crop occurred. Glyphosate application coincided with crop germination, after which the site gained carbon (125 g C m^{-2}) as it matured. The oat crop was cut and harvested late in the year, because the field was too wet and the crop was badly lodged. Small spring carbon losses occurred in 2011 (<50 g C m^{-2}) and excess moisture prevented seeding. Weeds proliferated and cattle grazed for a short period, during which time no carbon was gained or lost. Herbicide application occurred in late summer and was followed by three tillage events through the fall, which resulted in a carbon loss of 175 g C m^{-2}. Without including harvest removals or manure applications, the HayOatFal site was a carbon source of 500 g C m^{-2} at the end of the study period.

The Hay Site gained 200, 225 and 50 g C m^{-2} each summer in 2009, 2010, and 2011. The site gained back 50 g C m^{-2} in each of 2009 and 2010 after recovering from hay cut losses. In 2011, this amount was negligible (<25 g C m^{-2}) but equal to the loss. The cattle grazed the pasture for approximately one month in the fall of 2009 and 2010, and for two months in the fall of 2011. Each winter exhibited small carbon losses (<25 g C m^{-2}). Without including harvest removals, the Hay site was a carbon sink of 550 g C m^{-2} at the end of the study period.

2.4.3 Cumulative gross ecosystem productivity and cumulative ecosystem respiration

NEP can be partitioned into GEP and ER to examine the main driving processes and provide insight into how each are affected by management practises and climate variability (Figure 2.4).

The OatCanOat site cumulative GEP follows a similar pattern of increase in 2009 and 2010, while it gained less for a shorter period of time in 2011. GEP was static each winter due to lack of photosynthesis, while cumulative ER had increases of 50 to 100 g C m^{-2} each year. The OatCanOat site had the lowest cumulative ER (1400 g C m^{-2}) values, with the smallest increases being in 2011.

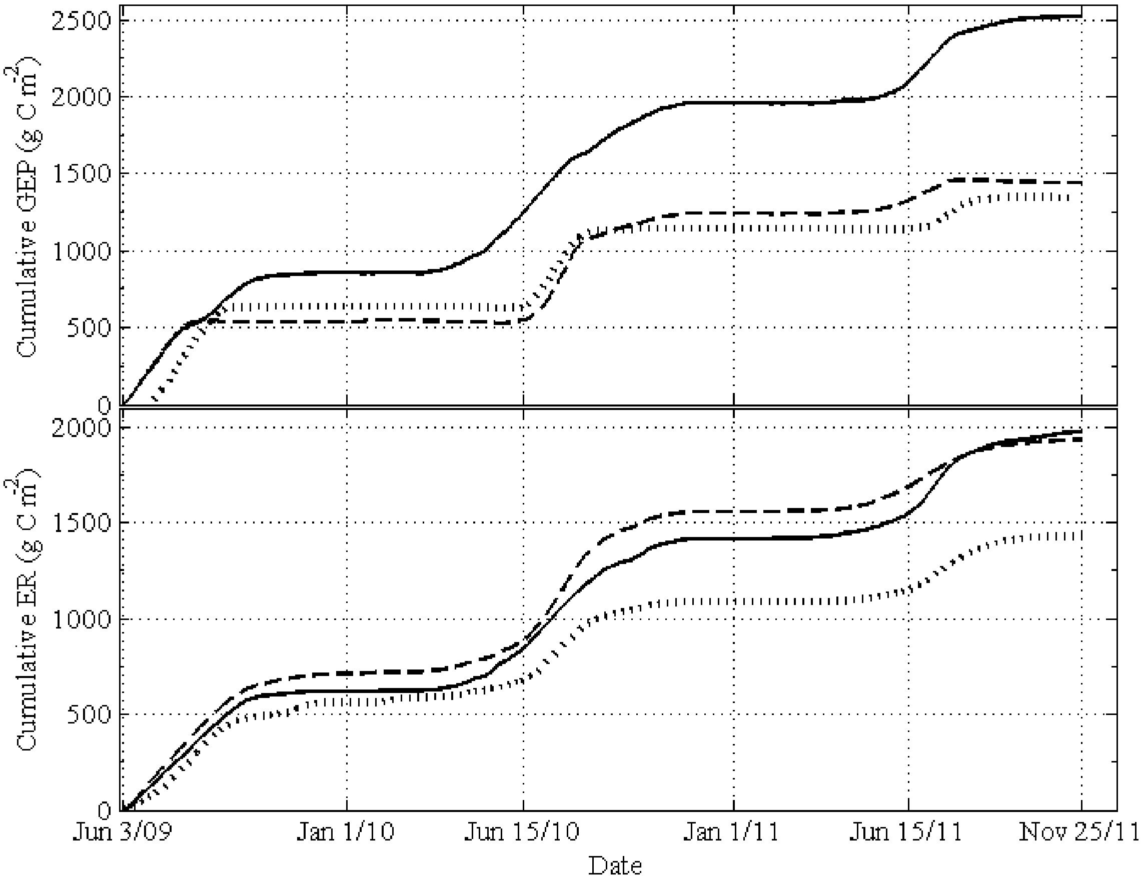

Figure 2.4 Cumulative gross ecosystem productivity and cumulative ecosystem respiration for all three sites, June 3, 2009 to November 25, 2011. OatCanOat (dots), HayOatFal (dash), Hay (solid line) are shown. Biomass removals and additions are not included.

The HayOatFal site gained carbon at the same rate as the Hay site in the summer of 2009, until the hay was cut and GEP levelled out. It had similar GEP gains as the

OatCanOat site in 2010, though in the fall GEP continued to increase. GEP had minor gains in 2011, before the site stopped accumulating carbon and remained static for the rest of the summer. ER increased the most in 2010, and the least in 2011. The site had small ER gains during each winter (50 to 100 g C m^{-2}). By the end of the study period, the HayOatFal cumulative ER (1950 g C m^{-2}) was similar to the Hay site ER, and its cumulative GEP (1400 g C m^{-2}) was similar to the OatCanOat.

The Hay site's GEP exceeded the two annual sites by >150 g C m^{-2} by the end of 2009. This gap grew to a difference of >1000 g C m^{-2} at the end of the study period. GEP continued to rise later through the fall of 2009 than either of the two annual sites. The Hay site had the largest seasonal GEP gain of 1050 g C m^{-2} during the summer of 2010. It had the largest cumulative GEP (2525 g C m^{-2}), and its cumulative ER (2000 g C m^{-2}) was slightly higher than the HayOatFal site at the end of the study period.

2.4.4 Impacts of biomass additions and removals on the carbon budget

Eddy covariance measures NEP, but we need to account for biomass removals or additions to estimate the full carbon budget of the site (Figure 2.5). The carbon budget of the OatCanOat site was affected by annual crop harvest, straw baling, manure application, and cattle grazing. In 2009, an oat crop was harvested and baled, removing 330 g C m^{-2} from the field. The 2010 canola grain harvest removed 90 g C m^{-2} of seed, and the straw was left on the field. In the fall, a custom application of solid beef cattle manure mixed with straw added 300 g C m^{-2}. The amount of carbon added with the canola seed was negligible, whereas the oat seed added 5 g C m^{-2}; this value is not included in the figure due to its small amount. The oat harvest in 2011 removed 30 g C m^{-2}. With harvest removals and manure accounted for, the OatCanOat site was a carbon source of 240 g C m^{-2} at the end of the study period.

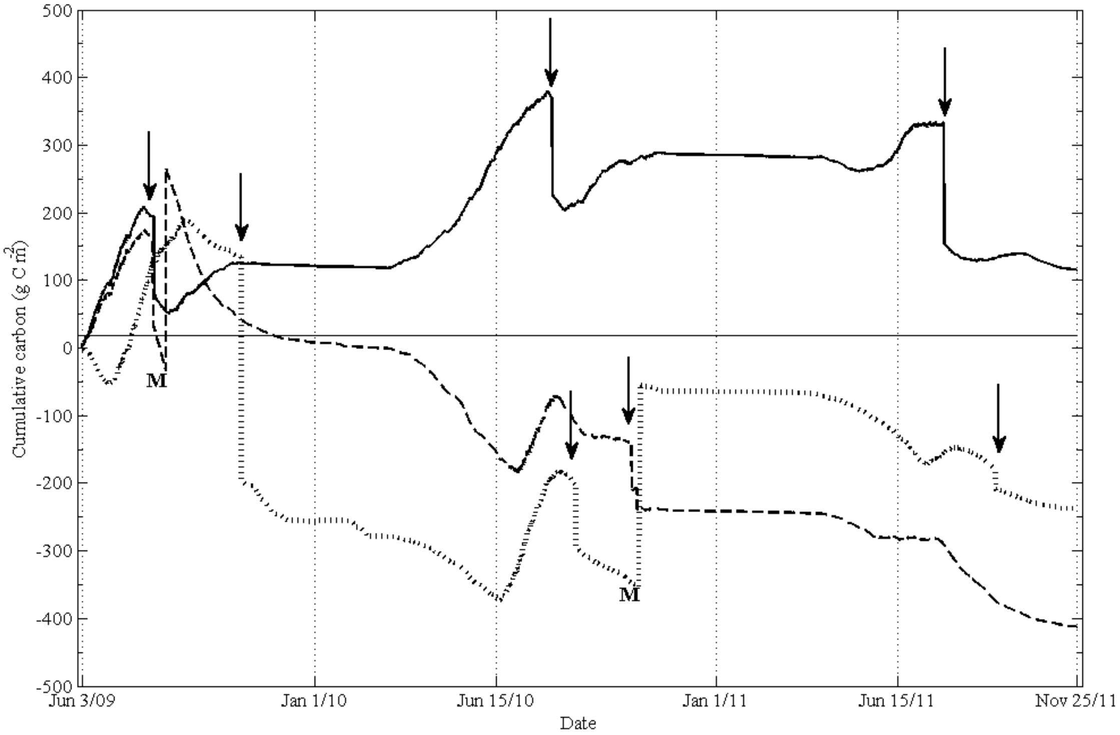

Figure 2.5 Cumulative carbon budget for all three sites during the study period, with biomass additions and removals. Harvest exports are arrows, manure applications 'M'. OatCanOat site (dots), HayOatFal (dash), Hay (solid line) are shown. Harvest removals were calculated from producer yields.

The HayOatFal site carbon balance was affected by hay removal, annual crop harvest, baling, and manure application. In 2009, the hay harvest removed 120 g C m^{-2} from the site, and a custom manure application after the field was tilled added 300 g C m^{-2}. The oat crop in 2010 removed 100 g C m^{-2} through the grain and bales taken from the straw. The oat seed itself added 5 g C m^{-2} when planted; this value is not included in the figure. The field was left fallow in 2011. The HayOatFal site was the largest carbon source, losing 415 g C m^{-2} by the end of the study period.

The Hay Site had bale harvesting and cattle grazing. From 2009 to 2011, bale harvesting removed 110, 140, and 180 g C m^{-2} per year, respectively. By the end of the study period, the site was a carbon sink of 120 g C m^{-2}.

Examination of the net carbon budgets on a year-by-year basis (Table 2.11) shows that in years when manure was applied, the annual sites were carbon neutral or carbon sinks, while in years when only a harvest was taken, they were carbon sources. The hay site was a carbon sink in 2009 and 2010, while it was a carbon source in 2011. The years are calendar years.

Table 2.11 Net carbon budget (g C m^{-2} year^{-1}).

Year	Site	Crop	Yearly NEP	Manure	Harvest	Net
2009*	OatCanOat	oats	80		-330	-250
	HayOatFal	hay	-170	300	-120	10
	Hay	hay	230		-110	120
2010	OatCanOat	canola	-25	300	-90	185
	HayOatFal	oats	-145		-100	-245
	Hay	hay	310		-140	170
2011†	OatCanOat	oats	-155		-30	-185
	HayOatFal	fallow	-185		0	-185
	Hay	hay	10		-180	-170

* Measurements prior to June 3, 2009 unaccounted for.

† 2011 measured until November 25, 2011, the end of the study period.

Calculating the net carbon balance was complicated by uncertainty in the amount of carbon removed by the producer each year during harvest (Table 2.12). In 2009 and 2010, the Hay site was already swathed when biomass samples were taken. This may have increased the uncertainty of the biomass cuttings. The canola at the OatCanOat site in 2010 was swathed and lying on the ground when biomass clippings were taken. The canola was put in mesh bags for transport, resulting in a considerable loss of seed. This prevented the calculation of seed yield from the biomass clippings.

Table 2.12 A comparison of harvest exports during the study period.

			Reported export (rounded to 10 g C m $^{-2}$)		
Site	Year	Crop	Producer Estimate (A)*	Field Sampling (B)	A-B
OatCanOat	2009	grain	200	270	-70
	2009	bales	130	470	-340
	2010	grain	90	N/A	N/A
	2011	grain	30	10	20
HayOatFal	2009	hay	120	230	-110
	2010	grain	70	90	-20
	2010	bales	30	140	-110
Hay	2009	hay	110	210	-100
	2010	hay	140	170	-30
	2011	hay	180	180	0

* Value used in the calculation of net carbon budget.

Generally, the biomass clippings estimated greater amounts of carbon being removed from each site. Yields reported by the producer were chosen for the analysis because they were more consistent year-to-year and between sites. Differences between values may relate to cutting height of samples, loss by producer machinery when the harvest is collected, difficulty of sampling the biomass, insufficient number of biomass samples, improper handling of grain or biomass, or error in sample handling in the lab.

Based on average daily gains (967.5 g day^{-1}) of calves grazed on unfertilized meadow bromegrass pasture near Brandon, Manitoba (Kopp et al. 2003) and 0.228 kg C per kg of fresh, unprepared beef (Killough et al. 1984), we estimated the carbon removed by the cattle during each grazing period on each of the fields. Average daily gains for calves were used because Kopp et al. (2003) reported that cows lose weight when grazing in cow-calf pairs. When 35 cow-calf pairs grazed either of the annual sites, they gained an estimated 0.3 g C m^{-2}. When 100 to 120 cow-calf pairs grazed the Hay site during the study period, they gained an estimated 2.6 g C m^{-2}. These are small amounts related to the carbon budget components in Table 2.12.

2.4.5 Inter-annual variability

Measurements from June 3 to October 15 of each year at the Hay site are provided in Figure 2.6 and demonstrate how inter-annual variability influenced NEP during the cropping season. This time period was chosen because measurements were most consistent in the summer months, when there was enough sun for power generation and the fluxes were the greatest. This site was chosen because it had the same crop and management practises each year.

The 2009 growing season exhibited the greatest accumulation of carbon through late July (200 g C m^{-2}), showing a decline of 50 g C m^{-2} after the field was cut before gaining 80 g C m^{-2} through the late summer and fall. The site accumulated 240 g C m^{-2} by October 15, 2009. The site accumulated less carbon by late July 2010 (135 g C m^{-2}), and followed the same pattern of loss after cutting (30 g C m^{-2}) before gaining an additional 75 g C m^{-2} through the fall. This resulted in the accumulation of 165 g C m^{-2} by October 15, 2010. The 2011 growing season accumulated the least carbon through late July (55 g C m^{-2}), had the smallest loss after cutting (20 g C m^{-2}), and negligible recovery through the latter half of the summer and fall (10 g C m^{-2}). The site accumulated 40 g C m^{-2} by October 15, 2011.

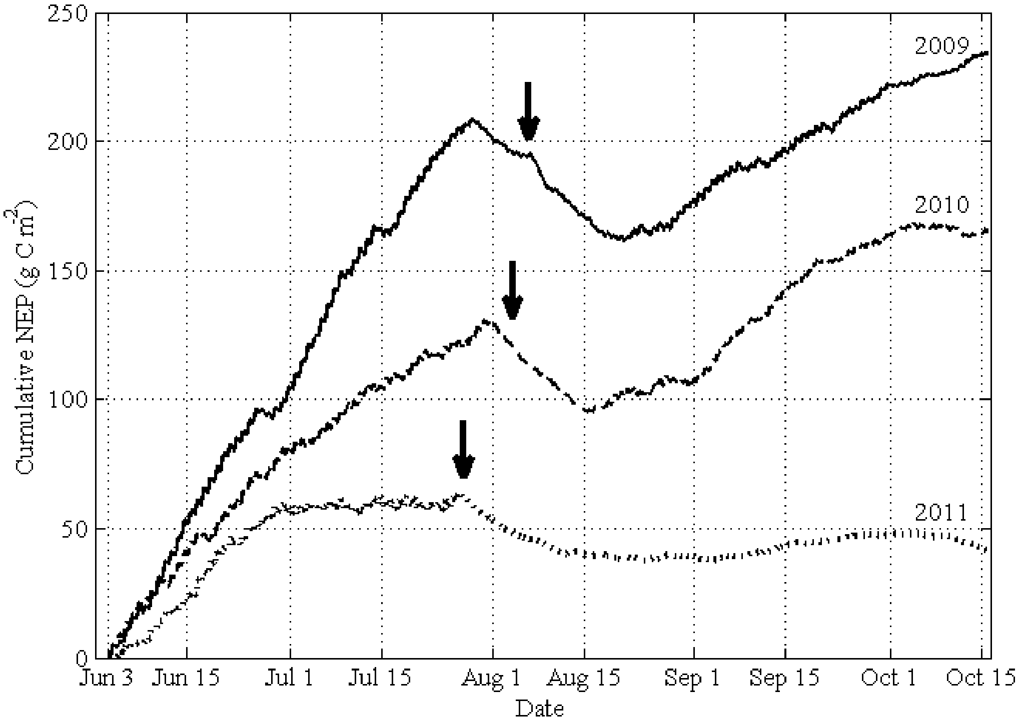

Figure 2.6 Hay site cropping season cumulative net ecosystem productivity from June 3 to October 15 in 2009, 2010, and 2011. Arrows indicate hay cuts. Biomass removals and additions are not included.

2.5 Discussion

2.5.1 Uncertainty

Due to the nature, scope, and complexity of flux research, a variety of factors contribute to the uncertainties involved in measurement, management of equipment, and analysis of measurements taken. An evaluation of the uncertainties in our measurements follows.

A *u** threshold of 0.19 m s^{-1} was applied to filter low-turbulence nocturnal fluxes. Critical friction velocity thresholds (*u**) for CO_2 fluxes range from 0.1 to 0.6 m s^{-1} (Baldocchi 2003), and are chosen dependent on the surface layer roughness over which measurements are being taken. Other eddy covariance research over agroecosystems have found *u** threshold values below 0.1 to 0.15 m s^{-1} produced unreliable fluxes (Baker and Griffis 2005; Li et al. 2006; Skinner 2007). Future work may be suited to the application of a variable *u** threshold dependent on the surface roughness, because of seasonal changes in canopy structure that are prevalent in agricultural systems due to changing crops and periods of bare soil, as was employed by Béziat et al. (2009).

The portion of good flux measurements that passed all quality controls (Table 2.13) represent the data present after *u** filtering and thresholds, or removal of known interruptions, and periods during which the IRGA and CSAT were absent. Three values year-by-year are given for each site: the complete study period from June 3, 2009 until November 25, 2011; the full period excluding the winter of 2010/2011, and the warm season from June 3 through October 15 each year only.

Table 2.13 Portion of quality flux measurements retained at each site and year.

Site	Year	Percent retained during study period*	Percent retained when instruments present*†	Percent retained, June 3 to Oct 15
OatCanOat	2009	39.4	39.4	58.5
	2010	40.1	51.2	54.0
	2011	33.6	49.4	60.3
	mean	37.6	47.7	57.6
HayOatFal	2009	50.9	50.9	54.1
	2010	28.9	37.0	45.7
	2011	32.4	45.8	45.8
	mean	35.3	43.8	48.5
Hay	2009	46.9	46.9	61.1
	2010	29.4	37.6	46.5
	2011	38.9	55.0	67.5
	mean	36.9	45.8	58.4

* Over the study period: 2009 measurements began Jun 3/09, 2011 measurements ended Nov 25/11.

† Winter 2010/2011 excluded. No flux instrumentation at the sites.

The exclusionary winter period represents 20% of the data at each site. June 3 to October 15 was used to analyse inter-annual variability (demonstrated in Figure 2.6) and represents the period where fluxes have the potential to be greatest. Short days in the winter limited power generation due to the low sun-angle, because the sites relied on solar energy for their power source. Winter fluxes were not a large portion of the flux.

Comparatively, the portion of flux measurements used from a variety of European agricultural sites ranged from 67-75% (Law et al. 2002), and was as low as 41% at a New Zealand pasture site (Mudge et al. 2011). Arrangement of eddy covariance equipment and warmer winters may contribute to better coverage at more temperate research sites. Flux measurements from Glenlea, Manitoba, Canada with the flux-gradient technique had 66% carbon dioxide flux coverage once data were filtered (Glenn et al. 2010).

Table 2.14 shows the percent of the dataset that could be affected by two of the quality thresholds applied to the data; this represents the maximum percent of the dataset affected, and there may be overlap between the two quality controls in application. Anemometer filtering depended on diagnostic warnings, often caused by rain, and fluxes were removed if $w < -0.05$ or $w > 0.5$ ms^{-1}.

Table 2.14 Percent of the complete flux data set filtered by applied thresholds.

Site	Data below $u*$ (%)	Data removed by filtering and w thresholds (%)
OatCanOat	22.2	13.8
HayOatFal	25.8	12.2
Hay	24.7	19.1

Gap filling algorithms used air temperature from the OatCanOat and HayOatFal sites. Thermocouples at 10 cm and 20 cm were present beneath each tower, but were too deep to characterize the environment for surface respiration. Soil temperature values were also missing for large portions of the winter 2010/2011, with snow cover and ground freeze preventing sensors from being fixed or reinstalled during the winter months. While thermocouples were placed at a depth of 5 cm in the spring of 2011, the values were not available for the entirety of the study period, so they were not used for gap-filling procedures. It may be prudent to adjust which temperature value is used for gap-filling based on the season, particularly in colder climes; Maier et al. (2011) found that a soil temperature measurement at a depth of 0.03 m was the best fit as a reference temperature, whereas 0.2 m was best in the cold season, which may reflect a shift in the active soil zones.

There are primarily two types of bias present within eddy covariance measurements that contribute to the underestimation of fluxes: the low nocturnal turbulence that necessitates the application of a critical friction velocity to filter inaccurate measurements (Baldocchi 2003), as addressed by u^* filtering, and the lack of energy balance closure, which is calculated by summing latent and sensible heat values to compare with available energy measurements (net radiation and ground storage).

Knowing the energy balance closure of a site can allow for indirect validation of CO_2 flux measurements; good closure can be indicative of good flux measurements, so long as variability is not specific to flux or energy balance exclusively (Moureaux et al. 2008). An analysis of the energy balance closure at the HayOatFal site and the Hay site are addressed in Appendix A of Fraser (2012). The energy balance closure was better at the Hay site (slope = 0.82) than the HayOatFal site (slope = 0.7). Comparable values (0.7-

0.95) were observed over an unmanaged prairie grassland (Flanagan et al. 2002), a corn-soybean rotation (Baker and Griffis 2005), spring barley (Davis et al. 2010), sugar beet/winter wheat (Moureaux et al. 2008), and an intensively grazed pasture (Mudge et al. 2011). Closing the energy balance could potentially increase flux values by approximately 20 to 30%, but would not affect the general patterns caused by management and inter-annual variability.

Instrumentation from both the HayOatFal and Hay site were co-located above the Hay site to measure concurrent CO_2 fluxes from May 12 to 15, 2012. For a 30-minute dataset of 86 points and utilizing the same quality control procedures, NEE had a mean flux of -3.65 µmol m^{-2} s^{-1} and the mean difference between the towers was 0.62 µmol m^{-2} s^{-1}, equal to 17%. During this period, the normalized covariance between the towers was 0.89 with a root mean square error of 1.35 µmol m^{-2} s^{-1}. A linear regression between the towers had a slope of 1.06, but an offset of 0.41 µmol m^{-2} s^{-1} indicates some bias. It should be noted that the instrumentation was removed from the sites in late fall 2011 and underwent cleaning and lab calibration before being installed above the Hay site in 2012. This bias may not have been present for the duration of the study period. This test measurement provided an estimation of the possible disparity between site measurements, and while it may contribute to the uncertainty of the specific values reported, it does not affect the conclusions drawn from the impacts of management, inter-annual variability, and harvest exports/manure additions.

When considering the factors that contribute to the uncertainty of flux measurements, uncertainty in annual NEP values range from 30 and 100 g C m^{-2} year $^{-1}$, though larger and smaller values have been reported (Baldocchi 2008), as seen in Table 1.1. This calculation was not determined for our sites, and annual values could possibly vary by this amount. While uncertainties can potentially create problems in measurements, the eddy covariance measurements aide in understanding ecosystem processes, inter-annual variability, and disturbance-based carbon-fluxes (Baldocchi 2008).

2.5.2 Management effects on cumulative net ecosystem productivity, cumulative gross ecosystem productivity, and cumulative ecosystem respiration

The sites have similar climate and soil characteristics. Bulk density was significantly higher at 15-30 cm than in the surface layer at all sites. There was no significant difference in total carbon between any of the sites or the two sampling depths. Fraser (2012) conducted soil testing in 2009 on two of the sites, and found that bulk density was significantly different between the HayOatFal and Hay site at the 0-15 cm depth. Fraser (2012) also found a difference between the total carbon, total organic carbon, and total inorganic carbon at the HayOatFal and Hay site, as well as between the 0-15 cm and 15-30 cm depths at these two sites; soil testing methods differed from this study. Organic carbon was significantly different between the two depths at all sites from samples taken in 2011, most likely due to the presence of plant matter at the surface, manure additions, and residues, all of which add organic matter at the surface.

The proximity and similarities between the sites allows for comparison to determine the impact of different management events at each site, and how they influence NEP, GEP, and ER. The impacts of biomass removal through harvest and the addition of manure are discussed in the context of estimating the carbon budget of each site.

2.5.2.1 Annual vs. perennial crop

The oat crop at the OatCanOat site gained more carbon in 2009 than the HayOatFal oat crop did in 2010. Fluxes not measured during the spring of 2009 may account for the differences in gains between 2009 and 2010. The oat crop in 2010 was lodged through the latter half of the summer, whereas the OatCanOat oat crop was stunted in 2011 because of drought. Soegaard et al. (2003) found an identifiable, distinct difference in CO_2 function amongst agricultural crops, based on time of growing season and species composition when comparing grains, grass and maize. Tillage events at both annual sites contributed to decreases in NEP and GEP, while encouraging ER. Tillage contributes to emissions of CO_2 in the spring and fall, halting weed regrowth (Béziat et al. 2009) and incorporating labile materials for soil organisms to consume and respire. Herbicide application on the HayOatFal site in 2009 and 2011 also contributed to carbon losses, causing a decrease in NEP and stopping GEP accumulation, while ER continued to increase. Herbicides removed the only source of carbon accumulation, live plants, and allowed ER to be the dominant process by providing carbon and nutrients to soil organisms.

The annual crops gained carbon at a higher rate than the Hay site as their respective crops matured; this is most visible in the 2010 GEP. A similar trend was observed by Stewart (2011). The perennial site had higher carbon gains than the annual crops each year, and gained twice as much during the 2011 drought. The Hay site was able to assimilate carbon earlier in the spring and later in the fall, while the annual rotations lost carbon by having little to no photosynthesis to counter respiration. This is observable in the cumulative NEP, cumulative GEP, and cumulative ER; in 2009, NEP and GEP increases at the two sites growing hay were apparent from the start of measurements, while uptake at the annual OatCanOat was delayed as the crop established.

Senescence is a clear point when the annual crops shifted from carbon uptake to emission (Soegaard et al. 2003). NEP and GEP at the two annual sites peaked before the crop was cut, showing the point where the crop senesced and carbon accumulation declined. There was visible weed regrowth on the HayOatFal site in 2010 while the crop was still on the field, which allowed GEP to continue increasing later in the summer and fall. Weed regrowth has been shown to contribute to increases in both ER and GEP after harvest (Béziat et al. 2009). The OatCanOat site lacked any weed regrowth after harvest in 2010 and there was no corresponding increase in GEP or ER after the canola was cut.

A peak in NEP carbon accumulation was also present at the perennial Hay site. The hay cuts caused NEP losses and a short-term reduction in GEP each year by interrupting CO_2 uptake (Prescher et al. 2010), indicative of how managed pastures are sensitive to practises applied (Seguin et al. 2007). GEP continued to increase at the Hay site after it recovered from the cut, when carbon accumulation had already stopped at the annual sites. Small ER increases were observed at the annual sites in the fall. Fall grazing pressures at the Hay site may have affected the site's ability to uptake carbon, though we cannot separate the effect on the flux.

The perennial Hay site had higher cumulative GEP each year than either of the annual rotations. Cumulative ER was highest at the HayOatFal site throughout most of the study period, except for the latter half of 2011, when the Hay site cumulative ER exceeded it. The higher rates of ER at the Hay site that year may be related to higher amounts of autotrophic respiration, because of its perennial crop. The conversion from perennial pasture must also be considered when evaluating losses at the HayOatFal site, in particular in the fall of 2009. The HayOatFal consecutively lost carbon each year, prior to including harvest removals. Fraser (2012) found that the effects of converting from a perennial to annual system were mostly related to the length of fallow and cropping season through their effect on gross primary productivity, and that conversion resulted in a loss of more than 245 g C m^{-2}. The HayOatFal site was left fallow in 2011, because excess moisture prevented the producer from seeding. Weeds grew from spring thaw until mid-July, providing an actively photosynthesizing plant cover. Similar results were observed by Hollinger et al. (2005). The impact that cattle grazing the weeds had on NEP, GEP or ER is unknown. Application of glyphosate at the end of July caused NEP losses and halted GEP by killing the plant cover. The tillage events that followed left the soil bare from mid-July until the end of the study period, and ER continued to rise – though at a slower rate than in 2009 or 2010. Ploughing immediately stops carbon assimilation and weed respiration, and may have long-term effects on soil structure and quality (Aubinet et al. 2009; Ceschia et al. 2010). Long periods of bare soil counteract carbon storage, as CO_2 is lost through heterotrophic respiration by soil organisms (Béziat et al. 2009).

The summer-fallow rotation during the cropping season at the HayOatFal site caused a carbon loss of 175 g C m^{-2} that accounted for 58% of the carbon uptake in the previous two cropping seasons. The ER losses during the fallow year were less than previous year and are not easily explained. No crop means there is no autotrophic respiration. Losses that do occur are related to there being little to no GEP to offset respiration.

2.5.3 Net ecosystem carbon budget

Prior to harvest removals and manure additions, the Hay site was a carbon sink of 550 g C m^{-2}, the OatCanOat site was a source of 100 g C m^{-2}, and the HayOatFal site was a source of 500 g C m^{-2}. Losses have been described in previous sections and are accounted for through the impact of management, fallow, winter, cutting, tillage, and inter-annual variation. Eddy covariance cannot measure all factors that influence a site's carbon budget, so they must be tabulated separately and measured if possible (Kutsch et al. 2010; Mudge et al. 2011). Leaching losses can be negligible where topography is flat (Mudge et al. 2011), and in this study it was assumed that dissolved carbon was equal to zero.

Inclusion of harvest exports resulted in both annual sites remaining carbon sources, and the Hay site remaining a carbon sink. Other studies have shown that including harvest exports switched potential carbon sinks to sources (Li et al. 2006; Glenn et al. 2010; Hussain et al. 2011), that grasslands could be carbon sinks and sources, and that grasslands and cropland respectively became carbon neutral and a source when net biome production was considered (Prescher et al. 2010). The amount of carbon removed by the harvest was greater than the carbon accumulated throughout each study year at the annual sites, and at the Hay site in 2011. When a crop is harvested, photosynthesis and autotrophic respiration cease, leaving NEP to be regulated by heterotrophic respiration from soil organisms, as reflected in the dominance of ER.

Removal of straw biomass in addition to grain accounts for the large export at the OatCanOat site in 2009. Higher carbon emissions can occur when more than just the grain is exported from annual crop rotations, especially if no manure or animal fertilizers are used to offset the removal (Ceschia et al. 2010). The fate of the biomass taken from each of the sites determines where the carbon will end up, but is subject to speculation once it has left the field gate. The producer whose land was used in this study is also a dairy farmer. Baled straw may be used for bedding, which will decompose and break down into more recalcitrant organic carbon or be respired when it is consumed by decomposers at a different site. Residues left behind on the field would be subject to a similar fate, but remain within the study area and would not be counted as an export. Crop residues left on fields increase respiration but also contribute to forming soil organic carbon (Prescher et al. 2010).

Harvest removals may have a minimal impact if GEP and ER are already reduced due to drought conditions (Mudge et al. 2011). This is demonstrated in 2011 at the OatCanOat site, whose NEP, GEP and ER are suppressed due to drought conditions; the oat crop was unable to uptake carbon, reducing yields and the amount of exportable carbon.

Determining the amount of biomass removed from each site contributed to the uncertainty of calculating the net ecosystem carbon balance, because of the disparity between biomass collection methods, samples taken by researchers, and the yields reported by the producer. Export values used in the net carbon balance calculation are based solely on the producer reported values to maintain consistency in comparison. In a comparison of the harvest export methods used during the study (Table 2.12), field sampling of baled hay or straw bales were more variable from the producer’s reported values than the grain samples. This may relate to the method of sampling, whereby biomass samples were taken by hand and the amount of carbon removed was calculated based on the area of the field, versus the physical number of bales and their average weight reported by the producer. A greater number of biomass samples collected may enable a more accurate reflection of the amount of carbon removed. Had the biomass samples been used in calculating the carbon removed by harvests, it would affect the conclusions drawn by this study; for example, the manure added to the OatCanOat in 2009 would not compensate for the amount of carbon removed by the harvest. Overall, the annual sites would be larger carbon sources, and the Hay site would be close to carbon neutral if carbon exports had been calculated from the biomass sampling.

During years that manure was applied to the annual sites, the net balance was neutral or a carbon sink, compared with years that no manure was applied and the sites were carbon sources. This supported that carbon losses can be amended by organic fertilizer inputs (Prescher et al. 2010). Soussana et al. (2007) found that only large imports of manure compensated for harvest exports at the European sites they examined. At our sites, the manure additions were less than the cumulative harvest exports.

Pasture growth typically stops below 5 °C (Parsons 1998); temperatures during the late fall grazing period ranged from 7 to -3°C, with the lack of GEP demonstrating the lack of plant growth. Cattle grazed the HayOatFal site for less than one month in June/July 2011, and the OatCanOat site was grazed for two weeks at the end of September 2011, each contributing to the total NEP measured. Grazing events can reduce mid-day NEE, and on-site herbivory does contribute to measured respiration values (Soussana et al. 2007). The cattle roamed the entire field and were not always within the flux footprint, making it difficult to determine their respiration contribution to the measured fluxes. We cannot determine how cattle grazing affected the NEP of each site. Measurements of the contribution cattle make on carbon cycling are often done with fewer cattle and on smaller paddocks (Baron et al. 2002), and few measurements have evaluated the impact cattle have on CO_2 fluxes at a field scale, or the farm-gate C-value of what they remove from a field. From our estimate, grazing accounted for a very small portion of each year's carbon budget at all sites.

2.5.4 The impact of inter-annual variability

Landscape fluxes can vary greatly year-to-year based on variations in weather (Flanagan et al. 2002; Moureaux et al. 2008; Béziat et al. 2009; Glenn et al. 2010; Prescher et al. 2010). Year-to-year variability of climatic conditions have been noted to affect agroecosystem NEP fluxes more than natural ecosystems that have continuous cover due to the relationship between climate-effect and changing management or crop (Kutsch et al. 2010). Figure 2.6 demonstrated the variability of wet, normal, and drought conditions on fluxes, using the Hay site as an example. This site was best suited for comparison because of the consistent crop and management applied during the study period. The difficulties and impacts of winter measurements are also addressed in this section.

Carbon budget differences among years often relate to variation in precipitation and temperature (Li et. al. 2006), because of their influence on plant growth and respiration rates. Uptake was delayed at the Hay site in 2011 due to excess moisture in April and May, whereas accumulation began a month earlier in 2010. As the soil dried in 2011, the rates of GEP and ER were equal, but their duration was shortened. The end of year cumulative NEP was at least 150 g C m^{-2} less than the previous two cropping years. Other studies have found that GEP, ER (Flanagan et al. 2002) and net ecosystem exchange (Mudge et al. 2011) were lower during drought years. Summer drought may have a greater impact on colder, higher-latitude pastures, because there is no winter growth to amend losses. Overall, this reinforces the importance of including climate variations in site comparisons, because carbon fluxes at agricultural sites will be impacted differently, dependent on inter-annual variability.

The cumulative NEP of the three Hay site cropping seasons portrayed in Figure 2.6 varied almost 200 g C m^{-2} between the drought year of 2011 and the average year of 2009. As indicated in section 2.5.3, harvest removals in 2011 had a larger relative impact on the carbon balance that year. The effects of drought were prevalent at the OatCanOat site, which had smaller NEP during 2011 than 2009, with lower GEP and ER, and stunted oat yields. Dry summer-fallow years have been shown to contribute less CO_2 to the atmosphere than wet ones (McGinn and Akinremi 2001), by limiting autotrophic respiration, and providing less carbon for soil organisms to consume and respire.

Cumulative NEP measurements through the winter of 2009-2010 showed small respiration losses at all three sites. The sites were gap-filled October 25, 2010 to mid-April 2011, because the flux instrumentation was removed for calibration, cleaning, and maintenance. Although the winter of 2010-2011 was warmer than the 30-year climatic mean, there was little difference in that year’s gap-filled fluxes than when compared with the average winter of 2009-2010. Maier et al. (2011) found that soil temperature could explain flux variation better than air temperature during the cold season, accounting for upwards of 85% of the soil respiration variation. Use of air temperature at our sites could mean that greater extremes of temperature were used for the gap-filling routines, and may have contributed to our uncertainty in gap-filled values during the winter months. Winter CO_2 losses at our sites did not comprise a large amount of the total annual ER. Losses relate to the length of the non-growing season, because lack of vegetation or negligible plant activity (Béziat et al. 2009) when temperatures are below zero inhibit photosynthesis. For example, mean daily air temperature at the HayOatFal site in 2010 was ≤ 0°C 134 days out of the year, making GEP = 0 for one third of the year. Freezing temperatures may also limit ER by limiting the activity of soil organisms.

2.6 Conclusions

Observing three cropping systems over three years showed the implications that a variety of management practises can have on the carbon budget of an agroecosystem. The conversion to annual cropping from perennial pasture may have increased carbon loss at the HayOatFal and OatCanOat. Soils with high carbon content like those in our study have the highest potential to lose following these conversions. The annual sites gained carbon more quickly for shorter periods of time, while the perennial Hay site was able to uptake carbon earlier in the spring and later in the fall by having a persistent plant cover. During spring and fall fallow periods, the annual sites were dominated by ER because the soil was bare. Both annual systems were carbon sources prior to and with the inclusion of harvest exports, while the perennial grass was still a carbon sink once harvest removals were accounted for. Manure additions were not enough to compensate for the amount of carbon removed by harvesting at the end of the study period, but the carbon addition was important. Moisture levels impacted carbon exchange more than temperature year-to-year. The drought in 2011 reduced the ability of all sites to uptake carbon, and the Hay site was able to produce a crop comparable to other years, while the OatCanOat did not. Weed growth on the HayOatFal site during the 2011 fallow year helped to gain carbon and dry conditions that year likely reduced ER. Colder winters and shorter growing seasons restricted the time during which the sites could lose or gain carbon, when compared with more temperate climates.

The ability to run concurrent sites on adjacent farmland allowed for the direct comparison of management practises, removing the impact of spatial variation often present in broader comparisons. Measurements taken on land directly managed by an independent producer provide an analogous, real-world story that reflects the complex issues driving the decisions and practises they apply to their fields and how they influence carbon exchange. Carbon dioxide represents one portion of the on-farm greenhouse gas budget, but a broader accounting should include methane and nitrous oxide. Future work to measure other gases in conjunction with CO_2 would help to quantify the impact that managements have on the broader greenhouse gas budget would provide a more accurate picture of agricultural impacts.

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3. OVERALL SYNTHESIS

Producers may consider converting marginal pasture lands to annual cropping systems dependent on economic pressures. Ecosystem models can give ideas about the interactions and relationships among management, climate, and CO_2 flux, but require measured data to verify their conclusions where possible. This research project was conducted in that spirit, with the aim of contributing to the global understanding of how CO_2 ecosystem interactions are directly impacted by human choices. This synthesis will summarize the thesis and provide reflection and speculation upon the outcomes and possible ramifications of the research, and methods that may expand understanding in future projects.

3.1 Summary

Through use of the eddy covariance technique, direct, continuous CO_2 flux measurements were made on three adjacent fields approximately 75 km north-west of Winnipeg, Manitoba, Canada. Two fields supported annual cropping systems recently converted from perennial pasture, whereas the third was a perennial hay/pasture that had been undisturbed for more than 20 years. The crops and management techniques applied were determined by an independent producer without any influence from the researchers. Measurements were taken from June 3, 2009 through to November 25, 2011, with a gap from mid-October 2010 to mid-April 2011 when instrumentation was removed for calibration and repair.

Our objectives were to identify how the ecosystem processes (as measured by NEP, GEP, and ER) of each site were affected by management practises, evaluate the impact year-to-year weather variability could have, and find which practises were sensitive to change. Once this was established, the net ecosystem carbon balance was calculated by including manure additions and harvest removals. During the study period, the fields were subjected to herbicide and fertilizer application, tillage events, cattle grazing, fallow, crop harvest and straw removal. Weather events that affected the sites were excess moisture, high summer winds, above-average summer rain, freezing winter conditions, and a drought in 2011.

Independent of harvest removals, the Hay site was a carbon sink, while both of the annual sites were carbon sources. Conversion likely played a role in the degree at which carbon was lost from both the annual sites, as does the high soil organic carbon of the Ortho-Black Chernozem soil at the sites. The large glyphosate application on the HayOatFal site in 2011 killed all weeds on the field and left respiration as the dominant process, causing an efflux of CO_2 from the ground to the atmosphere. After senescence and cutting, the annual sites continued to lose carbon, while the Hay site was able to recover and fix it throughout the fall.

Harvest exports accounted for an annual removal of 30 to 330 g C m^2, making it vital to include such values in the evaluation of net carbon. Manure additions at the annual sites added carbon and helped to offset the harvest removals. Cattle grazing events were not evident in the flux measurements, and appeared to have minimal farm-gate impact on CO_2 flux. The annual sites were sources when removals and additions were accounted for, and the hay site was a smaller carbon sink.

The Hay site was used to assess inter-annual variability. Moisture had a larger impact on fluxes than temperature did. Cropping season rain in 2009 was average, 2010 was wetter, and 2011 was a drought. NEP, GEP, and ER were affected most by the drought year, where GEP was small and ER was the dominant process. The perennial Hay site was able to produce a crop comparable to previous years, while the OatCanOat did not. The losses seen at the fallow HayOatFal site may have been lessened by the drought. Winter fluxes were a small portion of the cumulative NEP.

3.2 Significance

This project provided the carbon budget of three different agricultural systems in order to gain insight into the impact of their management practises and the variability possible. Annual and perennial agricultural land needs to be separated in modelling and policy to address the disparity between their cumulative carbon fluxes. Agriculture cannot be considered as one entity that is a sink, source, or neutral because of the dynamics possible between the crops grown and managements applied. While the perennial site in our study was able to accumulate more carbon, the possible implications of increasing animal production systems were outside the scope of the project. Both systems affect the exchange of multiple greenhouse gases, not just CO_2. Conversion to perennial cropping may be best suited where annual agriculture is limited and requires excessive inputs to improve site capability. The performance of a site in relation to the managements applied needs to be considered within the context of its suitability for agriculture. Given that our site was Class 4 agricultural land, it may be better suited to perennial crops because of the limitations imposed on it for growing field crops.

This project demonstrated the organic matter recycling possible through an integrated, large-scale farming system. Manure added to the annual sites helped to offset carbon lost through harvesting, while also adding nutrients. Cattle were able to graze the fallow-site weeds and the stunted oats during the drought year in 2011, converting them into a value-added product for the producer. While cattle are associated with the emission of methane and nitrous oxide, perennial forages such as those on the Hay site use less energy to grow and harvest than annual crops (Vergé et al. 2008). Increasing the diversity of farming systems increases their ability to survive under a variety of conditions. The inclusion of other management practises such as reduced-tillage may also help contribute to maximizing the carbon that a system is able to accumulate.

The use of perennial crops within a diversified farming system could also provide income for farmers during drought years, because of its ability to survive during more diverse year-to-year weather conditions. The oat crop at the OatCanOat site in 2011 had poor yields because of the drought, whereas the HayOatFal site was unable to be planted with a crop due to excess moisture that spring. The Hay site was able to tolerate the extremes of excess moisture and drought experienced in 2011 to produce yields comparable to the previous two years, and also be grazed by cattle in the fall. Perennials also required fewer inputs (like herbicide) to fix greater amounts of carbon annually. Whole carbon accounting and life cycle analysis would help quantify the farm- or ecosystem-scale carbon balance to assess the impact of inputs and lateral carbon transfers.

Higher winter temperatures in lower latitudes or from climate change could impact these measurements in the future, in particular at perennial sites. Later freeze-up and earlier thaw could allow plant growth to begin earlier and continue longer, increasing carbon uptake for perennial crops. These would be able to photosynthesize longer and uptake more carbon, whereas annual cropland may be bare for longer periods of time. During 2010 when the mean annual temperature was warmer than the climatic average, GEP carbon accumulation began earlier in the year and continued longer in the fall. A longer growing season may encourage more producers to take two hay-cuts a year, though many already do. Removing more carbon from the field en masse may make these sites more likely to be carbon neutral or sources. A longer cropping season could potentially allow for farmers to use cover-cropping on annual sites more effectively to increase carbon uptake and potentially nitrogen fixation.

3.3 Improvements

Improvements in collection methods and techniques could help reduce the uncertainty within the system and set-up used in our experiment. Establishment of set protocols for data and sampling collection (such as biomass) and analysis would help maintain consistency between years, technicians, researchers, and summer students. Consistently cataloguing site visit times would allow data to be filtered through processing programs rather than through a secondary threshold in post-processing, as human respiration could contribute to spikes in the flux. A protocol could improve dialogue between the producer and researchers, allowing for more specific reporting through easy to follow forms or emails, established and explained from the start of the project.

Instrumentation configuration could improve. Inclusion of a 5-cm soil temperature probe at all sites throughout the study period would allow for its use in gap-filling instead of air temperature. Using multiple soil temperature probes could address the issue of the near-surface thermocouples popping out or surfacing during the winter and help to prevent data gaps. Consistent power was an issue at all of the sites. Scheduled, periodic battery testing and power system walkthroughs may help maintain the system and catch problems before they arise. To maintain battery integrity and due to small winter fluxes, it may be prudent to only run sites when air or soil temperatures rise above freezing. Data processing may be improved through filtering out wind data that are affected by the physical position of the tower upon which the instrumentation are, as it can affect air turbulence and flux values as a result.

Other projects have employed a variety of techniques to expand the data collected and contribute to the holistic understanding of agroecosystem processes and impacts. If available, LANDSAT imagery may provide information regarding the history of a research site and how management has affected it and the crop coverage within the flux footprint.

3.4 Future projects

This project showed that the perennial system had higher GEP than either of the annual systems in the spring and fall. Persistent plant cover allowed the perennial site to uptake carbon in these shoulder seasons, when both the annual sites were dominated by respiration losses. This may bode well for the inclusion of cover crops into annual rotation, or the inclusion of a perennial crop for 2-3 years of a rotation to take advantage of growth potential at the tail ends of the growing season and add soil organic carbon. Ceschia et al. (2010) found that maintaining vegetative crop cover may reduce C-emissions.

The possible role of cattle was not a focal point within this project. Flux measurements over cattle herds on pasture are difficult to measure, due to their movement. Researchers have studied the digested percent of ingested organic matter (Soussana et al. 2007), weight gain of grazing cow-calf pairs (Kopp et al. 2003), and the digested-C and excreted faecal matter-C of cattle (Baron et al. 2002), but identifying how much carbon a cow takes with it at the farm-gate dependent on feed and age was not quantified in any of the eddy covariance studies surveyed.

Farm equipment emissions were not within the scope of this research project, and were not separately measured, but they do contribute to the measured CO_2 fluxes within our flux footprint when vehicles were present on the field. Including their contribution to flux research is necessary to determine the whole carbon budget of the farm. Vergé et al. (2008) identified six main sources of CO_2 emissions on farms; fieldwork, hauling with trucks, electricity, heating (grain drying), manufacture/supply of farm machinery, and synthetic fertilizers. Other processes emit CO_2 indirectly, such as the Haber-Bosch process used to manufacture ammonia fertilizers. Gases like methane and nitrous oxide also contribute to the agroecosystem greenhouse gas budget. For example, over European crop sites, average emissions from the lifecycle of fertilizers is 51.4 ±34.9 g CO_2-equivalent m^{-2} $year^{-1}$, and emissions from the equipment on the field for soil preparation and harvest ranges from 2.5 – 12.3 g CO_2-equivalent m^{-2} $year^{-1}$ (Ceschia et al. 2010).

Projects that measure multiple greenhouse gases at such a large scale are difficult to coordinate due to their complexity, but help provide valuable information on the true-cost of conventional farming methods. While singular flux measurements may indicate that a field is a carbon sink or source, they do not reflect the full range of activities that contribute to their respective energy or nutrient cycles. Life cycle analyses try to account for the full scope of greenhouse gases influenced by agricultural activities. They seek to quantify all the activities involved with crop and animal production and how they relate to each other, to better understand the true impact that management practises have on greenhouse gas cycles.

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