CARBON DYNAMICS OF PERENNIAL GRASSLAND CONVERSION FOR ANNUAL CROPPING

BY

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ABSTRACT

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Sequestering atmospheric carbon in soil is an attractive option for mitigation of rising atmospheric carbon dioxide concentrations through agriculture. Perennial crops are more likely to gain carbon while annual crops are more likely to lose carbon. A pair of eddy covariance towers were set up near Winnipeg Manitoba, Canada to measure carbon flux over adjacent fertilized long-term perennial grass hay fields with high soil organic carbon. In 2009 the forage stand of one field (Treatment) was sprayed with herbicide, cut and bailed; following which cattle manure was applied and the land was tilled. The forage stand in the other field (Control) continued to be cut and bailed. Differences between net ecosystem productivity of the fields were mainly due to gross primary productivity; ecosystem respiration was similar for both fields. When biomass removals and manure applications are included in the carbon balance, the Treatment conversion lost 149 g C m^{-2} and whereas the Control sequestered 96 g C m^{-2}, for a net loss of 245 g C m^{-2} over the June to December period (210 days). This suggests that perennial grass converted for annual cropping can lose more carbon than perennial grasses can sequester in a season.

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1 INTRODUCTION

1.1 A Brief Overview of Soil Organic Carbon Dynamics in Agriculture

Anthropogenic activities have altered the global carbon cycle causing the global atmospheric carbon dioxide concentration to increase. Increasing atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2) will alter the amount of energy retained by the atmosphere leading to an increase in global average temperature (Forster et al., 2007). Since the original conversion of native vegetation to agricultural land, a large decrease in soil organic carbon (SOC) and a subsequent decline in soil fertility have been observed (Smith et al., 2000). Data from 2000 indicate that soils remain a substantial global pool of carbon (1500 Pg C), containing about twice the amount of the atmospheric pool (780 Pg C) (Janzen, 2005). Restoring agricultural soils by sequestering atmospheric carbon would reduce atmospheric CO_2 while enhancing soil fertility and soil physical properties. This would in turn increase agricultural yields and work towards improving food security and agricultural sustainability (Lal, 2007; Lal et al., 2007). Increased yields and the creation of carbon credit trading markets will provide new revenue to agricultural producers. Sequestration of atmospheric carbon in soil presents a variety of benefits which make this an attractive option for mitigating a portion of the rising atmospheric CO_2 levels.

When a soil system that is at or near equilibrium is perturbed, the SOC content will eventually equilibrate to its new conditions (Janzen et al., 1998b); whether the new SOC content is higher or lower depends on the new conditions imposed. By encouraging management practices that will enhance the SOC and discouraging practices that will deplete SOC, a portion of the atmospheric carbon pool can be moved into the soil. However the ability of soils to sequester carbon is not indefinite; once a new practice is imposed a new equilibrium will eventually be reached putting a limit on the total quantity of carbon that can be moved into soil (West and Post, 2002).

Carbon can be added to the soil in the form of plant biomass, compost, manure or any other organic amendment (Janzen et al., 1998a). Regardless of its source, organic carbon brings nutrients with it that can be mineralized becoming available for crop uptake. Increased SOC can also alter soil properties such as improving water holding capacity, soil structure and cation exchange capacity (Janzen et al., 1998a; Kay, 1998). Management practices that increase the amount of organic carbon added to the soil will potentially aid in sequestering atmospheric carbon as SOC (Janzen et al., 1998b). Conversely practices that decrease the amount of organic carbon added to the soil or enhance the breakdown of current SOC stocks by stimulating soil respiration, will decrease the amount of SOC sequestered. The net effect between these two simultaneous processes represents the flux of carbon between SOC and atmospheric CO_2. SOC stocks can take a long time to build as stable forms. Recently added carbon will tend to be in a more labile form with the potential to become depleted rather quickly (Janzen et al., 1998b), highlighting the importance of maintaining and building the current stock of SOC.

Many management practices can have a large impact on SOC content. The elimination of fallow in favour of continuous cropping systems can affect SOC by a number of mechanisms. Fallow decreases the amount of new carbon added to the soil through biomass production while soil respiration continues; breaking down current stocks of SOC. Conversely continuous cropping should increase the amount of biomass produced while decreasing the fraction of the year when soil respiration is active while photosynthesis is not (Janzen et al., 1998b). Tillage disrupts soil structure causing SOC to become more available for breakdown through weathering processes and microbial action. Incorporating air into the soil during tillage can make the soil more aerobic stimulating respiration. Conservation and zero tillage systems can help preserve or increase SOC by increasing the surface litter, lowering the soil temperature and preserving soil structure; all of which reduce soil respiration and SOC breakdown (Jabro et al., 2008). The benefits of reduced and conservation tillage practices for SOC retention have been shown directly through flux measurements by Reicosky (1997) and Reicosky et al. (2005) and modeled by Smith et al. (2000). Conservation and zero tillage practices will also serve to reduce the amount of field operations minimizing the fossil fuel carbon released (Dyer and Desjardins, 2003; Dyer and Desjardins, 2005).

1.2 Quantifying Soil Carbon Fluxes

After altering management of an agricultural system, equilibrium can take a very long time to be reached (McLauchlan et al., 2006; West and Post, 2002) reducing our capacity to assess the effect of a particular management practice from short term studies. Soil sampling methods can be used to determine SOC at particular locations and repeated sampling can be used to determine the change in SOC. However small changes in SOC are difficult to differentiate from the high natural variability found in soils. Furthermore, management practices such as tillage may cause a redistribution of SOC within the soil profile which can be difficult to detect with standard sampling methods (Baker et al., 2007). High vertical and horizontal variability means that large numbers of soil samples are required to accurately characterize the treatment effects, which is a labour intensive undertaking (VandenBygaart et al., 2007; Yang et al., 2008). Chamber techniques can be used to eliminate the effect of SOC redistribution in the soil profile because the flux of CO_2 from the surface is measured directly. However chambers can only determine fluxes over a small surface area of a field at a particular point in time. Therefore many replicate chambers are required to account for lateral variability in fluxes (Davidson et al., 2002; Law et al., 2001). It is difficult to determine net ecosystem productivity by chamber techniques which are generally used to measure respiration. Long-term and high-frequency changes in CO_2 flux are also difficult to determine by chamber methods, making this technique better for determining event-driven fluxes than seasonal carbon balances or environmental drivers of CO_2 fluxes. Soil sampling and chamber techniques may also disturb the soil and surrounding crop causing interference and potential biases.

Micrometeorological techniques are capable of measuring fluxes continuously and non-destructively over long periods of time making them more suitable than chambers for determining the environmental drivers of fluxes. Eddy covariance is a direct flux measurement, can resolve fluxes as low as ±50 g C m^{-2} yr^{-1} (Baldocchi, 2003), and has previously been used successfully at agricultural sites examples include Anthoni et al. (2004), Hollinger et al. (2005) and Verma et al. (2005).

Fluxes from an eddy covariance system are calculated from the covariance of the atmospheric CO_2 concentration and the vertical wind. To avoid measurement bias, eddy covariance requires three assumptions for ideal conditions: the surface should be flat, the atmospheric conditions should be stationary, and the surface should be uniform in the upwind direction. Deviation from these assumptions can lead to systematic errors in the flux calculation (Baldocchi, 2003). These assumptions are in place because eddy covariance relies on the stability conditions of the atmosphere, the wind vector and the eddy size. Small deviations from ideal conditions can be accounted for through procedures such as co-ordinate rotation and footprint analysis. A u* (friction velocity) threshold must be chosen so data can be discarded when the wind speed is too low to create turbulent flow. Although there are issues associated with the use of a u* threshold (Acevedo et al., 2009), it is a common practice. Low wind speed, rain and sensor malfunctions create numerous gaps in the data that must be filled. Small gaps can simply be interpolated but larger gaps must be filled using models. At night when photosynthesis is not active, empirical relationships with soil temperature can be used to calculate missing values. During the day soil temperature and photosynthetically active radiation are commonly used to fill gaps (Falge et al., 2001).

Energy balance closure is a comparison between energy balance as measured by the eddy covariance equipment and the available energy as measured by a set of independent sensors; the difference between these two measurements is used to evaluate the eddy covariance systems ability to measure turbulent fluxes accurately. Energy balance closure remains a problem for eddy covariance systems, which consistently underestimate energy balance when compared to the independent measurements (Baldocchi, 2003; Pattey et al., 2006). There are a number of theories on why this occurs including: advection, the footprints observed by the eddy covariance system versus the footprint viewed by the independent probes, filtering (Baldocchi, 2003), lack of fetch, low sensor frequency, sensor separation and tower interference (Pattey et al., 2006). Some believe that energy balance closure should be forced which may correct for potential errors in the flux measurements (Twine et al., 2000), however Baldocchi (2003) and Pattey et al. (2006) recommend reporting of unadjusted data and percent energy balance closure until there is increased confidence that forced closure is correct. Underestimates of turbulent energy fluxes implies a potential underestimate in the carbon flux.

1.3 Objectives

Guo and Gifford (2002) found that perennial vegetation will generally have a greater beneficial effect on SOC when compared with annual cropping systems. Continuous cover, lack of tillage and alteration of soil temperature and moisture regimes to become favorable for the reduction of soil heterotrophic respiration should all contribute to SOC equilibrating to a higher level under perennial vegetation than annual vegetation. Conversely, if a landscape was to be converted from perennial to annual vegetation, the SOC may equilibrate to a lower level causing a net flux of CO_2 to the atmosphere. How fast will changes to SOC stocks occur? Smith et al. (2000) predicted that the implementation of zero tillage and conservation tillage will result in a slight increase in SOC by 2010 in Canada, but what happens when these practices are not continuous? Will recently sequestered carbon be released when management practices are changed? Can the periodic inclusion of annual crops in perennial rotations negate the carbon sequestration benefits of perennial cropping systems? Answering these questions would provide valuable data which could be used to design, calibrate and verify process-based carbon models; improve GHG inventories and budgets; create and assess beneficial management practices; create carbon credit trading systems and improve long term soil fertility and food security.

A paired flux tower study investigating a perennial grassland to annual crop conversion event with respect to an unaltered perennial grassland would likely show the carbon content of the fields diverging but the rate and drivers of this divergence require investigation.

The objectives of this study are to:

1. Design and establish two identical micrometeorological systems,
2. collect carbon flux data during a perennial to annual cropping system landscape conversion event and use these data to investigate the carbon dynamics following a long-term perennial grassland to annual cropping landscape conversion event,
3. determine the carbon flux of an unaltered grassland field and

4. finally to determine divergence between the carbon fluxes of these fields in the year of conversion to investigate the effect of perennial to annual agricultural landscape conversion with respect to an unaltered field.

This thesis required the assembly and programming of the flux towers, data loggers and data storage and retrieval systems. Although setup and data analysis only constitutes a small portion of the text, I would like to acknowledge the considerable amount of time and effort required to accomplish this portion of the project.

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2 CARBON DYNAMICS OF PERENNIAL GRASSLAND CONVERSION FOR ANNUAL CROPPING

2.1 Introduction

Anthropogenic activities have altered the global carbon cycle causing an increase in the global atmospheric carbon dioxide concentration. As a greenhouse gas, carbon dioxide (CO_2) increases the amount of energy retained by the atmosphere, causing an increase in global average temperature as the atmospheric CO_2 concentration increases (Forster et al., 2007). Since the original conversion of native vegetation to agricultural land, a large decrease in soil organic carbon (SOC) and a subsequent decline in soil fertility have been observed in Canada (Smith et al., 2000). Soils remain a substantial global pool of carbon (1500 Pg C), containing about twice the amount of the atmospheric pool (780 Pg C) (Janzen, 2005). Restoring soils by sequestering atmospheric carbon could reduce atmospheric CO_2 while enhancing soil fertility, increasing yields, improving food security and improving agricultural sustainability (Lal, 2007; Lal et al., 2007). This makes sequestering of carbon in soils an attractive option for mitigation of rising atmospheric CO_2 levels.

When a soil system that is at or near equilibrium is perturbed, the SOC content will begin to equilibrate to its new conditions (Janzen et al., 1998); whether the new SOC content is higher or lower depends on the new conditions imposed. By encouraging management practices that will increase SOC and discouraging practices that will deplete SOC, a portion of the atmospheric carbon pool could be moved into the soil. However the ability of soils to sequester carbon is not indefinite. Once a new practice is imposed the new equilibrium will eventually be reached putting a limit on the total quantity of carbon that can be moved into soil (West and Post, 2002). Smith et al. (2000) predicted that the implementation of zero tillage and conservation tillage would cause a slight increase in SOC in Canada. SOC stocks take a long time to build and recently added carbon are generally in more labile forms with the potential to be depleted rather quickly (Janzen et al., 1998). When improved practices are discontinued, recent gains in SOC may be lost.

Any management practice that increases the amount of organic carbon added to the soil or limits its breakdown such as continuous crop cover, elimination of fallow, increasing yield or manure applications will potentially aid in sequestering atmospheric carbon as SOC (Janzen et al., 1998). Practices such as bare fallow, tillage or crop residue removal increase the breakdown of SOC or decrease the amount of organic carbon added to the soil. The net effect between the two simultaneous processes of carbon inputs and carbon breakdown represents the net flux between SOC and atmospheric CO_2. Continuous cover, lack of tillage and favorable alteration of soil temperature and moisture regimes (for the reduction of soil heterotrophic respiration) should all contribute to SOC equilibrating to a higher level under perennial vegetation than annual vegetation. Converting a landscape from long-term perennial vegetation to annuals may cause SOC to equilibrate to a lower level leading to a net flux of CO_2 to the atmosphere. Although in Manitoba perennial crops are commonly grown on land considered marginal for annual crops, an increase in annual crop prices or a change in a producer’s feed requirements may provide incentive for perennial to annual crop conversions. Perennial to annual conversions may also be part of a producer’s normal crop rotation. Fluxes following perennial grassland to annual conversions and their temporal distribution and environmental drivers are not well studied.

After a system is perturbed, equilibrium may take decades to be reached (McLauchlan et al., 2006; West and Post, 2002) making determining the effect of a particular management practice from a short-term study very difficult. Large, level agricultural fields are common in southern Manitoba and are ideally suited for the eddy covariance method. An unaltered field is expected to display very different fluxes from an altered field, therefore determining the full effect of changing management practices requires measurements from both a treated and an unaltered field. A paired approach has been used successfully for similar studies by Amiro (2001) and Ammann et al. (2007).

The objectives of this study are to establish identical eddy covariance systems on adjacent fields and collect one field season of measurements to determine the carbon flux on a grassland field converted to annual cropping, determine the carbon flux on an unaltered grassland field and determine the divergence between the net flux of these fields in the year of conversion. Data on this topic would be valuable for the creation, calibration and verification of process-based carbon models; creating GHG inventories and budgets; creating and assessing of beneficial management practices; creating carbon credit trading systems; and improving long-term soil fertility and food security.

2.2 Methods

2.2.1 Site Description

The study site is situated northwest of Winnipeg in Woodlands Manitoba (50.16 Latitude, -97.87 Longitude). This area is commonly associated with pasture and hay crops due to the soils limited suitability to annual crops. Soils of this region are classed as clacic rego-black chernozems or rendzinas due to thin dark grey to black A horizons and the high lime content of their calcareous boulder parent materials. These soils are of Isafold association for their characteristically thin, clay to clay-loam, lacustrine surface which is commonly underlain by gravel (Ehrlich et al., 1957; Ehrlich et al., 1953). Two adjacent fields of 28.4 ha (Treatment) and 39.6 ha (Control) were selected for their similar backgrounds of long-term perennial management. Both fields had typically been cropped with fertilized perennial grass hay which was cut or grazed by cattle. Hay species composition and abundance of the Control field was determined on July 15, 2011 using the Braun-Blanquet method (Braun-Blanquet, 1965). The Control field species composition was found to be 37.5% Timothy Grass *(Phleum pratense)*, 37.5% Rough Fescue *(Festuca campestris)*, 15% Smooth Brome *(Bromus inermis)*, 2.5% Alfalfa *(Medicago sativa)*, 2.5% Sow Thistle *(Sonchus arvensis),* 2.5% Dandelion *(Taraxacum officinale)* and 2.5% miscellaneous forbes.

Thirty-year mean, 2009 mean, thirty-year June to August mean and 2009 June to August mean air temperature and precipitation data were collected from the Winnipeg James

Armstrong Richardson International Airport (WIA; approximately 55 km away from the Woodlands site). Climate data collected from WIA and onsite were then used to assess the assumption of 2009 as a typical year with respect to climate.

2.2.2 Experimental Design

One limitation of eddy covariance systems is the inability to easily and cost effectively include replicates in the experimental design. Due to this limitation we require fields that are uniform and initially identical to enable accurate comparisons between treatments. The close proximity and similar histories of the fields would suggest that they may behave similarly under identical conditions. To investigate this assumption a flux tower was placed in each of two fields for a six-week calibration period before imposing any treatments. The calibration period occurred from Day of Year (DOY) 156 to 200 in 2009. During this time no management events took place. The fluxes generated during the calibration period were used to statistically test the uniformity of the fields and our ability to measure carbon fluxes accurately. The full field season was considered to be from the date both towers were operational to the end of the 2009 calendar year; DOY 156 to 365.

2.2.3 Agronomic Practice

One of the fields was converted from perennial to an annual cropping system (Treatment) while the adjacent field (Control) was maintained under the current perennial cropping system as a reference to the treated field. Dates of management events for both treatments are reported in Table 1. The perennial to annual conversion consisted of spraying with glyphosate to prevent re-growth then harvesting the hay crop by cutting the hay, baling and removing the cut material. Cattle manure was applied at 27.8 tonne ha^{-1} (7.4 tonne ha^{-1} dry) followed by three rounds of tillage with a discer to a depth of 12.7 cm. The field then remained bare into the winter. The Treatment field was sprayed with glyphosate on DOY 211 followed by harvesting on DOY 218, the Control field was harvested on DOY 210 but was allowed to re-grow afterward. Late in the season 100 cow-calf pairs were grazed on the Control field. Moving point sources of carbon such as cattle may affect the measured fluxes in an unpredictable way, so the period where cattle were present, DOY 293 to 324, has been replaced using gap-filling procedures. Before the start of data collection (approximately DOY 152) urea, mono-ammonium phosphate and potash fertilizers were broadcast over both fields at rates of 67.5 kg N ha^{-1}, 17 kg P_2O_5 ha^{-1}, 11 kg K_2O ha^{-1} and 1-2 kg S ha^{-1}. The production and land conversion practices described are typical of the Interlake region of Manitoba.

Table 1. Management Events

Periods	DOY (2009)	Date (2009)
Calibration Period	156-200	June 5 - July 19
Treatment Period	200-365	July 19 - Dec 31
Study Period	156-365	June 5 - Dec 31

	Date (DOY) [¶]				Date	
Events	Treatment		Control		Treatment	Control
Fertilizer[†]	152		152		June 1	June 1
Glyphosate[§]	211	A			July 30	
Cutting	218	B	210	A	Aug 6	July 29
Baling and Removal	222-230	C	230-247	D	Aug 10 - Aug 18	Aug 18 - Sept 4
Manure	222-230	C			Aug 10 - Aug 18	
Tillage 1	240-241	D			Aug 28 - Aug 29	
Tillage 2	274-280	E			Oct 1 - Oct 7	
Tillage 3	293	F			Oct 20	
Grazing			293-324[‡]	G		Oct 20 - Nov 20[‡]

[†] Fertilizer application date is an approximation; 67.5 N, 17 P_2O_5, 11 K_2O, 1-2 S (kg ha^{-1})

[‡] Period was gap filled due to EC method limitations; cattle leading to a non-uniform surface.

[§] Glyphosate was applied as Round-Up™ at a rate of 2.5 L ha^{-1}

[¶] Letters correspond to DOY markers on all figures

2.2.4 Soil, Biomass and Manure Measurements

Soil sampling and analysis was completed to characterize the fields. A set of surface soil samples was taken from each field using a 3.8 cm diameter Dutch auger soil sampler for the 0-15 cm depth and 2.5 cm diameter Dutch auger for the 15-30 cm depth. A smaller auger was chosen for the lower depth both to prevent contamination from upper depths and to better penetrate into the underlying soil. Five sampling locations were selected in 20 m increments to 100 m from each instrument tower along three transects (North West, South West and South East). Samples were not collected from a North East transect due to anticipated infrequent winds from this direction and the smaller impact that this direction would have on measured carbon fluxes. Each surface sample consisted of a composite of three cores taken from random locations around each sampling site. Surface samples were analyzed by the Manitoba Agriculture, Food and Rural Initiatives Soil Survey Department for total carbon (combustion by Leco) and organic carbon (Walkley-Black); carbonates were determined by subtraction. Walkley-Black analysis used a correction factor of 1.33 to account for 75% oxidization of organic carbon. Field composite samples were sent to ALS Laboratory Group (Winnipeg, MB) for site characterization analysis including total carbon (combustion by Leco), inorganic carbon (pressure following acid addition), organic carbon (by subtraction), texture (hand texture), NO_3-N ($CaCl_2$ colourimetric), P (Olsen P), K (modified Kelowna), S ($CaCl_2$ ICP), pH (1:2 water) and Electrical Conductivity (EC: 1:2 water). A 7-cm diameter tulip bulb planter was used to take bulk density samples of 0-15 cm and 15-30 cm depths from the 40 m and 80 m sampling locations of each transect. The cylindrical planter was pressed into the soil to 15 cm, for 15 to 30 cm measurements the 0-15 cm soil layer was removed before inserting the planter. The cores were then retrieved and the 15 cm core length was verified. The soil was dried at 105 ˚C until no further decrease in mass was observed then the mass of the core was divided by the calculated volume of the core to determine bulk density. Deeper soil cores were collected in duplicate from the end point of each transect (100 m) using a 3.8 cm diameter tractor mounted Giddings soil probe with a carbide gravel tip. The maximum depth of the cores varied due to the presence of large stones and gravel at depth; the average maximum sample depth was 60 cm. The cores were transported intact in polycarbonate sleeves and were cut into 15-cm increments. Only full 15-cm increments were analyzed. First bulk density was determined then a subsample was ground to pass through a 150 µm screen and analyzed by Soil Survey for total carbon and organic carbon.

The method of analysis employed by Soil Survey involved fine grinding and sieving soil to 150 µm before analysis. Since soils of this region contain a variety of textures, gravel and carbonaceous parent materials, it was suspected that the sieving may have introduced bias into the measurement by excluding particulates of sizes greater than 150 µm. This was investigated by repeating analysis on a subset of soil samples (0-15 and 15-30 cm) which were finely ground and sieved to 2 mm.

A 0.25 m^2 ground level clip-plot biomass sample was taken every 20 m along each transect before harvest. Samples were collected on DOY 208 and 211 for the Treatment and Control fields respectively. All samples for a single transect were placed in the same bag. Each sample was air dried for several weeks and weighed then the air-dried mass was corrected to oven-dried with a sub-sample oven-dried at 70 °C for 48 hours. Some biomass samples from the Control field could not be collected because these locations had been harvested before the time of biomass sampling. Full samples were collected from the 40 m, 60 m, 80 m and 100 m locations along the South West transect. The remaining biomass was collected from all other sampling locations and kept separate; these “stubble samples” were used to estimate the vegetation remaining following harvest and correct clip plots for harvest height when calculating biomass carbon exports. A producer’s estimate of harvested biomass was calculated from the harvested surface area, bale count, bale moisture and the mass per bale. The harvested surface area was determined by GPS measurements; bale count, moisture and mass were collected from the producer’s records. These producer yield estimates were then compared with the clip plot data to verify that up-scaled clip plot data gives reasonable values for the entire field.

A single composite manure sample was collected from the ground at various locations on the field after application. The sample was dried at 40 °C for several days, ground and sent to ALS Laboratory Group (Winnipeg, MB) for total carbon (combustion by Leco), total N (total Kjeldahl Nitrogen), total P, total K and total S analysis (acid digestion ICP). This analysis was used to estimate the carbon imported to the system during the manure application.

2.2.5 Carbon Flux and Meteorological Measurement

An eddy covariance system was installed near the center of each field; Figure 1 shows a diagram of the general site layout. A detailed description of tower design and instrument placement can be found in Appendix A. Each system was mounted on three towers; two towers for power generation equipment and one for instrumentation. On each field the towers were aligned in the producer’s preferred direction of field operations, north to south, with all instrumentation on the south-most tower. Ground-based instruments such as thermocouples, tipping bucket precipitation gauges, ground heat flux plates and soil moisture probes were placed between the towers. Guy-wires were avoided by strapping each of the triangular tower segments to a fence post. This configuration was chosen to allow for continuous data collection throughout the field season by eliminating the need to dismantle the towers during management events. Once a management event had occurred on either field, hand tools were used to complete the management practices between the towers. Power was supplied by a 12V DC battery bank composed of eight deep cycle 98 Ahr gel batteries charged by four 85 W solar panels (Kyocera Solar, Inc., Scottsdale, AZ) and a 400 W wind generator (Air Industrial: Southwest Windpower, Inc., Flagstaff, AZ). Power generation was controlled by two charge controllers one for solar (TriStar: Morningstar Corporation, Washington Crossing, PA) and one for wind (Trace C-40: Southwest Windpower, Inc., Flagstaff, AZ). Due to potential power limitations all possible attempts were made to conserve power, including the installation of data-logger-controlled relays. The relays switch off the pump, infrared gas analyzer and sonic anemometer during periods of low voltage. The estimated maximum amperage required for all equipment is 5.3 A.

Two sets of instrumentation were deployed on each field that included Eddy Covariance (EC) instrumentation and supporting meteorological instrumentation. Identical instrumentation was also deployed in a third adjacent field; these data are not reported but were used to fill gaps in meteorological supporting data of the two reported fields where appropriate. Data were typically downloaded weekly.

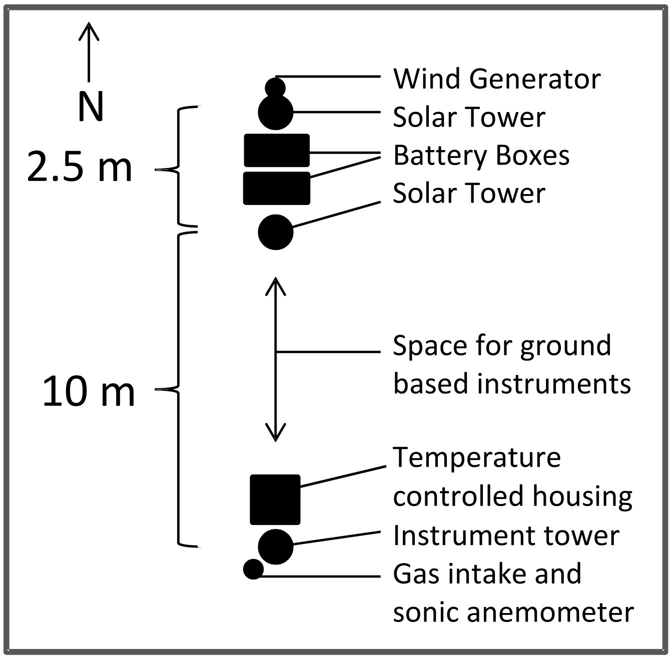

Figure 1. Diagram of Site Layout.

Eddy Covariance

The EC instrumentation consisted of an LI-7000 closed-path infrared gas analyzer (IRGA, LI-COR Inc., Lincoln, NE, USA) for determining atmospheric carbon dioxide and water vapour concentrations and a CSAT3 sonic anemometer-thermometer (SA, Campbell Scientific Inc., Logan, UT, USA) for wind velocity and virtual air temperature.

The SA and intake for the IRGA were placed at approximately three meters above the ground on an extension to the south west of the tower; approximating the direction of the prevailing wind. A 3.0 µm filter (Pall Corporation, Ann Arbor, MI, USA) was placed on the sample intake and 4 meters of 3.18 mm inner diameter Bev-A-Line IV (Cole-Parmer, Vernon Hills, IL, USA) was used to bring the gas sample to the IRGA. The IRGA was encased in a Temperature Controlled Housing (TCH, University of British Columbia, Biometeorology Group) which also contained solenoids and rotameters for daily automated calibration of the IRGA. The pumps (Model UN815KNDC; KNF Neuberger inc., Trenton, NJ, USA) produced a flow of approximately 10 L/min; this varied slightly with voltage and from tower to tower. Delays between the SA and IRGA signals were commonly between 6 to 8 tenths of a second for the Treatment field and 11 to 15 tenths of a second for the Control. Eddy covariance data were logged at 10 Hz and saved to a 2 GB data card in a CR1000 data logger with an NL 115 card reader (Campbell Scientific Inc.).

Supporting Meteorological Measurements

Meteorological instrumentation was deployed to collect environmental data and to provide the basis for gap filling and energy-balance closure calculations. Instruments included a net radiometer (Model CNR1; Kipp and Zonen, Delft, The Netherlands), a tipping bucket rainfall sensor (Model series 525; Texas Electronics, Inc., Dallas, TX, USA), an air temperature and relative humidity probe (Air Temp and RH, Model HMP45C212; Campbell Scientific Inc.), two ground heat flow transducers placed at 1-cm depth (Model HFT-3.1; Radiation and Energy Balance Systems Inc., Bellevue, WA, USA), two soil moisture probes spanning the 0-cm to 30-cm depths (Model CS616;

Campbell Scientific Inc.), two Chromel-Constantan Thermocouples placed at 10-cm and 20-cm depths and both an incoming and outgoing photosynthetically active radiometer (PARin and PARout, Model PARlite; Kipp and Zonen). All supplemental measurements were collected independently on both fields with the exception of precipitation, PARin, Air Temp and RH; these sensors were only present on the Treatment field. Meteorological data were collected on a second CR1000 data logger at 1 Hz and averaged over thirty-minute periods.

2.2.6 Data Processing

All data processing and statistical analyses were performed in MatLab (MathWorks Inc., Natick, MA, USA) using the same eddy covariance and gap-filling protocols as those used by the FluxNet Canada Research Network (FCRN) and described by Amiro et al. (2006). High-frequency data were split into manageable half-hourly files to facilitate data retrieval and manual error checking. Data were then fed a day at a time into a script which applies daily CO_2 calibration curves and generates coordinate rotated (Tanner and Thurtell, 1969) half-hourly cross products. Non-rotated thirty-minute cross-products were also calculated by the data logger and stored separately from the high-frequency data as a check and backup in the event of high-frequency data loss. Half-hourly supporting and meteorological measurements were aligned and appended to the cross-products data and then fluxes for the entire season were calculated. Carbon dioxide flux can be calculated by the general equation below (Webb et al., 1980).

$$F_c = \rho_a \overline{w' s_c'} \tag{1}$$

where F_c is the flux of CO_2 (μmol m^{-2} s^{-1}), ρ_a is air density (mol m^{-3}), w' is the instantaneous deviation of the vertical wind velocity from the mean (m s^{-1}) and s_c' is instantaneous deviation of the mole mixing ratio of CO_2 from the mean (μmol mol^{-1}). The overbar in equation 1 represents half-hourly time averaging.

Quality-control measures were imposed when obvious interruptions to data collection occurred. This involved removing bad 30-minute data points which would later be replaced with calculated values through gap-filling procedures. The quality-control measures followed Amiro (2010) and verbatim are "Missing anemometer counts were greater than 5% in a 30-min period; the standard deviation of the anemometer-thermometer temperature or vertical wind velocity was zero; the vertical mean velocity was >0.5 or <-0.5 m s^{-1}; the standard deviation of the CO_2 concentration was >1mmol m^{-3}; the mean CO_2 concentration was <13 or >20 mmol m-3; the calculated CO_2 eddy flux was >30 or <-30 μmol m^{-2} s^{-1}". Exceptions to quality control measures found in Amiro (2010) are carbon storage, which was assumed to be negligible at a height of three meters over a cropped canopy and u* threshold, which was calculated as 0.19 m/s. The u* threshold was determined as the point on the regression of CO_2 flux versus u* which corresponds to 80% of the maximum observed nighttime flux (Mkhabela et al., 2009). Automated zero and span CO_2 calibrations were performed daily at 4:30 AM until DOY 361 when the calibration time was changed to 3:30 PM due to night-time power limitations. The data during calibration events were used to adjust for instrumental drift then were removed from the raw high-frequency data. Missing CO_2 calibrations were estimated as the mean of the previous 10 successful calibrations. IRGA water vapour calibration of both fields occurred only once during the 2009 field season on DOY 272. Missing or bad water vapour flux data, which occurred following an unsuccessful water vapour calibration, was replaced with good data from the other towers. Replacement data for the Treatment field came from the third tower and replacement data for the Control field came from filled Treatment field data. Filled and replaced water vapour flux data were only used to calculate the Webb-Pearman-Leuning (Webb et al., 1980) term, since closed path IRGAs were used this will only have a small impact on the results. The delay between the SA and IRGA signals was determined as the delay yielding maximum covariance between the two signals. The automated calculation occasionally gave unrealistic values; so the mode of the calculated delay times for each day was used as a fixed delay to avoid using any extreme values. Delays did not change frequently from day to day so the delay from the previous day was often used to reduce re-calculation time. Occasionally a pump connection would break or a filter would become clogged causing changes to the internal IRGA pressure. These changes were used to flag bad IRGA data for removal. Upper and lower internal IRGA pressure thresholds were chosen manually; data were discarded when outside of the 50 to 83 kPa pressure range. Fluxes were slightly underestimated due to loss of high frequency signals in the sampling lines. These losses were determined to be 5% (Appendix B). To correct for high frequency losses, F_c was multiplied by a factor of 1.05.

Raw measured net ecosystem exchange (NEE) data were discarded when outside the -30 and 30 μmol $m^{-2}s^{-1}$ range. Gross primary productivity (GPP), ecosystem respiration (ER) and the gap-filled versions of NEE, GPP and ER were calculated using scripts developed by FCRN and described by Amiro et al. (2006). GPP was calculated as the sum of ER and net ecosystem productivity (NEP = -NEE). Missing GPP data were modeled using the relationship between GPP and PARin. ER was estimated as NEP during periods of no photosynthesis; at night and at low temperatures. Gaps in ER were modeled through the relationship between ER and soil temperature. When used in the gap-filling model the shallowest soil temperature available (10 cm) did not yield reasonable calculated values for GPP and ER. When soil temperature was used in the gap-filling models, gap-filled GPP became negative several times during the season. The decision was made to use air temperature because we did not have a measure of shallow (2 or 5 cm) soil temperature. Energy balance closure was calculated for ideal conditions selected from both fields using equation 2.

$$H + LE = R_n - G - S \tag{2}$$

where sensible heat flux (H) and latent heat flux (LE) are calculated through the eddy covariance system and net radiation (R_n), ground heat flux (G) and ground heat storage (S) are measured by independent sensors. Energy balance closure adjustments were not applied to the reported fluxes. A full description of energy balance closure calculations can be found in Appendix B.

2.3 Results

2.3.1 Climate

The 2009 year was similar to the 30-year mean from WIA for both temperature and precipitation (Table 2). The mean 2009 June to August temperature (16.5 ºC) falls within the ±1.8 °C standard deviation of the 30-year June to August mean (18.3±1.8 ºC) and the

2009 June to August precipitation (235.2 mm) was within three mm of the 30-year average (232.0 mm). The average precipitation from June to August 2009 gives a value very close to the 30-year June to August mean but when months are looked at separately July was quite wet whereas June and August were drier with respect to 30-year monthly averages. The mean temperature for 2009 (2.1 ºC) falls within the ±1.3 °C standard deviation of the 30-year mean (2.6±1.3 ºC); 2009 total precipitation (520.5 mm) was within 7 mm of the 30-year mean (513.7 mm). The on-site temperature and precipitation are similar to both the 30-year mean and the 2009 seasonal data from the WIA. On-site temperature of 16.3±5.4 °C is almost identical to the 2009 WIA data and overlaps standard deviations with the WIA 30-year mean. The on-site precipitation of 242.1 mm was slightly higher than the WIA 30-year and 2009 June to August values. Temperature and precipitation data are shown in figure 2.

Table 2. Climate

	Temperature (°C)		Precipitation (mm)	
Source	30 Year Mean	2009 Mean	30 Year Mean	2009 Cumulative
Yearly (WIA)	2.6 ± 1.3	2.1	513.7	520.5
June to August (WIA)	18.3 ± 1.8	16.5	235.2	232.0
June to August (On-site)		16.3 ± 5.4		242.1

WIA = Winnipeg at James Armstrong Richardson International Airport
Temperature error is reported as standard deviation.
On-site data recorded on the treatment field.

2.3.2 Soil Characterization

Analysis of a single composite soil sample from the 0-15 cm and 0-30 cm depths of each field showed that soil texture differed slightly between the fields (Table 3). The Treatment field has a finer texture (clay loam and clay) than the control field (loam, clay

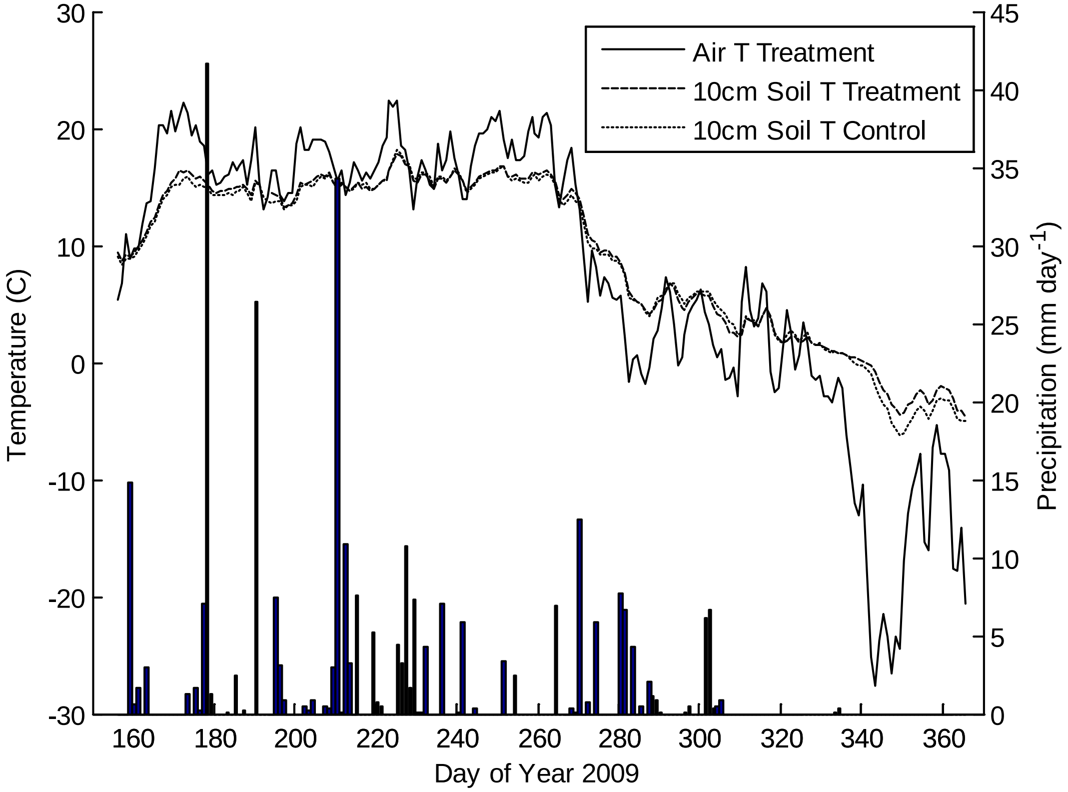

Figure 2. 2009 On-Site Climatic Conditions
Mean air temperature of the study period was 8.0˚C. Total measured precipitation was 321mm.

Table 3. Soil Characteristics

	Texture		pH		EC (mS cm^{-2})		NO_3-N (ppm)		P (ppm)		K (ppm)		S (ppm)	
Depth (cm)	T	C	T	C	T	C	T	C	T	C	T	C	T	C
0-15	Clay Loam	Loam	8.0	8.0	0.4	0.3	3	4	13	11	152	145	5	5
15-30	Clay	Clay Loam	8.3	8.4	0.3	0.3	3	3	N/A	N/A	N/A	N/A	5	4

T = Treatment, C = Control. One composite sample was analysed per field per depth.

Texture is by hand texture method. pH and EC were on an extract of 1 Soil to 2 Water. NO_3-N is extracted in $CaCl_2$ with colourimetric analysis.

S is extracted in $CaCl_2$ solution followed by ICP analysis. P is by the Olsen method and K is by Modified Kelowna.

Treatment field samples collected DOY 208, Control field samples collected DOY 211 loam) for both the 0 to 15 and 15 to 30 cm depths. Both fields are basic with pH ranging from 8 to 8.4. EC and nutrient analyses show that these fields are similar for all other measured parameters.

Two methods of soil carbon analysis were completed by Soil Survey. Soil samples were divided in two and sieved to both <150 μm and <2 mm. Analysis from the two screen sizes were then compared using a two-tailed t test. The test determined that for both total and organic carbon there was a significant difference between the finely ground and coarsely ground soils for all fields and depths except for the organic carbon of the Control field in the 15-30 cm depth. Where differences were detected, the means of all finely sieved samples were higher than those of the coarsely sieved samples. All p-values were of a similar order of magnitude <0.001 except for those of the organic carbon in the 15-30 cm depth; $p = 0.02$ and 0.11 for Treatment and Control respectively. The sieving process appears to be introducing some bias in the site characterization measurements causing the <150 μm reported values for total and organic soil carbon (Table 4a) to be higher than those of the <2 mm soil fraction. Independent analysis of a single composite soil sample per field-depth by ALS Laboratories confirmed that the soil organic carbon of these fields may be lower than reported by the previous analysis (Table 4b).

Table 4. Carbon Analysis

a. Carbon Analysis: Soil Survey

			Total Carbon (g C kg^{-1})			Organic Carbon (g C kg^{-1})			Inorganic Carbon (g C kg^{-1})		
Depth (cm)	n T	n C	T	C	P value	T	C	P value	T	C	P value
0-15	15	15	105.3	101.7	0.47	91.2	88.1	0.62	14.1	13.6	0.91
15-30	15	15	86.5	80.0	0.17	41.9	34.2	0.28	44.6	45.7	0.85
30-45	5	4	75.4	66.8	0.15	2.9	2.6	0.81	72.6	64.2	0.14
45-60	4	2	73.2	58.5	0.12	1.8	1.9	0.90	71.4	56.6	0.10
60-75	2	1	75.1	56.1	N/A	0.8	2.0	N/A	74.3	54.1	N/A
75-90	1	1	76.3	70.3	N/A	1.0	0.0	N/A	75.3	70.3	N/A

T = Treatment, C = Control. Soils for carbon analysis are ground to pass through a 150 μm sieve.
Treatment field samples collected DOY 208 (0-30 cm), DOY 300 (> 30 cm).
Control field samples collected DOY 211 (0-30 cm), DOY 300 (> 30 cm).
* Significant at α = 0.05. P-values are calculated in Matlab using a two-tailed t test.

b. Carbon Analysis: ALS Laboratories

			Total Carbon (g C kg^{-1})		Organic Carbon (g C kg^{-1})		Inorganic Carbon (g C kg^{-1})	
Depth (cm)	n T	n C	T	C	T	C	T	C
0-15	1	1	82.9	64.5	66.2	51.7	16.7	12.8
15-30	1	1	68.5	55.1	33.9	28.5	34.6	26.6
30-45	1	1	62.5	53.0	5.3	<1.0	57.2	54.8
45-60	1	1	66.5	51.8	6.9	4.3	59.6	47.5
60-75	1	1	70.2	57.3	6.1	1.9	64.1	55.4
Manure	1	0	280.0	N/A	N/A	N/A	N/A	N/A

T = Treatment, C = Control.
Treatment field samples collected DOY 208 (0-30 cm), DOY 300 (> 30 cm).
Control field samples collected DOY 211 (0-30 cm), DOY 300 (> 30 cm).
A single composite sample was submitted for analysis for each depth.
Manure applied to the Treatment field DOY 222-230 at a rate of 27.8 tonne ha^{-1} (7.4 tonne ha^{-1} dry), dried before analysis.

Table 4a shows that total soil carbon, soil organic carbon and soil inorganic carbon contents of the two fields were not significantly different. The P values from these tests range from 0.9 to 0.1. Bulk density (Table 5) was found to be significantly different for the soils of the 0-15 cm depth only.

Table 5. Bulk Density (Mg m^{-3})

Depth (cm)	n T	n C	T	C	P value	
0-15	6	6	0.91	1.12	0.04	*
15-30	6	6	1.34	1.43	0.51	

P-values are calculated in Matlab using a two-tailed t test.
* Significant at α = 0.05.

2.3.3 Dry Matter Yield

Clip plot data, corrected for harvest height, indicate that at harvest 150±20 g C m^{-2} and 130 g C m^{-2} were removed from the Treatment and Control plots, respectively. Unfortunately error could not be calculated for the clip plots of the Control field because several of the clip plot locations had been harvested before samples could be taken leaving the number of replicates too low to calculate a standard deviation (Treatment n = 3, Control n = 1). The clip plot values compare moderately well with the producer's yield estimates of 160 g C m^{-2} and 150 g C m^{-2} from the Treatment and Control fields respectively.

2.3.4 Performance of EC system

Gap Filling

About 50% of the data from the Treatment field and 60% from the Control were gap filled. Much of the missing data occurred at night during low wind speeds the remaining missing portions are due to instrument issues. A higher amount of gap filling was required for data from the Control field when cattle were grazing on this field late in the season (DOY 293 – 324). Data from this period were intentionally excluded because of the suspected impact of moving carbon sources on the fluxes.

Calibrations and Error Analysis

DOY 156 to 200, the time from deployment of the two towers to the management of the fields began to diverge, was considered to be a calibration period. The calibration period was used to assess the assumptions of these two fields as replicates and that they will show similar fluxes under the same environmental conditions. A plot of half-hour NEP of the Treatment versus the Control during this period (Figure 3) shows that the scatter of points lays nearly centered on the 1:1 line.

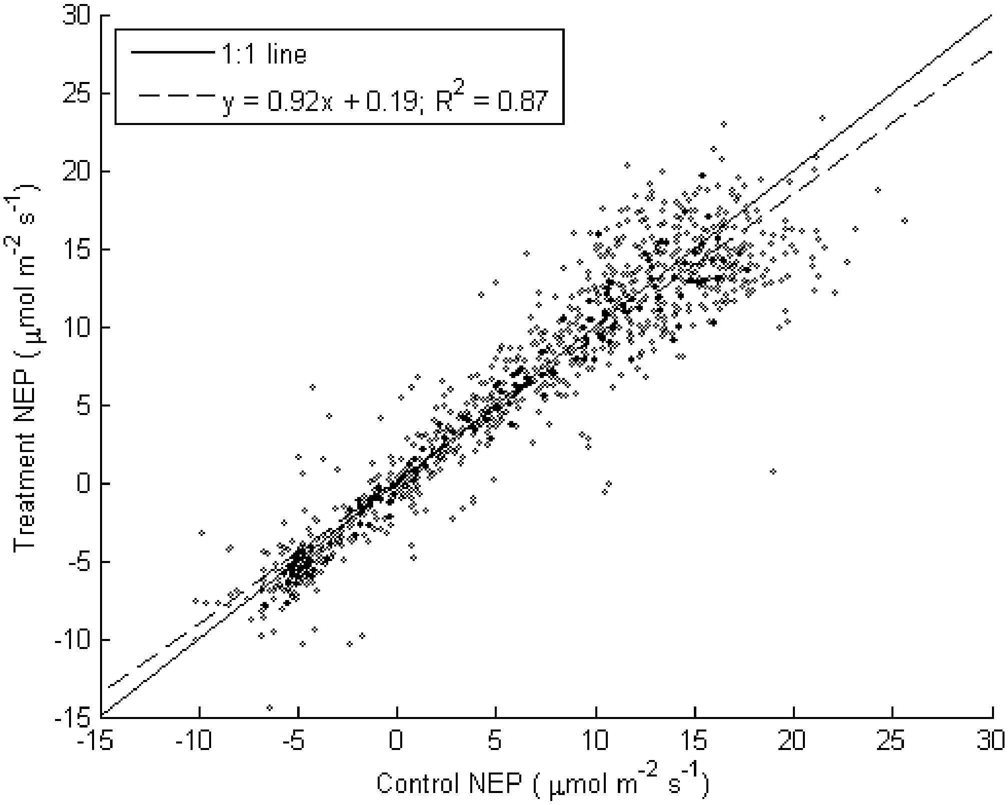

Figure 3. Validation of the Fields as Replicates.
30-min average non-gap-filled NEP of the Treatment versus Control fields.
DOY 156-200. n = 1055, only points which exist for both fields are included.

Two statistical tests were performed on the NEP of the calibration period to examine the validity of these fields as replicates and our ability to make comparisons between them. The first was a paired t-test, performed on the daily average gap-filled NEP of the two fields. This test determined that the fluxes from the two fields are significantly different with a P value of <0.001 (n = 45). Daily average fluxes are a gap-filled term. To test that differences were not a result of the gap-filling procedures, the test was repeated on non-gap-filled half-hourly fluxes yielding a P value of <0.001 (n = 1001). The second test was an analysis of covariance performed on daily and non-gap-filled half-hourly averages. In this test the slope of the Treatment versus Control NEP line was compared with a dataset of perfect covariance. The perfect covariance dataset was created by plotting Control NEP versus Control NEP. By using only values which correspond to non-null values from the treatment field, the perfect covariance dataset was provided with the same number of usable data points as the Treatment versus Control dataset (daily, n = 45; half hourly, n = 1001). The resulting P values of the daily and half hourly tests were both <0.001, again indicating that the two fields had different carbon fluxes during the calibration period.

To assess our ability to compare the two eddy-covariance systems, the non-gap-filled thirty-minute average carbon dioxide concentrations were compared between the two sites during the calibration period. The half-hourly average CO_2 concentration footprint is much larger than the CO_2 flux footprint, so mean CO_2 concentration measured on each field should be nearly identical. Deviations of the half-hourly average CO_2 concentrations from a one-to-one relationship would indicate differences in the calibration of the IRGA between the fields. The regression line plotting the half-hourly average CO_2 concentration of the Control field versus the Treatment field gave a slope of 1.04 and an offset of -9.3 ppm ($R^2 = 0.90$, n = 1575). An analysis comparing the covariance of the half-hourly CO_2 concentration against a dataset of perfect covariance gives P values of 0.002 and <0.001 for intercept and slope respectively. The Control field consistently showed higher fluxes during the calibration period. The mean NEPs of the two fields over the calibration period were 3.06±0.3 g C m^{-2} d^{-1} for the Treatment field and 4.41±0.4 g C m^{-2} d^{-1} for the Control, a difference of 1.34±0.2 g C m^{-2} d^{-1}. Energy balance closure was determined to be 82% and 59% for the Treatment and Control fields respectively (Appendix B). Reported NEP was not corrected for energy balance closure.

2.3.5 Net Ecosystem Productivity

Five-day average NEP of the Control and Treatment fields are shown in Figure 4. Throughout the calibration period (DOY 156-200) both fields show positive NEP, centered approximately on 3.5 g C m^{-2} d^{-1}. The NEP of the Control field was consistently higher than the Treatment field during this period. No management events occurred during the calibration period, so variability in the NEP of both fields at this point are due to changes in environmental conditions and both fields appear to respond similarly. At DOY 210 the Control field was cut causing a large decrease in NEP which levels off at -2 g C m^{-2} d^{-1}. On DOY 211 the treatment field was sprayed with glyphosate followed by cutting on DOY 218. Following glyphosate application there was a large decrease in the NEP of the Treatment field. NEP continued to decrease until it reached -6 g C m^{-2} d^{-1}. The NEP increase of both fields on DOY 225 indicates that both fields have begun recovering or acclimatizing to their disturbances. The NEP of the Control field increased to a maximum of 2 g C m^{-2} d^{-1} on DOY 245, much lower than before the cutting event. The Control field then remained near this level until DOY 275 when air temperature began to decrease, causing NEP to approach 0 g C m^{-2} d^{-1}. Manure was applied to the treatment field between DOY 222 and 230. No immediate effect of manure application

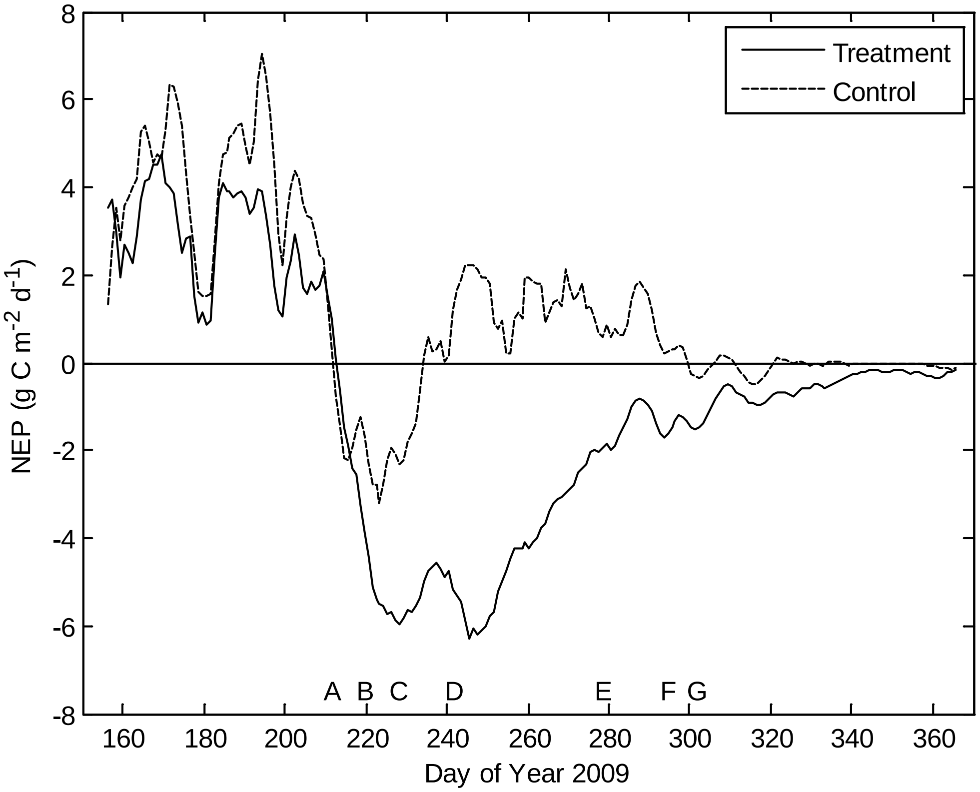

Figure 4. 5 Day Average NEP for the Treatment and Control Fields
A: DOY 210 Control Cutting, DOY 211 Treatment Glyphosate;
B: DOY 218 Treatment Cutting;
C: DOY 222-230 Treatment Baling, Bale Removal and Manure Application;
D: DOY 240-241 Treatment Tillage 1, DOY 230-247 Control Baling and Bale Removal;
E: DOY 274-280 Treatment Tillage 2;
F: DOY 293 Treatment Tillage 3;
G: DOY 293-324 Control Grazing (Gap Filled).

can be seen in the NEP data. The increasing NEP of the Treatment field beginning on DOY 210 peaked below -4 g C m^{-2} d^{-1} on DOY 240-241. At this point, the field was disked causing NEP to decrease back to -6 g C m^{-2} d^{-1}. The NEP of the Treatment field slowly increased for the rest of the season but remained below 0 g C m^{-2} d^{-1} into the winter. Repeated tillage events on DOY 274-280 and 293 had little visible effect on the NEP of the Treatment field. The cutting of the Control field affected NEP slightly faster than the glyphosate application affected the Treatment field, as can be seen by the slope of the NEP lines shortly after DOY 210-211. However the cumulative effect of the glyphosate and cutting was much greater than cutting alone.

2.3.6 Gross Primary Productivity

Figure 5a shows the five-day average GPP of both the Control and Treatment fields. During the calibration period (DOY 156-200) the GPP of both fields is centered on approximately 9 g C m^{-2} d^{-1}. The GPP of the Control field was consistently higher than GPP of the Treatment field by a very small amount. At DOY 210 the cutting of the Control field caused GPP to decrease to approximately 3 g C m^{-2} d^{-1}. GPP then recovered to a maximum of 7.5 g C m^{-2} d^{-1}, less than before the cutting. GPP remained below this level until DOY 275 when the temperature decreased; causing GPP to approach 0 g C m^{-2} d^{-1}. The combined glyphosate and cutting of the Treatment field, DOY 211 and 218 respectively, decreased GPP to near zero where it remained until the end of the season although for a short time following the initial tillage event (DOY 240-241) GPP did decrease further.

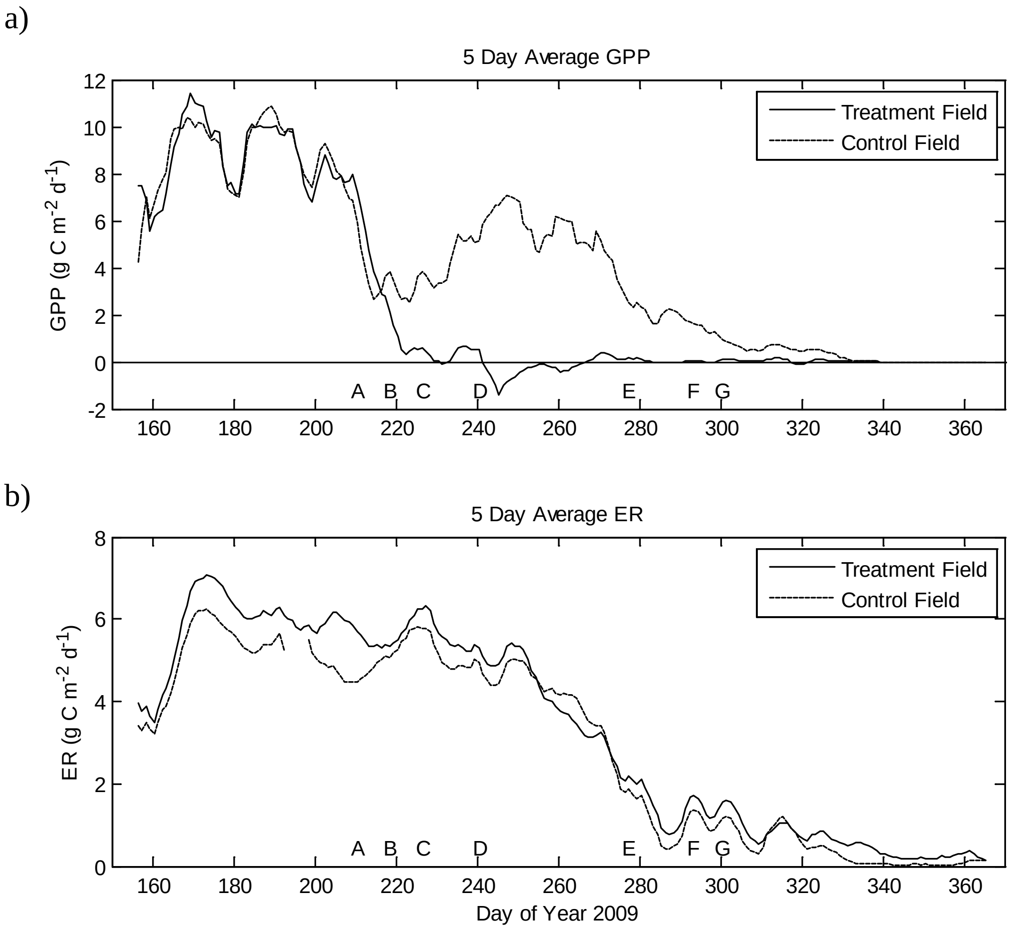

Figure 5. a) Treatment and Control 5 Day Average GPP, b) Treatment and Control 5 Day Average ER

A: DOY 210 Control Cutting, DOY 211 Treatment Glyphosate;
B: DOY 218 Treatment Cutting;
C: DOY 222-230 Treatment Baling, Bale Removal and Manure Application;
D: DOY 240-241 Treatment Tillage 1, DOY 230-247 Control Baling and Bale Removal;
E: DOY 274-280 Treatment Tillage 2;
F: DOY 293 Treatment Tillage 3;
G: DOY 293-324 Control Grazing (Gap Filled).

2.3.7 Ecosystem Respiration

Figure 5b shows the five-day average ER of both the Control and Treatment fields. Both fields were rarely more than 1 g C m^{-2} d^{-1} from each other regardless of the differences in management of the fields. The ER of the Treatment field was slightly higher than that of the Control field during the calibration period (DOY 156-200). Following glyphosate and cutting of the Treatment field (DOY 211 and 218) respiration remained relatively stable while following the cutting event on the Control field ER increased, slightly narrowing the difference between the ER of the Treatment and Control fields. For the remainder of the season ER of the two fields were similar; decreasing with temperature and generally with the Treatment field above the Control.

2.3.8 Effect of Perennial to Annual Conversion on NEP

Figure 6 shows the difference between the NEP of the Treatment and Control Fields. This difference illustrates the effect of converting a perennial landscape into annual crop production in the year of conversion. The NEP of the Control field was higher than that of the Treatment field for the majority of the season causing the difference to be negative. During the calibration period the difference is consistently near -1 g C m^{-2} d^{-1}, again showing that the NEP of the Control field was consistently higher than that of the Treatment field before disturbance. There was a spike near DOY 210-211 when the glyphosate and cutting occurred. This spike is related to offset treatment dates and the different rates at which the disturbances took effect. The deep trough at DOY 245 occurs when the decrease in the NEP of the Treatment field immediately after the first tillage

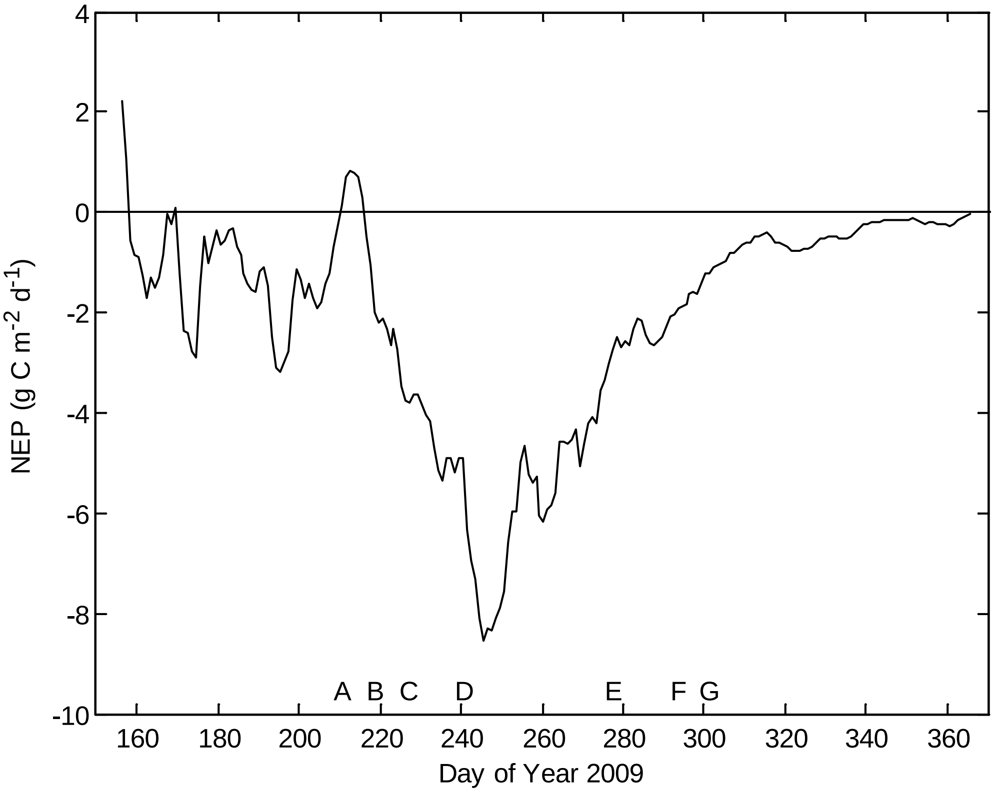

Figure 6. Treatment Field NEP Minus Control Field NEP; Effect of the Treatment Relative to the Control.
A: DOY 210 Control Cutting, DOY 211 Treatment Glyphosate;
B: DOY 218 Treatment Cutting;
C: DOY 222-230 Treatment Baling, Bale Removal and Manure Application;
D: DOY 240-241 Treatment Tillage 1, DOY 230-247 Control Baling and Bale Removal;
E: DOY 274-280 Treatment Tillage 2;
F: DOY 293 Treatment Tillage 3;
G: DOY 293-324 Control Grazing (Gap Filled).

event aligns with the recovery of the biomass on the Control field. Although it may appear that repeated tillage events are visible in this plot, late season variability in the difference between NEPs is more related to weather acting on the vegetation (and NEP) of the Control field. The NEP of both fields approaches zero into the winter so the difference also approaches zero. The difference between NEPs remains slightly negative through the winter indicating more carbon lost by the Treatment than the Control.

2.3.9 Effect of Perennial to Annual Conversion on GPP and ER

The difference between the GPP of the Treatment and Control fields and the difference between the ER of the Treatment and Control fields are shown in Figure 7. This figure displays the contribution of GPP and ER to the difference between the NEP of the Treatment and Control fields (Figure 6). The difference between ERs is positive and within 1 g C m^{-2} d^{-1} of zero for the majority of the season indicating that the treatment field generally had higher respiration. GEP shows similar trends to the difference between NEPs. The difference between GEPs begins the season centered on zero, spikes, decreases to a minimum at tillage (DOY 240-241) then increases; approaching zero in the winter.

2.3.10 Cumulative Fluxes and Carbon Balance

The cumulative NEP, GPP and ER (cNEP, cGPP and cER) for both fields are shown in Figure 8. Carbon balance can be found in Table 6, where seasonal totals are denoted by

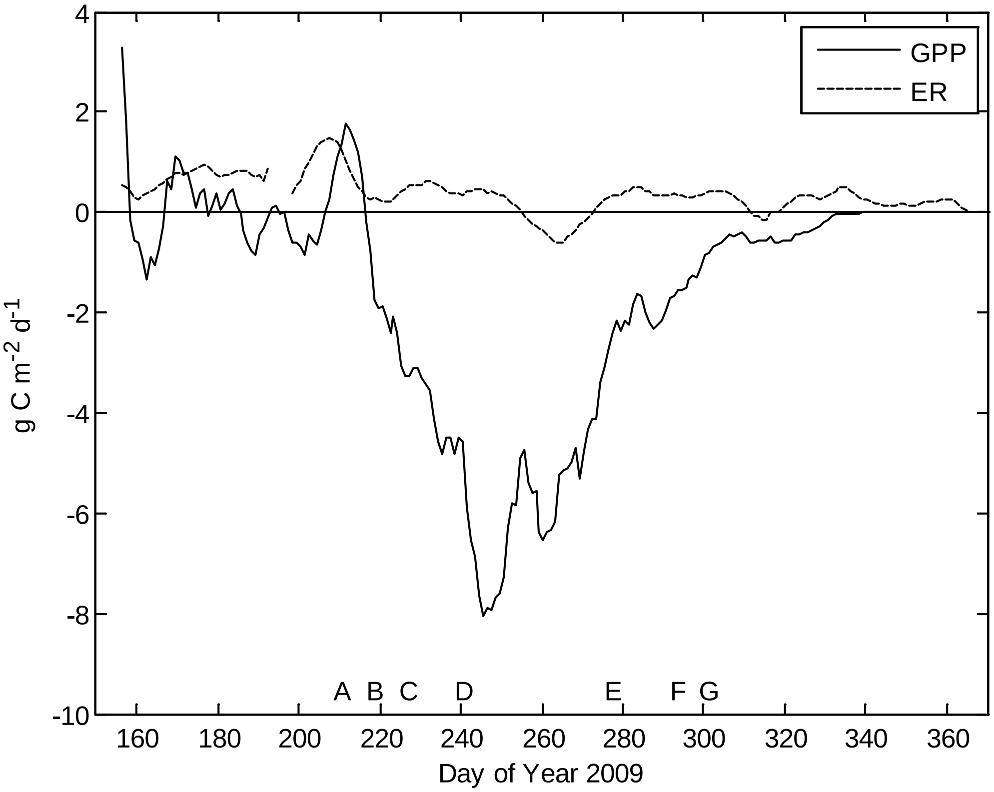

Figure 7. Treatment Field GPP and ER Minus Control Field GPP and ER; The Effect of Treatment on GPP and ER, Relative to Control GPP and ER.
A: DOY 210 Control Cutting, DOY 211 Treatment Glyphosate;
B: DOY 218 Treatment Cutting;
C: DOY 222-230 Treatment Baling, Bale Removal and Manure Application;
D: DOY 240-241 Treatment Tillage 1, DOY 230-247 Control Baling and Bale Removal;
E: DOY 274-280 Treatment Tillage 2;
F: DOY 293 Treatment Tillage 3;
G: DOY 293-324 Control Grazing (Gap Filled).

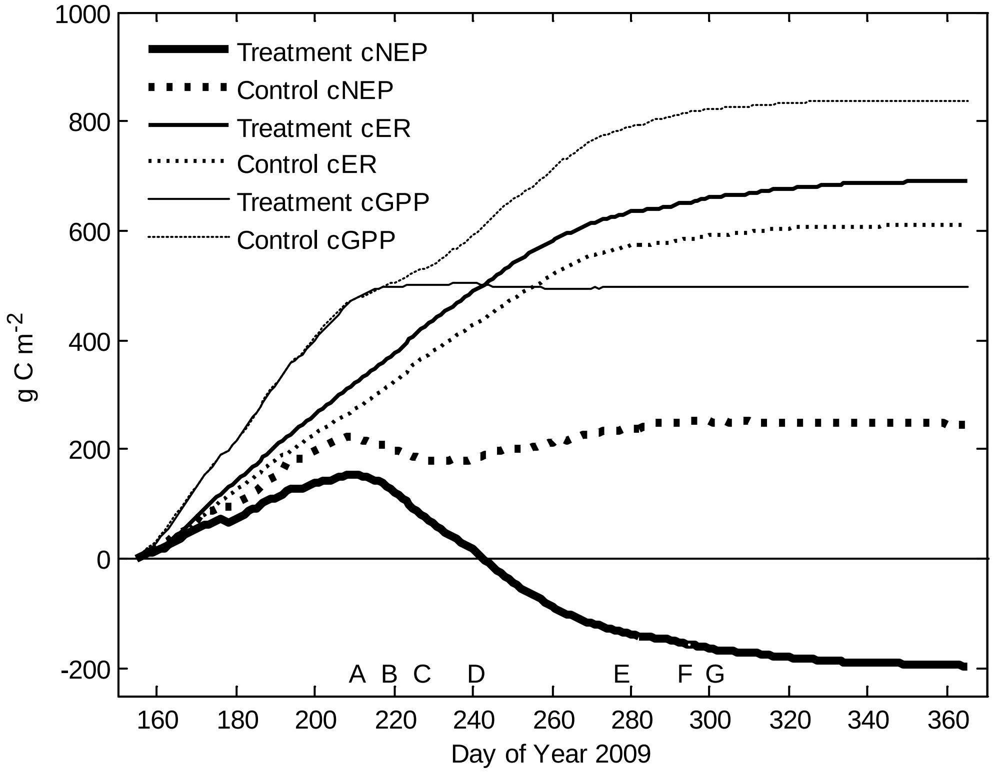

Figure 8. Cumulative NEP, GPP and ER
A: DOY 210 Control Cutting, DOY 211 Treatment Glyphosate;
B: DOY 218 Treatment Cutting;
C: DOY 222-230 Treatment Baling, Bale Removal and Manure Application;
D: DOY 240-241 Treatment Tillage 1, DOY 230-247 Control Baling and Bale Removal;
E: DOY 274-280 Treatment Tillage 2;
F: DOY 293 Treatment Tillage 3;
G: DOY 293-324 Control Grazing (Gap Filled).

Table 6. Carbon Balance for DOY 156-365 (g C m^{-2})

	Treatment	Control	Difference
ΣNEP[§]	-195	246	-441
ΣGPP[§]	498	837	-339
ΣER[§]	693	610	83
Manure	206 [†]		206
Total Above Ground Biomass	230	210	20
Biomass Removed	160 [‡]	150 [‡]	10
Carbon Balance or NBP	-149	96	-245

[†] Manure C application was estimated from the producer application rate of 28 tonne ha^{-1}, at average beef manure dry matter of 26.4% from the Tri-Provincial Manure Application and Use Guidelines (PPCLDMM, 2004) and dried manure total carbon analysis. Appendix C.

[‡] Determined from producers estemate of number of bales and bale mass.

[§] Fluxes are not corrected for energy balance closure.

ΣNEP, ΣGPP and ΣER. This figure illustrates that the observed differences between NEPs of the calibration period (DOY 156-200) are due to differences between ERs of the two fields. cGPPs are virtually identical until treatment (DOY 210 and 211) while cERs diverge at a relatively constant rate for the entire season. The plots of cER accumulate to 693 and 610 g C m^{-2} for the Treatment and Control fields, respectively a difference of 83 g C m^{-2}. There is a large difference between the final cGPP of the two fields, 498 g C m^{-2} for the Treatment field and 837 g C m^{-2} on the Control a difference of 339 g C m^{-2}. Final cNEP for the treatment field was -195 g C m^{-2} and 246 g C m^{-2} for the Control field, a difference of 441 g C m^{-2}. When accounting for manure carbon additions and biomass removals the carbon balance or net biome productivity (NBP) during the observed field season becomes -149 g C m^{-2} for the Treatment field and 96 g C m^{-2} for the Control field, a difference of 245 g C m^{-2}.

2.4 Discussion

2.4.1 Uncertainty

Initial differences between fields included a slightly finer texture on the treatment field and a difference between the bulk density of the surface soils (0-15 cm). Although the proportion of soil carbon was determined to be nearly identical for all depths, when used to calculate the initial mass of total carbon, the higher bulk density for the 0-15 cm depth of the Control field translates into a greater mass of carbon per surface area of the Control field (Total Carbon 0-15 cm: Control 17 kg C m^{-2}; Treatment 14 kg C m^{-2}). The different masses of carbon per surface area may be partly responsible for the observation of higher NEP from the control field during the calibration period.

Covariance analysis comparing the half-hourly NEE of the fields to a dataset with perfect covariance showed that intercepts and slope were significantly different. These results indicate that the fields were initially different.

The intercept and slope of the regression between half hourly average CO_2 concentration of the Treatment and Control fields were -9.3 ppm and 1.04. The intercept indicates that the IRGA of the control field generally recorded 9.3 ppm higher than the IRGA of the treatment field. Since these analyzers are calibrated daily, the offset between fields is likely a real difference between the CO_2 concentrations measured above these fields. This would indicate that there was more photosynthesis or less respiration occurring on the control field; which was observed in the flux data. Had the offset been due to poor calibrations, flux data would be impacted minimally. Since fluxes are calculated from deviations from the mean half hourly CO_2 concentration (Equation 1), offset biases such as this would be minimized through time averaging. Biases in the slope of the regression between the Treatment and Control fields would have a greater impact on the comparison between fields. The slope of this regression was very close to one (1.04), indicating that fluxes from these fields during the calibration period responded similarly to changing environmental conditions. The above tests show that these fields should respond similarly to treatment effects although the magnitude of fluxes may vary somewhat.

During the calibration period (DOY 156-200) the average NEP was 3.06±0.3 g C m^{-2} d^{-1} and 4.41±0.4 g C m^{-2} d^{-1} for the Treatment and Control, respectively. Comparison of NEPs showed that on average the Control field produced 1.34±0.2 g C m^{-2} d^{-1} more than the Treatment field throughout the calibration period. The fact that the standard error reduced from ±0.3 and ±0.4 to ±0.2 g C m^{-2} d^{-1} for the calculated difference between the fields again shows that these fields are well correlated. The inequality of 1.34±0.2 g C m^{-2} d^{-1} between fields, although small, sums to 60.3 g C m^{-2} over the entire calibration period; before any divergence of management occurred. Is this difference during the calibration period real or is this an artifact of systematic errors in the flux measurement? Estimates of error from similar sites are typically reported based on yearly carbon balances. Since we do not have a full year of data we can assume that error bounds from this study will be lower than reported values from similar sites with full yearly balances. Flux error is preferentially generated during times of year with larger fluxes; this study contains much of the season when large fluxes were occurring so error may be similar to that of annual fluxes regardless of the short season.

Error analysis of annual NEP totals from eddy covariance measurement of several forested sites produced error bounds of ±30 g C m^{-2} y^{-1}, ±40 g C m^{-2} y^{-1} and ±68 g C m^{-2} y^{-1} (Baldocchi, 2003). Grassland sites from a karst region reported by Ferlan et al. (2011) produced error bounds of (126) ±14 g C m^{-2} y^{-1} for a typical grassland and (-353) ±72 g C m^{-2} y^{-1} for an adjacent site with some secondary succession species. Meyers (2001) found errors of (118) ±36 g C m^{-2} y^{-1} for a rangeland in non-drought years. Ammann et al. (2007) reported fairly high errors on intensively managed grassland (147)

±130 g C m^{-2} y^{-1} and extensively managed grassland (-57) +110 or -130 g C m^{-2} y^{-1} sites. The increased error seen by Ammann et al. (2007) may be related to limited field size requiring strict quality-control measures and increased amounts of discarded data. If we can assume that error bounds on our flux measurements are similar to those found using similar eddy covariance systems, error bounds for the seasonal flux totals of this study should fall within ±30 to ±100 g C m^{-2} y^{-1} which is a general range of eddy covariance error bounds proposed by Baldocchi (2008). Using a similar paired eddy covariance system, Ammann et al. (2007) stated that due to proximity between fields, identical climatic conditions and the fact that errors in yearly flux totals are due mainly to systematic errors, fluxes from both fields will be highly correlated causing a comparison between fields to cancel systematic errors common to both fields and decrease the error of the calculated difference between fields relative to that of individual fields. This means the range of ±30 to ±100 g C m^{-2} y^{-1} is likely too large for error in the difference between fields.

If the cumulative difference between the NEP of the two fields during the calibration period of 60.3 g C m^{-2} can be attributed to errors in the flux measurement instead of physical differences between the fields, much of the yearly error has been accounted for within the first 45 days of measurements especially when considering that the difference between fields should produce less error than the individual fields. It is likely that the observed differences during the calibration period are due to real measured fluxes.

If we assume that the difference between the fields during the calibration period would have remained stable throughout the measured growing season had we not imposed a treatment, this would sum to 281.4 g C m^{-2}. It is very unlikely that the difference would remain so large through the fall and winter while fluxes from the Control field are slightly negative; therefore if we assume that following DOY 274 this difference is negligible the seasonal sum reduces to 159.5 g C m^{-2}. The difference between fluxes of the Treatment and Control field are likely to scale with the magnitude of fluxes this will cause the total to decrease substantially since the highest magnitude fluxes are during the calibration period. Figure 8 and Table 6 show that the differences between NEP of the calibration period are due mainly to ER and that the cERs diverge at a relatively constant rate throughout the season. This also indicates that these fields are initially different but only by their respiration rates which appear to be relatively constant for each field. This means that the difference between the cumulative respirations (83 g C m^{-2}) of these fields may also be a good estimate for uncertainty in the seasonal difference between these fields.

Can we resolve treatment effects if there is already a difference between fluxes before the treatment was imposed? If effects observed immediately following treatment are large with respect to the initial difference between fluxes of the calibration period the treatment effect may be resolved in spite of the initial differences between the fields. Immediately following the cutting and glyphosate treatment there was a large decrease in the measured NEP of both fields. Drops of approximately 5.5 g C m^{-2} d^{-1} on the Control field and 8 g C m^{-2} d^{-1} on the Treatment field correspond to decreases of 4 and 6 times the difference between the mean NEP of the fields during the calibration period. Following treatment, the difference between the NEP of the fields changes from 1.34 g C m^{-2} d^{-1} to approximately 3 g C m^{-2} d^{-1} on DOY 225. When we consider that the difference between fluxes had low variability throughout the calibration period, ±0.2 g C m^{-2} d^{-1}, the effects observed due to treatment are strong enough that they can be observed by a direct comparison between fields. Initial differences between fluxes of the fields will have the effect of shifting the carbon balance of the Control field NEP higher with respect to the Treatment field, slightly increasing the observed treatment effects. There are several low wet spots in the footprint of the Treatment field tower while the Control tower rests on a slight ridge; this may partially explain some of the initial differences between fields.

2.4.2 Effects of Specific Events

Glyphosate and Cutting

When the Control field was cut, there was a quick decrease in GPP whereas the glyphosate application on the Treatment field took several days to decrease GPP to the same level. It is difficult to see this relationship in the 5-day average plots because averaging makes the decline in the NEP of the Control field look as though it occurs over a full five days. Half-hourly data showed the decrease in NEP occurred within the first day after cutting and the decrease in NEP of the Treatment field took several days to reach a minimum.

The observed reductions in NEP could be caused by decreasing GPP, increasing ER or some combination of both. Figure 5a shows the decrease in living vegetation from both fields decreased GPP contributing to the large reductions in NEP shortly after glyphosate and cuttings. A larger decrease in GPP was observed on the Treatment field which is related to the differing amounts of living vegetation remaining on the fields after glyphosate and cuttings. ER should decrease as autotrophic respiration decreases but ER may also increase as soil heterotrophic respiration increases with the addition of new labile carbon sources. Figure 5b shows that following glyphosate and cuttings ER did not change greatly on either field. The ER of the Control field increased slightly matching the treatment field more closely, although the magnitude of the increase is similar to the variability seen during the calibration period and may not be treatment related. Eugster et al. (2010) also observed a time lag between a herbicide application and its effects. The greatest changes in ER from a seven-day comparison were following tillage and irrigation events; however from a 28-day comparison, herbicide applications were second only to effects from irrigation (Eugster et al., 2010). Approximately 20 days following cutting of the Control field the vegetation had recovered sufficiently to begin sequestering carbon again. Similarly, the grassland studied by Hussain et al. (2011) took approximately 20 days to recover from cutting events and showed that repeated cuttings (or increased harvest) can lower the sink potential of a grassland.

Calculating the difference between the GPPs and ERs (Treatment - Control) of the two fields (Figure 7) removes the effect of events common to both fields such as weather. The spike in the difference between GPPs at the time of cutting is due to offset treatment dates. Following the glyphosate application GPP decreased on the Treatment field relative to the Control field while the difference between ERs was unaffected. This clearly shows that the difference between the effect of cutting and the effect of cutting and glyphosate lies mainly in changes to GPP not ER.

Killing and removing the above-ground portion of the vegetation from the Treatment field and removing the above-ground vegetation from the Control field had little impact on ER as a whole. According to Byrne and Kiely (2006) autotrophic respiration accounts for between 38% and 50% of grassland ER. If this holds true for our site there must have been additional heterotrophic respiration occurring on these fields making up for the lost autotrophic respiration. In this case the additional respiration must have been of a similar magnitude to the respiration of the removed biomass.

Manure

Solid cattle manure was added to the Treatment field between DOY 222 and 230. No manure was added to the Control field, excluding what was left by grazing cattle late in the season during the gap-filled period. The solid cattle manure application and incorporation events on the treatment plot were not followed by any immediate noticeable changes to NEP, GPP or ER. Eugster et al. (2010) also found that respiration does not generally increase following organic fertilizer applications. The input of nutrients and long-term breakdown of manure may still be affecting the fluxes but over a period of time that is too long to observe directly or link to any specific manure application event.

Tillage

Increased fluxes of CO_2 are expected from soil immediately following tillage events and these fluxes should be proportional to the intensity of the tillage event; more specifically tillage depth and post tillage surface roughness (Reicosky, 1997; Reicosky and Lindstrom, 1993; Reicosky et al., 2005). The first round of tillage on the Treatment field (Figure 4: DOY 240-241) reduced NEP to its lowest observed level, similar to the combined glyphosate-cutting event (DOY 225). The decrease in NEP could be due to either a reduction in GPP or an increase in ER. Since there was very little photosynthesizing vegetation on the field at the time of tillage we would expect the changes in NEP to be due mainly to ER. Figures 4a and b show GPP decreased following tillage of the Treatment field (DOY 240-241), which lowered GPP to below zero while there was little change to ER. A negative GPP is not possible. Since GPP is calculated as NEP minus ER, ER at night is equal to the measured NEE and daytime and gap-filled ER is modeled through its relationship with air temperature; a negative GPP is caused by uncertainty and variability in our estimation of NEP and ER. The decreases in NEP seen following tillage were likely due in part to increasing ER.

There were no measureable changes in fluxes from any tillage events following the original conversion tillage event. No previous studies could be found which investigate the effect of tillage events spaced throughout a season but several studies were found that may be related. Reicosky (1997) found that several passes of tillage can limit emissions by reducing the surface roughness and size of air-filled pores, although in this study all subsequent tillage occurred immediately following the original event and were not spaced throughout the season. A review of European cropland studies by Eugster et al. (2010), found ER increased following early season tillage but little to no increase followed late season tillage. Reicosky (1998) found the opposite to be true but linked the differences between spring and fall tillage events more to temperature than timing. Had the original tillage event not occurred, the observed increases in NEP (Figure 4; beginning DOY 225) may have continued causing the cumulative loss of carbon from the Treatment field to be lower. In this case delaying tillage until temperature is lower may be an effective method of minimizing carbon loss due to conversion.

Winter

As winter approached, air temperature decreased causing photosynthesis on the Control field to slow and eventually stop, marked by reductions in NEP, GPP and ER. The Treatment field had little to no photosynthesis occurring when the temperature began to decrease so temperature reductions were marked by increasing NEP due to decreasing ER. Differences can be seen by the 10-cm soil temperatures (Figure 2) because the soil temperature of the Treatment field is slightly higher than the Control field into the winter. Respiration was also greater on the Treatment field throughout the winter. Although the difference between the winter fluxes of the fields is small, winter in this region lasts several months so small fluxes have time to accumulate to significant levels. The Control field has higher NEP during both the calibration period and throughout the winter. So although there are valid explanations for the observed differences between NEPs, we cannot entirely rule out the possibility that an inherent offset between the fields is causing this difference.

2.4.3 Initial Effects of Land Conversion on Soil Carbon

The large reduction in the cumulative NEP of the Treatment field following cutting, glyphosate and tillage shows that conversion of this field from long-term perennial pasture to annual crop production caused a flux of accumulated carbon to the atmosphere in the year of conversion; opposed to the carbon gains observed on the unaltered continuous perennial Control field. Even when accounting for manure carbon imported to the treatment field the net carbon loss due to the conversion process was 245 g C m^{-2} (Table 6).

A full year of data was not collected in the 2009-2010 field season. The missing period from January to thaw is likely to have a slightly negative NEP; similar to the measurements from late October to December of the Control field (Figure 4; DOY 300-365). At some point following thaw NEP of both fields would have increased. Had this been a full year of flux data it is likely that the final cumulative NEP of both fields would have been different, although the difference between fields would have been similar to the reported value.

Note that the divergence of 245 g C m^{-2} reported in Table 6 accounts for the manure addition to the Treatment field. The addition of manure carbon reduces the observed divergence between the carbon content of the Treatment and Control fields. Values from Table 6 are also not corrected for energy balance closure. This correction would increase the carbon gains by the Control field and increase the losses by the Treatment field causing divergence to increase. These factors together indicate that the effect of conversion may be greater than 245 g C m^{-2}.

2.4.4 Implications for Greenhouse Gases and Soil Carbon Management

Data collected during the 2009 field season can be considered typical for the Woodlands region since 2009 climatic conditions were very close to 30-year seasonal averages. However, high surface soil organic carbon content and carbonate rich sub-soils indicate that caution should be used when extrapolating these results to other locations. To put the Woodlands soil carbon content in perspective, average soil organic carbon content of the 0 to 30 cm depths for all soil orders in Canada range from 4.9 to 18.7 kg C m^{-2} (Lacelle, 1997) while the 0 to 30 cm soil organic carbon content of the Treatment and Control fields are 20.9 and 22.1 kg C m^{-2} respectively (Table 4a). Even when using the lower estimates from Table 4b the 0 to 30 cm soil organic carbon of these fields is high ranging from 14 to 16 kg C m^{-2}.

To put the observations from this study in perspective, carbon emissions from the Treatment field following conversion were similar to the losses from established annual crops, and the carbon gains observed on the Control field were similar to other established grassland sites. A loss of 149 g C m^{-2} was observed from the treatment field following the perennial to annual conversion. Fluxes of similar magnitudes have also been observed from annual cropping systems not undergoing cropping system conversion events; such as Glenn et al. (2010) observed a mean net loss of 106±51 g C m^{-2} yr^{-1} from a 3-year annual rotation based south of Winnipeg and all annual rotations investigated by Kutsch et al. (2010) were net carbon sources with a mean of 95±87 g C m^{-2} yr^{-1}. The carbon gains from the Control field (96 g C m^{-2}) are similar to other grassland sites; 126±14 g C m^{-2} y^{-1} (Ferlan et al., 2011), 118±36 g C m^{-2} y^{-1} (Meyers, 2001), and 147±130 g C m^{-2} y^{-1}. However, Ammann et al. (2007) did report a non-significant loss of -57 +110 or -130 g C m^{-2} y^{-1} from a grassland site.

Sequestering soil carbon with perennial crops may occur relatively quickly but newly gained carbon may also be lost relatively quickly by periodic inclusion of annual crops in rotation (Janzen et al., 1998). Under these conditions crediting or otherwise giving producers incentives to convert annual cropland to perennial grasslands for the purpose of removing carbon from the atmosphere may only be valid if grasslands remain under perennial management indefinitely.

It is apparent that carbon sequestration benefits increase with the length of the perennial grassland rotation but it is not reasonable to expect producers to maintain pastures indefinitely. It may be possible to minimize carbon losses following perennial to annual conversions by using beneficial management practices such as using reduced intensity tillage practices (Jabro et al., 2008) and delaying tillage until the soil is cool (Reicosky, 1998), which will help reduce the fallow proportion of the growing season and reduce ER following the conversion events. Perennial and annual rotations may be alternated but by extending the perennial phase of a crop rotation with respect to the annual phase; slow, long-term increases in SOC may be possible.

2.5 Conclusions

Since the difference between the fields following conversion can be seen mainly in GPP while ER was affected relatively little, the overall effect of conversion seems to be most strongly related to the relative length of the cropped and fallow periods within the growing season.

ER remained relatively constant for each field throughout the season and explained the majority of the difference between NEPs during the calibration period. Therefore the difference between cERs of 83 g C m^{-2} provides a reasonable estimate of uncertainty in the difference between cNEPs.

The perennial system gained 96 g C m^{-2} and the transitional system lost 149 g C m^{-2}. The net effect of conversion from a perennial to annual cropping system in the year of conversion was the loss of more than 245 g C m^{-2}. By comparing the converted Treatment field to a Control field the full loss of carbon from conversion, including avoided carbon sequestration, can be measured. From this scenario of potential repeated carbon gains by an unaltered system and potential repeated losses by the converted system the organic carbon content of the fields will diverge relatively quickly. At the current rate of divergence, at least 245 g C m^{-2} (2.5 tonne C ha^{-1} yr^{-1}) of atmospheric carbon could be avoided by maintaining this perennial grassland cropping system. The rate at which the fields carbon contents diverge may change in the future when the spring period, which will be fallow on the Treatment field and cropped on the Control, are included. When repeated carbon losses are weighed against repeated carbon gains, the benefits of extending perennial rotations becomes clear. When it is not possible to maintain perennial grassland rotations indefinitely, it may be possible to minimize losses with beneficial management practices and increase the relative length of the perennial grassland phase in crop rotations. Increasing the length of the perennial grassland phase of rotations may change the equilibrium between potential soil carbon losses during annual phases and potential gains during the perennial phases to favour long-term gains.

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3 GENERAL SYNTHESIS

3.1 Brief Overview of Findings

The effects of landscape conversion were seen mainly in GPP while ER remained constant. This finding is supported by literature. Baldocchi (2008) stated that the greatest sequestration rates are generally from the longest growing seasons and the greatest losses are from disturbed ecosystems. Svejcar et al. (2008) found perennial rangeland sites could be either source or sink depending on management and climatic conditions and stated that maximum CO_2 uptake can be achieved by ensuring that management does not limit plant growth. Ammann et al. (2007) stated that carbon sequestration generally increases with GPP of an ecosystem and showed that drought causes decreased sequestration because lack of moisture suppresses plant growth causing decreasing GPP while ER remains somewhat constant. This does appear to be the dominant mechanism behind the observed net effect of landscape conversion, however, Eugster et al. (2010) showed that a number of management practices can affect ER fluxes; the most relevant being cutting, tillage and herbicide applications. Management effects on ER may have been small with respect to normal variability so they may not be detectable or the procedures used to partition NEP into GPP and ER may have attributed fluxes to GPP when in fact they were due to ER. An example of a time when this was likely is following tillage of the treatment field (Figure 5: DOY 240-241). GPP reduced following tillage ending below zero. Negative GPP is not logical so the likely solution is that a spike in ER was attributed to an underestimate of GPP.

Since the difference between ERs of the fields remained relatively constant and this difference explains much of the difference between NEPs during the calibration period the comparison between fields could be calibrated for comparison by providing error bars for the difference between NBP based on cER measurements. These error bars would be in addition to any error generated by the eddy covariance systems. This is the only paired study I am aware of that was able to use this approach.

This study has shown that the perennial system gained 96 g C m^{-2} while the annual system lost 149 g C m^{-2}. However the value of this study lies in the correlation between the fields allowing them to be compared directly to determine the amount of carbon which could have been sequestered by maintaining the perennial rotation and the full impact of landscape conversion. The effect of the conversion event was a loss of 245 g C m^{-2} yr^{-1}; This was likely an underestimate when accounting for the for energy balance closure and the manure application which was applied to the treatment field only.

3.2 Detection Limits and Justification of Methodology

To investigate the impact the measured fluxes will have on current carbon stocks we can calculate the theoretical percent decrease in current soil organic carbon stock from the observed fluxes. This calculation is an approximation so the average bulk density and average soil organic carbon of the two fields will be used as well as the assumption that the majority of the fluxes are generated from the 0-30 cm depths. From the average bulk densities of 1.02 Mg m^{-3} for the 0-15 cm and 1.39 Mg m^{-3} for the 15-30 cm depths we find that a 1 m^2 soil slice which is 30 cm deep will weigh 360000 g. The average soil organic carbon contents from Table 4a are 8.97% and 3.81% for the 0-15 cm and 15-30 cm depths; or 5.99% for the 0-30 cm depth when adjusted for bulk density differences. This corresponds to 21500 g C m^{-2} of SOC in the 0-30 cm depth. A flux of 245 g C m^{-2} y^{-1} would amount to a loss of 0.068% by soil mass or a loss of 1.14% of the current SOC stock. Keep in mind the flux of 245 g C m^{-2} yr^{-1} is composed of a measured loss of 149 g C m^{-2} from the Treatment field and an avoided gain of 96 g C m^{-2} on the Control field. This loss and gain correspond to 0.69% and 0.45% changes to the current SOC stock.

Yang et al. (2008) found that due to the natural variability of soils the minimum detectable difference between soil carbon contents for soils above the 30 cm depth was in the range of 0.18-0.46% by soil mass. Smaller differences could be detected but would involve a large numbers of replicates or several years for changes to accumulate to the detectable range. The carbon fluxes detected in this study amount to a difference of 0.068% by soil mass, which decreases further when we consider that only a portion of this difference was generated on each field (Treatment 0.041% and Control 0.027%). Assuming that fluxes are constant from year to year; carbon fluxes of this magnitude would require a minimum of 7 to 17 years for carbon losses from the Control field to become detectable by standard soil sampling techniques. This illustrates the sensitivity of eddy covariance instrumentation for detecting changes in soil carbon stocks and its usefulness as a tool for detecting the effects of short term or periodic changes to soil or crop management practices.

The Treatment field lost 149 g C m^{-2} in 2009; however the carbon loss only amounts to 0.69% of the current SOC stock. This highlights the size of the pool of carbon which could be lost to the atmosphere over time under similar management scenarios. A seemingly large flux of carbon amounting to a relatively small change in carbon stock also speaks to the sink potential of low SOC soils. Since there is a maximum amount of SOC which can be sequestered in soil (West and Post, 2002), low carbon soils have the potential to store a larger mass of atmospheric carbon in a shorter time than high SOC soils. But this should not undermine the importance of preserving current carbon stocks.

3.3 Implications and Future Work

For the purposes of this study fluxes generated during cattle grazing were replaced using gap-filling procedures. However cattle have other impacts on the carbon balance of these fields which were not considered in the scope of this study. Biomass which was eaten and respired, manure remaining and cattle weight gain exported will impact the overall carbon balance of these fields and will need to be included should this study continue into the future.

This study indicates that carbon can be lost relatively quickly from fields with high initial SOC content. It is important to note that the value of 245 g C m^{-2} is the difference in carbon with respect to an unaltered field. The soil carbon content of the Treatment field would only decrease by 149 g C m^{-2}, but 96 g C m^{-2} would have been gained on an unaltered field. Assuming the measured rate of loss is constant it would take 36 years for ¼ of the SOC stock of the treatment field to become depleted. It is very likely that the rates will change in the future. As the spring fallow period is included in the measurements the losses may increase, although the field may also acclimatize to annual cropping decreasing the fluxes from fallow and tillage events. Manure rates are also likely to change in the future.

This study has shown that on a high SOC soil, carbon losses from a perennial to annual conversion may occur faster than carbon gains from long-term perennials. Moreover West and Post (2002) have stated that it may take 5-10 years for carbon sequestration rates to peak following improvements to rotation and tillage systems. This means if perennials were reseeded or tillage systems were improved it may be several years before any substantial amount of carbon can be sequestered. Faster carbon losses from the conversion event would imply that short rotations of perennials may not sequester any new carbon because longer perennial rotations may be required to offset the carbon lost during conversion to annual crops. A longer study will be required to determine if this is the case; such a study could also serve to address the issue of inter-annual variability. Many studies including Ammann et al. (2007) show that year-to-year changes in climatic conditions can impact the fluxes and the conclusions drawn from a study. Allowing these towers to continue measurements for several years would provide some insight into how these high SOC soils respond to changing environmental conditions in conjunction with management decisions. If the changes to the management of the Treatment field continue SOC will eventually equilibrate to the new cropping system (Janzen et al., 1998; Smith et al., 2000). West and Post (2002) have stated that some management changes may cause fluxes to equilibrate within 40-60 years. This is a very long time for a flux study and is therefore not feasible although carbon flux rates for several years may be used to estimate when equilibrium will be reached.

If carbon which has been sequestered over several years can be released by periodic conversion to annual crops, carbon credit systems which account for carbon sequestration by perennial crops may need to be re-evaluated. It is true that perennial crops have the ability to sequester atmospheric carbon however the crop rotation should also be considered. Maintaining a perennial rotation indefinitely simply to preserve sequestered carbon may not be feasible for many producers. Carbon release to the atmosphere may potentially be reduced by maintaining perennial crops for longer intervals before conversion to annual crops. Minimizing the losses from a perennial to annual conversion event may also be possible by maximizing yields for the warm season (Ammann et al., 2007; Baldocchi, 2008; Svejcar et al., 2008) while waiting for the soil to cool before beginning the conversion process (Reicosky, 1998). The process of trying to optimize a perennial to annual conversion event would also make for an interesting future study.

3.4 References

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4 APPENDICES

Appendix A. Tower Design

Appendix A contains a number of photos displaying tower position, instrument position and construction details. Figure A1 shows the position of the various tower components. The blades of the wind generator are in the process of being installed in the photo.

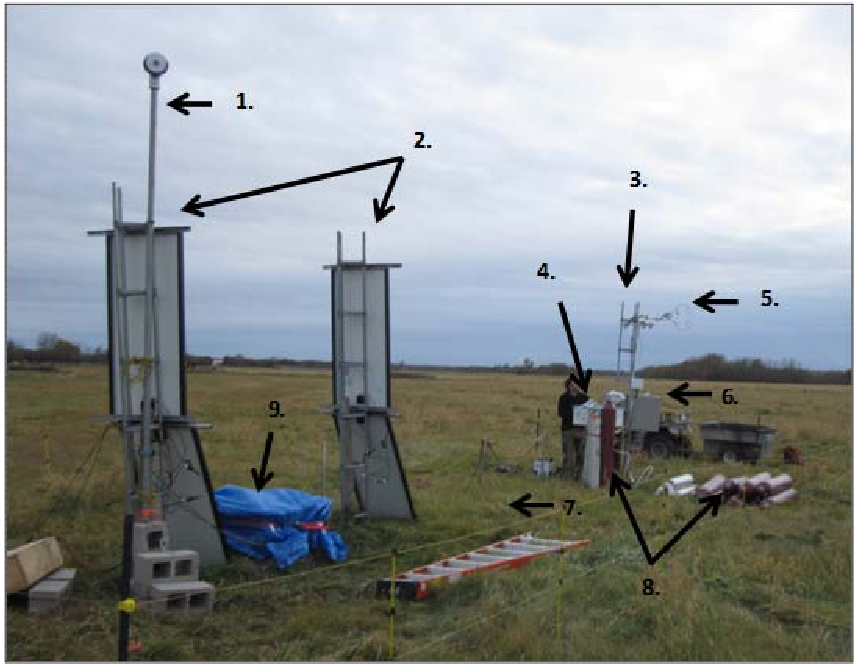

Figure A 1. Tower Components and Their Positions.

1. Wind Generator Post
2. Solar Panels on Power Towers
3. Instrumentation Tower for Sonic Anemometer, Relative Humidity, Air Temperature, Solar Radiation and Photosynthetically Active Radiation
4. Temperature Controlled Housing for the Infrared Gas Analyzer
5. Location of the Sonic Anemometer and Gas Intake
6. Logger, Pump and Power Boxes
7. Location of Ground Heat Flux Plates, Moisture Probes, Rainfall Gauge and Thermocouples
8. Tanks for Reference and Calibration Gasses

The temperature controlled housing (TCH), depicted in figure A2, is designed to keep the infrared gas analyzer (IRGA) at optimal operating temperature. The TCH also contains the hardware necessary for automated calibration of the IRGA. The TCH is composed of an inner box which contains the instrumentation and an insulated outer box. Air can be circulated between the two layers to cool the IRGA. The TCH also contains a heater to raise the temperature of the IRGA.

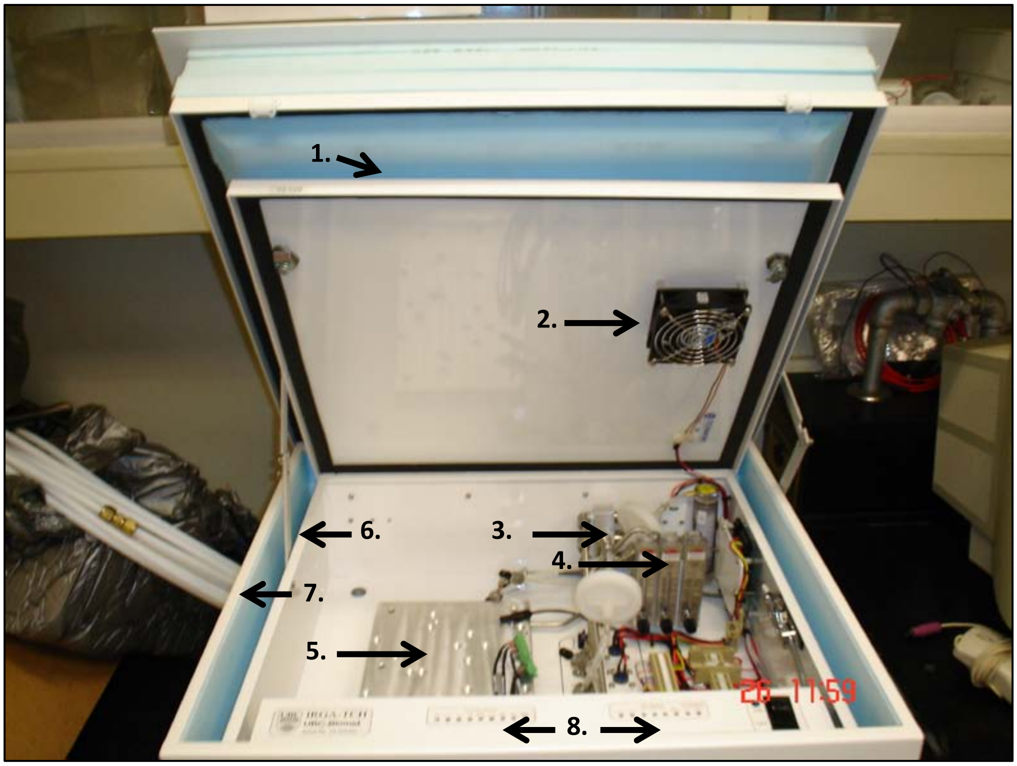

Figure A 2. Inside the Temperature Controlled Housing.

1. Vented Cooling Fans Between the Two Boxes
2. Internal Box Air Circulation Fan
3. Solenoid Valves for Automated IRGA Calibration
4. Rotameters for Limiting Reference, Calibration and Sample Gas Flow Rates
5. Heated Mounting for the IRGA
6. Inner Box
7. Insulated Outer Box
8. TCH Diagnostic Lights and Power Switch

Figures A3 to A6 show the contents of the data logger, pump and power boxes. Note that relays were installed after these photos were taken. Relays were installed in the boxes which contains the terminal strips and pump. The terminal strips have been divided into “direct” and “relay” sections. The portion labeled “direct” is powered directly from the batteries while the portion labeled “relay” was routed through the logger controlled relay switch. The pump, IRGA and Sonic Anemometer were powered through the relay; all other devices were powered directly from the batteries or through the data loggers.

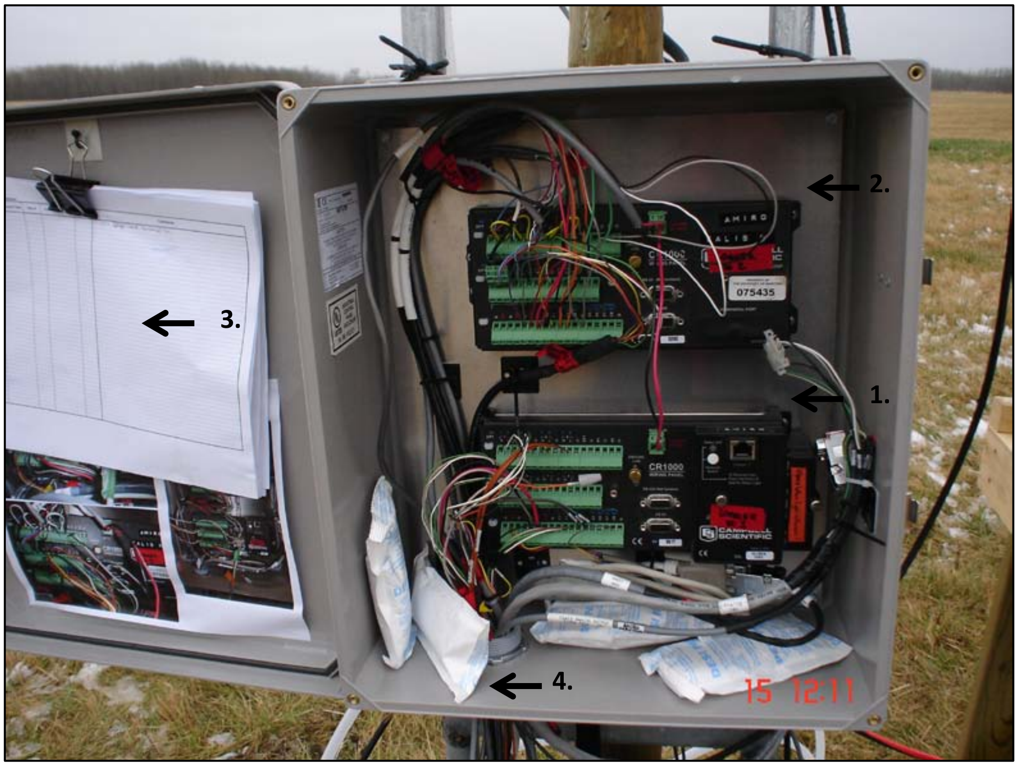

Figure A 3. The Treatment Field Logger Box.

1. Logger 1: Primarily for High Frequency Data Collection
2. Logger 2: Primarily for Supporting Meteorological Data Collection
3. Log Sheets
4. Packaged Desiccant

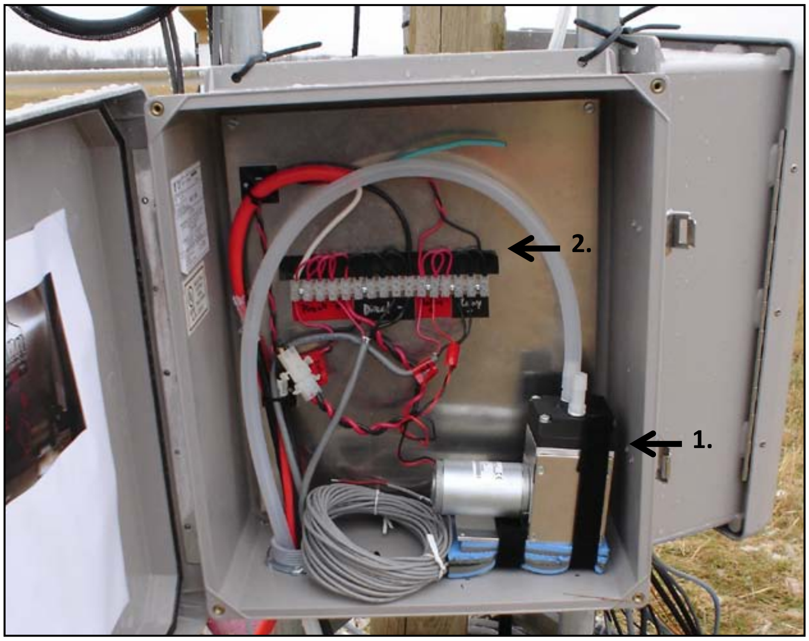

Figure A 4. The Treatment Field Pump and Terminal Strip Box

1. Pump
2. Power Terminal Strips: Direct on Left, Relay on Right

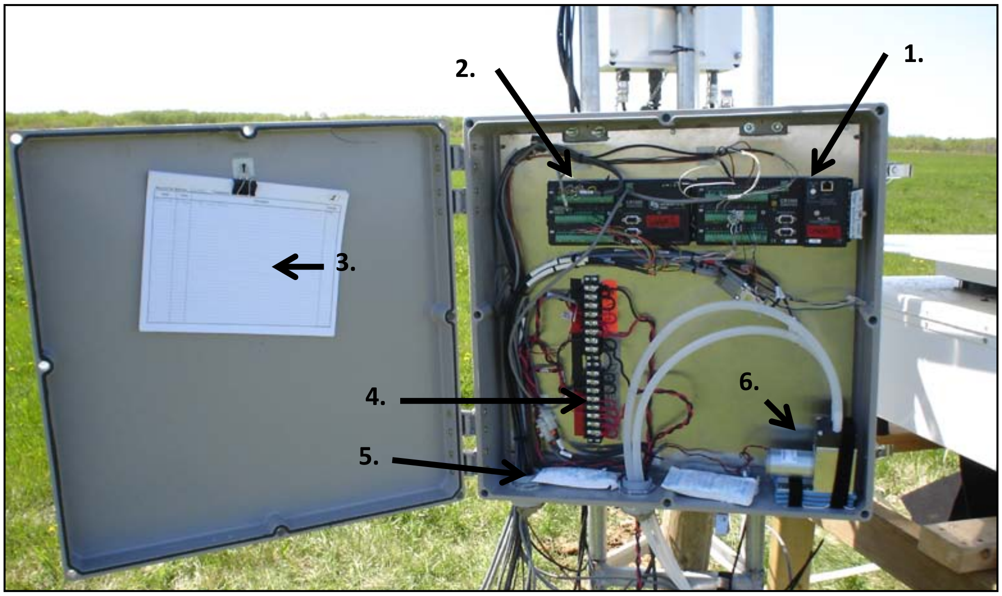

Figure A 5. The Control Field Logger, Pump and Terminal Strip Box

1. Logger 1: Primarily for High Frequency Data Collection
2. Logger 2: Primarily for Supporting Meteorological Data Collection
3. Log Sheets
4. Power Terminal Strips: Relay on Top, Direct on Bottom
5. Packaged Desiccant
6. Pump

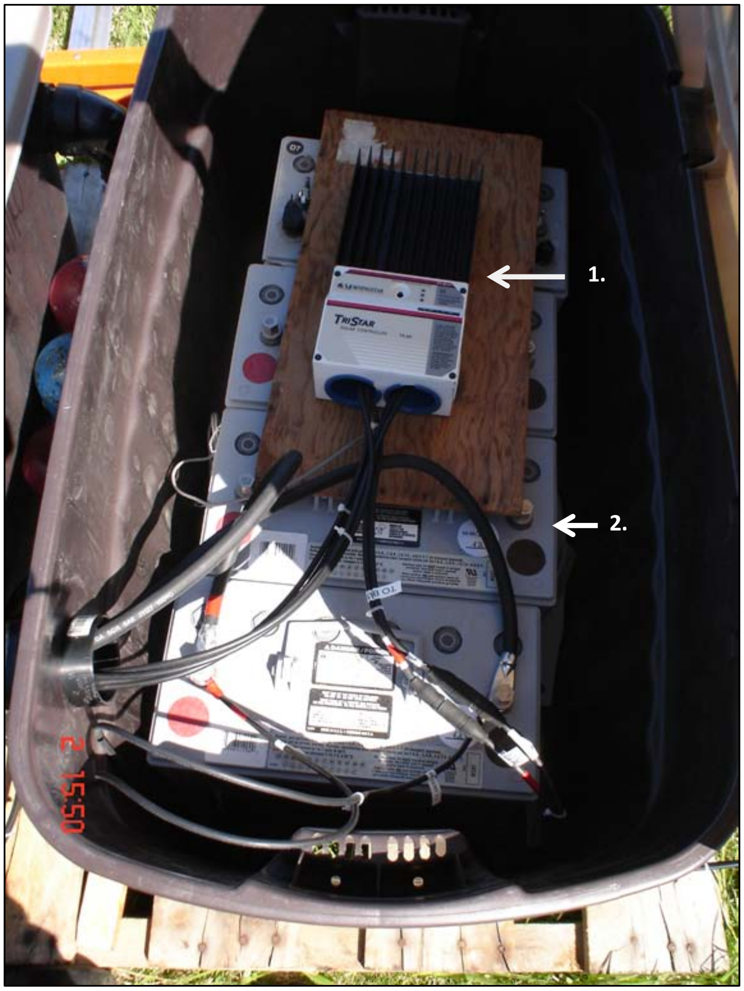

Figure A 6. Power Box

1. Solar Charge Controller
2. Batteries

Appendix B. Flux Data Corrections

Brian Amiro and Trevor Fraser

B1. Introduction

This Appendix outlines some technical issues related to measurement of eddy fluxes using the instrument system. This Appendix was largely written by Brian Amiro, the advisor of Trevor Fraser, and this Appendix does not form part of the thesis contribution of the student. However, this section helps to explain some of the possible issues and biases that are inherent in the flux measurement system.

B2. High-frequency losses

Part of the turbulent flux signal can be lost in transit through the tubing to the infrared gas analyser in closed path systems. The relative loss can be computed for a system by comparison to the sensible heat flux measurement from the sonic thermometer-anemometer with the assumption that it has no frequency loss. Losses in the sampling tubing are preferentially at the high end of the spectrum.

We estimated high-frequency losses by selecting four 30-min periods in 2010 on July 23 (1300), August 13 (1300), August 16 (1300) and August 16 (1500). We calculated the spectral energy in sensible heat flux (H), latent heat flux (LE) and carbon dioxide flux

(NEE). For various frequency bands, we used the “tstool” function in Matlab to create the spectra and used the integration tool that allowed for calculation of the % of the total variance in a given band width. This was done for each of H, LE and NEE in a given 30-min data set. The energy loss in LE and NEE was determined by subtracting the % of the flux for each of these from the % of the flux that was in H for the band, starting cumulatively from the high range at 5 Hz. We then took this % loss and multiplied it by the % of H at this band width to give the contribution loss for a band width. The results in Figure B1 indicate that a maximum of about 5% is lost for both LE and NEE in our system. Although we expect some differences during different atmospheric conditions, we use a correction of 1.05 to increase the LE and NEE fluxes based on these tests.

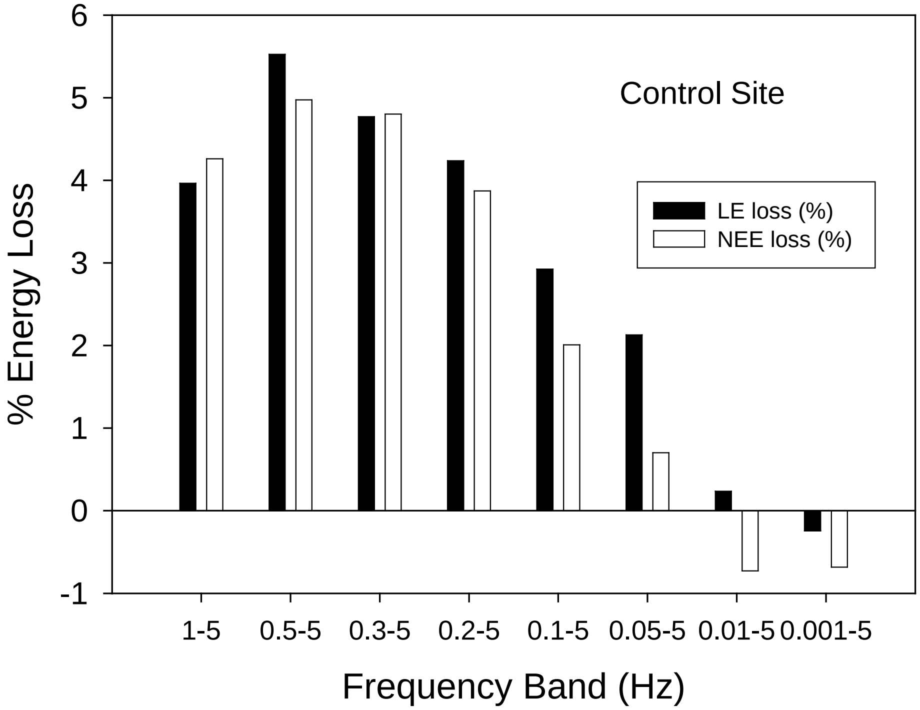

Figure B 1. Percentage loss of energy at high frequencies for LE and NEE in the closed path system.

B3. Energy Budget Closure

Closure of the energy budget is accomplished if the turbulent terms (sensible (H) and latent heat (LE) fluxes) are equal to the available energy (net radiation (Rnet) minus ground heat flux (G) and storage terms (S)). For many of the global FLUXNET sites, about 20% of the energy is typically not accounted (Wilson et al. 2000). There is debate whether this missing energy should be considered as an underestimate of the turbulent flux terms, such that all turbulent flux terms (including NEE) should be increase by the fraction of missing energy. To a large extent, the flux community supports the idea of reporting energy closure, and then estimating the possible bias in the NEE measurements if the values are not adjusted for closure. This makes the possible correction transparent and typically, NEE could be increased by 10 to 20% if we assume that lack of energy closure is a diagnostic on the underestimation of turbulent fluxes.

For this particular study, we calculated energy closure at each site by comparing H + LE to Rnet-G-S. Rnet was determined from the CNR1 net radiometers; G from the mean of the two soil heat flux plates, and S term (W m^{-2}) was calculated as $0.55.*2.*10^6$*Tdiff*0.05/1800, where Tdiff is the change over 30 minutes in the mean of the air temperature (at 3 m height) and the soil temperature at the 10-cm depth to approximate the near-surface temperature for a 2-cm slab of soil. Typically, S is small relative to the other terms.

We found that scatter was greatly reduced by selecting data under "ideal" conditions, defined as:

- Friction velocity > 0.5 m s^{-1}
- Wind direction on axis when the wind velocity in the on-axis direction > 1 m s^{-1}
- At the treatment site for DOY 180 to 250, and control site for DOY 160 to 250.

For the treatment site, the regression was H+LE = 0.82*(Rnet-G-S) + 6.0 (units W m^{-2}) with $r^2 = 0.98$, n = 83 (Figure B2).

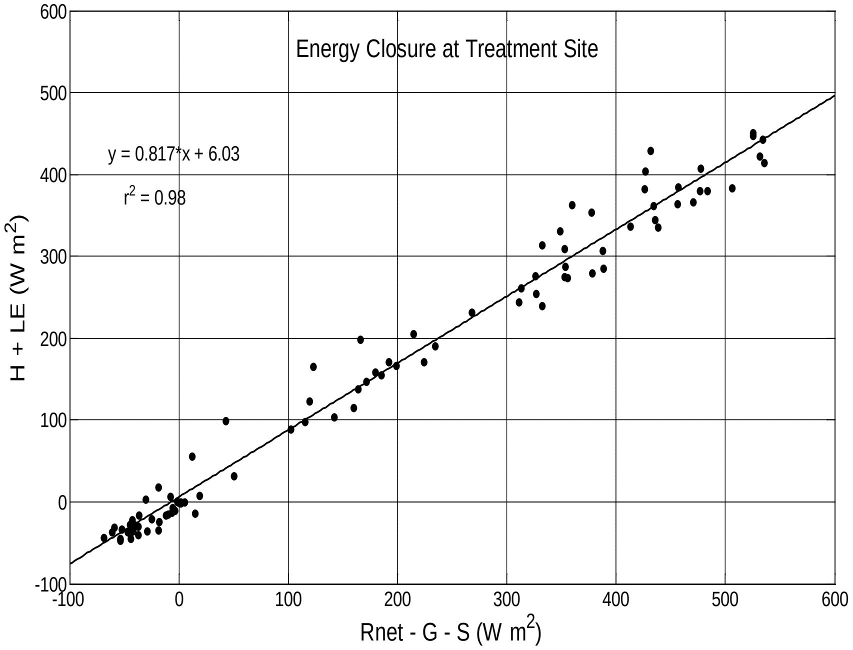

Figure B 2.Energy Closure at the Treatment Site

We applied the same conditions at the Control site, but the closure was poorer with H+LE = 0.59*(Rnet-G-S) + 17 (units W m^{-2}). One concern was the possibility that the CNR1 net radiometer may be giving high radiation values. Previous comparison of our CNR1 radiometers and NR-Lite radiometers showed that the CNR1 gave an average of 22% greater net radiation (Barker et al. 2009). To test this possibility, we compared the CNR1 radiometer against a new CNR4 radiometer (Kipp and Zonen, Delft, The Netherlands) at the control site during May 2011. The relationship was (CNR1) = 1.17 * (CNR4) – 6.3 (units = W m^{-2}), with a mean ratio of CNR1/CNR4 = 1.096 for the population of data. Hence we believe that the actual energy closure at this site is actually better than the initial regression, once we account for the net radiometer uncertainty (bias). Taking this into account, closure is still poorer than at the Treatment site with H+LE = 0.7*(Rnet-G-S) - 21.4 (units W m^{-2}) with $r^2 = 0.90$, n = 141 (Figure B3).

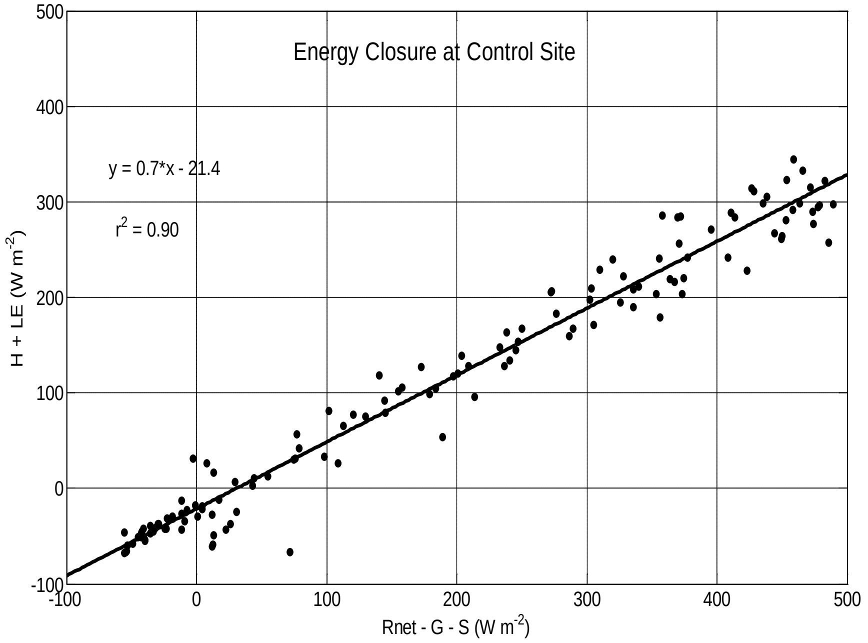

Figure B 3. Energy Closure at the Control Site

Our conclusion here is that the energy balance is poorer than we would hope but is not abnormal compared to measurement made at FLUXNET sites globally. We do not yet understand why closure is poorer at the Control Site than at the Treatment Site. Assuming that the net radiometers are accurate, it is possible that we are underestimating the turbulent terms by 20 to 30%, depending on the site. This could create an overall bias of this magnitude in the NEE measurements as an underestimate.

B4. References:

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Appendix C. Soil Carbon Analysis; Soil Carbon in the 0-30 cm Depth

Appendix C shows the calculation of the 0-30 cm soil carbon content. Table C1 uses values directly from table 4 a and 4 b. The sample numbers used are identical to the values from the table 4 a and 4 b.

Table C 1. Soil Carbon in the 0-30 cm Depth.

Soil Survey Analysis

	TC kg m^{-2}		OC kg m^{-2}		IC kg m^{-2}	
Depth	T	C	T	C	T	C
0-15	14.38	17.08	12.45	14.80	1.93	2.29
15-30	17.39	17.15	8.43	7.34	8.96	9.81
Total	31.77	34.24	20.88	22.14	10.89	12.10

ALS Analysis

	TC kg m^{-2}		OC kg m^{-2}		IC kg m^{-2}	
Depth	T	C	T	C	T	C
0-15	11.32	10.84	9.04	8.69	2.28	2.15
15-30	13.77	11.82	6.81	6.11	6.95	5.71
Total	25.08	22.65	15.85	14.80	9.23	7.86

ALS data is calculated using analysis from a single composite sample.

Appendix D. Manure Application and Analysis

Manure samples were collected in a partially dried state; the original moisture is unknown. Samples were then fully dried and sent for analysis. The application rate of 28 tonne/ha was calculated using the average dry matter of beef manure as reported in the Tri-Provincial Manure Application and Use Guidelines (PPCLDMM, 2004).

Table D 1. Cattle Manure Dry Analysis and Application Information.

	Manure	TC	TN	P	K	S
ppm		280000	10750	2350	3500	2150
kg/ha	7400[†]	2058.4	79.0	17.3	25.7	15.8
g/m^2	740[†]	205.8	7.9	1.7	2.6	1.6

[†] Manure application was estimated from the producer application rate of 28 tonne/ha, at average beef manure dry matter of 26.4% (Tri-Provincial Manure Application and Use Guidelines).

D1. References

PPCLDMM. 2004. Tri-Provincial Manure Application and Use Guidelines – Manitoba Version [Online]. Available by The Prairie Provinces' Committee on Livestock Development and Manure Management http://www.gov.mb.ca/agriculture/livestock/beef/pdf/baa08s01a.pdf (verified July 19, 2012).