SURFACE-ATMOSPHERE EXCHANGE OF CARBON DIOXIDE, WATER, AND HEAT ACROSS A DRYLAND WHEAT-FALLOW ROTATION

by

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# TABLE OF CONTENTS

1. INTRODUCTION
   - Contribution of Authors and Co-authors ................................................. 1
   - Manuscript Information Page ........................................................................ 1
   - Abstract ............................................................................................................. 2
   - Introduction ....................................................................................................... 2
   - Materials and Methods ..................................................................................... 2

2. THE INFLUENCE OF DRYLAND AGRICULTURE
   WHEAT-FALLOW ROTATION ON THE EXCHANGE
   OF CARBON, WATER, AND HEAT WITH THE
   ATMOSPHERE ..................................................................................................... 3

   - Site Description.................................................................................................. 3
     - Agricultural Fields in the Judith River Basin .................................................. 3
   - Measurements .................................................................................................... 3
     - Meteorological Measurements ..................................................................... 3
     - Turbulent Flux Measurements .................................................................... 3
   - Gapfilling and Data Processing ....................................................................... 3
     - Gapfilling Soil Heat Flux ............................................................................. 3
     - Gapfilling Carbon Dioxide Flux .................................................................. 3
     - Gapfilling Latent Heat Flux ........................................................................ 3
     - Gapfilling Sensible Heat Flux ..................................................................... 3
   - Uncertainty Analysis ......................................................................................... 4
   - Energy Balance ................................................................................................. 4
   - Results ................................................................................................................ 4

BIBLIOGRAPHY ........................................................................................................ 5

Scientific Background ................................................................................................. 5
Global Wheat Production ............................................................................................ 5
   - Global Overview and National Statistics ......................................................... 5
Wheat in Montana ...................................................................................................... 5
   - Statewide Overview and Statistics ................................................................ 5
   - Wheat/Fallow Rotations .................................................................................. 5
Sustainability ............................................................................................................... 6
Fallow Avoidance and Canadian Prairies ................................................................. 6
Previous Eddy Covariance Measurements in Wheat ............................................... 6
Fallow Management Practice ................................................................................... 6
   - Water Savings and Management .................................................................. 6
   - Carbon Loss ..................................................................................................... 6
Study Objectives ....................................................................................................... 6

Global Wheat Production ........................................................................................ 6
   - Wheat/Fallow Rotations .................................................................................. 6
Sustainability ............................................................................................................... 6
Fallow Avoidance and Canadian Prairies ................................................................. 6
Previous Eddy Covariance Measurements in Wheat ............................................... 6
Fallow Management Practice ................................................................................... 6
   - Water Savings and Management .................................................................. 6
   - Carbon Loss ..................................................................................................... 6
Study Objectives ....................................................................................................... 6
### TABLE OF CONTENTS

General Weather Conditions ................................................................. 27  
Soil Moisture .......................................................................................... 27  
Plant Height Growth .............................................................................. 28  
‘u’ Thresholds ....................................................................................... 28  
Energy Balance Closure ....................................................................... 29  
Carbon Dioxide Fluxes .......................................................................... 29  
Evapotranspiration ................................................................................ 30  
Sensible Heat Fluxes .............................................................................. 31  
Atmospheric Boundary Layer Modeling .................................................. 31  
Discussion ............................................................................................. 32  
Carbon Dioxide Exchange ..................................................................... 32  
Management Impacts on Hydrology ......................................................... 36  
  Soil Moisture ....................................................................................... 36  
  Evapotranspiration .............................................................................. 37  
  Sensible Heat Fluxes and ABL Simulations .......................................... 38  
Conclusion ............................................................................................ 40

3. FUTURE DIRECTIONS ....................................................................... 58

BIBLIOGRAPHY .................................................................................... 61
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. List of Equation Variables and Abbreviations with Definitions</td>
<td>42</td>
</tr>
<tr>
<td>2. Measurement and Instrumentation Type at Site Location</td>
<td>44</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top Five Wheat Producing Countries</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>Conceptual Figure</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Site Map</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>Air Temperature</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>Soil Moisture plots at 5 cm and 10 cm</td>
<td>46</td>
</tr>
<tr>
<td>6</td>
<td>Canopy Height</td>
<td>47</td>
</tr>
<tr>
<td>7</td>
<td>Energy Balance Closure</td>
<td>48</td>
</tr>
<tr>
<td>8</td>
<td>Cumulative Sum C-CO₂</td>
<td>49</td>
</tr>
<tr>
<td>9</td>
<td>Monthly total C-CO₂</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>Cumulative Sum ET</td>
<td>51</td>
</tr>
<tr>
<td>11</td>
<td>Monthly total ET</td>
<td>52</td>
</tr>
<tr>
<td>12</td>
<td>Cumulative Sum H</td>
<td>53</td>
</tr>
<tr>
<td>13</td>
<td>Monthly total H</td>
<td>54</td>
</tr>
<tr>
<td>14</td>
<td>Atmospheric Boundary Layer Height</td>
<td>55</td>
</tr>
<tr>
<td>15</td>
<td>Snow Depth Photo Example</td>
<td>56</td>
</tr>
<tr>
<td>16</td>
<td>CO₂ Uptake/Crop Height Relationship</td>
<td>57</td>
</tr>
</tbody>
</table>
ABSTRACT

Summerfallow – the practice of keeping a field out of production during the growing season – is a common practice in dryland wheat (Triticum aestivum L.) cropping systems, including those of Montana. It is currently unknown how seasonal patterns of carbon dioxide, water, and heat flux between ecosystems and the atmosphere differ between fallow and wheat. This study quantifies the impact of dryland wheat vs. chemical fallow agricultural management practices on these important surface-atmosphere exchanges using the eddy covariance method across a winter wheat – spring wheat – fallow rotation in the Judith Basin, MT. I used a suite of meteorological sensors to measure relative humidity, air temperature, soil moisture, wind speed and direction, incident and reflected shortwave radiation, upwelling and downwelling longwave radiation, crop height, and soil heat flux to further quantify the impacts of this cropping sequence on biophysical attributes of the land surface and to model turbulent fluxes. Both wheat fields were carbon sinks on the order of 110 to 205 g C m\(^{-2}\) during the April to September study periods of 2013 and 2014, while the fallow field was a carbon source to the atmosphere on the order of 135 g C m\(^{-2}\) during the April to September study period of 2014. Evapotranspiration (ET) was over 100 mm greater in a spring wheat field than in a simultaneously measured fallow field during the 2014 study period, and modeled maximum daily atmospheric boundary layer height was up to 800 m higher in fallow compared to spring wheat. Results demonstrate that fallow has a detrimental impact to soil carbon resources yet is less water intensive, with consequences for regional climate via its impacts on atmospheric boundary layer development and global climate via its carbon metabolism.
CHAPTER 1

INTRODUCTION

Scientific Background

Global Wheat Production:

Global Overview and National Statistics. Croplands and pastures comprise ca. 38% of the global land surface (Foley et al., 2011). Wheat provides more than 20% of calories and proteins for the global population (Hawkesford et al., 2013) and, as the third-highest wheat-producing country (Figure 1), the United States plays a large role in feeding the world.

The challenge is to sustain our agricultural output and ensure future yields on a planet where temperatures continue to rise due to accumulation of anthropogenic greenhouse gases in the atmosphere (Stocker et al., 2014; IPCC, 2007). Efforts are ongoing to limit warming to under 2 °C from baseline conditions (Meinshausen et al., 2009), often called the limit for ‘dangerous climate change’ (Smith et al., 2009). Yet models suggest that temperature increases of only 2 °C may cause a 50% reduction in wheat yield in major growing areas (Asseng et al., 2011) and that global wheat production may fall by 6% for each further degree °C of temperature increase (Asseng et al., 2015). We need a stronger understanding of how climate impacts agricultural output and how in turn agriculture impacts climate in order to gain a better understanding of the sustainability of current agricultural cropping practices.
Wheat in Montana:

Statewide Overview and Statistics. Wheat production is a major contributor to Montana’s economy and makes up a large proportion of the state’s land area. Montana ranks 3rd among the United States for wheat production, yielding ca 55,000 tonnes in 2013, equating to $1.39 billion in production value (NASS, 2014). In 2013 close to 1.2 million ha of spring wheat was planted which was harvested later in 2013. Later that year, about 800,000 ha of winter wheat was planted, which was harvested in 2014 (NASS, 2013). The wheat produced in Montana is important not only to the United States, but globally as well; ca. 80% of the wheat produced in Montana is shipped overseas to Japan, Taiwan, The Philippines, and South Korea while the other 20% remains in the United States (Consumer Education, 2013). The 2012 census of agriculture revealed that 28.5% of the land in farms and ranches across Montana was cropland, of which 4.6% was cultivated summerfallow (NASS, 2014).

Wheat/Fallow Rotations. Wheat production in Montana continues to be dominated by dryland farming, where a rotation sequence includes various cereal grains and summerfallow. Summerfallow is the practice of leaving areas of production without plant cover, with the goal of limiting transpiration and allowing stored soil water to accumulate for higher production in the following crop rotations. Alternative cropping strategies including the use of pulse crops and cover crops to avoid fallow have become more common over the past decades (Miller et al., 2002; Miller et al., 2003), especially in the northeastern part of the state (Long et al., 2014). Understanding how the wheat/fallow
rotation strategy impacts biogeochemistry (like the exchange of carbon between ecosystems and the atmosphere), hydrology, and the flux of heat into the atmosphere will help us identify how agriculture and climate interact and help identify sustainable land management strategies.

**Sustainability:**

Current summerfallow practices may have economic benefits over the short-term, but may also cause long-term degradation of ecosystem services. Therefore, these practices need to be reconciled for the continued provision of agricultural products to a growing populace (Foley et al., 2005, Bagley et al., 2012). Summer fallow is a common management practice in the dryland wheat growing regions of the Northern Great Plains of the USA, but fallow increases erosion (Wischmeier, 1959) and soil carbon loss (Cihacek and Ulmer, 1995), and summerfallow-small grain management strategies are not considered sustainable from the soil conservation perspective (Merrill et al., 1999). It is important for cropping systems to not only maintain, but to increase soil organic matter, if possible. Increased organic matter enhances the water holding capacity of the soil, as well as the availability of nutrients and the sequestration of carbon (Tilman, 1998; Lal, 2001). Croplands have the potential to sequester carbon on the order of 50-100 Tg C per year (Smith et al., 2000), which benefits not only atmospheric carbon dioxide concentrations but also the quality of soil (Lal, 2004). Differences in the atmospheric carbon exchange among fallow and wheat fields during the growing season are not well understood as comparative measurements have never been made. It stands to reason that
the wheat crop sequesters carbon and a fallow field will lose carbon to the atmosphere, but the magnitude of these fluxes has yet to be ascertained.

Fallow Avoidance and Canadian Prairies:

Large-scale changes in land use away from fallow practices have been suggested to result in a cooler and wetter regional climate (Gameda et al., 2007). Trends away from fallow have impacted regional climate, but the mechanisms by which this occurred is not entirely clear (Tanaka et al., 2010). The widespread decline of fallow in agricultural areas of the Canadian Prairie Provinces since the 1970s has coincided with an increase in cloudiness and precipitation (on the order of 10 mm per decade), a decline in maximum temperatures on the order of nearly 2 °C, and a decline in radiative forcing on the order of 6 W m$^{-2}$ (Gameda et al., 2007; Betts et al., 2013a,b). For comparison, the increase in global radiative forcing since 1750 due to anthropogenic activities is on the order of 2.5 W m$^{-2}$ (IPCC, 2013). Regional climate change in the Canadian Prairies is thought to be due to a decrease in atmospheric boundary layer (ABL) height that favors cloud formation processes as cropping systems that support more latent heat flux (evapotranspiration) over sensible heat flux replace fallow. Using a conceptual model, Gameda et al. (2007) argued that fallow supports an ABL height on the order of 2-3 km but only 0.5 km over crops. These values have not been supported by observations or models, in part because the impacts of field-scale management changes on the surface atmosphere exchange of sensible and latent heat – which help determine ABL height - have not been measured to date in wheat-fallow rotations. The role of wheat-fallow rotation management on the coupled carbon dioxide, water, and heat remains to be
ascertained. As the climate changes and global population increases it is important that wheat producers in Montana are able to adjust to new conditions without a decrease in production, and these new conditions include changes in climate that are in part due to agricultural management (Mahmood et al., 2014). Detailed studies of the relationship between wheat-fallow management and the atmosphere are an important first step for understanding interactions between land management and climate.

**Previous Eddy Covariance Measurements in Wheat:**

Many studies to date have used the eddy covariance technique to find that crops tend to be a strong carbon sink at the field scale during the growing season, but are infrequently a net annual carbon sink (Baker and Griffis, 2005; Anthoni et al., 2004; Li et al., 2008; Schmidt et al., 2012; Moureaux et al., 2012, and others). With respect to wheat, Anthoni et al., (2004) used the eddy covariance technique to assess the ecosystem carbon balance of a winter wheat crop in Thuringia, Germany. They found that the study field was a sink for atmospheric carbon dioxide during the growing season but a source of carbon annually with a net biome productivity (NBP) of 45 to 105 g C m⁻² indicating a loss of C to the atmosphere when the end products of the wheat crop were accounted for. Béziat et al. (2009) measured the carbon balance of a three-crop succession in southwestern France, one of which was a winter wheat rotation. They found that management had a large impact on CO₂ flux as plowing disturbed voluntary re-growth, which appeared to limit carbon loss after harvest. At the Lamasquère site where the winter wheat crop was grown, Béziat et al. (2009) found that annual net biome productivity (NBP) was -161 +/- 66 g C m⁻² y⁻¹ indicating a carbon sink while the maize
crop at the same site a year earlier was a carbon source of 372 +/- 78 g C m$^{-2}$y$^{-1}$ demonstrating the importance of management impacts on carbon fluxes but also substantial uncertainties in the NBP estimate. Largely missing from the body of research to date are studies on the surface-atmosphere exchange of the wheat/fallow rotations common to the dryland cropping ecosystems of Montana; little research has been done to date in the northern Great Plains with respect to the surface-atmosphere exchange of carbon dioxide, water, and heat in wheat crop rotations and no till fallow.

Fallow Management Practice:

Water Savings and Management. Montana is located in a water-limited region (Miller et al., 2002) and precipitation in the form of snow is important for soil moisture replenishment in agricultural fields (Caprio et al., 1981). Producers now usually rely on no-till management, which refers to the practice of leaving stubble from the previous years harvest instead of the traditional method of tilling the stubble into the ground.

Wheat has a very low canopy resistance and consequently high latent heat flux; about three times more latent heat flux than a Jack Pine forest or an Oak savanna under similar conditions (Bonan, 2008). The combination of dryland wheat being grown in a water-limited region in conjunction with wheat having a very high latent heat flux during the growth period results in the need for producers to focus efforts on water savings techniques. Dryland farming success in the Great Plains is dependent on resourceful use of precipitation (Nielsen et al., 2005). Water use efficiency can be subsidized by management practices that increase water use efficiency by implementing cropping
sequences that reduce fallow periods (Nielsen et al., 2005). It is well-understood that fallow decreases evapotranspiration, but the seasonal patterns of water loss between fallow and wheat fields have not been measured to date.

**Carbon Loss.** Carbon is a key component to soil and crop health and neglecting to understand how fallow affects carbon fluxes may lead to unintended consequences. Management practices such as fallow can be detrimental to the available carbon in the field. Blair and Crocker (2000) suggest that producers should avoid long-term fallowing and move towards no-till practices in addition to returning crop residues to the field as they have a slower breakdown rate which is likely to aid in soil carbon increase and soil structure improvement. In Sidney, NE, Doran et al. (1998) studied fallow management and found that the no-till practice resulted in cooler and more moist conditions in the upper soil than tilling or sub-tilling and also enhanced the opportunity for plant available N to be tied up in organic forms. In other words, carbon, nutrient, and water management are intertwined and the hydrologic consequences of fallow – namely water losses to the atmosphere - also need to be ascertained for a comprehensive understanding of the impacts of agricultural management on water resources.

**Study Objectives:**

The objective of this study is to explore how wheat and summerfallow (specifically chemical fallow) rotations impact the exchange of carbon dioxide ($F_c$), latent heat ($LE$), and sensible heat ($H$) between the surface and the atmosphere. We used meteorological data and eddy covariance measurements of $F_c$, $LE$, and $H$, as well as
modeling exercises in order to fill common missing data (‘gaps’) to provide seasonal sums of surface-atmosphere exchange at two flux tower sites separated by 1.2 km in the Judith Basin of central Montana.

A collection of meteorological sensors were installed on and near the tower in the wheat field (which measured winter wheat in 2013 and spring wheat in 2014) and the tower in the fallow field (which was active during 2014) for measuring each variable in the energy balance as well as driving variables for modeling turbulent fluxes. The wheat rotations were used to analyze differences in the timing of turbulent flux exchange between crop types (winter and spring wheat). As winter wheat begins growing before spring wheat and stops growing prior to spring wheat we would expect the timing of the fluxes to differ between the two, but the magnitude is uncertain. It was not possible in this study to compare winter and spring wheat growth directly under identical climate conditions. However, during 2014 a direct comparison can be made between spring wheat and fallow as the study fields were separated by the distance of one field (1.2 km).

A conceptual model for carbon dioxide, latent heat, and sensible heat fluxes in a wheat fallow rotation is presented in Figure 2. For example, I would expect LE to be greater in the wheat fields as opposed to the fallow field due to the presence of a transpiring crop and a direct path for water to enter the atmosphere from the rooting zone through the xylem. In contrast, we would expect H to be greater in the fallow field than the wheat fields due to the absence of a crop and the added moisture due to transpiration that accompanies a crop. With regards to $F_c$, we would expect net uptake during the growing season by the wheat fields and net release by the fallow field.
Figures

Figure 1. The top five wheat producing countries in the world (FAO, 2013).

Figure 2. A conceptual figure of surface-atmosphere fluxes in a no-till fallow field (left) and a wheat field (right). The fallow field has less latent heat ($LE$), more sensible heat ($H$), and is a net carbon source (flux of carbon ($F_c$) out of soil) while the wheat field is the opposite (carbon sink) with more $LE$, less $H$, and is a net carbon sink during our study period (Apr. – Sept. 2014). *Arrow size not indicative of amount of $LE$, $H$, $F_c$. 
BIBLIOGRAPHY


CHAPTER 2

THE INFLUENCE OF DRYLAND AGRICULTURE WHEAT-FALLOW ROTATION ON THE EXCHANGE OF CARBON, WATER, AND HEAT WITH THE ATMOSPHERE

Contribution of Authors and Co-Author

Manuscript in Chapter 2

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Contributions: Conceived and implemented the study design. Collected and analyzed data. Wrote first draft of the manuscript.

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Abstract

Wheat (*Triticum aestivum* L.) is the most commercially important crop in Montana, and fields are often left fallow during summer under the notion that fallow conserves water and breaks the pest cycle. However, fallow is known to deplete soil carbon stocks and thereby soil quality. To determine the impact of a wheat/summerfallow rotation on ecosystem carbon and water resources, the surface-atmosphere exchange of carbon dioxide, water (latent heat flux), and heat (sensible heat flux) was measured during the April - September study period in a wheat cropping sequence in the Judith Basin of central MT. Winter wheat (2013) and spring wheat (2014) fields gained 205 ± 53 g C m⁻² and 110 ± 31 g C m⁻² from the atmosphere, while the fallow field (2014) lost 135 ± 76 g C m⁻² to the atmosphere during the study period. Evapotranspiration (ET) in the winter and spring wheat fields was 410 ± 35 mm and 440 ± 50 mm for during the study period. The fallow field ET during the same period was 315 ± 44 mm. Winter moisture inputs from stubble snow capture based on observed snow depth in early spring would not appreciably offset the difference in water use between wheat and fallow. The cumulative sensible heat flux during the study period from the wheat fields was *ca.* 1/3 less than the fallow field and modeled daily maximum atmospheric boundary layer height was up to 800 m higher during the crop growth period under the fallow. Fallow diminishes soil carbon resources while losing only *ca.* 1/3 less water to the atmosphere during the growth period. Future research should investigate how other crops common to Montana impact the biogeochemistry and biogeophysics of the soil - vegetation – atmosphere pathway.
Introduction

Wheat provides more than 20% of calories and proteins for the global population (Hawkesford et al., 2013). The challenge to meet the global demand of wheat to a growing population is made more difficult due to rising temperatures and rainfall distribution alterations as a result of climate change (Parry and Hawkesford, 2010). Therefore, maintenance of the global diet requires studies of agronomic systems that will aid in determining which cropping systems will provide sustainable wheat yields.

In Montana’s largest wheat growing region, MLRA 52 in north-central MT, wheat-fallow rotations leave up to 40% of the area in fallow during a typical growing season, even though this cropping system is known to reduce soil quality over the long term. Efforts to introduce alternate cropping systems to avoid summerfallow are the subject of ongoing research (Miller et al. 2002, 2003, 2005, 2015; Burgess et al., 2012) and these alternative practices are being increasingly adopted, especially in the northeastern corner of Montana (Long et al., 2014).

Surface-atmosphere interactions in agricultural systems remain rarely studied even though the effects of cropping systems on soil quality is fundamentally determined by carbon, water, and energy exchanges with the atmosphere. The difference in evapotranspiration between wheat and fallow fields is rarely measured, nor is the surface-atmosphere exchange of sensible heat which has important consequences for atmospheric boundary layer height and the probability of convective precipitation (Luyssaert et al., 2014; Juang et al., 2007a,b; Betts et al., 2013b; Gameda et al., 2007). Reducing fallow may have positive benefits for regional hydroclimatology; In the Canadian Provinces
reduction in summer fallow from 10 Mha to 3.5 Mha was related to an increase in summertime precipitation on the order of 10 mm/decade, a decrease in maximum temperature and diurnal temperature range of 1.7 °C/decade and 1.1 °C/decade, respectively, and a 6 W m$^{-2}$ decrease in summertime radiative forcing due largely to an increase in cloudiness (Betts et al., 2013a; Gameda et al., 2007). Such a cooling effect of widespread fallow reduction may help buffer the impacts of heat on the wheat crop and place Montana producers at a competitive advantage against global wheat producers who are experiencing a decline in wheat production due to increasing global temperatures (Asseng et al., 2013).

Here, we use the eddy covariance technique to measure the surface-atmosphere exchange of carbon dioxide, water, and sensible heat in two fields at different points in a winter wheat- spring wheat - fallow sequence. This study was carried out in the Judith Basin region of Montana, for the purpose of quantifying the impacts of fallow on field-scale carbon, water, and energy exchange with the atmosphere. The specific objectives of the project are to:

1. Quantify and compare the differences in carbon uptake by wheat fields through crop growth and harvest and carbon dioxide loss from the fallow field.
2. Analyze the water use between wheat and fallow rotations assess the water savings in comparison to the carbon losses.
3. Determine differences in sensible heat flux and modeled atmospheric boundary layer height between wheat and fallow rotations to improve mechanistic
understanding of the role of agricultural management on regional hydroclimatology.

4. Determine the relationship between carbon dioxide, water, and heat flux and measurable variables like canopy height to support development of models of the impacts of agricultural management on carbon and water resources.

We focus on two comparisons: 1) between the winter wheat (WW) and spring wheat (SW) field which represented different wheat growing season treatments and different climatological conditions between 2013 (WW) and 2014 (SW); and 2) between the SW and fallow fields which were measured under similar climatological conditions in 2014 and separated by the distance of 1.2 km.

Materials and Methods

Site Description:

Agricultural Fields in the Judith River Basin. The study sites are located near the town of Moore in the Judith River basin of central Montana (Figure 3). In March of 2013 a 3 m tower with eddy covariance and micrometeorological instrumentation – hereafter the ‘wheat tower’ – was installed at 46° 59’ 41.100” N, 109° 36’ 49.500” W in a winter wheat field (WW, see Table 1 for a list of abbreviations). The tower was left until September 2013 after the winter wheat crop was harvested on August 7, 2013, at which point instruments were removed for calibration and reinstalled in October 2013. The entire tower was briefly taken off the field and reinstalled in the same location to accommodate the planting of spring wheat (SW) on May 5, 2014. The tower was later
removed in September 2014 following the harvest on August 18, 2014. A second tower – hereafter the ‘fallow tower’ – was installed at 46° 59’ 44.800” N, 109° 37’ 46.300” W in a no-till chemical fallow field in October 2013, two fields to the west of and 1.2 km from the wheat field tower (Figure 3). The fallow tower was installed for the purpose of comparing agricultural management practice effects on surface-atmosphere exchanges of CO₂, latent heat and sensible heat fluxes as well as other meteorological variables to the wheat tower. For the purposes of this study, measurements from all fields are studied for the April-September period, hereafter the ‘study period’, that encompasses the main growing season.

**Measurements:**

**Meteorological Measurements.** Micrometeorological variables - including those for interpreting the surface-atmosphere energy balance - were measured at both towers (See Table 2). Canopy heights and snow depths were measured with a Campbell Scientific SR50A-L sonic depth sensor. Incident shortwave ($SW_{in}$), outgoing shortwave ($SW_{out}$), incident longwave ($LW_{in}$) and outgoing longwave ($LW_{out}$) radiation were measured using a NR01 four-component net radiometer (Hukseflux, Delft, The Netherlands). Air temperature ($T_a$) and humidity ($RH$) were measured using a HMP45C instrument (Vaisala, Helsinki, Finland). Soil heat flux ($G$) was measured using a self-calibrating HFP01 heat flux plate (Hukseflux) at 5 cm below the soil surface. Soil moisture was measured at 5 cm and 10 cm using two CS616 sensors time domain reflectometer (TDR) sensors (Campbell Scientific) in the wheat field and two CS650
TDR sensors (Campbell Scientific) in the fallow field. Soil temperature was measured at multiple depths using thermocouples in the wheat field and the CS650 sensors in the fallow field. Measurements were made every minute and half-hour averages were stored using CR3000 and CR1000 data loggers (Campbell Scientific).

**Turbulent Flux Measurements.** The surface-atmosphere flux of latent heat ($LE$), and carbon dioxide ($F_c$) were estimated using the eddy covariance technique. This involved the coupling of CSAT-3 sonic anemometers (Campbell Scientific Inc., Logan, UT) with enclosed path LI-7200 CO$_2$/H$_2$O infrared gas analyzers (LiCor, Lincoln, NE) installed 1.8 meters above the ground surface on both towers. Sensible heat exchange ($H$) was measured using the sonic anemometers. Data were recorded at 10 Hz on a CR3000 data logger (Campbell Scientific) and then processed into half-hourly flux sums using EddyPro (LiCor). Eddy covariance processing was based on double rotation for the axis rotation for tilt correction, block averaging for turbulent fluctuations, covariance maximum for time lag compensation, and plausibility ranges for the spike count/removal of five standard deviations from the mean for vertical velocity and 3.5 standard deviations from the mean for CO$_2$ and H$_2$O concentrations.

Surface-atmosphere fluxes are typically underestimated by eddy covariance measurements during periods of insufficient turbulent exchange (Aubinet et al., 2000; Falge et al., 2001; Gu et al., 2005; Papale et al., 2006; Reichstein et al., 2005). A friction velocity ($u^*$) filter following Reichstein et al. (2005) was applied to the data set to identify and filter periods of insufficient turbulence. Nighttime $F_c$ observations, defined as periods for which the solar zenith angle exceeded 90°, were binned into six $T_o$ classes.
for three month periods and further binned into twenty $u^*$ classes. The $u^*$ filter was chosen to be the value at which the mean value of the $F_c$ observations in a given $u^*$ class first exceeded 95% of the remaining $F_c$ observations at higher values of $u^*$. $u^*$ threshold values determined using this approach exhibited trivial differences from a statistical approach in which the $u^*$ threshold was determined as the $u^*$ class at which the $F_c$ observations were not statistically different than $F_c$ observations at higher $u^*$ as determined by a one-sided t-test following Papale et al. (2012).

**Gapfilling and Data Processing:**

Missing data occurred due to power outages, equipment malfunction, as well as damage to wires by rodents. Missing incident shortwave radiation, relative humidity, and air and soil temperature data were gapfilled using linear regression from the neighboring tower if data were available. If data from the neighboring tower were also missing, data from the Moccasin SCAN site, located 25 km from the study fields, were used in the gapfilling routine.

**Gapfilling Soil Heat Flux.** Missing soil heat flux observations were gapfilled by establishing a linear relationship between measured $G$ and net radiation ($R_n$) on a daily basis, relating the resulting slope and intercept parameters with canopy height, and gapfilling using regression parameters that varied as a function of canopy height. If measured $R_n$ data were not available from either tower, a linear relationship between tower $R_n$ and $SW_{in}$ from the Moccasin SCAN site was established and used for gapfilling $G$. 
Gapfilling Carbon Dioxide Flux. Rapid changes in canopy biomass during the growth period and during harvest, as well as non-vegetated conditions during different periods at all fields, necessitated the use of a gapfilling model that accounted for both photosynthetic and respiratory processes. To gapfill $F_c$, a rectangular hyperbolic model for ecosystem production and the respiration model of Lloyd and Taylor (1994) were coupled:

$$F_c = -\frac{\alpha \beta SW_{in}}{\alpha SW_{in} + \beta} + R_{10} \exp\left(\frac{1}{T_{10} - T_t} - \frac{1}{T_a - T_t}\right)$$

(1)

Where $\alpha$ is the initial response of the light response curve ($\mu$mol CO$_2$ J$^{-1}$), $\beta$ is the gross ecosystem productivity (GEP) at light saturation ($\mu$mol CO$_2$ m$^{-2}$ s$^{-1}$), $R_{10}$ ($\mu$mol CO$_2$ m$^{-2}$ s$^{-1}$) is ecosystem respiration at an air temperature ($T_a$) of 10 °C ($T_{10}$), $E_0$ is the activation energy parameter (K), and the reference temperature $T_t$ is set to 227.13 K following Falge et al. (2001). Parameters were fit using least squares regression for observations within a seven-day moving window of $u^*$ threshold and filtered $F_c$, $SW_{in}$, and $T_{air}$ observations. Parameter sets during periods for which the parameter estimation routine did not converge to an optimal solution or for which observations were not available were estimated using the previous day’s values for the case of small gaps of two days or less, and linear interpolation from preceding and subsequent periods for large gaps of more than two days.

Gapfilling Latent Heat Flux. Latent heat flux observations that were missing were gapfilled using the Priestley-Taylor model (Priestley and Taylor, 1972) adjusted to include an uncertainty term, $\epsilon_{PT}$, that functions as an intercept parameter:
\[ ET_0 = \frac{1}{\lambda} s \frac{(R_n - G)}{s + \gamma} \alpha_{PT} + \varepsilon_{PT} \]

Where \( \lambda \) is the latent heat of vaporization, \( R_n \) is the net radiation, \( G \) is the soil heat flux, \( s \) is the slope of the saturation vapor pressure-temperature relationship, \( \gamma \) is the psychrometric constant, and \( \alpha_{PT} \) is the Priestley-Taylor coefficient. \( \alpha_{PT} \) and \( \varepsilon_{PT} \) were determined for the WW, SW, and fallow sites individually for each day using linear regression against measured \( ET \). \( \alpha_{PT} \) and \( \varepsilon_{PT} \) for days during which insufficient data were available for its calculation was estimated using the previous day’s parameters for the case of small gaps of two days or less, and linear interpolation from the parameters of preceding and subsequent periods for large gaps of more than two days.

Evapotranspiration \(( ET \)) was calculated as \( LE \) divided by the latent heat of vaporization with units adjusted to equal mm per half hour to calculate seasonal sums.

**Gapfilling Sensible Heat Flux.** \( H \) was gapfilled by fitting a daily linear regression between observed \( H \) and \( R_n \) including a slope and an intercept parameter similar to equation 2; missing \( H \) values were filled using the results of this regression. As with the other flux gapfilling routines, parameters which were unable to be calculated due to missing data were estimated using the previous day’s parameters for the case of small gaps of two days or less, and linear interpolation from the parameters of preceding and subsequent periods for large gaps of more than two days.
Uncertainty Analysis:

Uncertainty in eddy covariance observations is often on the order of 10-15% (see Goulden and Crill, 1997), and varies as a function of flux magnitude (Richardson and Hollinger, 2007; Richardson et al., 2008). The total uncertainty in eddy covariance measurements is a function of observational uncertainty (Moncrieff et al. 1997), gapfilling uncertainty (Falge et al. 2001), and spatial uncertainty due to the assumption that a spatially variable flux can be expressed as an average on a square meter basis (Oren et al., 2006).

We applied the approach of Richardson et al. (2008) to estimate the random uncertainty of $F_c$, $LE$, and $H$. Briefly, data from the same half hour period of consecutive days were screened for similar micrometeorological conditions defined as those for which $R_n$ differed by less than 75 W m$^{-2}$, air temperature differed by less than 3 °C, and average wind speed differed by less than 1 m s$^{-1}$ under the assumption that fluxes measured during these conditions on consecutive days should be similar and any differences are related to the random error of eddy covariance measurements. Differences in $F_c$, $LE$, and $H$ identified using this approach were found to be linearly related to the mean flux, the model for which is taken to be the random uncertainty of the flux measurements. Random uncertainty of the seasonal sums of $F_c$, $LE$, and $H$ is taken to be the mean absolute value of these fluxes multiplied by the percent random uncertainty following Stoy et al. (2006a,b).

Random uncertainty was propagated through the gapfilling routines following the recommendations of Motulsky and Ransnas (1987) by perturbing the input flux.
observations with a random value drawn from a normal distribution multiplied by the random uncertainty calculated using the Richardson et al. (2008) routine. This procedure was repeated 100 times for each day of observations, and 100 parameter sets for the gapfilling model were subsequently fit for each day using least squares regression. Each of the corresponding parameter sets was tested for convergence of the optimization routine (for the case of CO₂ flux), and all parameter sets were adjusted for missing values using the routines for large and small gaps described above. Gapfilling uncertainty was then determined as the standard deviation of the (April – September) seasonal flux sum. Total uncertainty for each flux over the study periods was then calculated by summing the variance attributable to random uncertainty and that attributable to gapfilling parameter uncertainty, noting the propagation of random error into the estimate of gapfilling uncertainty, in order to obtain a conservative value of total flux uncertainty for each field for each study period.

Energy Balance:

The surface-atmosphere energy balance is rarely closed using the eddy covariance and micrometeorological measurements of \( R_n, G, LE, \) and \( H \) at a single tower (Stoy et al., 2013; Franssen et al. 2010; Wilson et al.2002). I calculated the energy balance closure for the WW, SW, and fallow rotations by establishing the relationship between \( R_n - G \) and \( H + LE \) on a half-hourly basis.
General Weather Conditions:

In general, 2014 was cooler, cloudier, and wetter than 2013. Mean annual $T_a$ during 2013 was 7.0 °C and mean April-September $T_a$ was 14.3 °C (Figure 4). In 2014 mean annual $T_a$ (6.5°C) and April-September mean $T_a$ (13.7 °C) during 2014 were about 0.5 °C cooler. The maximum observed $T_a$ was 35.8 °C on August 16th, 2013 and 36.1 °C on August 12th, 2014. The annual cumulative incident $SW_{in}$ was 3% greater in 2013 (5290 MJ m$^{-2}$ year$^{-1}$) than in 2014 (5140 MJ m$^{-2}$ year$^{-1}$), and the study period cumulative incident $SW_{in}$ was 5% greater in 2013. Cumulative precipitation measured at the Moccasin SCAN site was 452 mm in 2013 and 503 mm in 2014, an increase of 10%. The study period cumulative precipitation was 360 mm in 2013 and 391 mm in 2014, 162 mm of which fell during a large precipitation event during Aug. 21-24 shortly after the harvest of the wheat field on Aug. 18, 2014.

Soil Moisture:

Soil moisture tended to be above 0.3 m$^3$ m$^{-3}$ at both 5 cm and 10 cm in the WW rotation during the slightly drier 2013 until the first week of July (Figure 5), after which it decreased to 0.2 m$^3$ m$^{-3}$ in about one week, then declined at a slower rate that coincided with the cessation of canopy height growth (Figure 6) until a rain event on the evening of July 17. Near-surface soil moisture remained near or above 0.3 m$^3$ m$^{-3}$ at both the wheat and fallow fields during the entire study period of 2014, and the shallow soil water
content was generally higher in the spring wheat field than the fallow field until the harvest.

**Plant Height Growth:**

Canopy height was near zero after the 2012 Fallow growing season that preceded WW planting, and measurable WW growth began in early May, 2013 (Figure 6). The WW crop reached its maximum height of 0.64 m on July 9, 2013. The canopy was reduced to stubble measured at 0.2 m after harvest on August 7, 2013. With the exception of variation due to snow cover, the plant canopy remained at 0.2 m during the 2013/2014 winter, and was effectively 0 m after SW crop planting on May 2, 2014. Measurable SW crop growth began on May 26, and reached 0.83 m on July 25 (i.e. *ca.* two weeks after the WW crop reached its maximum height in 2013), and likewise was reduced to stubble of 0.2 m after harvest on Aug. 18, 2014.

**$u^*$ Thresholds:**

The Reichstein et al. (2005) algorithm selects a unique $u^*$ threshold for three month periods, which correspond to April through June and July through September timeframes during the study period. The identified $u^*$ threshold was 0.077 m s$^{-1}$ for the WW crop, 0.048 m s$^{-1}$ for the SW crop, and 0.073 m s$^{-1}$ for the Fallow rotation during the April through June period, and 0.054 m s$^{-1}$ for the WW crop, 0.092 m s$^{-1}$ for the SW crop, and 0.057 m s$^{-1}$ for the Fallow rotation during the July through September period. Turbulent flux observations taken during periods where measured $u^*$ was less than these
values during nighttime were removed from the observational record and filled using the gapfilling procedures.

Energy Balance Closure:

Energy balance closure was calculated as the slope of the relationship between radiant and conductive fluxes \((R_n - G)\) and turbulent fluxes \((LE + H)\) during periods when turbulent fluxes were directly measured (i.e. above the \(u^*\) threshold). Energy balance closure calculated using this approach during the study period was 79% at the WW field, 87% at the SW field, and 96% at the fallow rotation (Figure 7).

Carbon Dioxide Fluxes:

Cumulative sum of \(F_c\) in units of carbon in \(\text{CO}_2\) (\(\text{C-}\text{CO}_2\)) in all fields during the study period is shown in Figure 8. The WW field became a net sink of carbon (since April 1, 2013) on May 8, 2013, and the SW field became a net sink of carbon (since April 1, 2014) on May 23, 2014. The WW field had a cumulative \(\text{C-}\text{CO}_2\) uptake of \(-205 \pm 53\) g C m\(^2\) during the study period (expressed as the mean of the gapfilling model simulations plus or minus one standard deviation of random plus gapfilling uncertainty), and the SW field took up \(-110 \pm 31\) g C m\(^2\) during the study period in part because of enhanced RE during the rainy post-harvest period (Fig. 9). The fallow field lost \(135 \pm 76\) g C-\(\text{CO}_2\) to the atmosphere during the Apr. – Sept. growing season with two brief periods of net C-\(\text{CO}_2\) uptake of \(\text{ca.} \ 10-20\) g C m\(^2\) corresponding to weedy growth near the tower during late June and the rainy period after the SW harvest in August. The larger uncertainty for carbon fluxes in the fallow field is attributable to greater uncertainty in net respiratory
fluxes calculated by the Richardson et al. (2008) algorithm, and the larger uncertainty in carbon fluxes at the WW field versus the SW field is due in part to the larger uncertainties attributable to larger flux values.

Maximum monthly C-CO$_2$ uptake occurred at the WW field in June at $-185 \pm 48 $ g C-CO$_2$ mo.$^{-1}$. It occurred at the SW field one month later at $-115 \pm 33 $ g C-CO$_2$ mo.$^{-1}$, which is of greater magnitude than C-CO$_2$ observed in June at SW at $-110 \pm 29 $ g C-CO$_2$ mo.$^{-1}$ as identified by a two-sided t-test ($p < 10^{-17}$, Figure 9). C-CO$_2$ efflux from the Fallow field peaked in July at $40 \pm 22 $ g C-CO$_2$ mo.$^{-1}$.

**Evapotranspiration:**

Cumulative ET was $410 \pm 35 $ mm during the study period in WW (Figure 10), significantly less than the $440 \pm 50 $ mm observed for SW during the cooler and wetter 2014, but only by some 6% and reflective of the differences in April-September precipitation observed between years. The rate of increase in cumulative ET flux in the fallow rotation was not as steep as that in the WW and SW fields, and the Apr. – Sept. total reached $315 \pm 44 $ mm, ca. 2/3 of observed ET from SW.

Monthly total ET for WW peaked in June at $130 \pm 9 $ mm and monthly total ET at SW peaked in July at $145 \pm 13 $ mm (Figure 11), mirroring the monthly patterns of C-CO$_2$ uptake (Figure 9). Monthly total ET in the Fallow treatment peaked in June and July at $70 \pm ca. 11 $ mm.
Sensible Heat Fluxes:

$H$ for all treatments before WW and SW crop growth began was similar at ca. 2.5 MJ m$^{-2}$ day$^{-1}$. After crop growth initiated, of the increase in cumulative $H$ diverged between the SW and fallow fields (Figure 12). The WW (SW) fields had similar totals of $H$ of 445 ± 60 (465 ± 71) MJ m$^{-2}$ for the study period and $H$ at the fallow rotation reached 760 ± 105 MJ m$^{-2}$ for the study period, an increase in $H$ proportional to the decrease in $ET$ (Figures 10 and 12). Monthly $H$ was greater at the fallow field than the wheat fields until harvest in August, especially at WW which ceased growth and was harvested sooner than SW (see e.g. Figures 6 and 13).

Atmospheric Boundary Layer Modeling:

I sought to test the conceptual model of Gameda et al. (2007), which assumes that fallow results in an atmospheric boundary layer (ABL) height on the order of 2-3 km and vegetated surfaces result in an ABL height on the order of 500 m for cropping systems of the Canadian Prairies. ABL height ($h$, m) was modeled for each of the management practices following Luyssaert et al. (2014):

$$\Delta h = (H_v \Delta t) / (\rho_a c_p \gamma_v)$$

Where $\Delta h$ is the change in height of the ABL in meters per unit time ($\Delta t$), $\rho_a$ is the air density in kg m$^{-3}$, $c_p$ is the specific heat capacity in J kg$^{-1}$ K$^{-1}$, $\gamma_v$ is the virtual temperature inversion strength in K m$^{-1}$ set to 0.003 K m$^{-1}$, and $H_v$ is the virtual heat flux in W m$^{-2}$ obtained by the measured $H$ and $LE$. 
$H_v = H + 0.07LE$

Equation 3 was calculated for each day during the study periods and $h$ was set to 150 m at the start of each day following Luyssaert et al. (2014). Figure 14 shows the differences in the ABL for the wheat fields and the fallow field indicating that the ABL height is higher for the fallow field than the wheat fields during the peak wheat growing period.

Discussion

It is important to recall that the 2014 study period was cooler and wetter than 2013 and comparisons between WW measured in 2013 and SW measured in 2014 are subject to these differences in micrometeorology. I focus my discussion on a comparison between the SW and fallow treatments and compare $F_c$, $LE$, and $H$ observations against wheat crops from different regions.

Carbon Dioxide Exchange:

Both wheat fields were a net sink of CO$_2$ during the study period on the order of 200 g C m$^{-2}$ for WW and 100 g C m$^{-2}$ for SW, and the fallow field was a net source of CO$_2$ of over 100 g C m$^{-2}$. The differences among wheat fields may be due to a number of causes, including: 1) differences in canopy height growth as a surrogate for leaf area index and CO$_2$ uptake; 2) the loss of ca. 40 g C-CO$_2$ m$^{-2}$ for SW during April and May after planting (i.e. an artifact of the sampling period studied); 3) respiratory losses from organic matter left from WW (noting that chemical fallow preceded WW); 4) differences
in climatological variables between growing seasons; or 5) differences in the response of plants and soils to climate variability via the parameters in the gapfilling models.

In this case, the differences between canopy height and CO₂ uptake, I plotted daily CO₂ uptake as a function of the height of both wheat canopies during the period when canopy height growth was positive (Figure 16). The relationship between canopy height and $F_c$ was greater in WW, but perhaps more importantly there were 19 days in which $F_c$ at WW was more negative (indicating greater CO₂ uptake) than the greatest CO₂ uptake at SW. Recent research has emphasized the importance of maximum CO₂ uptake for determining the annual ecosystem C balance (Xia et al., 2015), although the causes of these periods of greater CO₂ uptake by WW are unclear. It is apparent from this analysis that canopy height is an incomplete descriptor of factors that are more strongly related to CO₂ uptake like the leaf area index given that WW, with lower height growth, exhibited greater CO₂ uptake.

In this case, the difference in net CO₂ uptake between WW and SW during the study period can be entirely explained by the 19 days when daily CO₂ uptake in WW (with a mean of -7.5 g C-CO₂ m⁻² day⁻¹) exceeded the day of greatest CO₂ uptake in SW (with a mean of -3.6 g C-CO₂ m⁻² day⁻¹ such that WW C-CO₂ uptake was 74 g C m⁻² greater during these periods) and the 40 g C that SW lost between the start of the study period and the day at which net C-CO₂ uptake was positive around May 29, 2014. The causes however remain uncertain and cannot be explained by height of the plant as noted.

To test the effects of the cooler and wetter conditions on determining 2014 fluxes, I parameterized the daily $F_c$ model using 2014 flux and micrometeorological observations
and forced it with 2013 $SW_{in}$ and $T_a$ observations. The cumulative sum of $F_c$ during the study period using the 2014 models forced by 2013 meteorology was -120 g C-CO$_2$ m$^{-2}$, only a ca. 10 g C-CO$_2$ m$^{-2}$ per study period difference. These results suggest that differences in C-CO$_2$ uptake are not due to direct effects of micrometeorological conditions alone but rather the response of the ecosystem – via the optimized parameter sets – to differences in meteorological conditions. These findings are in agreement with those of Richardson et al. (2007) that biological response to climate, rather than climate itself, is an important consideration for interpreting temporal variability of CO$_2$ exchange, although intrinsic differences in wheat variety are also likely to be important for ecosystem carbon dioxide exchange and should be the topic of future research.

It is important to note that there is an enhanced respiratory source in SW that explains part of the difference in C-CO$_2$ uptake during the growth period. Average $R_{10}$ (Table 1) during the crop growth period is 1.7 µmol C m$^{-2}$ s$^{-1}$ for WW but 3.1 µmol C m$^{-2}$ s$^{-1}$ for SW. In other words, at the same temperature, respiration of SW was 45% less than that of WW during the period of positive crop height growth. Consistent with Schmidt et al. (2012), the existence of plant residues after the 2013 WW harvest that remained in SW during 2014 (noting that chemical fallow preceded WW) cannot be excluded as a cause of the differences in C-CO$_2$ uptake between these two treatments.

C-CO$_2$ losses between the SW and fallow fields were similar for April and May and amounted to a 40 g C-CO$_2$ m$^{-2}$ flux to the atmosphere before SW growth (Figures 6, 8, and 9). Differences in C-CO$_2$ flux during the crop growth phase were of course substantial, but C-CO$_2$ losses were greater in SW during August (SW: 66 ± 48 g C-CO$_2$...
m$^{-2}$ mo.$^{-1}$, Fallow: $22 \pm 20$ g C-CO$_2$ m$^{-2}$ mo.$^{-1}$, Figure 9). This is for two reasons: the brief net carbon uptake event in the fallow field attributable in part to weedy growth that coincided with the large precipitation event on August 21-24, and the large C-CO$_2$ loss from SW that corresponded to this event, likely due to the respiration of labile organic material after harvest. The dynamics of the carbon balance during planting and harvest, and as a result of stubble and straw management, continues to elude ecosystem models (Sus et al., 2010), which emphasize the important role that agricultural management practices play in ecosystem-scale carbon metabolism. Schmidt et al. (2012), for example, argued that plant material from previous crops left on a winter wheat field were likely a large contributor to the carbon balance of their agricultural ecosystem (for which annual $F_c$ was -270 g C-CO$_2$ m$^{-2}$ year$^{-1}$, greater than our -205 g C-CO$_2$ m$^{-2}$ per study period noting unmeasured non-growing season C-CO$_2$ losses to the atmosphere).

Anthoni et al. (2004) found a relationship as we did in carbon uptake increasing as a function of wheat canopy height, which is consistent with our observations. The winter wheat crop in the Thuringia, Germany study by Anthoni et al. (2004) had a higher maximum crop height (1 m) than both of our wheat crops. Anthoni et al. (2004) found a net annual C-CO$_2$ uptake of -185 to -245 g C m$^{-2}$ year$^{-1}$ and Schmidt et al. (2012) found a net annual C-CO$_2$ uptake of -270 g C m$^{-2}$ year$^{-1}$, both in wheat fields in Germany that experienced cooler and wetter conditions than our study site. If we assume a C-CO$_2$ loss on the order a ca 10 g C m$^{-2}$ month$^{-1}$ during the non-growing season (Figure 9), annual C-CO$_2$ uptake by our wheat fields is of a lesser magnitude. Anthoni et al. (2004) took into account the 290 g C m$^{-2}$ year$^{-1}$ of biomass removed from their wheat field to quantify a
loss of Net Biome Productivity on the order of 50 to 100 g C m\(^{-2}\) year\(^{-1}\), and Schmidt et al. (2012) calculated an annual NBP loss of over 200 g C m\(^{-2}\) year\(^{-1}\) for their study field over both years of winter wheat observation. The net carbon balance of a crop depends on the use of the plant material after harvest, and wheat biomass does not enter long-term storage pools when removed from the field.

Management Impacts on Hydrology:

**Soil Moisture.** Agricultural managers often choose fallow in part for a soil water savings benefit (Lindwall and Anderson, 1981). Fallow can store some 33-71% more soil water to 1.7 m depth in the wheat-fallow systems of Montana (Tanaka and Aase, 1987). Our results demonstrate that any water savings effect is unlikely to occur in the top 10 cm given similarities in the soil moisture profiles (Figure 5) and sustained ET from all fields during the study period (Figure 10). This suggests that research should focus on soil moisture dynamics at greater depths across wheat cropping sequences as, for example, Thorup-Kristensen et al. (2009) found that rooting depths in winter wheat can exceed 2 m although, in the colder climates of MT this value has not been observed to exceed 1.5 m (Miller and Holmes, 2012).

Based on the estimated water balance, the amount of water that would need to be replenished to equal the water savings conferred by fallow during the peak growth period is on the order of 100-150 mm. Stubble height in our case is 0.2 m (Figure 6), and snow tends to accumulate to stubble height in the study fields (Figures 6 and 15). If we assume a characteristic snow density for short-statured vegetation in MT to be on the order of
0.08 g cm\(^{-3}\) (Jacobson and Ten Hoeve, 2012), the depth of water that corresponds to 0.2 m of snow of this density is 16 mm of water, an order of magnitude less than the amount of water that needs to be replenished to account for water use of the wheat fields. In other words, changes in stubble management are unlikely to make up the difference in water lost to the atmosphere among the wheat and fallow fields.

**Evapotranspiration.** Daily ET sums quantified here are similar to or greater than other studies. Maximum daily ET in the study ecosystems was *ca.* 7 mm day\(^{-1}\) for the WW crop (in June) and the SW crop (in July), which corresponds to low surface resistance to water of the wheat crop (Bonan, 2008) during periods with sufficient soil moisture and the high incident radiation load of the study sites. That being said, the maximum value of \(\alpha_{PT}\) calculated by the gapfilling models was 0.75 for WW and 0.85 for SW, far less than the theoretical maximum of 1.26 described by Priestley and Taylor (1972) and values found for well-watered wheat crops (e.g. 1.17-1.26; Zhang et al., 2004). Anthoni et al., (2004) found maximum rates of ET on the order 3-4 mm per day in mid-May in a winter wheat crop in Germany. We can estimate \(SW_{in}\) from PPFD observations at the Gebesee study site of Anthoni et al. (2004) and approximate annual \(SW_{in}\) to be on the order of 3500 – 4010 MJ m\(^{-2}\) year\(^{-1}\), which is approximately 2/3 of the annual \(SW_{in}\) received by the Judith Basin study sites.

ET was predictably higher in WW and SW fields than fallow fields (Figure 10), suggesting that fallow does have potential to promote soil water storage. Total ET for the WW study period was 410 mm, which was *ca.*, 90% of the total precipitation based on the data from the Moccasin SCAN site in 2013 for the same study period, noting that
precipitation maps suggest that Moore receives more precipitation than Moccasin on average due to topographical influence. Total ET for the SW and fallow study period was 440 mm and 315 mm, which was ca. 90% and 60% respectively of the total precipitation based on the data from the Moccasin SCAN site in 2014. In other words, wheat cropping returns almost all incident precipitation to the atmosphere while the fallow period leaves over 100 mm available versus SW for a subsequent crop, or for deep drainage. It is important to note that ET may be underestimated as the energy balance at the wheat fields was not closed (Figure 7). Future studies of the water balance should seek to understand differences in water use among different vegetation types in the watershed including alternate cropping sequences that include pea and lentil, and native vegetation including conservation efforts like those of the conservation reserve program (CRP). In addition the water storage potential of soils should be considered in order to achieve quantitative assessment of water balance through rotational sequences.

**Sensible Heat Fluxes and ABL Simulations.** The cumulative $H$ at both wheat fields was ca. 450 MJ m$^{-2}$ during the study period, with important seasonal differences due to crop development and harvest, as well as the differences in meteorological conditions; $R_n$ was 15% lower in SW than WW during the study period, while the SW $H$ for the study period was 125 MJ m$^{-2}$. Based on the findings that the WW rotation used more than 90% of the precipitation that fell during the study period we also see that it has a higher $H$ than SW, meaning the convective heat transport occurring in the WW field was more than that occurring in the SW field by 5%. This makes sense because the WW field was harvested eleven days earlier during August when warm, dry, and sunny
conditions prevailed, and because the 2013 growing season was warmer, drier, and sunnier than 2014. $H$ is more than 80% greater in the fallow field than SW due to the higher temperature of the surface of the fallow field from a lack of evaporative cooling.

Gameda et al., (2007) studied the impacts of fallow reduction on regional climate in the Canadian Prairie Provinces and used a conceptual model to argue that fallow results in (modeled) ABL height on the order of 2-3 km but ABL height resulting from vegetated surfaces is on the order of 0.5 km. Their reasoning for this is that $R_n$ in fallow is greater due to lower albedo and is preferentially partitioned into $H$, which results in greater virtual heat flux following equation 4, while vegetated surfaces partition $R_n$ preferentially into $LE$ resulting in a cooler and shallower ABL. Figure 14 agrees with the findings of Gameda et al. (2007) in that we can see a higher modeled ABL over the fallow field relative to the SW field, but not to the same degree. Namely, modeled ABL height over the fallow field is on the order of 2 km but is only around 500 m greater than SW during peak vegetative growth early in the growing season. The details of these differences – and similarities – among modeled ABL height as they impact cloud formation processes and convective precipitation over wheat growing areas has yet to be ascertained, but our results suggest that the conceptual model of Gameda et al. (2007) underestimates ABL height in wheat scenarios. This suggests that evaluation of the climate impacts of fallow replacement merits determination of ABL height in pulse or cover crop scenarios.
Conclusion

Modeled and measured meteorological variables were gathered for two fields during winter wheat, spring wheat, and fallow crop rotations. Measurements were taken from April-Sept of 2013 and 2014. After the SW and WW crops matured and canopy height plateaued, the fields rapidly became carbon sources rather than sinks. Following the harvest of the SW field, the carbon flux is similar to the fallow field, suggesting that the two fields are roughly equivalent during the non-growing season.

From a hydrologic perspective, soil moisture that was measured in the top 10 cm of the soil column showed little meaningful difference between SW and fallow rotation. However, comparison of evapotranspiration rates suggested fallow fields retained more water, perhaps deeper in the soil column. It is likely that deeper soil moisture varied more, and future work should examine this, along with water storage potential of soils, which is known to be limited in this area and variable based on soil textural sequences (Fergus County Soil Survey). Evapotranspiration was comparable prior to crop growth between the fallow and SW fields. Increases in evapotranspiration in SW were related to increases in crop height. There was subsequently a large difference in total evapotranspiration between the wheat and fallow field as crop presence aids in increased water output to the atmosphere via transpiration.

Measurements of the $H$ for the different management practices allowed inferences about differences in the ABL height. A higher $H$ resulted in a higher modeled ABL for the fallow field, which had the highest $H$ out of the 3 fields that were measured. This suggests that summerfallow influences the ABL to be higher and drier which is not
conducive to cloud formation and a moister atmosphere for rain events. From a regional perspective the less fallow occurs and the more vegetative fields are planted the more evapotranspiration will occur resulting in a lower and more moist atmosphere to promote precipitation events.

My research emphasizes that a fallow rotation may not be the best agricultural management practice when balancing water storage savings against maintenance of soil carbon. Results show that a fallow rotation results in a carbon source that we measured was on the order of 52% of the carbon uptake by the SW rotation. Sensible heat fluxes in the fallow field were 83% higher than those of the SW field resulting in a higher ABL attributable to the fallow field during the peak growing period, though we did not observe the degree of difference suggested by other studies.

Future efforts need to focus on scaling up crop fluxes from a modeling perspective as individual field sites and meteorological years can be considered unique. Also, more studies should direct their efforts to how soil organic carbon is affected in relation to the $F_c$ measured by the eddy covariance method. This investigation fills a gap in literature, highlighting the differences between carbon, latent and sensible heat fluxes occurring on WW, SW, and fallow fields.
### Abbreviation/Variable | Definition
--- | ---
\( \alpha \) | Initial Light Response of the Light Response Curve
\( \alpha_{PT} \) | Priestley-Taylor Coefficient
\( \beta \) | GEP at Light Saturation
\( \gamma \) | Psychrometric Constant
\( \gamma_v \) | Virtual Temperature Inversion Strength
\( \Delta h \) | Change in Height of the Atmospheric Boundary Layer
\( \varepsilon_{PT} \) | Priestley-Taylor Uncertainty Term
\( \lambda \) | Latent Heat of Vaporization
\( \rho_a \) | Air Density
\( c_p \) | Specific Heat Capacity
\( E_0 \) | Activation Energy Parameter
\( \text{ET} \) | Evapotranspiration
\( F_c \) | Carbon Dioxide Flux
\( G \) | Soil Heat Flux
\( \text{GEP} \) | Gross Ecosystem Productivity
\( h \) | Height of the PBL
\( H \) | Sensible Heat Flux
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_v$</td>
<td>Virtual Heat Flux</td>
</tr>
<tr>
<td>$LE$</td>
<td>Latent Heat Flux</td>
</tr>
<tr>
<td>$LW_{in}$</td>
<td>Incident Longwave Radiation</td>
</tr>
<tr>
<td>$LW_{out}$</td>
<td>Outgoing Longwave Radiation</td>
</tr>
<tr>
<td>ABL</td>
<td>Atmospheric Boundary Layer</td>
</tr>
<tr>
<td>RE</td>
<td>Ecosystem Respiration</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>$R_n$</td>
<td>Net Radiation</td>
</tr>
<tr>
<td>$R_{10}$</td>
<td>Ecosystem Respiration at an Air Temperature of 10°C</td>
</tr>
<tr>
<td>$s$</td>
<td>Slope of the Saturation Vapor Pressure-Temperature Relationship</td>
</tr>
<tr>
<td>SW</td>
<td>Spring Wheat Field</td>
</tr>
<tr>
<td>$SW_{in}$</td>
<td>Incident Shortwave Radiation</td>
</tr>
<tr>
<td>$SW_{out}$</td>
<td>Outgoing Shortwave Radiation</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Air Temperature</td>
</tr>
<tr>
<td>$T_{10}$</td>
<td>Air Temperature of 10°C</td>
</tr>
<tr>
<td>$T_r$</td>
<td>Reference Temperature set at 227.13K</td>
</tr>
<tr>
<td>$u^*$</td>
<td>Friction Velocity</td>
</tr>
<tr>
<td>WW</td>
<td>Winter Wheat Field</td>
</tr>
</tbody>
</table>

Table 1. List of equation variables and abbreviations with their definitions.
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sensor</th>
<th>Site Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incoming Shortwave Radiation</td>
<td>NR01 Net Radiometer</td>
<td>WW, SW, F</td>
</tr>
<tr>
<td>Outgoing Shortwave Radiation</td>
<td>NR01 Net Radiometer</td>
<td>WW, SW, F</td>
</tr>
<tr>
<td>Incoming Longwave Radiation</td>
<td>NR01 Net Radiometer</td>
<td>WW, SW, F</td>
</tr>
<tr>
<td>Outgoing Longwave Radiation</td>
<td>NR01 Net Radiometer</td>
<td>WW, SW, F</td>
</tr>
<tr>
<td>Canopy Height</td>
<td>SR50 Sonic Distance Sensor</td>
<td>WW, SW</td>
</tr>
<tr>
<td>Air Temperature/RH</td>
<td>HMP-50 Temp/RH probe</td>
<td>WW, SW, F</td>
</tr>
<tr>
<td>Ground Heat Flux</td>
<td>HFP01 Heat Flux Plate</td>
<td>WW, SW, F</td>
</tr>
<tr>
<td>Sensible Heat Flux</td>
<td>CSAT 3 and LI-7200</td>
<td>WW, SW, F</td>
</tr>
<tr>
<td>Latent Heat Flux</td>
<td>CSAT 3 and LI-7200</td>
<td>WW, SW, F</td>
</tr>
<tr>
<td>CO₂ Flux</td>
<td>CSAT 3 and LI-7200</td>
<td>WW, SW, F</td>
</tr>
</tbody>
</table>

Table 2. Variables measured at each site (see Table 1) along with sensor type. WW: Winter Wheat (2013), SW: Spring Wheat (2014), F: Fallow (2014).

Figure 3. A map of the winter wheat (2013), spring wheat (2014) and fallow (2014) study sites near Moore, MT in the Judith Basin. (Image date: 10/14/2013, Google Earth)
Figure 4. Half hourly air temperature ($T_a$) at the wheat study site during both 2013 and 2014. The dashed line denotes the 2013 WW harvest and the solid line denotes the 2014 SW harvest.
Figure 5. Soil moisture at 5 cm (top) and 10 cm (bottom) below the soil surface for the winter wheat (WW, 2013, blue), spring wheat (SW, 2014, green) and fallow (2014, blue) study sites near Moore, MT. The dashed line denotes the 2013 WW harvest and the solid line denotes the 2014 SW harvest.
Figure 6. The daily maximum canopy height or snow height for the winter wheat (WW) and spring wheat (SW) rotations. Canopy height was assumed to be near zero before winter wheat growth began in earnest in early May, 2013. Stubble left on the winter wheat field in 2013 measured ca. 0.2 m, and was assumed to drop to 0 m following the planting of spring wheat on May 2, 2014.
Figure 7. The instantaneous (half-hourly) energy balance closure of available energy (net radiation, $R_n$, minus soil heat flux, $G$) versus turbulent fluxes of sensible heat ($H$) plus latent heat ($LE$) for the winter wheat (2013, A), spring wheat (2014, B), and fallow (2014, C) fields near Moore, MT.
Figure 8. The cumulative sum of the flux of carbon in CO$_2$ (C-CO$_2$) between the winter wheat (WW), spring wheat (SW), and fallow fields and the atmosphere during the April-September study period. Negative number refer to carbon uptake by the biosphere.
Figure 9. Monthly total flux of carbon in CO$_2$ (C-CO$_2$) to the atmosphere in the winter wheat (WW), spring wheat (SW), and fallow fields during the April-September study period. Negative numbers refer to carbon uptake by the field.
Figure 10. The cumulative sum of evapotranspiration (ET) from the winter wheat (WW), spring wheat (SW) and fallow study fields. WW was measured in 2013 and the other fields in 2014. Uncertainty bars represent one standard deviation from the sum of the April – September study period.
Figure 11. The monthly sum of evapotranspiration (ET) from the winter wheat (WW), spring wheat (SW) and fallow fields during the April-September study period. Error bars represent one standard deviation from the monthly sum.
Figure 12. The cumulative sum of sensible heat flux ($H$) for the winter wheat (2013, WW), spring wheat (2014, SW) and fallow (2014) fields during the April-Sept. study period.
Figure 13. The monthly sum of sensible heat flux ($H$) from the winter wheat (WW), spring wheat (SW) and fallow fields during the April-September study period. Error bars represent one standard deviation from the monthly sum.
Figure 14. The maximum daily height of the atmospheric boundary layer (ABL) modeled using surface virtual heat flux measurements (see equation 3) and a one dimensional boundary layer model following Luyssaert et al. (2014). Dots represent daily maximum modeled ABL height and lines represent a seven day digital filter.
Figure 15. Example of snow depth in 0.2 m stubble in the wheat field during the transition from winter wheat to spring wheat.
Figure 16. The blue and green lines represent the WW and SW relationship between canopy height and CO$_2$ uptake respectively.
CHAPTER 3

FUTURE DIRECTIONS

There are many opportunities for future research that can build off of this study, and for these reasons initial data have been provided to collaborators and complete datasets will be made available to the public Ameriflux database after research has been accepted in a peer-reviewed journal. Opportunities to build from the present measurements include the creation of models of carbon dioxide, water, and energy fluxes, measurements and models of soil moisture across the crop rooting depth, and further models and measurements of the atmospheric boundary layer (ABL) across various agricultural management practices such as continuous wheat rotation or a combination of wheat and pea rotation with the incorporation of crop growth stages.

Following up with this study and the use of eddy covariance measurements of carbon, water, and heat flux across a fallow-winter wheat-spring wheat field rotation, new studies can focus on other rotations as well as longer study periods. For example, other field rotations that include crops such as pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medik.) to aid in the understanding of what happens with respect to land atmosphere interactions as they relate to atmospheric moisture and carbon fluxes with nitrogen-fixing crops. Does the inclusion of pea and lentil into a field rotation increase or decrease carbon flux? Is there more or less evapotranspiration when compared to fallow and wheat rotations and how might the seasonal timing of these fluxes differ? How does
the overall carbon, water, and heat flux change within a full field rotation with the replacement of fallow with, for example, pea?

Scientists have struggled with modeling wheat growth with respect to the timing and magnitude of carbon, water, and heat fluxes (Inwersen et al., 2010; Sus et al., 2010). It is imperative that we create well-informed models that can estimate carbon, water, and heat fluxes across rotations of interest, as we cannot measure every field and every rotation in every part of the world. One study approach could take into account the new data available from this study and incorporate it into a model. The added knowledge of what is occurring over fallow and spring wheat rotations from a carbon, water, and heat flux standpoint will help in better informing models.

Another area of research that could be better understood is the timing of the relationship of soil moisture and evaporation in a fallow field. This will help in our understanding of gradients created within the soil as water moves from depth towards the soil surface to be available for evaporation. With this additional knowledge we can answer questions such as: What portion of the total evaporation that occurs during fallow happens after rain events as a result of the top few centimeters of soil being replenished with moisture? What portion occurs as a result of soil moisture at depth moving to the surface to be available for evaporation?

A simple ABL model was used to estimate the influences of agricultural management on atmospheric dynamics. To further investigate the influence of agricultural management on the ABL I suggest taking the model used in chapter two and applying it to other crop rotations. When applying the model to other crop rotations such
as pea we can compare the model output to a fallow rotation. Pea has begun to replace fallow in some areas of Montana and it would be great to have added knowledge of how pea and fallow rotations differ with regards to ABL height and its influence on the microclimate and potentially regional climate.

The opportunities are endless as there are many unanswered questions as they relate to agricultural management and its impact on carbon, water, and heat flux. The suggestions and questions posed above are continuations of my thought process on the matter and intellectual gaps to be filled that I think are most important at this time. As research moves forward within the agricultural management realm it is most important that we as scientists focus our thoughts on how a changing climate affects our food supply as the global population increases.
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Parry, M.A., Hawkesford, M.J., 2010. Genetic approaches to reduce greenhouse gas emissions: increasing carbon capture and decreasing environmental impact. Climate Change and Crop Production 1, 139-150.


