Carbon Balance and Evapotranspiration Rates of a Restored Prairie and a Conventional Corn/Soybean Rotation.

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Titania Cadeen Markland

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Abstract

With our changing climate and growing population, it is important to reduce atmospheric carbon. A proposed strategy to reduce atmospheric carbon is the restoration of native prairies, thus converting croplands to prairies (grasslands). Using eddy covariance measurements, we investigated the carbon and water balance of two managed ecosystems over a 4-year period: A restored prairie and a conventional corn/soybean rotation system (cropland) that is tilled annually, at the University of Minnesota Rosemount Research and Outreach Center. The restored prairie is managed with a controlled burn every four years. Over the 4-year period, while the conventional corn/soybean rotation system had a somewhat greater Gross Primary Productivity (GPP) and also respired more carbon, the restored prairie had a much greater net gain of carbon (Net Biome Productivity; NBP); where the prairie experienced a net gain of 1127 +/- 30gC/m^2, and the cropland had a net loss of 279 +/- 94gC/m^2. The reason for this is that the carbon loss via burning from the prairie was much smaller (approximately 355gC/m^2) than the carbon "lost" from harvesting the grain (1172gC/m^2).

The conventional corn/soybean system had a greater cumulative evapotranspiration (ET) of 2112mm, while the Restored Prairie had a corresponding ET of 1772mm over the entire study period. The water-use efficiency (WUE) for both ecosystems were 0.84 g C mm^{-1} and 0.42 g C mm^{-1} for the prairie and cropland respectively. We find that prairie restoration is an effective measure to help reduce atmospheric carbon and reduce water use.

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ABBREVIATIONS

1. C – Carbon
2. CO_2 – Carbon Dioxide
3. D – Drainage
4. ET – Evapotranspiration
5. G – Ground Heat Flux
6. GPP – Gross Primary Productivity
7. H – Sensible Heat
8. Hz – Hertz
9. IPCC – Intergovernmental Panel on Climate Change
10. LE – Latent Heat
11. NBP – Net Biome Productivity
12. NEE – Net Ecosystem Exchange
13. NPP – Net Primary Productivity
14. P – Precipitation
15. R_E – Ecosystem Respiration
16. Rn – Net Radiation
17. WUE – Water-use efficiency

CHAPTER 1

Introduction

Human activities, such as cultivation, deforestation and urbanization have a great impact on global weather and climate. We modify land surfaces to meet our needs and desires, which contributes to the increase in greenhouse gases, such as CO_2, in the atmosphere. These gases influence climate change and global warming, as they have the ability to trap heat energy which causes an increase in the earth's temperature.

With our growing population, which is expected to reach 10billion within the 21st century, we have exploited the earth's resources and increased emission rates since the late 18th century (Crutzen, 2002). Scientists are now faced with the problems of feeding and housing our growing population while finding methods to protect the environment and to reduce atmospheric greenhouse gases.

Different regions of the world emit different amounts of CO_2 into the atmosphere through processes such as combustion, agricultural practices, and deforestation. In the Midwestern United States (Midwest), agriculture is the leading cause of land cover change and is also a key source of greenhouse gas emissions to the atmosphere. Therefore, land management is a very important climate mitigation strategy in the Midwest to help reduce atmospheric greenhouse gases and lower the rate of climate change.

In this thesis, two main studies were carried out at a restored prairie and a conventional corn/soybean rotation cropland at the University of Minnesota Rosemount Research and Outreach Center. The first study was a comparison of the carbon balance of both ecosystems (Restored Prairie vs Conventional Corn/Soybean Rotation System). The eddy covariance technique was used to collect data at the sites, which was then analyzed to compute gas exchange rates that were compared against each other. Ecosystems with great carbon sequestration ability can help enormously with the reduction of atmospheric CO_2 gas.

The second study was designed to analyze the evapotranspiration rates of both systems compared to their seasonal and annual Net Ecosystem Exchange of CO_2. This was done to investigate the water-use efficiency of the systems and to understand how the water balance is affected by management practices that favor carbon gain.

At the end of both studies we hope to answer the following research questions:

1. Which ecosystem has a better carbon balance?
2. Which ecosystem has the highest seasonal and annual evapotranspiration rates?

By combining the carbon and water data we will determine the water-use efficiency of these ecosystems. Studying these ecosystems is important for future land management strategies which can be beneficial in both feeding the growing population and minimizing climate change.

CHAPTER 2

Comparison of the Carbon Balance of a Restored Prairie with Corn/Soybean Cropland

1. Synopsis:

In the late 1800s a significant number of native prairies in the Midwestern United States were converted to croplands. Prehistorically, prairies covered approximately 170 million acres of North America, but today only 1% of this land remains (A Complex Prairie Ecosystem, 2018). This conversion has significantly contributed to the increase in atmospheric carbon dioxide (CO_2) concentrations. Reducing global atmospheric CO_2 is important in mitigating estimated global warming effects.

One of the proposed strategies is prairie restoration, under the premise that this can lower atmospheric CO_2 levels by essentially recovering the carbon lost during conversion to croplands. Here we investigate this by measuring the carbon (C) balance of two managed ecosystems: a conventional corn/soybean yearly rotation cropland and a former corn/soybean system that is undergoing prairie restoration. Eddy covariance measurements were used to measure carbon, water, and energy fluxes. We find, that over the 4-year period encompassing one prairie burn cycle the restored prairie had a Net Ecosystem Productivity (NEP) of 1483+/- 30gC/m^2 while the corn/soybean system only had 894 +/- 94gC/m^2. The corn/soybean system had a higher overall Gross Primary Productivity (GPP) of 3864 +/- 260 gC/m^2 over the 4-years, while the prairie had 2653+/-197gC/m^2 over the 4-year burn cycle. The Ecosystem Respiration (R_E) for the corn/soybean system greatly exceeded that of the prairie. The amount of C removed in grain harvest from the corn/soybean system was 1172.5gC/m^2, which was much greater than the C released by burning the prairie, 355.8gC/m^2. In summary, we found that the Net Biome Productivity (NBP) of the prairie was 282 +/- 8 gC/m^2/yr (1127 +/- 30gC/m^2 for the overall study period), which was approximately 3 times larger than that of the corn/soybean system -70.0 +/- 24 gC/m^2/yr (-279 +/- 94gC/m^2 for the overall study period), where the negative sign indicates a loss of C to the atmosphere.

2. **Introduction:**

As global temperatures continue to rise and atmospheric CO_2 concentrations increase, there is an urgent need for the removal of excess atmospheric carbon to help offset global warming. CO_2 is the primary anthropogenic greenhouse gas that has influenced climate change. Global emission of atmospheric CO_2 has increased throughout the Industrial Age, with a cumulative anthropogenic CO_2 emission of 2040+/- 310 $GtCO_2$ during the period of 1750 to 2011 (Pachauri & Meyer, 2014). Storing carbon in terrestrial ecosystems is one means of removing CO_2 from the atmosphere.

The CO_2 concentration of the atmosphere has been influenced by land use changes, where humans have modified more than 50% of the earth's ice-free land surface (Hooke, Martín-Duque, & Pedraza, 2012). The Midwestern United States, often referred to as the "Corn Belt", is one of the most agriculturally intense regions of the world, with corn and soybean as its most dominant crops. Over this region, the largest portion of land is used for the agriculture sector (5.5×10^{11} m^2) compared to grasslands (1.1×10^{11} m^2) (Loveland, et al., 2018). Deforestation for agricultural purposes and urbanization are two types of conversion that consume most of the land. These practices greatly influence changes in the global carbon cycling (Foley, et al., 2005). It has been estimated that soil has the ability to store over 2500Gt of carbon globally including 1550Gt of organic carbon and 950Gt of inorganic carbon (Lal, 2004). Carbon sequestration in the Midwest is important as most of the land in this area was converted from native prairies to croplands and, since then, has been experiencing a loss of soil carbon. Between 1964 and 2005, the Midwest lost over 51 Mt of carbon stored in the 0-30cm soil depth layer solely due to corn production (Minnesota specifically lost 4.1Mt) (Grace, et al., 2011). Historically in the Midwest, clearing of land for agricultural purposes by repeated plowing of soil caused oxidation of approximately 30 to 50% of the organic matter (Griffis, Baker, & Zhang, 2005). Tillage disrupts soil aggregates which alters soil carbon stocks and carbon sequestration.

Corn/soybean rotation is the dominant cropping system in a large portion of the Midwest. In a corn/soybean rotation, it is noted by Baker and Griffis (2005) that soybean is generally planted later in the year than corn, resulting in an incomplete usage of photosynthetically active radiation (PAR) in the spring of a soybean year (Griffis, Baker, & Zhang, 2005). Both corn and soybean can be classified as warm season crops with no tolerance for frost, thus they are unable to effectively photosynthesize during the extended period of freezing temperatures prevailing in the continental Minnesota climate (Griffis, Baker, & Zhang, 2005).

Most corn/soybean land in Minnesota is tilled every year, although in recent years there has been more emphasis on alternative management practices that use winter cover crops and reduced tillage. In comparing both management practices, a previous study showed that there was greater carbon loss in the conventional management than the alternative management (Griffis, Baker, & Zhang, 2005).

Prairies also benefit from management practices to enhance growth and development. One of the most-used management practices is prescribed burning, which is done to promote new growth, recycle nutrients, and eliminate succession of woody vegetation. Burns are often carried out in specific burn cycles. Despite these burn cycles, in comparison to agricultural lands, prairies are left undisturbed for longer periods and are therefore considered to be more stable, as there is no crop removal. Hence, conversion of native prairies to cropping systems results in the loss of soil carbon (Brye K. R., Gower, Norman, & Bundy, 2002).

To investigate if prairie restoration in fact leads to a more beneficial C cycling, this paper seeks to address three science questions:

1. What are the similarities and differences between patterns of carbon gain and loss in a restored prairie and a corn/soybean rotation cropland?
2. How much carbon might be stored annually by converting croplands to prairies?
3. How does prairie productivity change over the duration of a burn cycle (4-years)?

3. Methods:

3.1 Prairie site

Measurements were conducted from May 10, 2014 to May 10, 2018 which represents a burn cycle (i.e. every 4-years), at the University of Minnesota Rosemount Research and Outreach Center, (latitude 44.6781 degrees, longitude -93.0723 degrees, elevation of 274 m.a.s.l.). Pre-settlement vegetation in this area was upland dry prairie until the 1880's when the European settlers began farming in the region (Griffis, Baker, & Zhang, 2005). Waukegan silt loam is the predominant soil type at the prairie. The studied plot had an area of approximately 5.7 x 10^5 m^2. Restoration of the prairie site began in 2010, then it was burned on May 30, 2014, and May 10, 2018.

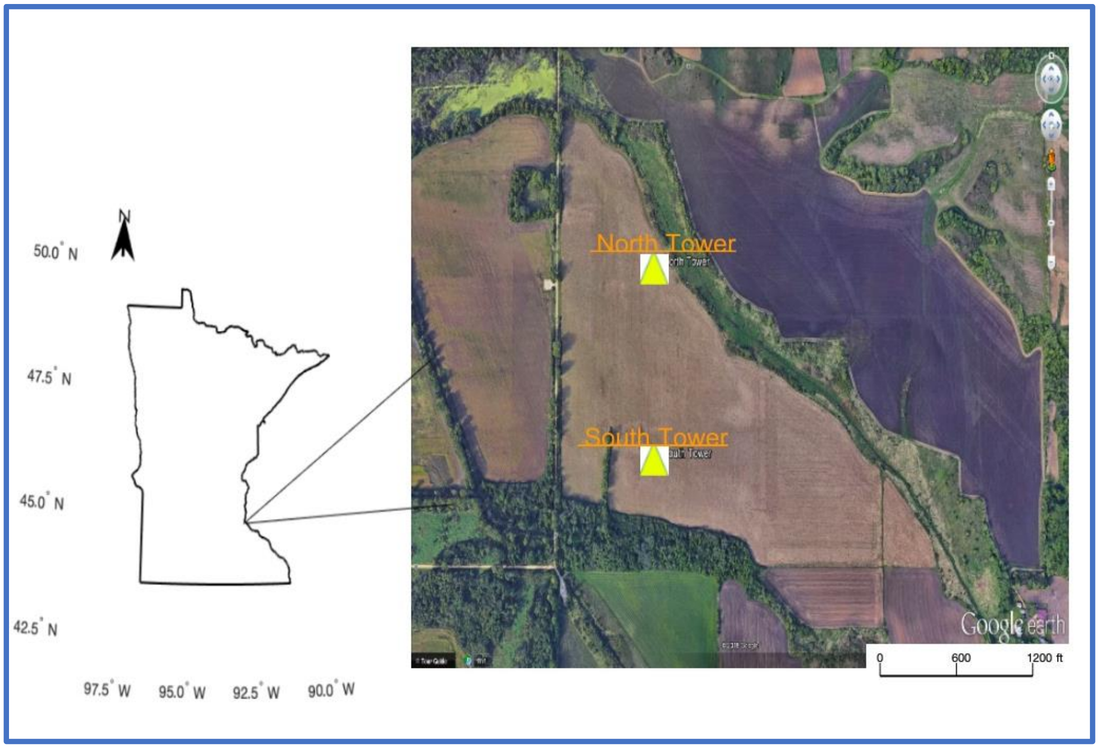


Figure 1: Layout of the Prairie in Rosemount. The yellow triangles represent the location of both the north and south eddy covariance towers located on the site. Latitude: 44.6781°, Longitude: -93.0723°, Elevation (m.a.s.l.): 274. The image was taken from Google Maps with enhancement done in photoshop

The restored prairie consists of various plants but is dominated mainly by *Andropon gerardii* commonly known as Big Bluestem, which is a C4 type of plant (NRCS, 2002). At the Prairie site, we established two eddy covariance flux towers, to compensate for the shape and dimensions of the prairie. In this way, we ensure homogenous up-wind fetches of at least 200m in each direction (Figure 1) (Zhang, Griffis, & Baker, 2006). Each tower is equipped with a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc.) and an open path infrared gas analyzer (LI-COR Inc., 7500 at the prairie and 7500RS at the agriculture site).

These sensors are sampled at 10Hz. Additional instrumentation at the site measures standard meteorological variables. Further, soil temperatures are measured along a vertical gradient from 2.5 to 10cm, along with soil heat flux plates (HFP01SC by Huskeflux) positioned at 10cm below the surface. Incoming and outgoing longwave and shortwave radiation are measured by a Kipp and Zonen CNR4 radiometer and photosynthetically active radiation (PAR) is measured using a quantum PAR sensor (Apogee Instruments SQ-311).

Eddy covariance data acquisition was carried out using a CR5000 Campbell Scientific Data Logger. Eddy fluxes were calculated for 30-min averaging intervals following standard methodology (Barr, et al., 2002) and (Griffis T. , et al., 2003). Also, de-spiking using methods described by (Papale, et al., 2006) was implemented. Gap-filling of Net Ecosystem carbon dioxide (CO_2) Exchange (NEE) was accomplished using a variation on the light response curve analyses discussed by (Reichstein, et al., 2005). Additional Filtering and gap-filling details are provided below.

Prescribed burning is the management practice implemented at the prairie site and this is carried out once every 4-years. During the winter months, above-ground biomass dies back. This biomass accumulates over the years, building a thick layer over the soil surface that delays warming in the spring. To assess the carbon released due to prescribed burn samples were taken of above ground biomass before and after the burn and were analyzed for total carbon (Vario Max analyzer, Elementar Inc.). Biomass samples were taken over 15 different sections of the prairie to account for spatial distribution using a circular ring of 88cm circumference.

3.2 Agriculture site

The agriculture site is a conventional corn/soybean cropping system (Baker & Griffis, 2005). It is in close proximity (within 4km) to the prairie and has nearly identical instrumentation. This study uses data collected from the year 2015 to the year 2018. For the corn/soybean rotation, corn was planted in 2015 then soybean in 2016. Due to landowner changes in 2017, the flux towers were moved from the original site (G21) to another corn/soybean rotation cropland which was under the same conventional management practice (I18S). At I18S the rotation started with soybean in 2017 and corn in 2018. The agriculture site was rainfed and no additional irrigation was applied. Fertilizer was applied at randomized dates throughout the study.

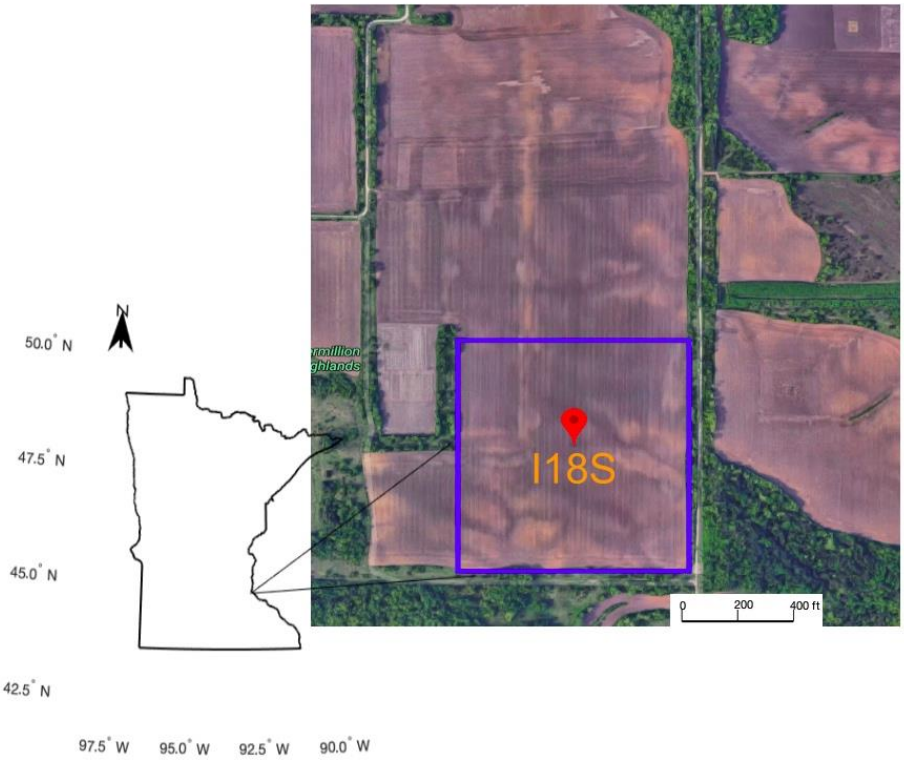


Figure 1: Cropland site location I18S- located at latitude 44.6910° and longitude -93.0576°.

Figure 2: G21 was located at latitude 44.7143° and longitude -93.0898°.

3.3 Energy Balance Closure

Energy balance closure (EBC) was calculated as a check on the performance of the measurement system (Wilson, et al., 2002). Ideally, the net radiant energy measured above the exchange surface should be balanced by a combination of latent heat flux, sensible heat flux, soil heat flux, and changes in canopy heat storage. Energy balance closure is then obtained from the following equation:

$$\text{EBC}= \frac{\text{LE}+\text{H}}{\text{Rn}-\text{G}} \qquad \text{(eq.1)}$$

Where:

EBC is energy balance closure, LE is latent heat, H is sensible heat, Rn is net radiation, and G is ground heat flux.

3.4 Calculations, Data handling, and gap-filling

The MATLAB programming software (MATLAB Version R2017b, The Mathworks Inc.) was used for final data processing. The REddyProc software (Version 1.2) (Wutzler, et al., 2018) was used to apply friction velocity thresholding, fill gaps and partition fluxes (both daytime and nighttime partition methods) for both sites in this study. This software uses the protocols and procedures explained in (Reichstein, et al., 2005), (Papale, et al., 2006) and (Lasslop, et al., 2010). Approximately 2 months (between January 28,2015 to March 30,2015) of NEE data for the prairie site were left unfilled by the REddyProc software, as there were no available environmental data available that are required for the gap-filling algorithms. This gap was then filled with an autoregressive modeling built-in function in MATLAB known as “fillgaps”, which replaces missing values with estimates extrapolated from forward and reverse autoregressive functions. The NEE of CO_2 between the atmosphere and the studied ecosystems were obtained from using the eddy covariance method, and the REddyProc software partitioning component was used to estimate the Gross Primary Productivity (GPP) which is the total amount of carbon fixed through photosynthesis by plants, and Ecosystem Respiration (R_E) refers to the sum of carbon loss from the ecosystem by living organisms (autotrophic and heterotrophic respiration combined) (Kirschbaum, Eamus, Gifford, Roxburgh, & Sands, 2001) .In this study Net Ecosystem Production (NEP) is negative NEE. To determine whether our ecosystems were carbon sinks or sources the Net Biome Productivity (NBP) was calculated by subtracting ecosystem disturbances (i.e. carbon lost through burning or grain harvesting) from the NEP.

3.5 Error estimation

Most measurements and calculations are subjected to errors. To estimate the uncertainty in this study, three main types of errors were investigated: random error, systematic error, and gap filling error: random errors were assessed using two tower approach (Hollinger, 2005), during periods when footprints for both towers represented the prairie. Resulting random error distribution from the prairie site was also used for the agriculture site because similar types of equipment and the same techniques were applied. Systematic errors were assessed by the use of different friction velocity thresholds output from REddyProc (Wutzler, et al., 2018). Distribution of gap-fill errors were obtained by introducing artificial data gaps and subtracting the original data (original NEE) from the gap-filled data (filled NEE). We then drew random numbers from the resulting error distribution and propagated these with systematic, and random errors in quadrature to infer the uncertainty of annual and total C-budgets.

4. **Results:**

4.1 Energy Balance Closure of sites

Throughout our study, the closure of both sites changes from year to year with a minimum 68% and a maximum of 82% as shown in Figure 4 and Figure 5, but the closures obtained are comparable to other agricultural sites (Imukova, Ingwersen, Hevart, & Streck, 2016). Surface energy balance closure has been an ongoing issue in the fluxnet community, where the lack of closure ranges from a magnitude of 20% to 30% and thus has been considered to bias CO_2 fluxes low (Wilson, et al., 2002). However the origin and propagation of errors due to a mismatch in EBC are controversial topics in the eddy flux community and the general recommendation in standardized flux processing protocols from global flux networks is not to correct for a lack of EBC, e.g. (Barr, Morgenstern, Black, McCaughey, & Nesic, 2006);. (Xin, et al., 2018).

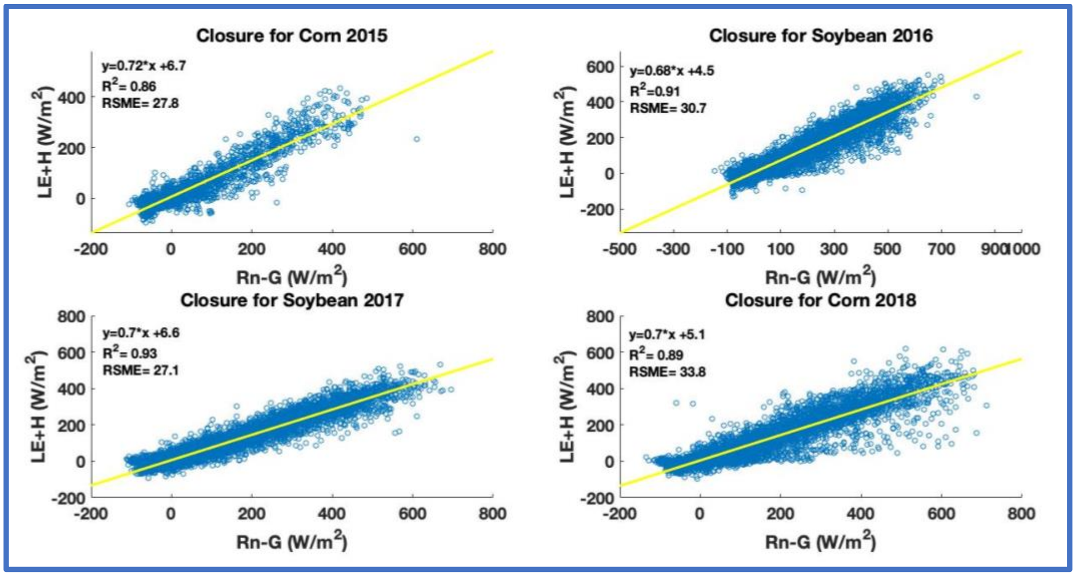


Figure 4: Energy Balance Closure of the Corn/Soybean Rotation site from 2015 to 2018. Closure vary between 0.68 and 0.72.

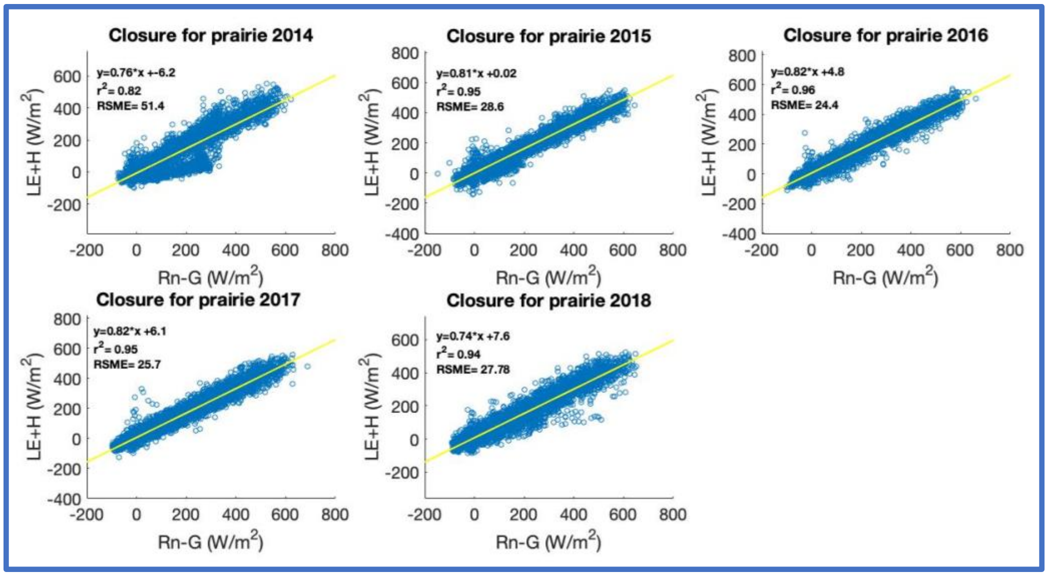


Figure 5: Energy Balance Closure of the Prairie site for year 2014 to year 2018. Closure changes over the years with the lowest closure being 0.74 and the highest 0.82.

Based on the EBC closures obtained for our sites, we find a lack of closure that ranges between 18% and 26% for the prairie system and between 28% and 32% for the corn/soybean rotation system. In this study we have not applied any corrections for the lack of energy balance closure.

4.2 Errors

Over the 4 years of the study, the prairie had a maximum gap filling error of 21 gC/m^2 while the corn/soybean rotation had a maximum gap filling error of 7 gC/m^2. The random error produced an uncertainty of +/- 11.6 gC/m^2/yr, while systematic error varies over the study period.

4.3 Carbon Flux

Between calendar years 2015 and 2018 there were two cycles of corn and 2 cycles of soybean planted. Ecosystem respiration is dominant during the spring for both ecosystems studied and it should be noted that carbon loss to the atmosphere in the spring of the soybean years is primarily a result of ecosystem respiration of corn residue from the previous year. Similarly, carbon loss in the spring of the corn year is largely a result of ecosystem respiration from soybean residue from the previous year. Figure 6 shows the general cumulative pattern of NEE for each crop, where the sites experienced a loss of carbon to the atmosphere between day of year (DOY) 1 and DOY 170 for the corn crops and DOY 1 to DOY 195 for soybean. Between DOY 170 and DOY 260 for corn crops and DOY 195 and DOY 260 for soybean crops the ecosystem represents a carbon gain, this period is considered to be the growing season. From DOY 260 to the end of the year a loss of carbon to the atmosphere is observed.

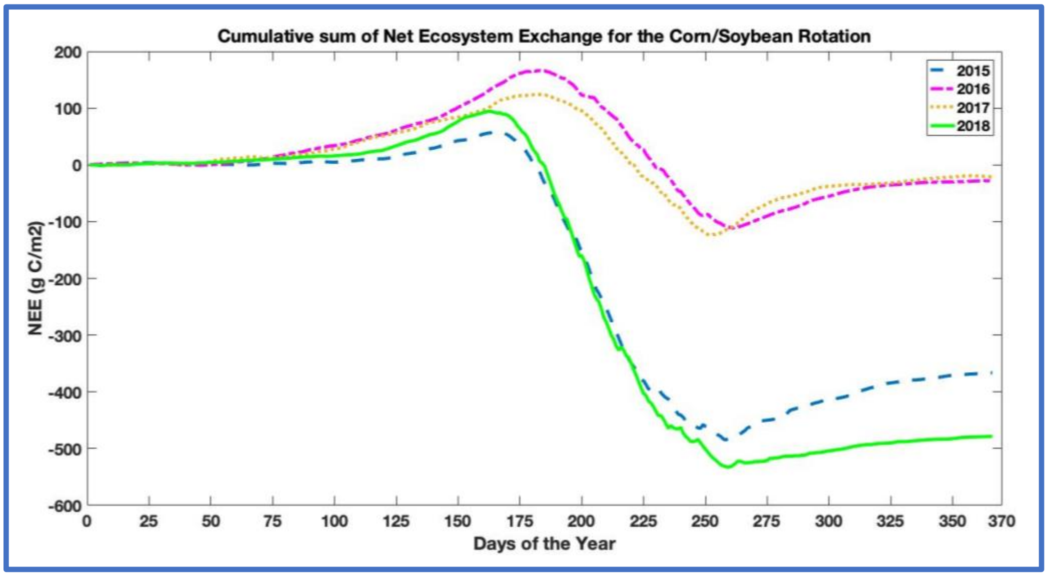


Figure 6: Cumulative carbon fluxes for both corn and soybean production for the Agriculture sites. 2015 was a corn year, 2016 a soybean year, 2017 a soybean year and 2018 a corn year.

The prairie reflects a similar cumulative pattern as that of the agriculture site as shown in figure 7. During the winter months, the prairie experienced a loss of carbon while during the late spring and summer months the prairie experienced an uptake of carbon. Between DOY 1 to 155 the prairie experiences a cumulative loss of carbon to the atmosphere but experiences a gain of carbon between DOY 155 to DOY 260. From DOY 260 to the end of the year both ecosystems experience a loss of carbon to the atmosphere. Differences in the timing of net carbon gains between the two ecosystems is based on the phenology of the vegetation, due to the fact that prairie grasses have an earlier emergence than the cultivated crops.

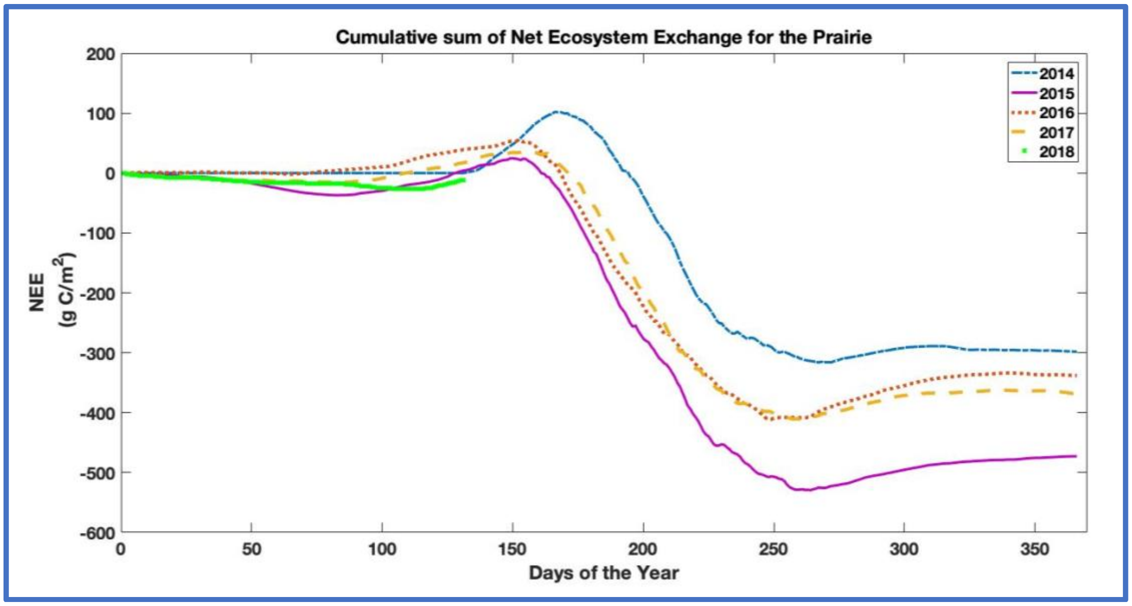
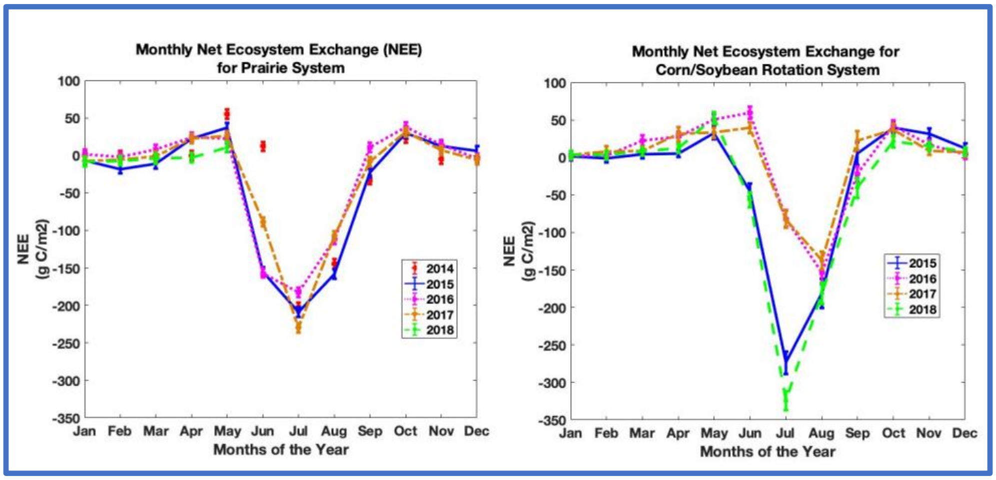


Figure 7: Cumulative grams of carbon for the prairie in Rosemount. Day of year 130 (May 10) for the year 2014 represents the day in which the first burn was carried out, thus the 4-year burn cycle spans from May 10, 2014, to May 10, 2018.

Along with the cumulative NEE of both ecosystems, the monthly trend of NEE for both systems was investigated and is depicted in Figure 8.

In summary, both ecosystems exhibit similar seasonal patterns in carbon gain and loss but experience a phase shift in the pivoting points between acting as sources and sinks. Further the rates of carbon gain and losses were of different magnitudes. Figure 10 shows the monthly breakdown of carbon fluxes between the atmosphere and the ecosystems with error bars that represent the error of monthly sums (combination of random, systematic, and gap-filling error).


Monthly Net Ecosystem Exchange (NEE) for Prairie System

Monthly Net Ecosystem Exchange for Corn/Soybean Rotation System

Figure 8: Monthly sum of carbon fluxes for both ecosystems. Between the months of January to May, there is a loss of carbon to the atmosphere, while between May and October a gain of carbon to the ecosystems is depicted. From October to December both ecosystems show a release of carbon to the atmosphere. Corn years for the cropland show large uptake of carbon which is in close comparison to the prairie while the soybean years shows a significantly lower carbon uptake. Negative signs represent an uptake of carbon by the ecosystem which reflects photosynthesis activity while a positive number represents a loss of carbon from the ecosystems which reflects ecosystems respiration. Error bars show the errors obtained from propagating systematic, random and gap-filling errors.

Based on Figure 8, it is evident that during the years when corn (years 2015 and 2018) was cultivated there was a larger carbon uptake in comparison to the years when soybean (years 2016 and 2017) was in the rotation. Carbon uptake of the prairie began earlier than the cropland especially when soybean was the crop planted as soybean was generally planted later in the growing season. Figure 9 shows a comparison of average monthly carbon fluxes between the prairie and the agricultural sites.

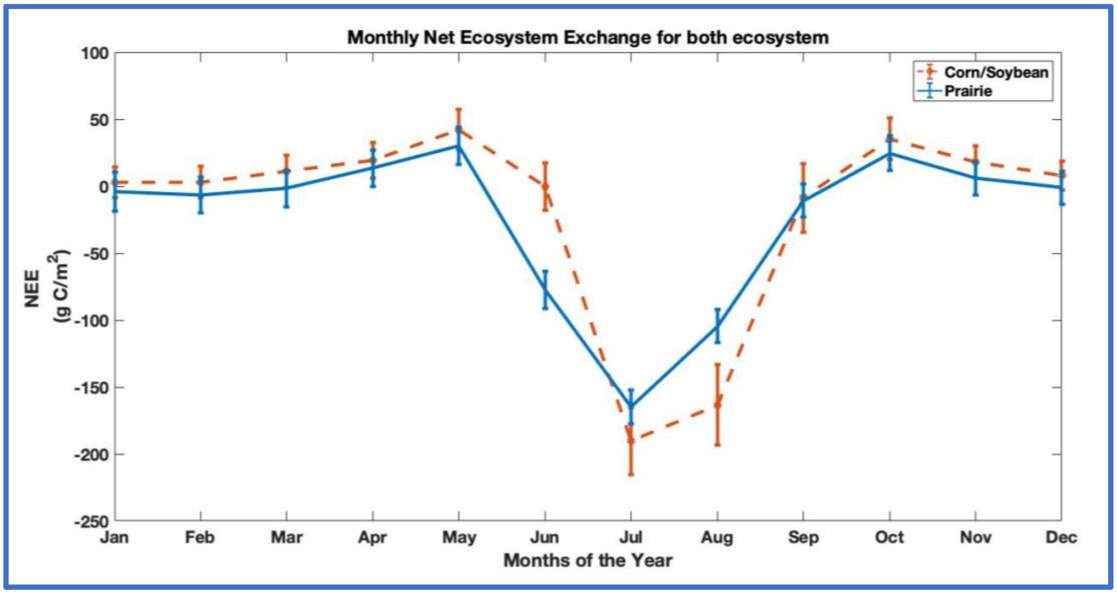


Figure 9: Mean monthly carbon fluxes for the prairie and corn/soybean rotation. During the winter months and early spring (non-growing season) both ecosystems are releasing carbon into the atmosphere due to the dominant process of respiration, but between May and October (which is the typical growing season in the Midwest) the process of photosynthesis dominates and both ecosystems experience an uptake of carbon. The prairie shows an earlier uptake of carbon which is due to the early emergence of the prairie vegetation.

Figure 9 shows the average monthly mean of carbon within both studied ecosystems. Here it is observed that the prairie reflects an earlier carbon uptake as uptake begins in May, but the agricultural sites show a later uptake. In late June to early July the agricultural sites carbon uptake exceeds that of the prairie and represents the time in which the cropland has developed a full canopy. During Mid-August the prairie starts to decline in its carbon uptake rates and shows signs of early senescence. Figure 10 shows the cumulative flux of NEE for both ecosystems.

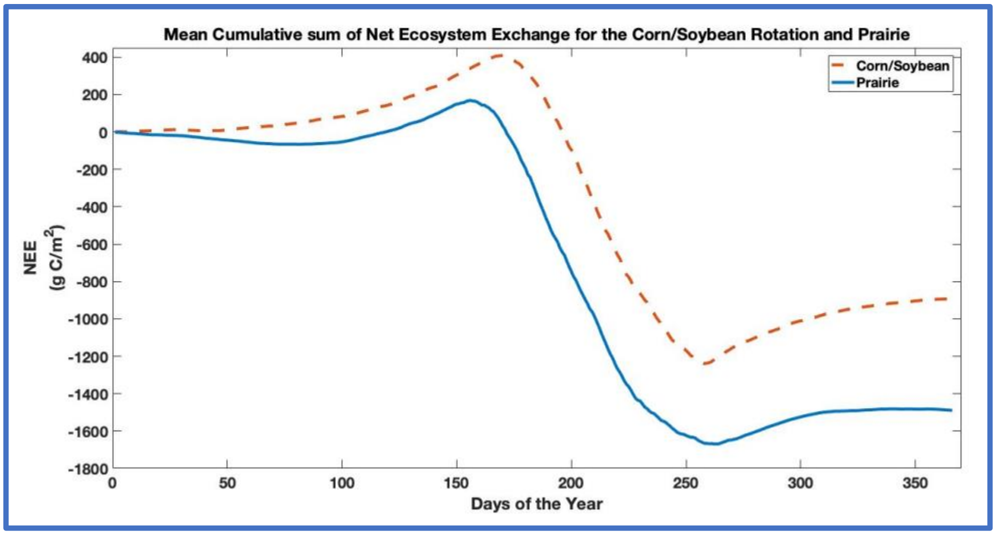


Figure 10: Mean cumulative carbon fluxes of both ecosystems averaged over a 4-year cycle. Cumulatively, the prairie releases less carbon and also sequesters more carbon in comparison to the corn/soybean rotation system.

Although the cropland's NEE exceeding that of the prairie during the mid-growing season, the prairie has greater cumulative NEE over the entire study period. The cropland released a greater amount of carbon to the atmosphere in comparison to the prairie as shown in Figure 10, where between DOY 1 to approximately 175 the cropland is losing carbon to the atmosphere while from DOY 155 the prairie is experiencing carbon uptake.

4.4 Restored Prairie Fire Management

The prairie experiences fast re-growth of plants after a prescribed burn, as depicted in Figure 11 and Figure 12. This increase in biomass and lushness of vegetation agrees with previous studies which claimed that fire potentially increases green biomass production (MacNeil, Haferkamp, Vermeire, & Muscha, 2008) (Fischer, et al., 2012). Increased biomass results in a greater leaf area to absorb more photosynthetically active radiation which is also expected to increase carbon sequestration (MacNeil, Haferkamp, Vermeire, & Muscha, 2008). Within one to two years, it is considered that carbon uptake after burning might offset the initial carbon loss from combustion (MacNeil, Haferkamp, Vermeire, & Muscha, 2008). In addition, the amount of carbon loss along with the effect of the fire depends on the intensity of the fire; as high-intensity fires result in the loss of carbon stocks in soils while low-intensity fires favor an increase in soil carbon (Alcaniz, Outeiro, Francos, & Ubeda, 2018). Despite variance in timing of prescribed burns across studies, the effects on biomass production are generally similar.

Figure 11: Rosemount prairie 20 days after Burn in 2018. The image was taken on Wednesday, May 30, 2018, at 13:25:16. Burning greatly influence the regrowth of plants in the prairie. (Image was obtained from phenocams installed at the sites).

Figure 12: Rosemount prairie 50 days after Burn in 2018. The image was taken on June 30, 2018, at 13:55:27. Within 50 days the land was fully covered.

In addition, burning of the prairie resulted in the oxidative loss of carbon in the above-ground biomass to the atmosphere. A sample of the results of the carbon analysis can be found in Appendix 4. Carbon loss due to prescribed burn is shown in Table 1.

Averaged Above-ground Biomass at Rosemount Prairie before and after Prescribed Burn	
Pre-burn Biomass (gC/m^2)	528
Post-burn Biomass (gC/m^2)	173
Total Biomass Loss (gC/m^2)	355

Table 1: Biomass loss from Rosemount Prairie. Data was obtained from sample collection before and after the burn. Green biomass was left to air dry. Samples were grounded then analyzed using Variomax analyzer to estimate total carbon loss due to burn.

Furthermore, burning results in an immediate and rapid loss of carbon from the ecosystem into the atmosphere.

4.5 Harvesting, GPP, NEP, Ecosystem Respiration and NBP

Similar to prescribed burns, harvesting in agriculture lands represents a relatively rapid loss of carbon, since it can be assumed that nearly all of the carbon in the grain will be respired by animals that consume it or released back to the atmosphere if used to produce biofuels. Table 2 shows the total grain yield each year from the study site.

Year of Study	**Grain Yield (gC/m^2)**
2015	449.4
2016	198.4
2017	136.8
2018	387.9
Total	1172.5

Table 2: Grain yields from 2015 to 2018. One year of Corn produced a greater grain yield than both years of Soybean combined.

Along with grain yields and carbon released from burning, ecosystem respiration is another component that releases carbon back into the atmosphere. Figures 13 through 15 show the cumulative sums of GPP, Ecosystem Respiration and NEP for both ecosystems, respectively.

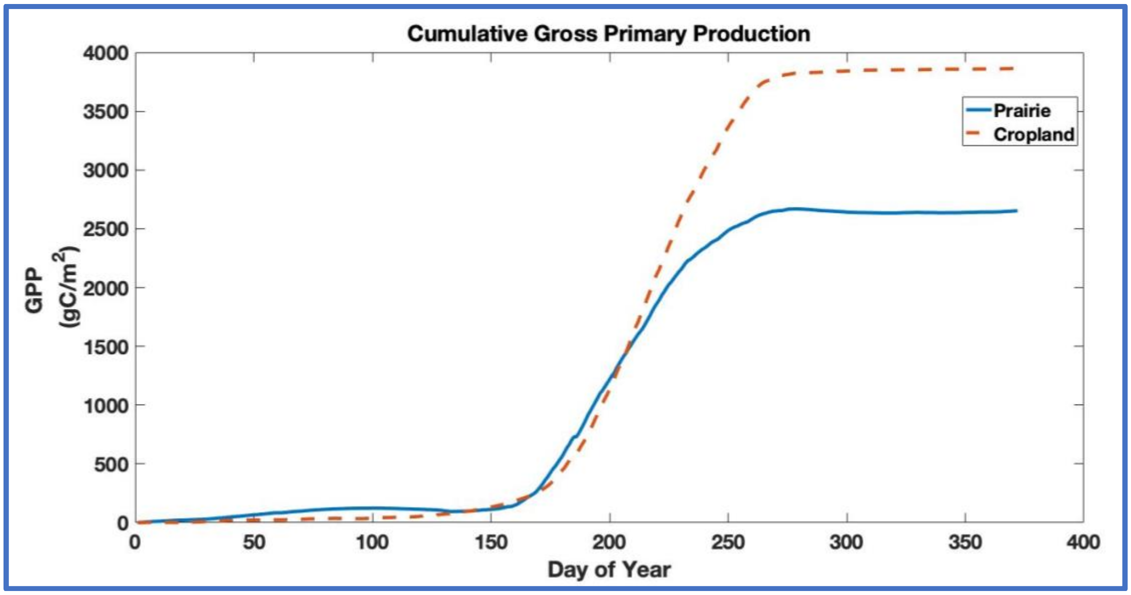


Figure 13: Gross Primary Production for both ecosystems. The cropland's GPP greatly exceeds that of the prairie.

GPP of the ecosystems varies, with the corn/soybean system having a higher cumulative GPP throughout the study. The corn/soybean system had a cumulative GPP of over 3860 gC/m^2 while the prairie had a GPP of approximately 2650 gC/m^2. Likewise, the corn/soybean also had higher cumulative R_E than the prairie site as depicted in Figure 14. The R_E of the cropland was 2970 +/-354gC/m^2 while the R_E of the prairie was only 1170 +/- 168gC/m^2. Annual tillage, crop residue remains along with leaving soil bare during the non-growing season are a few reasons which lead to higher R_E of the cropland in comparison to the prairie which is covered all year and does not experience annual tillage (Dold, et al., 2017).

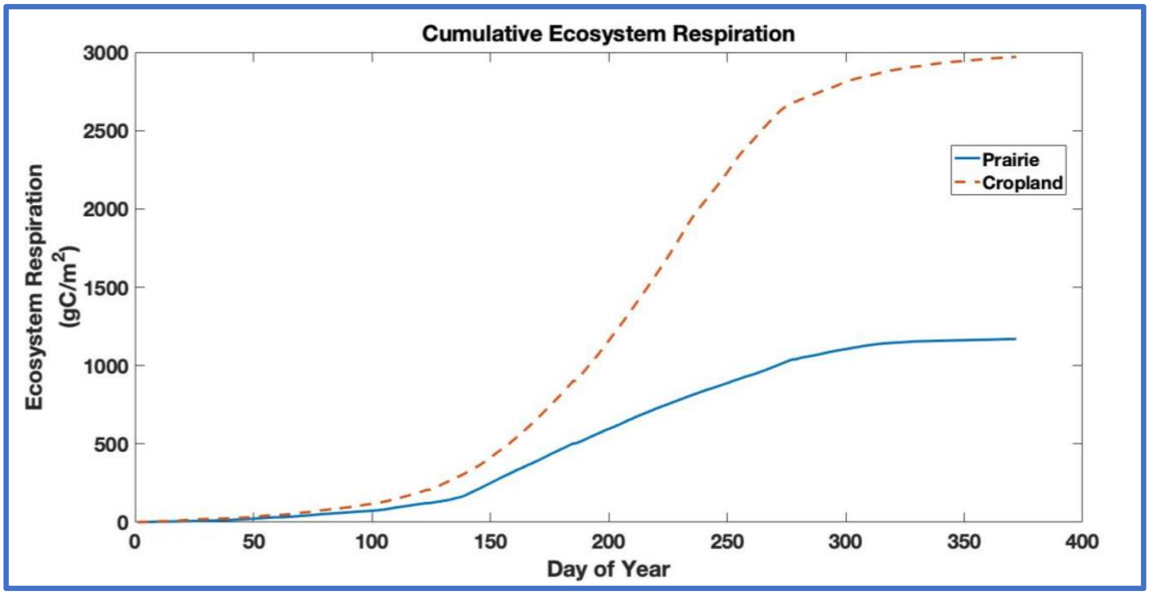


Figure 14: Ecosystem Respiration for both ecosystems. The corn/soybean rotation released the most carbon through respiration between both systems throughout the entire study.

In contrast to the previous trend, the prairie had higher cumulative NEP than that of the corn/soybean rotation system as shown in Figure 15. The prairie's NEP was 1483 +/-30gC/m^2 and the cropland's NEP was only 894 +/-94gC/m^2.

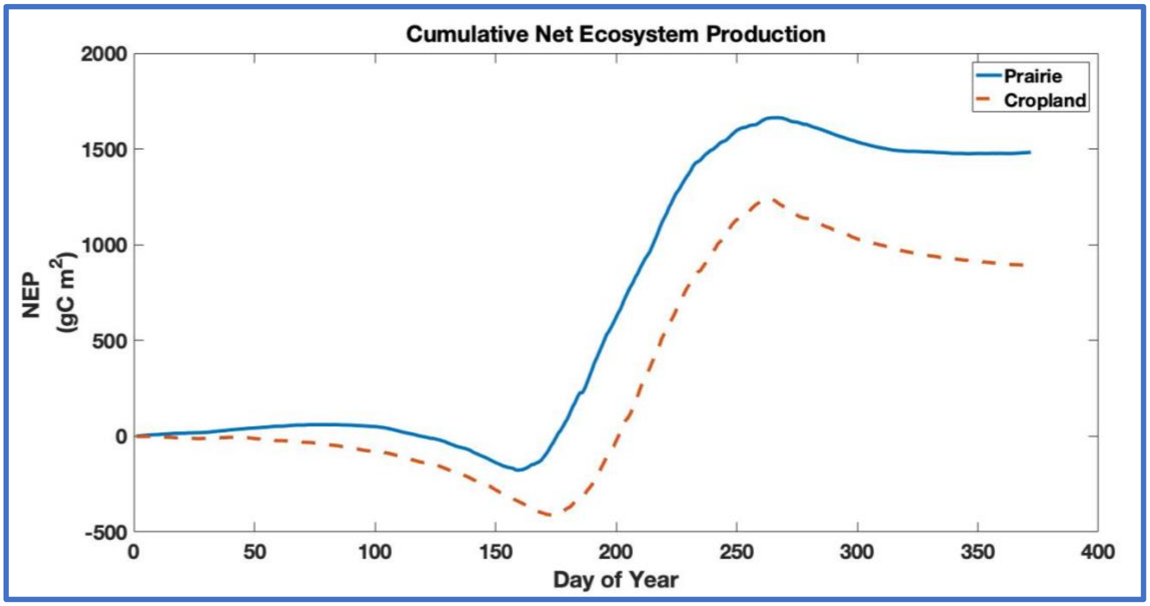


Figure 15: Net Ecosystem Production for both ecosystems. The prairie reflected the highest cumulative NEP.

As previously mentioned, the corn/soybean system had higher GPP and R_E than the prairie, but the prairie had a higher NEP.

Annual NBP of both ecosystems is displayed in Table 3. As hypothesized, the prairie had a higher NBP than the Corn/Soybean system, as the disturbances recorded for the cropland were approximately 3.3 times greater than the disturbances recorded for the prairie.

Net Biome Productivity for both Corn/soybean and Prairie ecosystems		
Ecosystems	Corn/soybean (gC/m^2/yr)	Prairie (gC/m^2/yr)
Calculated Net Biome Productivity	-70.0 +/- 24	282 +/- 8

Table 3: Net Biome Productivity: calculated by subtracting the carbon loss from carbon gain; loss included respiration, grain removal and prescribed fire while the gain is solely carbon obtained through photosynthesis. Negative sign represents a net loss while positive represents a net gain. The prairie had a net gain while corn/soybean rotation had a net loss.

To display the NBP of both ecosystems a cumulative plot was created and displayed in Figure 16. This figure shows that the prairie experiences an increase in C while there is a fluctuating decline in C at the cropland.

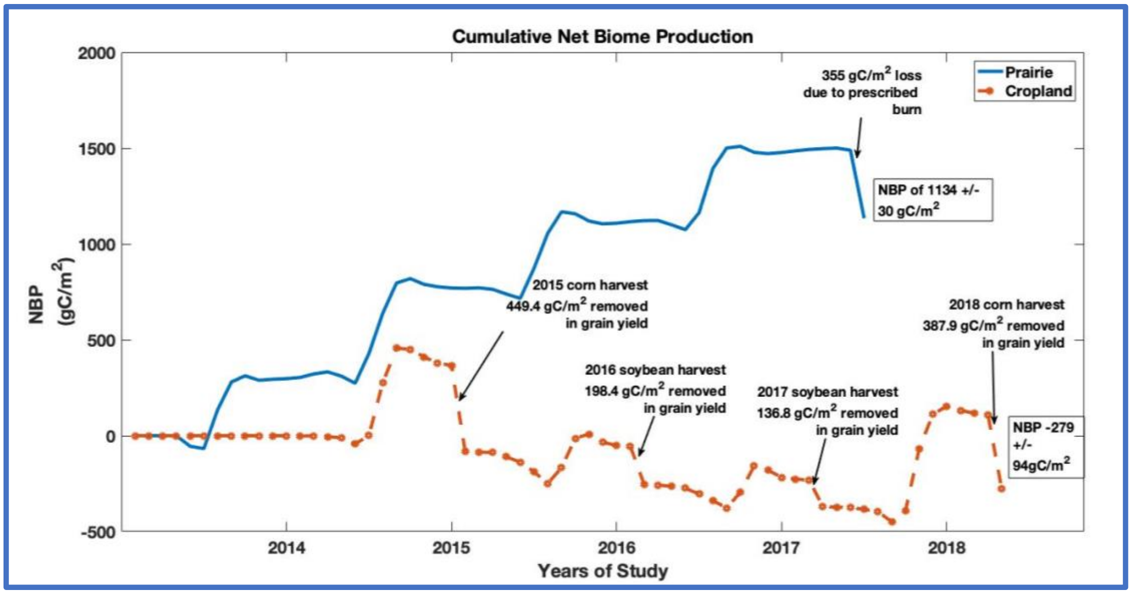


Figure 16: Cumulative Net Biome Production for both ecosystems. The NBP is the NEP of the ecosystem subtracting possible ecosystem disturbances; harvesting for the cropland and prescribed burn for the prairie. Due to prescribed burn the prairie loss approximately 355 gC/m^2 from above ground biomass while the cropland loss carbon in harvested grain which totals to approximately 1173 gC/m^2 from year 2015 to 2018. NBP of the prairie is greater than the cropland, as it lost less carbon to atmosphere due to disturbances. NBP depicts that the prairie is a net carbon sink while the cropland is a net carbon source.

Figure 16 shows that over the course of a 4-year cycle the prairie represents a net carbon sink while the cropland represents a net carbon source as the prairie had a cumulative NBP of 1134 +/- 30gC/m^2 while the cropland experienced a loss of 279+/-94gC/m^2. Annually our cropland experiences disturbances due to harvesting while only once every 4 years our prairie is disturbed due to fire.

5. Discussion:

Due to close proximity the ecosystems studied here experienced similar meteorological conditions. Management practices, on the other hand, differed and so did the carbon sequestration capabilities. Further, the timing of emergence and senescence played a vital role in the carbon budgets. The prairie experienced an earlier emergence in comparison to the cropland which provided an advantage in terms of annual carbon balance. Carbon loss from the cropland due to harvesting usually exceeds its NEP but this is not the same for the prairie as carbon loss from the prescribed burn was much lower than the prairie's NEP; thus, confirming that prescribed burns are valuable management practice for ecosystems, and that cropland conversion to prairies can be a mitigation strategy for reducing atmospheric CO_2 levels. It is of interest to understand if the above trends of C-sequestration of the Prairie site are able to be maintained over a longer time frame. Therefore, we aggregated literature reports from earlier years with our data which is displayed in Table 4. The ecosystems represented have various types of vegetation; however, three out of four are dominated by Big Bluestem. Additionally, burning is the main management strategy applied but within different time frames. Base on the NEP values in Table 4 it can be assumed that prairies experience a fluctuation in carbon gain which may be dependent on different meteorological variables, but overall, reflects a gain of carbon; this agrees with the assumption that prairie restoration can reduce atmospheric CO_2.

Date	**Vegetation type**	**Soil type**	**Management**	**NEP (gC/m^2)**	**Location**	**Author**
1997 1998 1999	Big bluestem	Silty Clay Loam	Burn spring each year	274 46 124	North Central Oklahoma near Shidler 36°56'N, 96°41'W	(Suyker, Verma, & Burba, 2003)
2005 2006	Big bluestem, Little bluestem	Norge Loamy prairie	Prescribed burn 2005	330 45	El Reno, Oklahoma 35°33'N, 98°02'W	(Fischer, et al., 2012)
2009 2010 2011 2012	Patchy woody plants - pubescent oak etc. interspersed by grassy gaps – brome, dwarf sedge	Rendzic Cambisol Lying on limestone bedrock	N/A	192 221 351 83	Podgorski plateau 45°32'N, 13°55'E	(Ferlan, Eler, Simončič, Batič, & Vodnik, 2016)
2014 2015 2016 2017 2018	Dominated by Big bluestem	Waukegan silt loam	4-year prescribed burn cycle	294 473 338 369 587	Rosemount Prairie	Our data

Table 4: Net Ecosystem Production of Prairies from the literature along with NEP from our research. Data ranges from 1997 to 2018 and ecosystems are located in various parts of the world. Table displays dominant vegetation type, soil type, type of land management practice applied, the NEP, location and authors. Majority of the ecosystems represented endures prescribed burns but in different time frame.

In comparison to the other prairies represented, our restored prairie is very productive - it has the highest average NEP as shown in Table 5.

Ecosystems	**Mean NEP (gC/m^2/yr)**
North Central Oklahoma	148
El Reno Oklahoma	188
Podgorski karts Plateau	212
Rosemount Prairie	412
Rosemount Cropland	224
Rosemount cropland soybean years	25
Rosemount cropland corn years	422

Table 5: Averaged NEP for the Prairie ecosystems presented in table 4 along with the averaged NEP for the cropland in our study. The types of crops planted in the cropland is also represented with the averaged NEP for the years corn was planted and also when soybean was planted.

According to the averages produced in Table 5, our cropland's NEP is greater than the NEP of the prairies' obtained from the literature ranging from a factor of 1.0 to 1.5, the cropland's NEP is a factor of approximately 1.8 lower than our prairie which shows that our prairie is more productive than the others.

Our prairie was also more productive in comparison to a 9-year study conducted in Ames Iowa which had an average NEP value of 61gC/m^2/yr, which is approximately 6 factors lower than the averaged NEP value of our prairie (412 gC/m^2/yr.) (Dold, et al., 2017); we hypothesized that due to annual burn this prairie experiences lower annual NEP values as recovery year after a burn usually have larger NEP in comparison to burn years.

The type of crop planted has a huge impact on the carbon balance of the ecosystem; during the years when soybean is the crop in the rotation the averaged NEP obtained by the cropland is 1.8 times lower than the lowest NEP recorded in Table 5.

However, prairies have the ability to sequester carbon for a very long time but a larger dataset in a specific restored prairie would be needed to evaluate whether or not restored prairies can maintain their C-sequestration ability/rate and for how long.

According to Dold, et al. there is hope that our prairie which experiences less disturbance may continue to reflect a carbon sink for a long period (2017).

Throughout the study, there were no extreme drought, and this limits our prediction on our prairie's behavior in an extreme drought. But it is noted that during mid to late summer when the air temperature is at its highest our restored prairie's productivity reduces and the cropland exceeds the prairie as shown in Figure 9.

Despite our limited dataset for our prairie, it represents a carbon sink while the cropland represents a carbon source. Data collection is ongoing which will provide the opportunity for future prediction for the prairie's sequestration time span.

6. Conclusion:

Overall, different ecosystems have varying patterns of photosynthesis, respiration and carbon flux, which affects their annual carbon balance. From this study we conclude that:

1. The type of crop planted in the rotation greatly affects the carbon cycle of the ecosystem as C4 plants are able to capture more carbon in comparison to C3 plants; when corn was the crop (C4 plant) planted it had a higher NEP versus when soybean (C3 plant) was planted. Carbon sequestration between the corn years and that of the prairie are very close in comparison but during the soybean years the prairie exceeded the cropland by a factor of approximately 1.7. Further analysis on crop types is necessary to understand the effects of crops on carbon sequestration.
2. Prescribed burning is essential for prairie management and growth as this method helps suppress succession towards woody vegetation. Prairie grasses are very lush after burn.
3. The amount of carbon loss to the atmosphere due to prescribed burn was a factor of 3.3 lower than the carbon loss due to grain harvest from the cropland over the 4-year burn cycle.
4. The prairie's NBP over the period of study was approximately greater than that of the cropland by a factor of 4. The prairie represented a carbon sink, while the cropland represented a carbon source.
5.

CHAPTER 3

Evapotranspiration and Carbon Balance of a Restored Prairie vs a Conventional Corn/Soybean Rotational Cropland

1. Synopsis:

Different land cover types show different seasonal and annual variations in energy budget variables such as evapotranspiration, and also show a variation in ecosystem services such as carbon sequestration. In this study, we investigate the seasonal and annual evapotranspiration and carbon balance of a restored prairie and a conventional corn/soybean rotational cropland in the Midwestern United States during calendar year 2015 to 2018 which included 2 years of corn production and 2 years of soybean production in the agricultural system and one burn cycle in the prairie system.

Over the 4-year period the prairie had a much higher Net Ecosystem Production (NEP) than the corn/soybean system, 1483 g C m^{-2} versus 894 g C m^{-2}. In the corn/soybean rotation 94% of the NEP occurred during the corn years, reflecting both higher photosynthetic rate of corn and the fact that much of the respiration of corn residue occurs during the following soybean year. After accounting for carbon (C) export via harvest in the corn/soybean system and via burn in the prairie, there was an even greater contrast in Net Biome Productivity (NBP), with a net gain of 1127 +/-30 g C m^{-2} in the prairie and a net loss of 279 +/-94 g C m^{-2} in the corn/soybean field. With respect to water use, the corn/soybean system had a cumulative evapotranspiration (ET) of 2112mm, while the corresponding ET of the prairie was 1772mm. There was surprisingly little interannual variability in ET for either systems (528 +/- 11mm and 443 +/- 17mm, respectively). If water use efficiency (WUE) is defined as NEP/ET, the prairie had a

WUE approximately twice that of the corn/soybean rotation system, 0.84 gC mm^{-1} versus 0.42 gC mm^{-1}.

2. Introduction:

Evapotranspiration is a primary component of the hydrological cycle. It includes evaporation from surfaces and transpiration from plants. ET varies annually, as a function of temperature, solar radiation, vapor pressure deficit and wind speed that influence evapotranspiration rates directly (Luo, Wang, Sauer, Helmers, & Horton, 2018), and indirectly through impacts on soil moisture availability and plant growth. The type of vegetation also influences ET and changes from one type to another can result in changes in evapotranspiration rates.

With the advancement of technology and the rapid growth of FLUXNET sites worldwide, the collection of necessary data to compute ET over different land use and land cover types has improved significantly, giving researchers the ability to study changes in ET and to predict future climatic changes. Human activities due to population growth has resulted in increased changes in the land surface which have impacted our climate and are projected to continue to influence climate change. According to the Intergovernmental Panel on Climate Change (IPCC), global warming will potentially increase to 1.5^0C in 2030 to 2052 if human activities which influence global warming continues to increase at current rates (Masson-Delmotte, et al., 2018).

Increasing global temperatures may cause an increase in evapotranspiration rates along with changes in precipitation duration and intensity. Thus, understanding how ET rates are affected by land cover and how this may affect the carbon cycle (as CO_2

concentration is one of the main drivers of global warming), can be vital in future climate change mitigation planning.

The Midwestern U.S. experienced a rapid conversion from natural land cover types such as native prairie to agriculture production, with corn and soybean as the most dominant crops. The Midwest experienced other land use changes such as urbanization, but agriculture is the most dominant conversion[1] (Brown, et al., 2014).

Different types of vegetation have different growing seasons and can have differing temporal patterns of soil moisture, which in turn affects evapotranspiration patterns from these ecosystems/ land types. It should be noted that evapotranspiration rates vary among vegetation types and also exhibits seasonal and interannual variability; in a previous comparison between a prairie and a wheat ecosystem, the prairie exhibited a greater ET during the growing season but the wheat had a higher annual ET (Burba & Verma, 2005). It has been estimated using model based simulations that the conversion from grassland (prairie) to corn/soybean system has resulted in an increase in ET of 2.58 x 10^{10} m^3/yr. for continuous corn production and 5.23 x 10^{10} m^3/yr. for a corn/soybean rotation system due to expansion in these crop types throughout the Midwest (Sun J. , et al., 2017). The main objective of this research was to answer the following questions for our study sites:

1. What are the seasonal differences in evapotranspiration for the restored prairie in comparison to corn/soybean rotational cropland?

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[1] See appendix 1 for a composition map for US land use.

2. What are evident relationships between ET rates and carbon balance in these ecosystems?
3. How do vegetation types, land use, and land cover change affect evapotranspiration?

3. Methods:

In an effort to better understand the effects of land cover type on evapotranspiration rates, and how this may potentially affect carbon movement, a continuous eddy covariance data set was collected at 10Hz and processed into 30min block averages. This was carried out at two land cover types: restored prairie (Latitude: 44.6781^0, Longitude: -93.0723^0, elevation: 274 m.a.s.l.) and a conventional corn/soybean rotation cropland (Latitude: 44.42^0, Longitude: -93.05^0, elevation 283 m.a.s.l.), at the University of Minnesota Rosemount Research and Outreach Center.

The prairie site has two eddy covariance flux towers, one in the north and the other in the south. This setup was implemented to solve the issue that this site does not have a sufficient homogeneous flux footprint in all directions. On the other hand, the cropland has one tower in the center of the field as there is sufficient flux footprint in all direction (200m or more from tower in all direction). At both sites, soil heat flux is measured at 10cm depth using two Huskeflux HFPOISC flux plate. The measured heat flux was corrected for calorimetric changes in the upper 10cm using type T thermocouples at three soil depths above the flux plate (2.5cm, 5cm, 7.5cm). Net Radiation (Rn) was computed from measurements obtained from a Kipp and Zonen4 component net radiometer (CNR4). Meteorological measurements included precipitation (a Geonor T200 weighing gauge), wind speed and direction (3-D sonic anemometer, Campbell Scientific CSAT3), and radiometric surface temperature (Apogee Infrared Radiometer) were also collected. An open path infrared gas analyzer was used in conjunction with the sonic anemometers to measure fluctuations in CO_2 and H_2O (LI-COR 7500 at prairie and LI-COR 7500RS at the corn/soybean site).

All eddy covariance flux data collection and initial processing was conducted with a CR5000 (prairie) and CR3000 (corn/soybean) Campbell Scientific Dataloggers. All 30min flux data were calculated using standard methodology described by (Barr, et al., 2002) and (Griffis T. , et al., 2003). De-spiking was implemented using methods described in (Papale, et al., 2006). Further quality filtering schemes, gap filling, and flux partitioning was done using the REddyProc software (Wutzler, et al., 2018) which uses protocols and procedures explained in (Reichstein, et al., 2005), (Papale, et al., 2006) and (Lasslop, et al., 2010). MATLAB programming software was used for further data processing, where additional gap filling was implemented, using an autoregressive modeling function called “fillgaps” that replaces missing values with extrapolated estimates from forward and reverse auto-regressive functions.

3.1 Calculations:

Comparison of ET between both ecosystems was done using daily and weekly variations along with cumulative annual and seasonal sums. With the available precipitation and evapotranspiration data the water budget of both ecosystems was calculated using equation 1.

$$P=ET + D + \Delta S_w \qquad \text{eq.1}$$

Where:

P=Precipitation

ET=Evapotranspiration

D=Drainage

ΔS_w = change in soil moisture

Over long-time scales (e.g. annual) ΔS_w is typically quite small relative to the other terms, so that drainage can be estimated with equation 2:

$$D= P - ET \qquad \text{eq.2}$$

Ecosystem WUE was calculated as the ratio of total NEP divided by total ET as shown in the equation 3.

$$WUE=\frac{NEP}{ET} \qquad \text{eq. 3}$$

3.2 Terminology:

Throughout this paper we refer to negative Net Ecosystem Exchange (NEE) as carbon gain while positive NEE is a release of carbon to the atmosphere.

3.3 Bowen Ratio Adjustment:

Eddy Covariance sites generally lack energy balance closure, meaning that the amount of available energy that is partitioned into latent heat and sensible heat does not always account for the total amount of energy received (net radiation) and stored (ground heat flux) by a system (Wilson, et al., 2002). To better evaluate this situation the energy balance closure of sites is typically calculated using the following equation:

$$\mathrm{EBC} = \frac{\mathrm{LE+H}}{\mathrm{Rn-G}} \qquad \text{eq.4}$$

Where:

EBC= Energy Balance Closure

LE= Latent Heat

H= Sensible Heat

Rn= Net Radiation

G= Ground heat flux

The lack of closure experienced at each ecosystem on a monthly basis during the months of May to October was used to calculate the Bowen Ratio Adjustment. It is expressed in previous studies that eddy covariance method tends to underestimate energy fluxes (Twine, et al., 2000). In our study, the Bowen Ratio adjustment was calculated by dividing the monthly Eddy Covariance evapotranspiration and net ecosystem exchange by the monthly EBC[2].

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[2] For a sample of monthly closure for both systems view appendix 2. Closure changes for both systems throughout the year.

4. Results and Discussion:

In this study, the growing season was defined to be between DOY 121 to DOY 275 and week 18 to week 40. Days and weeks outside these ranges are considered to be the non-growing season. During the growing season, evapotranspiration rates reach maxima for both ecosystems. The corn/soybean rotation system exceeds the prairie for much of the growing season, except for the early portion (DOY 150 to 190). Based on Figure 1, the prairie only had a higher ET between DOY 150 to DOY 190. At this point in the season, corn and soybean fields have a significant amount of bare soil, while the prairie has a full canopy of perennial grasses and forbs. As the growing season progressed, evapotranspiration of the prairie peaked earlier than the corn/soybean system between DOY 185 and DOY 200, while the corn/soybean system peaked between DOY 200 and DOY 215.

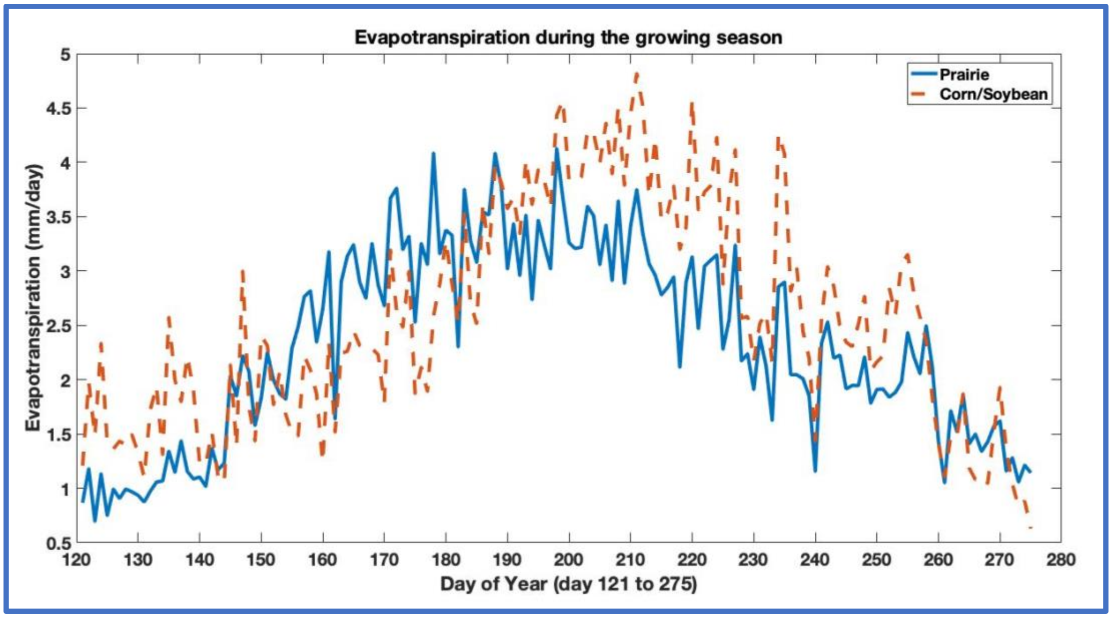

Figure 1: Evapotranspiration for both ecosystems during the growing season (DOY 121 to DOY 275). Dotted line represents the corn/soybean systems while the solid represents the prairie.

Based on the phenology of both sites, there are evident differences which help to influence the ET rates of these ecosystems. Figures 2 and 3 depict a visual difference between the studied ecosystems. The corn/soybean system has a lower albedo than the prairie in April, when the prairie consists of a blanket of dry biomass while the corn/soybean system is completely bare soil.

Figure 2: Corn/Soybean system April 10, 2017

Figure 3: Restored prairie on April 10, 2017

The differing seasonal patterns are depicted as weekly averages in Figure 4, with error bars to indicate the interannual variability. Differences in phenology of different ecosystems influence the differences in ET during the growing and non-growing season as different types of plants emerge earlier than others and also may experience senescence earlier or later (Burba & Verma, 2005).

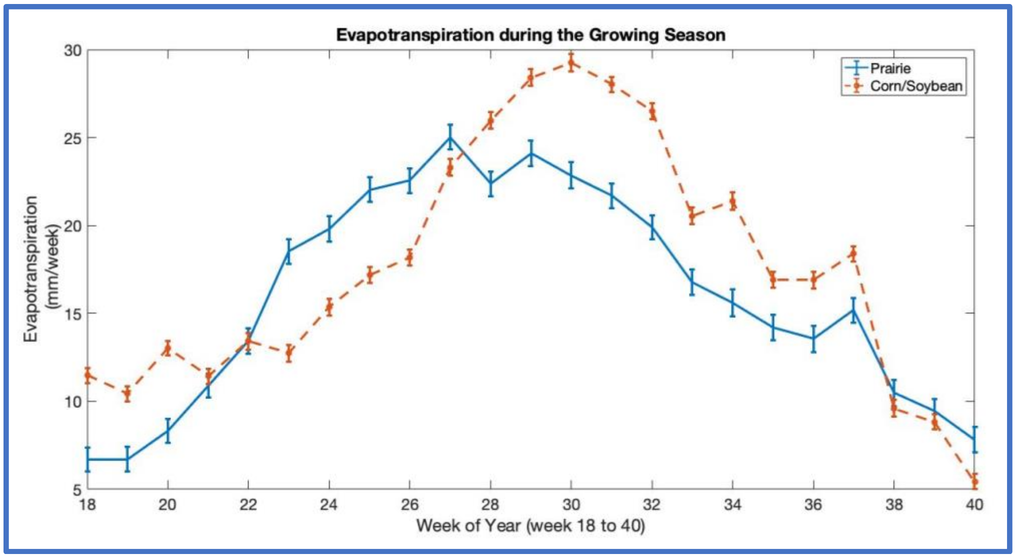

Figure 4: Weekly Evapotranspiration during the growing season (week 18 to week 40).

Notably, the comparative water use of the two systems changes as the annual crops develop a full canopy, so that during mid and late summer ET is lower in the prairie than in the cropped field.

Along with phenology, other factors that influence these seasonal patterns in ET include air temperature, albedo of the surfaces, and also surface temperatures. Photosynthetic differences between different types of plants (C3 vs C4) influence conductance of water vapor; as with increased temperatures, during mid to late summer, the ET rates in relation to absorbed photosynthetically active radiation of prairies generally decreases because prairies are predominantly composed of C4 plants (Still, Berry, Collatz, & Defries, 2003). Along with air temperature, the surface temperature also influences the ET rates of our ecosystems. As shown in Figure 5, the surface temperature of the corn/soybean system is generally higher than that of the prairie. Surface temperature is related to both ET and the albedo of the systems.

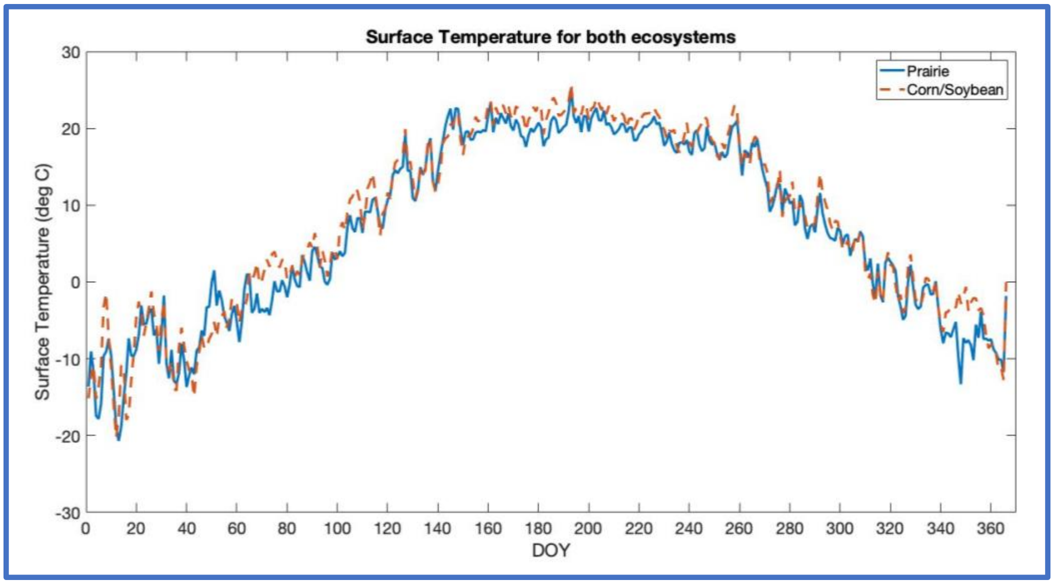

Figure 5: Averaged Daily variations in Surface Temperature at both ecosystems

The albedo of the surfaces also plays an indirect role in the evapotranspiration rates. The albedo effect impacts the surface temperature, since more absorption means more energy available for evaporation. As shown in the Figure 6, the prairie had a higher albedo than the corn/soybean system throughout most of the growing season. This is a result of the growth rate of these different plants as grasslands (prairies) tends to have an earlier emergence and later senescence in comparison to annual crops (corn/soybean) (Georgescu, Lobell, & Field, 2011) and (Eichelmann, Wagner-Riddle, Warland, Deen, & Voroney, 2016). Also, during late spring the corn/soybean system is bare and is darker in color in comparison to the restored prairie, as depicted in Figure 2 and 3.

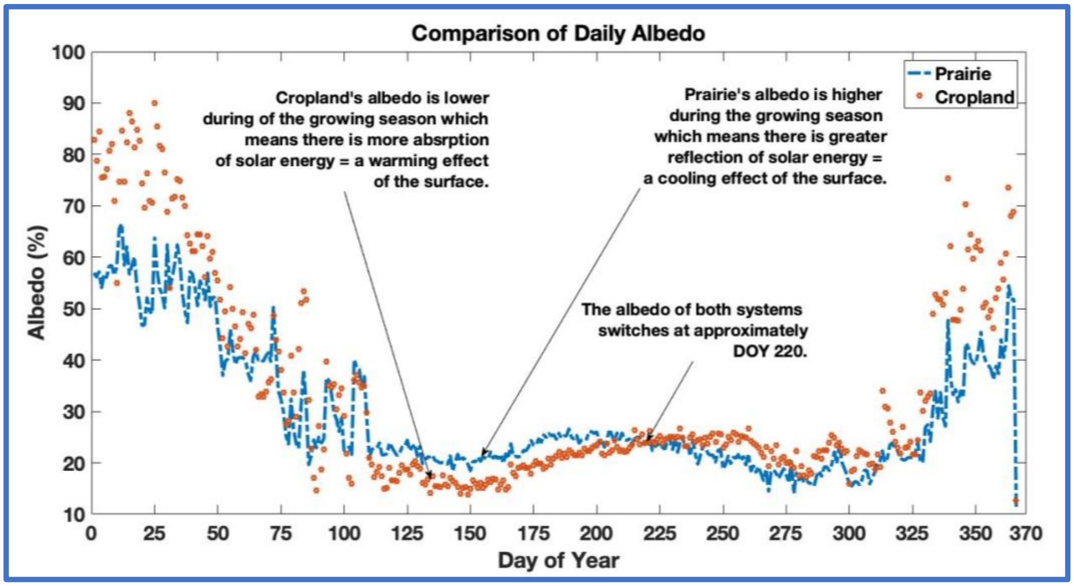

Figure 6: Albedo for both ecosystems. The corn/soybean system had a lower albedo throughout the growing season until DOY 220 where the corn/soybean system's albedo exceeds that of the prairie.

A combination of higher surface temperature and lower albedo leads the corn/soybean rotation system to have a higher annual ET in comparison to the restored prairie.

The partition of available energy to latent heat and sensible heat between the types of plant canopy influences water-use efficiency (WUE), as canopies that provide more available energy to sensible heat typically have a higher WUE (Still, Berry, Collatz, & Defries, 2003) , which can be suggested for our prairie site as shown in Figure 7. The prairie gained more carbon while having a lower ET rate in comparison to the corn/soybean rotation system and thus reflects a higher WUE. The WUE of the prairie was 0.84 gC mm^{-1} and the WUE for the cropland was only 0.42 gC mm^{-1}.

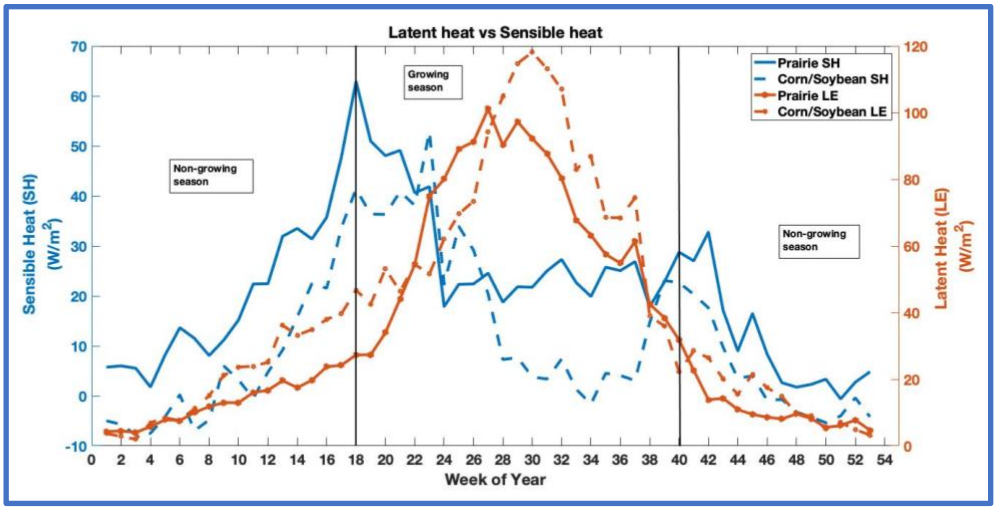

Figure 7: Partition of Latent Heat vs Sensible Heat for both ecosystems.

During the growing season both ecosystems partitioned most available energy to latent heat while in the non-growing season most available energy goes to sensible heat. Generally, the prairie has a higher sensible heat flux and a lower latent heat flux than the corn/soybean rotation. There are also seasonal differences between the systems as the prairie tends to peak earlier for both sensible and latent heat fluxes than the corn/soybean rotation system.

4.1 Difference Between Eddy Covariance Measurement and Bowen Ratio Adjustment Measurements

Both ecosystems' in our study showed a lack of closure which varied interannually. Studies have shown that eddy covariance methods produced lower energy fluxes in comparison to the Bowen Ratio method, in which closure is forced (Shi, et al., 2008). According to Figure 8 and 9, the values for both ET and NEE produced by the eddy covariance method is lower than that of the Bowen Ratio adjustment method, but in either cases the prairie had a higher NEE and a lower ET in comparison to the corn/soybean rotation system. The average ET value between the months of May to October for the prairie using the eddy covariance method and the Bowen ratio adjustment was 380.5 +/- 8.6mm/yr. and 488.3 +/- 11.2mm/yr. respectively. The average ET for the corn/soybean rotation system was 420.9 +/- 5.6mm/yr. and 554.9 +/-7.4mm/yr. using the eddy covariance and Bowen ratio adjustment methods respectively.

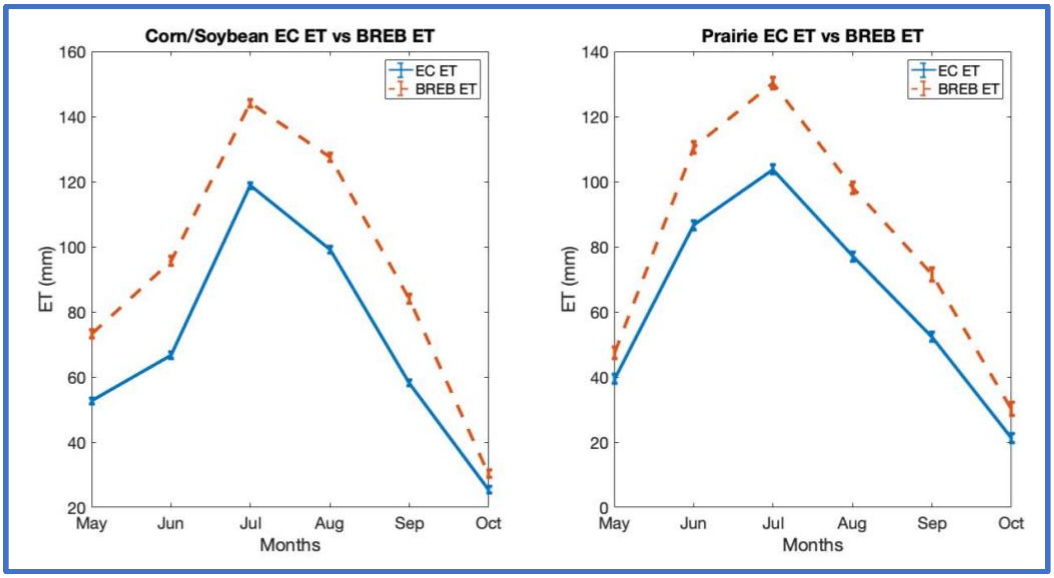

Figure 8: Evapotranspiration comparison of the Eddy Covariance method to the Bowen Ratio Adjustment method

The average NEE for the prairie site between the months of May to October was -380.3 +/- 37.5 g C/m^2/yr. and -479.5 +/- 48.6 g C/m^2/yr. using the eddy covariance and Bowen ratio adjustment methods respectively. The corn/soybean rotation system on the other hand had an averaged NEE of -285.4 +/- 26.3 g C/m^2/yr. using the eddy covariance method and -356.9 +/- 34.9 g C/m^2/yr. using the Bowen ratio adjustment method. Throughout the rest of the paper we only report eddy covariance data as it is being debated in the FLUXNET community as to whether energy balance closure should be applied to eddy covariance data (Barr, Morgenstern, Black, McCaughey, & Nesic, 2006).

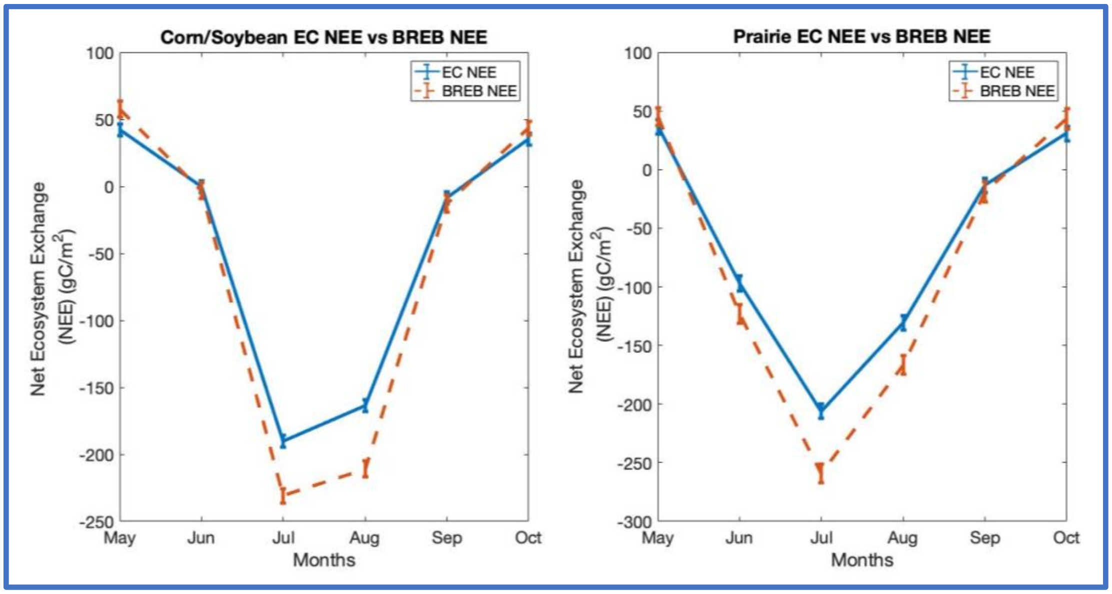

Figure 9: Net Ecosystem Exchange of both systems comparing Eddy Covariance method to Bowen Ratio adjusted calculation

4.2 What is the relationship between Evapotranspiration and Carbon Flux?

Carbon and water exchanges between the atmosphere and the ecosystem are both affected by available soil moisture, as with adequate soil moisture plants are able to effectively transpire thus opening their stomata, but soil moisture and ET have a more direct link to each other than the link between carbon fluxes and soil moisture (Kurc & Small, 2007).

During the growing season, the prairie had a mean cumulative evapotranspiration sum of 368 +/- 16mm while the corn/soybean system had a mean cumulative sum of 403 +/- 11mm. With respect to carbon, the prairie and corn/soybean systems had mean growing season NEE of -471 +/- 68gC/m^2 and -311 +/- 48gC/m^2 respectively. This indicates that the prairie had a higher water use efficiency as it is able to acquire more carbon in relation to water release into the atmosphere. A comparison of the weekly growing season ET and carbon gain is displayed in Figure 10.

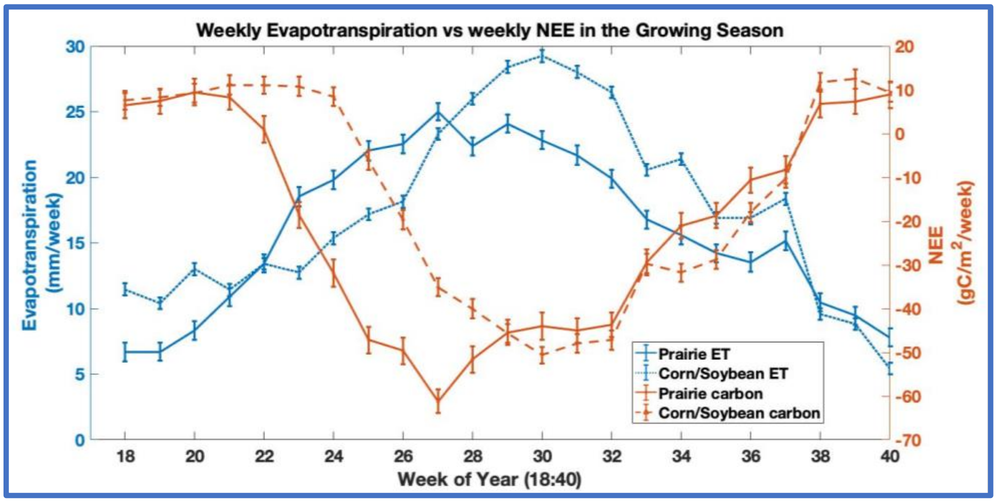

Figure 10: Weekly ET vs Weekly carbon sequestration during the growing season.

According to Figure 10, it is evident that the carbon flux peaks at the same week when the ET rate peaks.

During the non-growing season, which is represented as the time DOY 1 (week 1) to DOY 120 (week 17) and DOY 276 (week 41) to DOY 365 or 366 in a leap year (week 52), there is a lower rate of evapotranspiration and both ecosystems experiences a loss of carbon to the atmosphere which is displayed in Figure 11.

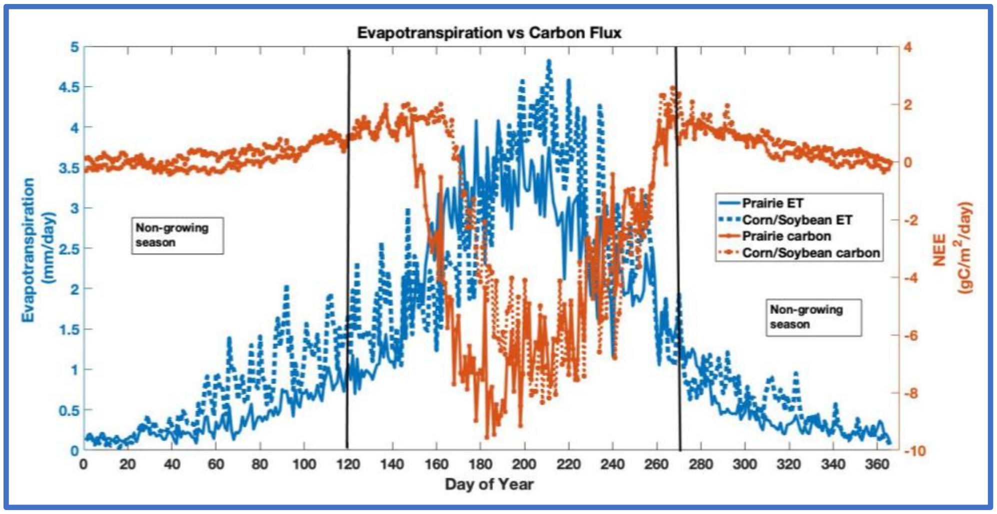

Figure 11: Displaying the non-growing season with a vertical black line to separate the growing season. In this, positive carbon values represent a loss of carbon to the atmosphere while negative carbon values represent a gain of carbon to the ecosystem.

During the non-growing season, both ecosystems experienced a loss of carbon to the atmosphere and low evapotranspiration rates between 0 and 2mm/day. The prairie had a NEE of 29 +/-87gC/m^2, and the corn/soybean system had a NEE of 87 +/-61gC/m^2. The prairie and the corn/soybean systems had cumulative ET rates of 75 +/-20mm and 125+/-13mm respectively. This pattern of evapotranspiration rates and carbon flux is depicted in other studies, and it is also noted that agricultural lands tend to lose more carbon and have a higher ET rate during the non-growing season in comparison to prairies (Bajgain, et al., 2018). The higher ET rates during the non-growing season for croplands verses the prairie can be highly influenced by the higher albedo experienced during this season as shown in Figure 6; as higher albedo results in increased evaporation.

4.3 The water budgets

Both ecosystems are in close proximity (approximately 4km) to each other and hence received the same amount of precipitation, but due to different types of vegetation and management strategies, they experience different evapotranspiration rates. The drainage of the ecosystems was calculated using equation 2 (eq. 2). With varying evapotranspiration rates at these ecosystems, the drainage varies inversely to ET. Thus, with increasing ET drainage of the systems decreases. Figure 12 shows the weekly variation in precipitation, evapotranspiration and drainage + ΔS_w patterns for both ecosystems.

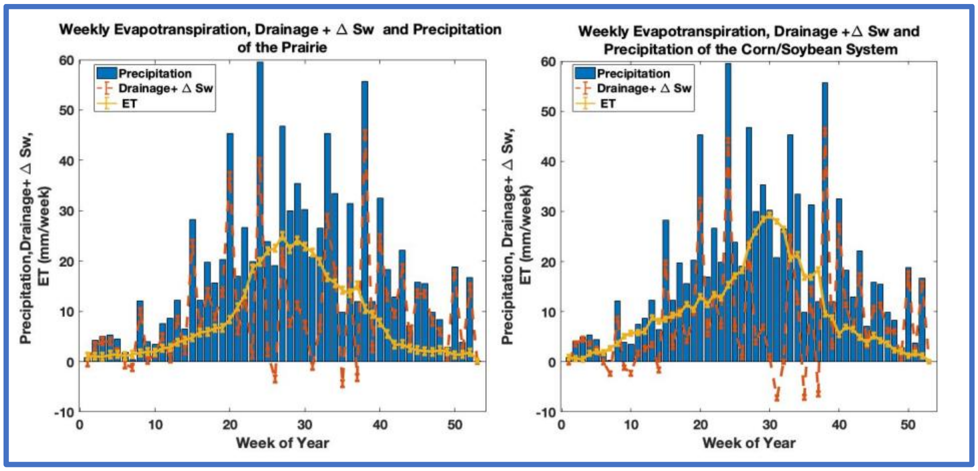

Figure 12: Weekly drainage + ΔS_w pattern for both ecosystems

When evapotranspiration constantly exceeds precipitation drainage and soil moisture content are depleted over time. With low evapotranspiration and high precipitation, drainage is correspondingly high.

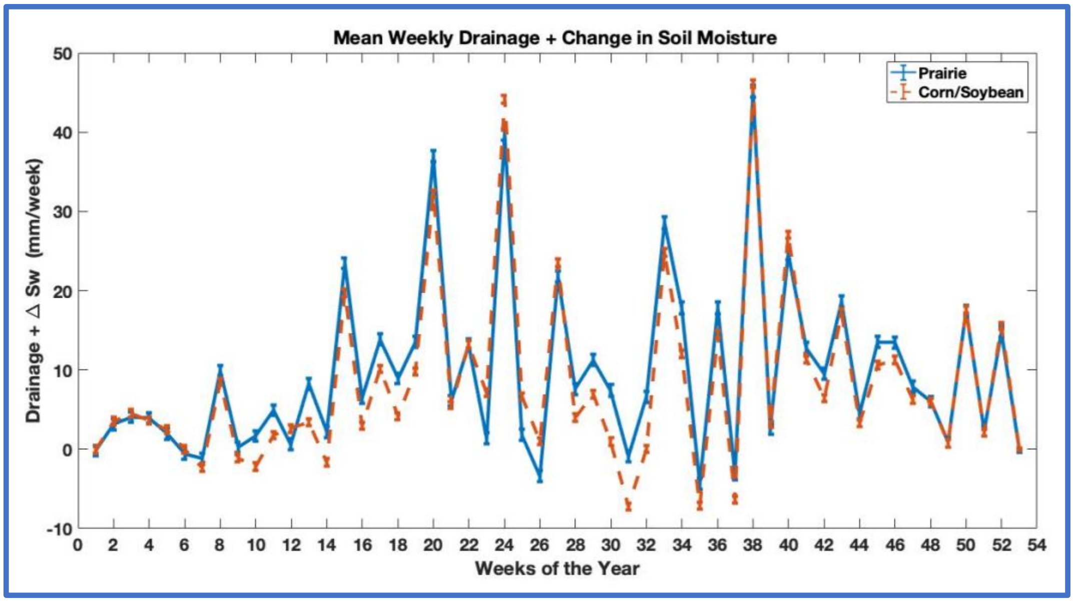

Figure 13: Weekly drainage +ΔS_w for both ecosystem

Annually drainage +ΔS_w fluctuates between the ecosystems as shown in Figure 13, but the prairie had a slightly higher annual drainage than the corn/soybean system. The prairie had a mean annual drainage of approximately 505 +/- 17mm and the cropland only had a mean annual drainage of approximately 430 +/- 11mm. In the non-growing season drainage +ΔS_w is slightly higher in the prairie system than the corn/soybean rotation system but during week 21 to week 28 which is the early phase of the growing season, drainage +ΔS_w of the corn/soybean system exceeds that of the prairie system. In this same time, the prairie is experiencing its highest rate of evapotranspiration. After week 28 the prairie then exceeds the corn/soybean system's drainage +ΔS_w, while during the non-growing season at the end of the year a fluctuation in highest drainage between both ecosystems is observed.

4.4 What are the effects of Land use and Land cover change along with vegetation type on Evapotranspiration rates?

The globe is constantly experiencing surface changes as we change land use and land cover to fulfill human needs and desires. These changes have potential effects on our atmosphere which influences our weather and climate. In the Midwest, most of the land area was predominantly native vegetation which has experienced drastic land use changes as depicted in Appendix 1, with agriculture being the most dominant type of conversion. In this study, we focused on two main types of land cover and land use (restored prairie vs a conventional corn/soybean rotation cropland), which resulted in different rates of evapotranspiration and carbon gain, which are greatly affected by the types of plants involved along with other environmental and meteorological factors.

Land use and land cover change have an impact on the evapotranspiration rate of an ecosystem, as the type of plant or surface cover affects the rate of ET along with influencing the drainage of the ecosystem (Zhang & Schilling, 2006). Based on model simulations results showed there is a decrease in annual ET from natural vegetation, but ET increases for the dominant type of crops within the Midwest region (corn and soybean) (Sun J. , et al., 2017), which agrees with our results as ET from the prairie was lower than the corn/soybean rotation system each year.

The Midwest, also classified as the US Corn Belt, is a region where acreage of corn dominates other crops and corn production is one of the largest throughout the globe (Wright & Wimberly, 2013). From our study, it was observed that, during the years when corn was the crop planted the corn/soybean system gained more carbon in comparison to the years when soybean was the crop in the rotation. Figure 14 shows the comparison of evapotranspiration and carbon flux, between the prairie and the cropland during the years when corn was the crop planted in the rotation.

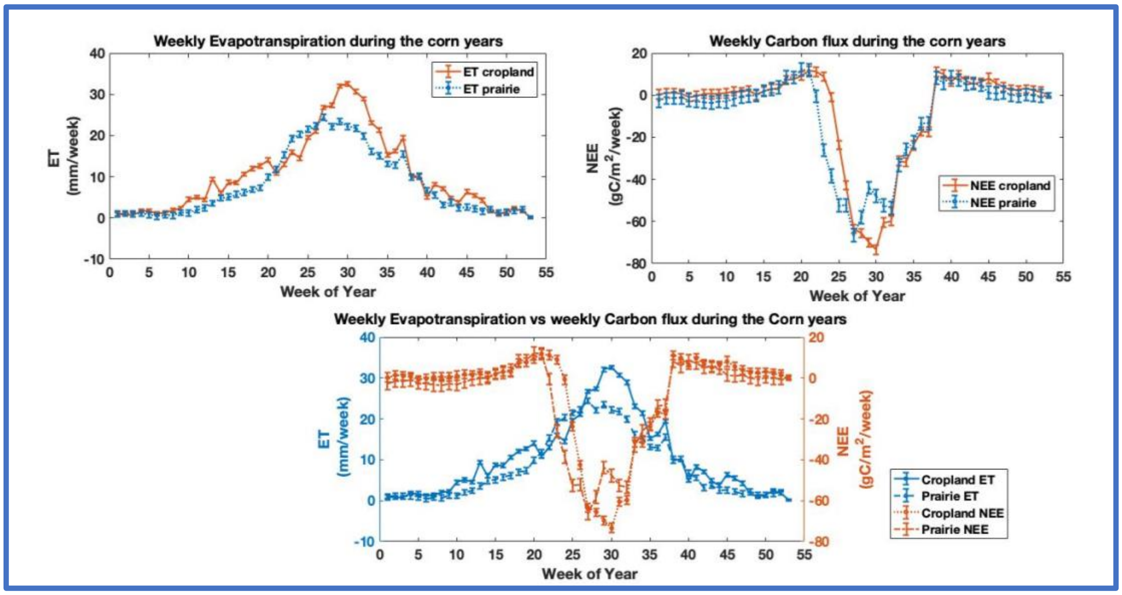

Figure 14: Corn years vs the Prairie

Corn was planted in the year 2015 and 2018. During these years the prairie's NEE was -473 +/- 75gC/m^2/yr. and -588 +/-74gC/m^2/yr. respectively, while the cropland's NEE was -366 +/-52gC/m^2/yr. and -479 +/-53gC/m^2/yr. respectively. During these same years the prairie's ET was 439+/-17mm/yr. (2015) and 436+/-17mm/yr. (2018), while the cropland's ET was 625+/-11mm/yr. (2015) and 476+/-11mm (2018). A similar comparison was made during the years when soybean was the crop planted in the rotation as shown in Figure 15. Calendar years 2016 and 2017 were the years of soybean production. There was a greater difference in the amount of carbon assimilated by the ecosystems during these years compared to the corn years. The corn/soybean system's NEE was only -28 +/-53gC/m^2/yr. and -21 +/-52.5gC/m^2/yr. while its evapotranspiration rate for the years was 511+/-11mm/yr. and 498+/-11mm/yr. in 2016 and 2017 respectively. On the other hand, the prairie's NEE was -338 +/-74gC/m^2/yr. and -368 +/-74gC/m^2/yr. with corresponding ET of 455+/-17mm/yr. and 441+/-17mm/yr. in years 2016 and 2017 respectively. On average the corn years had a higher ET than the soybean years, which agrees with a previous study by Suyker and Verma (2009). In contrast to our results, Hickman et al. (2010) suggested that grasslands produce a higher cumulative ET in comparison to a corn system. But annual ET from our study showed that during the corn years the corn/soybean rotation system had higher cumulative ET than the prairie during these same years, unlike results obtained in Illinois (Hickman, Vanloocke, Dohleman, & Bernacchi, 2010). This difference in results could be due to the specific type of grasses and their stomatal conductance ability, since decreasing stomatal conductance results in decreasing ET rates (Bernacchi, Kimball, Quarles, Long, & Ort, 2007).

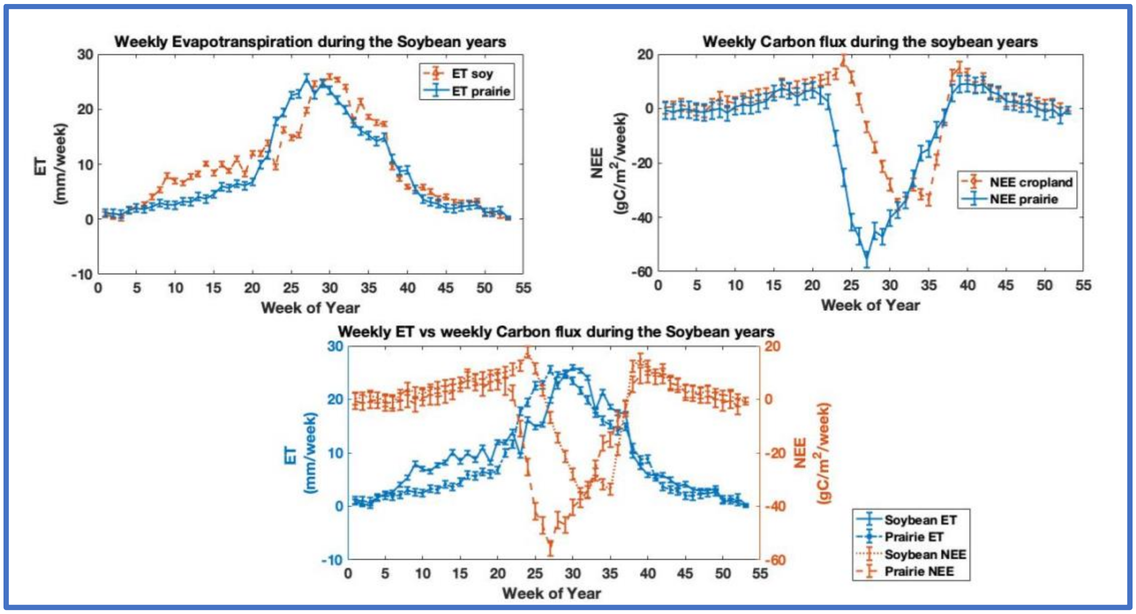

Figure 15: Soybean years vs Prairie

During the corn years the corn/soybean rotation system gained more carbon than during the soybean years but overall the prairie gained more carbon than the corn/soybean system. The cropland had higher annual ET rates than the prairie, regardless of which crop was planted in the rotation.

5. Summary and Conclusions:

Evapotranspiration at a restored prairie versus a corn/soybean rotation cropland shows that the prairie evapotranspiration peaks earlier in the growing season in comparison to the corn/soybean system, which is largely due to plant phenology as the grasses of the prairie usually emerge earlier than crops planted in the cropland.

Carbon gain increases with increasing evapotranspiration and they both reach their maximum values during the same time. The prairie has a higher water use efficiency than the corn/soybean system as it is able to acquire more carbon per unit of water loss to the atmosphere. Cumulatively during the growing season, the prairie had a total NEE of -471 +/-68gC/m^2 while the corn/soybean rotation system only had -311 +/-48gC/m^2. The ET during the growing season resulted to be 368 +/-16mm and 403 +/-11mm for the prairie and the corn/soybean system respectively. In the non-growing seasons, the cumulative ET of the prairie was 75 +/-20mm while the corn/soybean system was 125 +/-13mm.

In conclusion, during both the growing and non-growing seasons the evapotranspiration rate of the corn/soybean system was greater than that of the prairie. The corn/soybean system also released more carbon to the atmosphere during the non-growing season in comparison to the prairie, while during the growing season, cumulatively the prairie gained more carbon than the corn/soybean system. The type of land cover and land use also affect evapotranspiration rates as environmental factors such as surface temperature and albedo varies over different land surfaces.

Chapter 4

General Conclusion

Prairie restoration is effective in sequestering carbon thus helping to reduce atmospheric CO_2. Changes in the type of vegetation within the Midwest have led to an increase in atmospheric carbon as croplands release more carbon into the atmosphere in comparison to grasslands. The cumulative GPP of the ecosystems showed the cropland exceeding the prairie, with a GPP of 3864 gC/m^2 for the cropland and 2653 gC/m^2 for the prairie. However, the cumulative ecosystem respiration of both ecosystems was 2970 gC/m^2 for the cropland and 1170 gC/m^2 for the prairie resulting in greater cumulative NEP for the prairie than the cropland: 1489 gC/m^2 versus 894 gC/m^2.

The land management practices implemented at these ecosystems played a great role in the overall carbon balance as it produces additional disturbances which influences carbon loss. Due to prescribed burning the prairie lost approximately 355 gC/m^2, while the cropland experienced annual C removal due to harvesting, thus losing a total of 1173 gC/m^2 from total grain removed. With this additional loss of carbon, the NBP of the ecosystems reflected a carbon sink for the prairie and a carbon source for the cropland. The NBP of the cropland was approximately -70 $gC/m^2/yr.$ where negative represents a loss to the atmosphere while the prairie had an NBP of approximately 284 $gC/m^2/yr.$ where positive represents a gain to the ecosystem.

Additionally, both ecosystems varied in their evapotranspiration rates throughout the study. During the growing and non-growing season, the cropland had a higher cumulative ET than the prairie. During the non-growing season (week 1-17 and 41-52 of a calendar year) the prairie and cropland had cumulative ET values of 75mm/yr. and 125mm/yr. respectively. In the growing season (week 18-40 of a calendar year) the prairie and cropland had cumulative ET values of 368mm/yr. and 403mm/yr. respectively. Over the entire year the cropland had higher cumulative ET values in comparison to the prairie.

Comparing ET and carbon flux of the ecosystems it was observed that both ET and carbon flux peaked at the same time; so, when the ET of the prairie was at its maximum value so too was the prairie's carbon flux and similarly for the cropland. During the mid-growing season when temperature is at its greatest the prairie's productivity declined as the ET and carbon flux was lower than that of the cropland. ET rates of the prairie only exceeds that of the cropland during the early growing season due to the prairie having an earlier emergence and canopy development than the cropland.

Estimated drainage and change in soil moisture content of the ecosystems were different due to differences in ET, which resulted in the prairie having a higher drainage and soil moisture content than the cropland. The prairie also had a higher WUE than the cropland, as the prairie's WUE throughout the study was 0.84 gC/mm while the cropland's WUE was only 0.42 gC/mm.

The type of vegetation plays a significant role in the carbon flux as C3 plants tends to sequester less carbon than C4 plants. During the rotation for the cropland, when corn (C4 plant) was the crop in the rotation the cropland had a greater NEP in comparison to having soybean (C3 plant) in the rotation. In 2015 and 2018 when corn was planted the NEP of the cropland was 366 gC/m^2 and 479 gC/m^2 respectively, but during 2016 and

2017 when soybean was planted the NEP was only 28 gC/m^2 and 21 gC/m^2 respectively. Importantly, most of the respiration in the cropland during the soybean years is from corn residue from the previous year and vice versa during the corn years.

Our ecosystems provide different ecosystem services which are essential to the environment and the population. For example, prairies provide services such as nutrient cycling, maintaining biodiversity, prevent soil erosion, and providing habitat, while croplands provide food, bioenergy and income. The prairie thus provides environmental benefits but does not help to feed the growing population. With such drawback, is there an ecosystem that can be developed which will be able to display all the services of both ecosystems combined?

In conclusion, we found that restoring cropland to prairie can sequester C while releasing less water to the atmosphere through evapotranspiration. Based on the results, restoring prairies will reduce atmospheric carbon while the corn/soybean rotation will continue to release carbon to the atmosphere.

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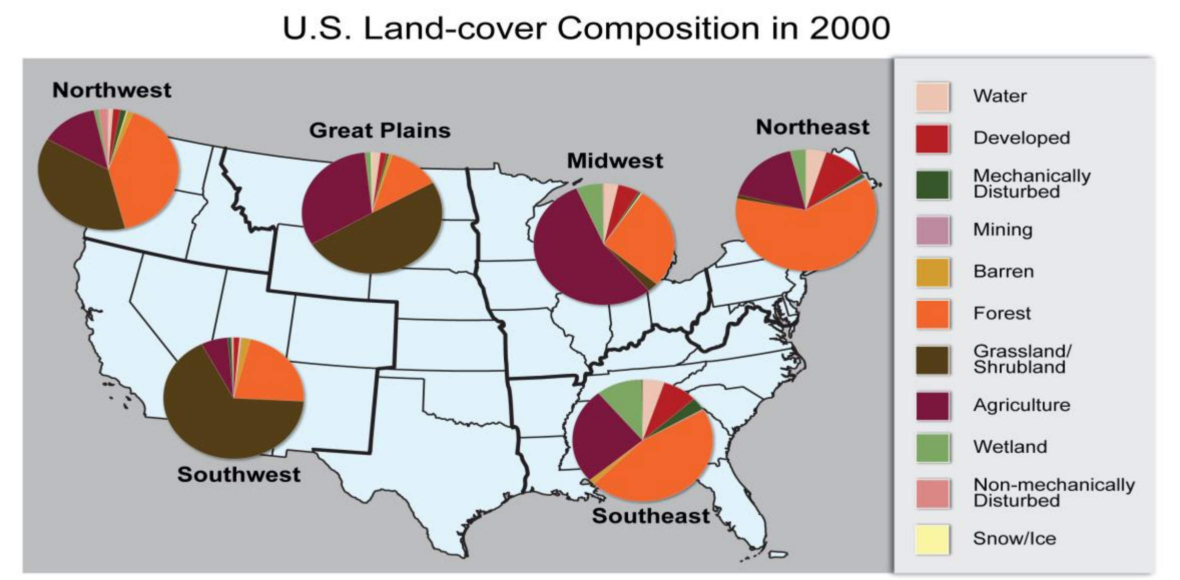
Appendix 1:

U.S. Land-cover Composition 2000



Map shows regional differences in land cover. These patterns affect climate and will be affected by climate change. They also influence the vulnerability and resilience of communities to the effects of climate change (Figure source: USGS Earth Resources Observation and Science (EROS) Center).

Appendix 2:

Ecosystems Energy Balance Closure

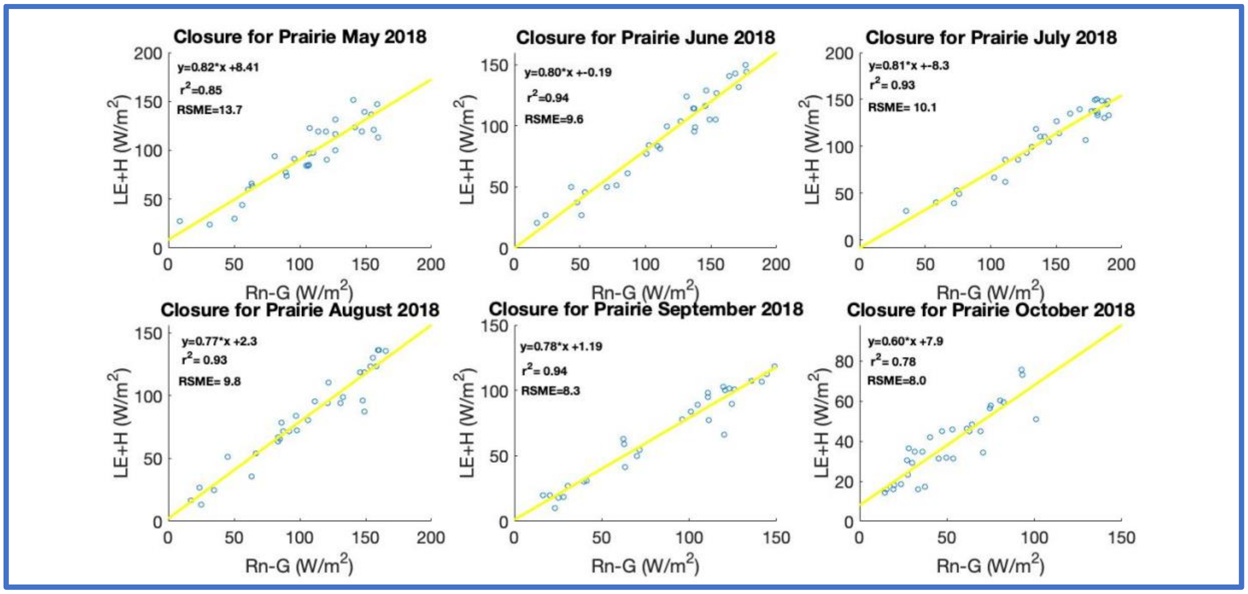


Figure 2(a): Monthly closure for the prairie between May to October of 2018. Throughout the few months the closure of the site varies as shown by the slope of the graphs.

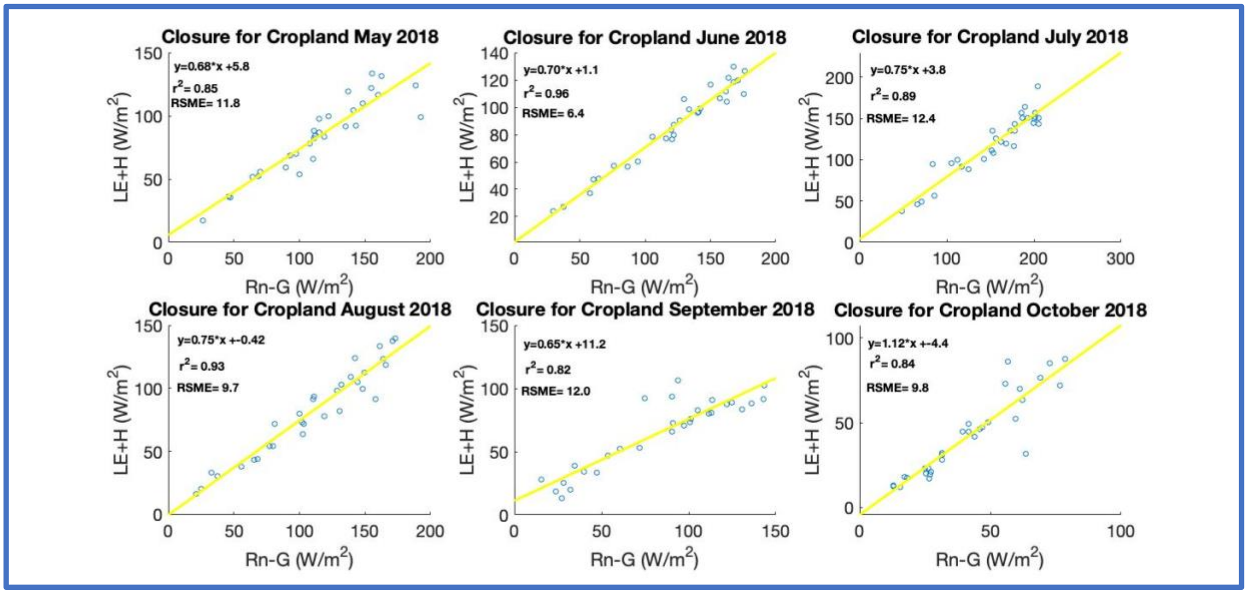


Figure 2(b): Monthly closure for the Corn/Soybean site between May and October 2018.

Appendix 3

Eddy Covariance Theory/Measurements

The Eddy Covariance (EC) fluctuation theory uses the conservation of mass theory as the basic framework for measuring and interpreting micrometeorological flux measurements. For a simple control volume, the conservation theory explains that the conservation of a variable of interest comes from a source and the change in concentration within a specified volume is affected by turbulent transport in the vertical and horizontal direction. The EC fluctuation theory is a set of methods used to measure how much of something passes through a unit area per unit time.

$$\underbrace{\partial\bar{\chi}/\partial t}_{(I)} = \underbrace{-\bar{u}\,\partial\bar{\chi}/\partial x - \bar{v}\,\partial\bar{\chi}/\partial y - \bar{w}\,\partial\bar{\chi}/\partial z}_{II}$$

$$\underbrace{-\,\partial\overline{u'\chi'}/\partial x - \partial\overline{v'\chi'}/\partial y - \partial\overline{w'\chi'}/\partial z}_{III} + D + S, \qquad (1)$$

Figure 1: Eddy Covariance fluctuation theory equation

The rate of change of the mean mixing ratio, which is the concentration of the gas of interest (CO_2 in our case) at a certain point in space (I) is balanced by the mean vertical and horizontal advection (II), the mean horizontal and vertical divergence or convergence of turbulent flux (III), by molecular diffusion (D), and by any source or sink (S) (Baldocchi, Hicks, & Meyers, 1998).

For the EC theory, experimental towers are set with various instruments to sample desired concentrations that are transported by eddies. Eddies contain a concentration, temperature, and humidity, thus knowing the speed of the eddy fluxes can be calculated.

Derivation of the Eddy Flux equation: (Burba G. , 2005).

1. $F = \overline{\rho_d w s}$ Vertical Flux

Using Reynolds decomposition, fluxes contains means and deviations:

2. $F = \overline{(\overline{\rho}_d + \rho_d')(\overline{w} + w')(\overline{s} + s')}$

Expanding this equation results in:

3. $F = \overline{(\overline{\rho}_d \overline{w}\overline{s} + \cancel{\overline{\rho}_d \overline{w} s'} + \cancel{\overline{\rho}_d w' \overline{s}} + \overline{\rho}_d w' s' + \cancel{\rho_d' \overline{w}\overline{s}} + \rho_d' \overline{w} s' + \rho_d' w' \overline{s} + \rho_d' w' s')}$

Averaged deviation from the average is zero thus simplifying the equation:

4. $F = (\overline{\rho}_d \overline{w}\overline{s} + \overline{\rho}_d \overline{w' s'} + \overline{w}\overline{\rho_d' s'} + \overline{s}\overline{\rho_d' w'} + \overline{\rho_d' w' s'})$

An important assumption made in this theory states that air density fluctuations are assumed to be negligible. Another assumption also states that mean vertical flow is assumed to be negligible for flat homogeneous terrain.

5. $F = (\overline{\rho}_d \overline{w}\overline{s} + \overline{\rho}_d \overline{w' s'} + \cancel{\overline{w}\overline{\rho_d' s'}} + \cancel{\overline{s}\overline{\rho_d' w'}} + \cancel{\overline{\rho_d' w' s'}}) = \cancel{\overline{\rho}_d \overline{w}\overline{s}} + \overline{\rho}_d \overline{w' s'}$

This then leads to the eddy flux equation:

6. $F \approx \overline{\rho}_d \overline{w' s'}$

This theory is applied at different ecosystems to measure various gas concentration. For best results setting up this technique in a flat homogeneous terrain with a large flux footprint to limit the influence of other ecosystems is important.

Appendix 4

Vario Max Analysis Sample Results

Weight [mg]	Name	Method	N Area	C Area	N [%]	C [%]
509.4	PRE 11 2018	plant500	4941	569189	0.387	41.612
508.9	PRE 12 2018	plant500	6573	565065	0.516	41.35
508.1	PRE 13 2018	plant500	7033	569039	0.553	41.708
505.5	PRE 14 2018	plant500	5356	559777	0.423	41.237
504.2	PRE 15 2018	plant500	5352	559529	0.423	41.325
509.3	PRE 21 2018	plant500	5104	570588	0.4	41.723
501.3	PRE 22 2018	plant500	5648	540285	0.45	40.128
505.2	PRE 23 2018	plant500	5107	577524	0.403	42.576
501.4	PRE 24 2018	plant500	4905	564152	0.39	41.9
501.7	POST 11 2018	plant500	5174	537231	0.412	39.698
504.8	POST 12 2018	plant500	4445	587692	0.351	43.179
509.4	POST 13 2018	plant500	6127	586656	0.481	42.713
507.3	POST 14 2018	plant500	4459	584314	0.351	42.718
508.2	POST 15 2018	plant500	4225	592896	0.331	43.271
509	POST 21 2018	plant500	6419	578256	0.504	42.132
506.6	POST 22 2018	plant500	5436	575943	0.429	42.161
501.7	POST 23 2018	plant500	4227	576848	0.336	42.64
504	POST 24 2018	plant500	5413	549684	0.429	40.438
504.9	POST 23 2018	plant500	5172	576751	0.409	42.363

Table 1: Sample data from vario Max analysis of the prairie's aboveground biomass before and after prescribed burn. Percentage of carbon in each sample is provided from the analysis, which was used to determine the approximate amount of carbon loss due to the burn.