Surface resistance controls differences in evapotranspiration between croplands and prairies in U.S. Corn Belt sites

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Abstract

Water returned to the atmosphere as evapotranspiration (*ET*) is approximately 1.6x greater than global river discharge and has wide-reaching impacts on groundwater and streamflow. In the U.S. Midwest, widespread land conversion from prairie to cropland has altered spatiotemporal patterns of *ET*, yet there is no consensus on the direction of change in *ET* or the mechanisms controlling changes. We aimed to harmonize findings about how land use change affects *ET* in the Midwest. We measured *ET* at three locations within the Long-Term Agroecosystem Research (LTAR) network along a latitudinal gradient with paired rainfed cropland and prairie sites at each location. At the northern locations, the Upper Mississippi River Basin (UMRB) and Kellogg Biological Station (KBS), the cropland has annual *ET* that is 84 and 29 mm/year higher, respectively, caused primarily by higher *ET*, likely from soil evaporation during springtime when agricultural fields are fallow. At the southern location, the Central Mississippi River Basin (CMRB), the prairie has 69 mm/year higher *ET*, primarily due to a longer growing season. To attribute differences in springtime *ET* to specific mechanisms, we examine the energy balance using the Two-Resistance Method (TRM). Results from the TRM demonstrate that higher surface conductance in croplands is the primary factor leading to higher springtime *ET* from croplands, relative to prairies. Results from this study provide critical insight into the impact of land use change on the hydrology of the U.S. Corn Belt by providing a mechanistic understanding of how land use change affects the water budget.

Keywords: Eddy covariance, rainfed cropland, prairie, land atmosphere interactions, surface resistance

Key Points:

1. Differences in evapotranspiration between croplands and prairies was quantified by a mechanistic Two Resistance Method.
2. Bowen ratio during springtime is higher in prairies than croplands.
3. Surface resistance is the primary factor causing springtime evapotranspiration differences between croplands and prairies.

1 Introduction

The Central and Upper Mississippi River basins have been subjected to some of the most extensive land use and land cover changes (LULCC) in the world. Beginning in approximately 1850, one of the most rapid, large-scale land conversions in the history of humankind converted millions of hectares of prairies to rainfed croplands (K. R. Robertson et al., 1997; Steyaert & Knox, 2008). Such large-scale transition undoubtedly impacted the water budget, but the magnitude of the impacts and the underlying mechanisms remain the subject of debate. Streamflow has been increasing since the 1940s because of both precipitation increases and land use changes that reduce evapotranspiration (*ET*) to create more baseflow (Zhang & Schilling, 2006). As LULCC and agricultural intensification has continued in the Mississippi River basin, precipitation has increased while the evaporative demand, measured by the reference *ET*, has decreased (Allen et al., 1998; Villarini et al., 2011). Modeling exercises have attributed the observed streamflow increases in the Mississippi River basin primarily to climate change, finding that converting grasslands to croplands resulted in less runoff by increasing *ET* (Frans et al., 2013). Because of these confounding factors, the impact of the conversion from prairies to croplands on the water budget remains challenging to quantify.

While considerable effort has been made to quantify the impact of land use change on the water budget in the U.S. Midwest, quantifying the impacts on *ET* specifically is challenging. This is due to the requirement of paired study sites and direct measurements of *ET*. High interannual variability in meteorological conditions make long-term measurements an additional requirement. Much of the recent work to examine how land use change impacts *ET* has been done through assessing the feasibility of biofuel production (Joo et al., 2017). While single species biofuel plots are not entirely representative of species-rich prairies, switchgrass (*Panicum virgatum*) is a common prairie species that has been proposed as a biofuel crop. For example, measurements of *ET* for various biofuel crops, including maize (*Zea Mays*), mixed perennial prairie, and monoculture switchgrass (*Panicum virgatum*), suggested LULCC between maize and perennial grasses may cause differences in seasonal *ET*, but the data did not show statistically significant differences in water use (Abraha et al., 2020; Hamilton et al., 2015). Modeling work in Iowa suggests that conversion from prairie to cropland decreased *ET* and that increases in biofuel switchgrass production would increase *ET*, reducing streamflow (Schilling et al., 2008). Several other studies using remote sensing (Baeumler et al., 2019), chamber measurements (Luo et al., 2018), the energy balance residual (Hickman et al., 2010), or eddy covariance (Schreiner-McGraw et al., 2023) have found that prairie has higher *ET* than cropland. In contrast, both models and observations have demonstrated that cropland can have higher *ET* than prairie (Frans et al., 2013; Twine et al., 2004). Furthermore, there is evidence that intensified cropland management has increased *ET* over most of the U.S. Midwest, resulting in increased humidity and decreased daily maximum air temperatures, creating the summertime "warming hole" over the region (Alter et al., 2018). This idea is supported by findings that agricultural intensification (via planting density, crop type, and fertilization) have increased *ET*, resulting in a cooling effect during daytime (Mueller et al., 2016).

As generally the second largest flux term of the water budget (following precipitation), changes in *ET* can have important impacts on the remaining terms, such as streamflow. Across much of the U.S. Midwest groundwater tables are shallow and the impact of storage change is small over longer time periods, making streamflow approximately equal to precipitation minus *ET* (Gupta, 1989). Additionally, the widespread use of tile drains and a warming trend that results in streamflow being more driven by rainfall than snowmelt, reinforce the streamflow response to precipitation (Dumanski et al., 2015; Kelly et al., 2017). While long term changes in climate may have contributed more to the observed trends in streamflow in the Mississippi River basin, LULCC played a role as well (Gupta et al., 2015; Xu et al., 2013). Land use change primarily altered streamflow by changing *ET*, which altered subsurface flow in soil and groundwater and had larger impacts on baseflow than total streamflow (Scanlon et al., 2007; Zhang & Schilling, 2006). Thus, it appears that land cover change can have wide ranging and contrasting impacts on the water budget by modifying the *ET*.

Ecosystem *ET* is affected by LULCC through several mechanisms that modify land surface characteristics. Land conversion from prairies to croplands resulted in soil compaction, altering soil properties, such as the water holding capacity and the infiltration rate, leaving less available water for plants (Veum et al., 2015). Model evidence suggests that conversion from prairies to croplands can increase net radiation by altering the surface albedo (Twine et al., 2004). Land conversion can also change the aerodynamic resistance which affects turbulent fluxes between the land surface and atmosphere, as well as the air temperature (Baldocchi & Ma, 2013). When considering conversion to croplands specifically, nitrogen fertilizers limit nitrogen stress, resulting in larger, healthier plants (Chapin et al., 1988; Jones et al., 1986). The plant species composition also affects the *ET* through root distribution, stomatal conductance, and water use efficiency (Asbjornsen et al., 2008; Caylor et al., 2005; Dold et al., 2017). Through these combined mechanisms, LULCC alters the land surface energy balance, making it a useful tool to understand how land use changes impact land surface processes. A recent energy balance approach to attribute changes in land surface behavior to physical mechanisms, the Two-Resistance Method (TRM) has been shown effective in attributing changes to the Bowen ratio caused by land use change to physical processes (Liao et al., 2018; Moon et al., 2020; Rigden & Li, 2017).

There is renewed interest in LULCC and/or management change in agricultural systems in the Midwest to promote climate smart agriculture and/or nature-based climate solutions (Hemes et al., 2021). Utilizing prairie in targeted locations to improve agricultural sustainability and sequester carbon is a promising technique (Schulte et al., 2017). The apparent conclusion from previous research on LULCC is that conversion from prairies to croplands, and vice versa, can have large impacts on the water budget, primarily by altering *ET*, but there is no consensus on the direction of the change and the specific mechanisms responsible. In this study, we quantified and compared the differences in *ET* between croplands and prairies, as well as the underlying mechanisms for the differences. We use long-term direct measurements of *ET* to address two primary research questions. The first question is whether *ET* is significantly different between croplands and prairies; and if so, how that difference is distributed throughout the year? The second research question is what mechanisms are responsible for any observed differences?

2 Methods

2.1 Study Sites

We used eddy covariance (EC) data spanning >5 years from paired cropland and prairie systems in three locations across the Midwest U.S. within the Long-Term Agroecosystem Research (LTAR) network (Figure 1). The LTAR locations included in this work were the Upper Mississippi River Basin (UMRB), Kellogg Biological Station (KBS), and the Central Mississippi River Basin (CMRB).

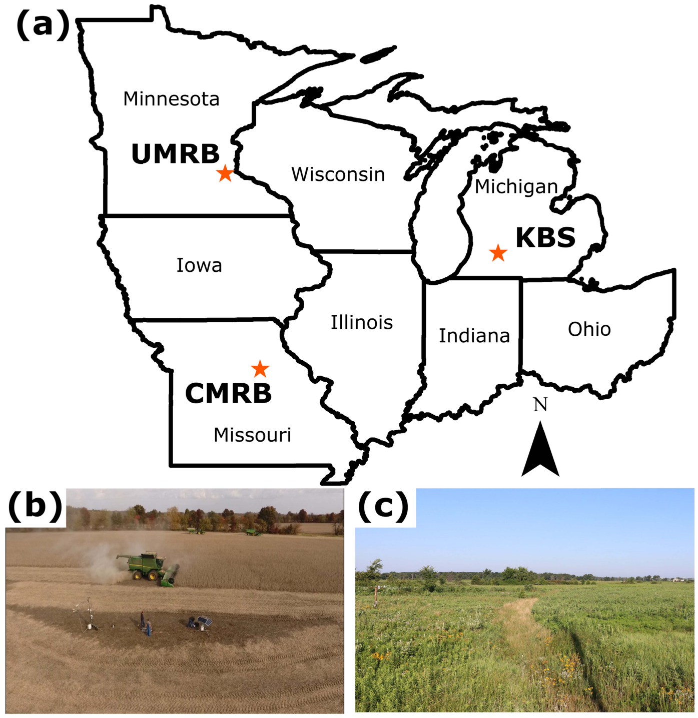

Figure 1: (a) Map of the Midwest United States with stars indicating the UMRB, KBS, and CMRB locations. (b) Photo of the cropland at the CMRB location. (c) Photo of the prairie at the CMRB location.

The UMRB LTAR location is in Rosemount Minnesota, approximately 40 km Southeast of Minneapolis. The mean annual precipitation (MAP) is 879 mm and the mean annual temperature (MAT) is 6.5 °C. The Köppen climate classification is, humid subcontinental (Dfa), which is characterized by severe winters and hot, humid summers. The cropland eddy covariance tower is located in a field that is managed following the dominant cropping practices in the region, i.e. - a maize-soybean rotation with chisel plow tillage during the fall following maize harvest and during the spring following soybean harvest. Data are available from 2003 through 2022, although only the most recent 9 years (2014-2022) were used, to match the available data from the prairie. In 2017, the University of Minnesota leased the land to a gravel mining operation, so it was necessary to move the tower to another nearby field in maize/soy rotation. Thus, from 2014-2016 the cropland data were obtained from the AmeriFlux tower US-Ro1 and from 2017-2022 it is obtained from AmeriFlux tower US-Ro5 (J. M. Baker & Griffis, 2005). Due to the field switch, there were 6 years with soybean and 3 years with maize, so while this rotation is intended to be maize-soybean, our data is more comparable to a maize-soybean-soybean rotation. The nearby prairie site is AmeriFlux ID US-Ro4. This is a restored tallgrass prairie planted in 2010 on former agricultural land and the dominant species include *Andropogon gerardii, Sorghastrum nutans* and *Elymus canadensis*. The prairie is managed by the Minnesota Department of Natural Resources and is burned every 4-6 years. None of the Rosemount sites are tile-drained; the region is a relatively flat glacial outwash plain characterized by silt loam surface soils underlain by sand and gravel.

The KBS towers are located in southwest Michigan at the Kellogg Biological Station. The MAP is 1,003 mm and the MAT is 10.2 °C. Although the location is slightly warmer and wetter than the UMRB location, the Koppen climate classification is still Dfa, characterized by severe winters and hot, humid summers. Data are available from 2010 to 2021. Both the cropland and restored prairie sites at KBS had been conventionally tilled maize-soybean annual rotations for decades prior to conversion to no-till soybean in 2009, and to no-till continuous maize and restored prairie systems from 2010 onward. The AmeriFlux ID for the maize and restored prairie sites at KBS are US-KL1 and US-KL3, respectively (Abraha et al., 2015). The maize system was planted in early May and harvested in October annually from 2010 onward. Maize stover was partially harvested (~27%) from 2015–2021 but left on-site in other years. Restored prairie was planted as polyculture with 19 species dominated by C3 plants but plant composition shifter over the years to higher C4 proportion with *Sorghastrum nutans* and *Andropogon gerardii* as dominant species (Abraha et al., 2016). The restored prairie system was harvested for biofuel in November/December after autumn senescence each year since 2011 except in 2018 when it was harvested in the spring of the following year. The maize system was fertilized at ~180 kg N ha^{-1} yr^{-1} but the restored prairie system was not fertilized. Soils at the sites are well-drained Typic Hapludalfs loam and sandy loam developed on glacial outwash intermixed with loess (Luehmann et al., 2016).

The CMRB LTAR fields are located near Centralia, Missouri. The MAP is 981 mm and the MAT is 12.0 °C, and the Köppen classification is humid subtropical (Cfa). This climate is characterized by mild winters and hot, humid summers. The CMRB cropland site (US-Mo3) is a conventionally tilled, maize-soybean-soybean rotation that does not use cover crops and is managed by a local farmer consistent with the dominant practices in the region (Schreiner-McGraw et al., 2023). The soils are Adco silt loam and are characterized by the presence of a restrictive claypan layer at approximately 30 cm depth that prevents the installation of tile drains. The CMRB prairie site (US-Mo2) is located at the Tucker Prairie. This is a native prairie that has never been plowed or used for agricultural production. Over 100 species of plants are present in the tallgrass prairie (Kucera, 1956, 1958). The soils have lower bulk density and higher surface infiltration rates than soil present at the CMRB cropland site (Mudgal et al., 2010). The prairie is burned in a rotation so that each parcel of land is burned twice in a five-year period.

2.2 Eddy Covariance Systems and Data Acquisition

Observations from EC towers were obtained from the AmeriFlux database that were processed following the specific protocols (references in section 2.1). In brief, from each site we acquired gap-filled ET, midday albedo (α), net radiation (R_n), incoming shortwave (S_{in}) and longwave radiation (L_{in}), and air temperature (T_a) at a half-hour time step. Additionally, we acquired the soil temperature (T_s) at 30-min interval at 5, 2, and 2.5 cm depths at the UMRB, KBS, and CMRB sites, respectively. We also obtained estimates of the normalized difference vegetation index (NDVI) from the MODIS Terra satellite (i.e., MOD13Q1) for each site at a 16-day temporal resolution.

We aggregate the 30-minute data to daily and monthly timescales to make the time series easier to interpret. We present the cumulative daily ET for each site to identify whether cropland or prairie ET was higher in each year. To examine the average annual cycles of ET, we also calculate the monthly mean and standard deviation of ET for each site. We calculated the Bowen ratio for each month as the total monthly sensible heat flux divided by the total monthly latent heat flux ($B = H/LE$). Finally, we estimate the monthly streamflow (Q) as: $Q = [P - ET]$.

2.3 Hypothesis testing and statistical analyses

Our first hypothesis is that annual *ET* is different between cropland and prairie sites. We use repeated measures t-tests to test this hypothesis at each location (e.g., UMRB cropland vs. UMRB prairie) and define the hypothesis substantiated if the mean annual *ET* is different with a p-value < 0.05. We repeat the t-tests in mean monthly *ET* to determine when during the year *ET* is different between cropland and prairie sites. Additionally, to examine the differences in *ET* limitation among the locations, we use a two-factor repeated measures ANOVA test with a post-hoc Tukey HSD test to check if the annual *ET* is different between the three locations (e.g., UMRB vs. CMRB). The ANOVA test is performed using the annual *ET* from both cropland and prairie sites at each location.

Our second hypothesis is that the vegetation structure controls the surface resistance, which in turn controls the springtime *ET* and the differences. We focus on springtime (March to May) because it is when streamflow is higher and when the differences in the Bowen ratio between prairie and cropland are most pronounced. We test this hypothesis using the Two-Resistance Method for attribution of Bowen ratio changes (section 2.4). We accept this hypothesis if the attribution exercise shows that the surface resistance is the most important factor creating differences in *ET* from cropland and prairie. This bulk surface resistance represents the resistance to *ET* through the vegetation and the soil surface. It contains information about plant water stress via stomatal conductance, resistance from the soil surface, and the leaf area index and canopy development. Expanding upon this test, we determine if vegetation or soil properties are most related to the surface conductance.

The vegetation portion of the surface resistance is dependent on the stomatal resistance and the leaf area index (LAI). There are likely to be differences between ecosystem stomatal conductance of cropland and prairie, but because prairie contains more than 100 species, we do not attempt to measure the stomatal conductance. We approximate the role of vegetation in the surface resistance by examining seasonal patterns of NDVI. If one of the paired sites has a higher NDVI in a particular month than the other, we assume that vegetation is better able to transpire water during that month. Thus, we use NDVI to quantify the relative length of the growing seasons between cropland and prairie sites.

2.4 Attributing differences in the Bowen ratio

We attribute differences in the Bowen ratio (β) between cropland and prairie sites using a modified version of TRM based on the energy balance (Moon et al., 2020). This allows attribution of changes in the β to changes in land surface or atmospheric properties that accompany land use change. The TRM method begins from the surface radiation and energy budget equations (Rigden & Li, 2017):

$$R_n = S_{in}(1-\alpha) + \varepsilon L_{in} - \varepsilon\sigma T_s^4 = H + LE + G \tag{1}$$

where R_n is the net radiation (W/m^2), S_{in} is the incoming shortwave radiation (W/m^2), α is the surface albedo, ε is the emissivity, L_{in} is the incoming longwave radiation (W/m^2), σ is the Stefan-Boltzmann constant (W/m$^2\cdot$K), T_s is the surface temperature (K), H is the sensible heat flux (W/m^2), LE is the latent heat flux (W/m^2), and G is the ground heat flux (W/m^2). The gradient relationships governing H and LE are

$$H = \frac{\rho\cdot C_p}{r_a}\cdot(T_s - T_a) \tag{2}$$

$$LE = \frac{\rho\cdot L_v}{r_a+r_s}\cdot(q_s^*(T_a) - q_a) \tag{3}$$

where ρ is the air density (kg/m^3), C_p is the specific heat of air at constant pressure (J/kg$\cdot$K), r_a is the bulk aerodynamic resistance (s/m), T_a is the air temperature (K), L_v is the latent heat of vaporization (J/kg), q_s^* is the saturated specific humidity at T_a (kg/kg), q_a is the atmosphere specific humidity (kg/kg), and r_s is the bulk surface or canopy resistance (s/m). The full derivation is presented in Moon et al. (2020), but when eqns. 2 and 3 are substituted into eqn. 1 and the first order derivative is taken, the following equation is obtained:

$$\Delta\beta = \frac{d\beta}{dS_{in}}\Delta S_{in} + \frac{d\beta}{dL_{in}}\Delta L_{in} + \frac{d\beta}{dq_a}\Delta q_a + \frac{d\beta}{dT_a}\Delta T_a + \frac{d\beta}{dG}\Delta G + \frac{d\beta}{dr_a}\Delta r_a + \frac{d\beta}{dr_s}\Delta r_s + \frac{d\beta}{d\alpha}\Delta\alpha \quad (4)$$

In this equation, Δ refers to changes in each variable with differing land cover (e.g., $\Delta G = G_{cropland} - G_{prairie}$) and the partial derivatives (e.g., $d\beta/dG$) quantify the sensitivity of β to changes in each variable. Partial derivatives are calculated numerically following Moon et al. (2020).

We apply the TRM to EC measurements from each of the three locations to attribute differences in the β caused by the land cover difference in the paired sites. Previous research has found that the TRM method should be applied at the daily scale because at shorter time periods R_n may be very low, which can lead to high uncertainty in the parameterization of r_a and r_s (Liao et al., 2018). Thus, we aggregated the daytime (S_{in} > 10 W/m^2) data to daily averages to perform the calculations. We measured H and LE at EC sites and used eqns. 2 and 3 to estimate the r_a and r_s for each day. Days when either of the estimated resistances were negative were removed. The analysis is performed for springtime (March-May). This leaves us with 360, 772, and 424 days for analysis at the UMRB, KBS, and CMRB sites, respectively. After determining the r_a and r_s values for each day, we model the β using the analytical equation from Moon et al. (2020):

$$\beta = \frac{C_p \cdot (T_s - T_a)}{\left(\frac{r_a}{r_a + r_s}\right) \cdot L_v \cdot (q_s^*(T_a) - q_a)} \quad (5).$$

We use eqn. 5 to calculate the partial derivatives that define the sensitivity of the β to changes in surface and atmospheric conditions defined in eqn. 4. Finally, the 'attribution' of changes in the β ($\Delta\beta$) to the various properties included in eqn. 4 as the partial derivative (i.e., sensitivity) multiplied by the observed change from the reference state (cropland) to the altered state (prairie). Thus, $\Delta\beta = [\beta_{cropland} - \beta_{prairie}]$.

3 Results

3.1 ET differences

Cropland *ET* was different than prairie *ET* in their annual sums and the intra-annual variations (Fig. 2). At the UMRB location, the cropland site had a higher total annual *ET* than the prairie site for each of the 9 years in the record (mean difference of 84 ± 44 mm/yr). At the KBS location, the cropland site had higher *ET* than the prairie site for 8 of the 12 years. Similar to the UMRB location, the prairie site at KBS was restored just before our study period begins (in 2009 at KBS) and the prairie is not in a stable state initially. During the first three years of observations, the cropland had 71 mm/yr greater *ET* than the prairie, which may be due to the establishment of vegetation at the prairie site. There was not a clear trend, however, in the difference in *ET* from cropland and prairie sites at the KBS location over time. In contrast, at CMRB, the cropland had higher *ET* than the prairie in only 1 out of the 5 years with observations. At the UMRB and CMRB locations the energy budget closure from the EC measurements ($LE + H / R_n + G$) is 6% higher at the prairie site than the cropland site while at the KBS location the closure at the two sites is within 1%. The difference in energy budget closure between croplands and prairies in individual years had no relationship with the difference in annual *ET*. Interestingly, upon closer inspection, we observed that croplands generally had higher *ET* during spring versus the prairies.

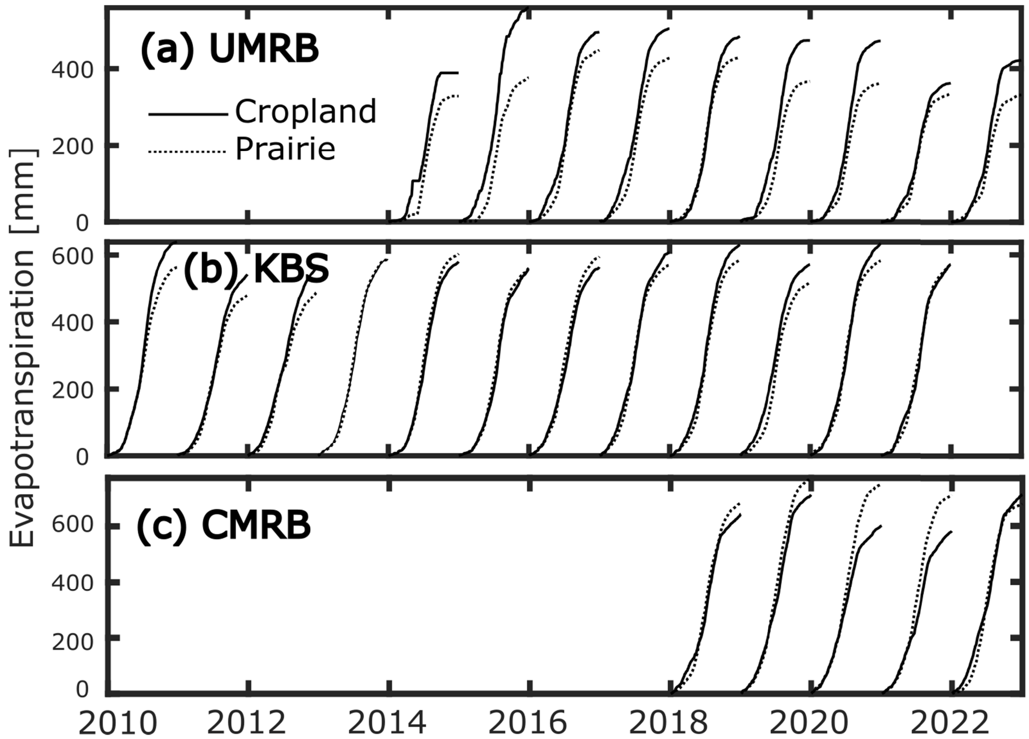

Figure 2: Cumulative sums of evapotranspiration (ET, mm) for each year of the record at the (a) UMRB, (b) KBS, and (c) CMRB locations. Note that there is a gap at the UMRB cropland site from Oct. 3 – Dec. 31, 2014.

The mean annual *ET* was 462 mm/yr and 379 mm/yr at the UMRB location; 588 mm/yr and 559 mm/yr at the KBS location; and 651 and 720 mm/yr at the CMRB location for the cropland and prairie sites, respectively (Fig. 3). At all three locations, there were significant difference in annual ET between the crop and prairie ($p < 0.001$ at UMRB; $p = 0.025$ at KBS; $p = 0.05$ at CMRB), though the signs of the differences varied (Fig. 3). At UMRB and KBS locations, annual cropland *ET* was higher, whereas at CMRB prairie *ET* was higher. When all three locations are combined, however, the difference between croplands and prairies is not significant ($p = 0.051$). In addition to identifying differences between prairie and cropland *ET*, we used a two-factor repeated measures ANOVA and found that there are significant differences in the mean annual *ET* between the locations. A post-hoc Tukey HSD test found that all three pairs of locations have significantly different annual *ET*. A separate ANOVA testing for differences in the annual *P* between the locations was not significant ($p = 0.07$). This demonstrates that, because the locations have similar precipitation and land covers, but different *ET*, there are differences in the atmospheric and energy limitations to *ET* between the locations.

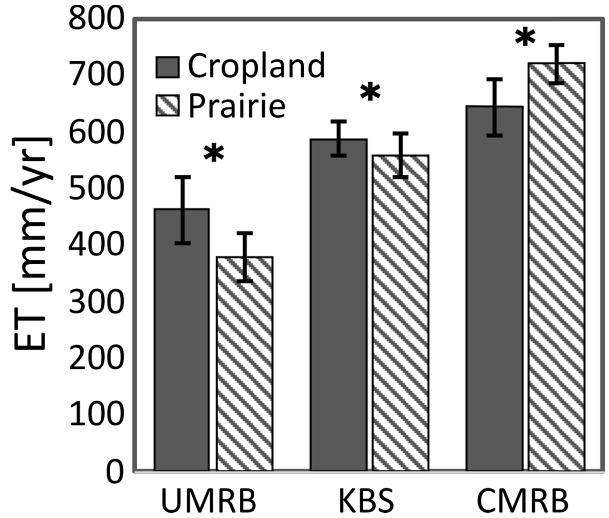

Figure 3: Mean annual evapotranspiration (ET) and standard deviation for the cropland (solid bars) and prairie (hatched bars) sites at each of the three locations. Asterisks indicate significant differences at $p < 0.05$.

We also found differences in the intra-annual changes of *ET* between the land cover types (Fig. 4). The monthly mean *ET* for the cropland was higher than the prairie during March and April at all three locations, though the differences are statistically significant ($p < 0.05$) at UMRB and KBS only. This was surprising because the cropland sites are fallow during this period and do not have vegetation present, while the prairie sites do, though prairie vegetation activity is limited during this period. At all three locations the prairie had significantly higher *ET* during June. This reflects that the recently seeded croplands have plants with small root systems and low leaf area during June. At UMRB and KBS, the cropland had significantly higher *ET* during July and August. In contrast, at CMRB the peak growing season *ET* at the cropland is matched by the prairie, while the prairie has a longer growing season extending into May, June, and October. The CMRB prairie *ET* is substantially higher than the cropland *ET* during the month of June by an average of 50 mm.

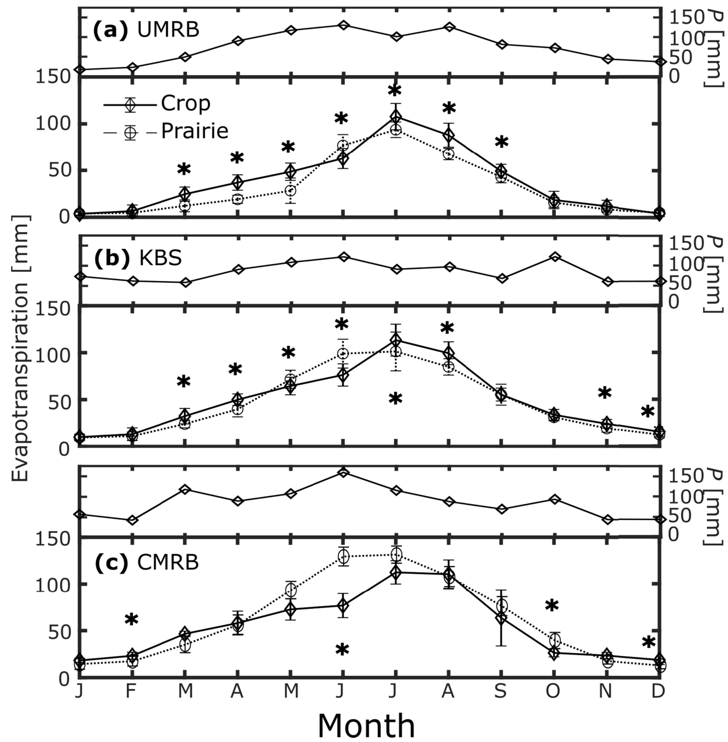

Figure 4: Mean monthly precipitation (*P*) and evapotranspiration (*ET*) for the three study locations. Error bars present the standard deviation of monthly *ET*. Asterisks indicate months where a t-test found significant differences ($p < 0.05$) between the cropland and prairie *ET*.

Conversion from croplands to prairies results in higher *Q* in the two northern locations (increase of 84 mm/yr and 28 mm/yr at UMRB and KBS, respectively) while decreasing *Q* at the southern CMRB location by 39 mm/yr. LULCC would have impacts on *Q* primarily during the March – August period at all three locations. At the UMRB and KBS locations, the prairies have higher *Q* during all the months except June at UMRB and May and June at KBS. In contrast, at the CMRB location, the cropland has higher *Q* from May – September. At all three locations the *ET* in at least one summer month exceeds *P* for that month, indicating that the crops are drawing on stored water from soil moisture or shallow groundwater (Fig. 5).

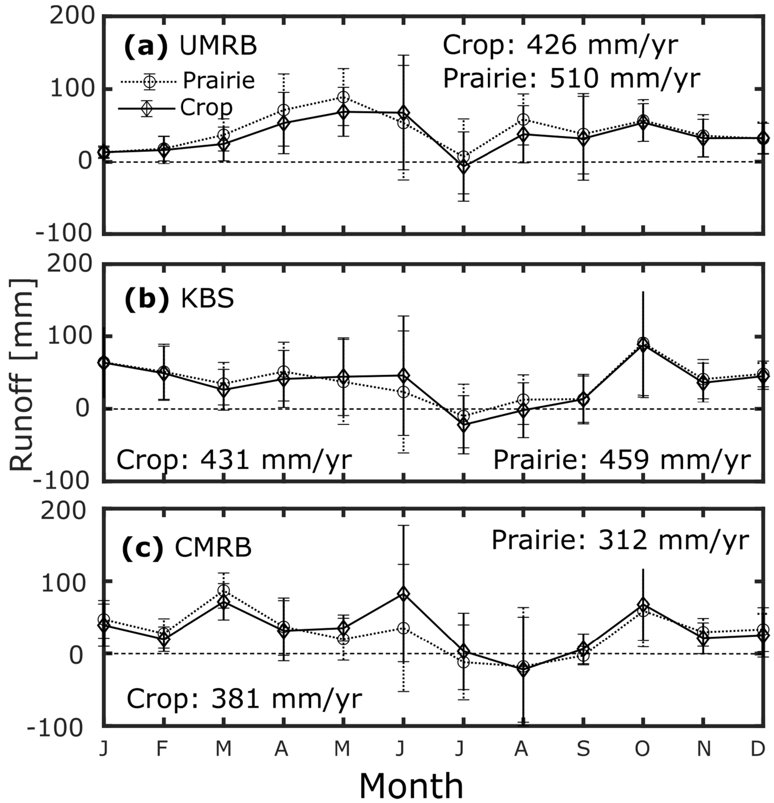

Figure 5: Mean monthly streamflow (Q), calculated as [$P - ET$] from the (a) UMRB, (b) KBS, and (c) CMRB locations. Error bars represent the standard deviation.

3.2 Attribution of the differences in ET to physical processes

Observed differences in *ET* between the cropland and prairie were reflected in the Bowen ratio, with substantial differences outside of the primary growing season (Fig. 6). At all three locations, the Bowen ratio was higher at the prairie than that at the cropland site for most of the winter and spring periods. Exceptions include February at KBS and April and May at CMRB. During the growing season, there were no consistent differences in Bowen ratios between croplands and prairies. At UMRB, the growing season Bowen ratio was significantly higher at the prairie site during July and August, which was not the case at KBS and CMRB. The magnitude of the difference between the cropland and prairie Bowen ratio during the January-April period was smallest at the KBS location, which may reflect the fact that the prairie is harvested for bioenergy each fall at this location. Harvest removes the layer of dead vegetation at the KBS prairie that acts as a buffer between the land surface and atmosphere at the UMRB and CMRB prairies.

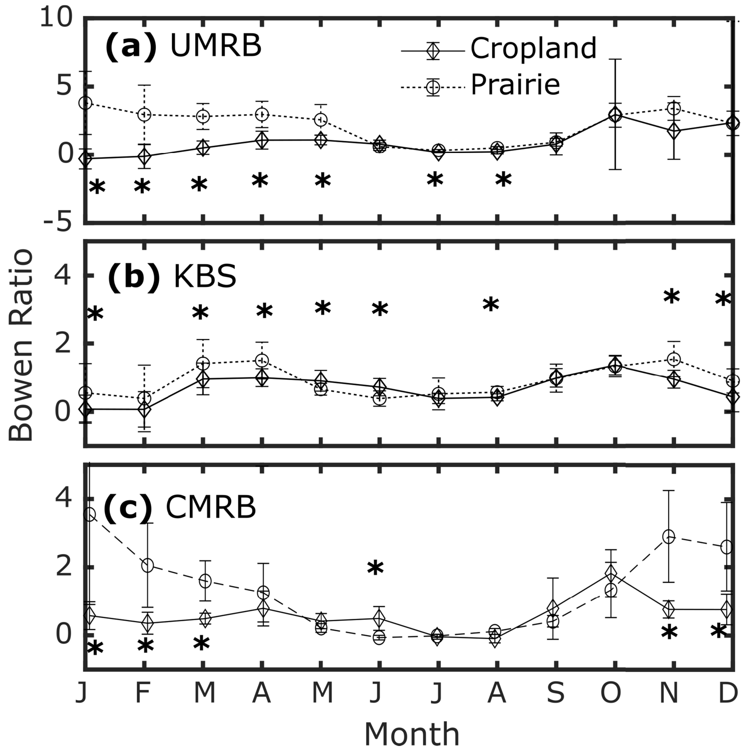

Figure 6: Monthly Bowen ratio values for cropland (solid lines) and prairie (dashed lines) sites at the (a) UMRB, (b) KBS, and (c) CMRB locations. Error bars represent the standard deviation of the observed mean values and asterisks indicate months where the difference between cropland and prairie Bowen ratio was statistically significant ($p < 0.05$). Note that the y-axis scale differs for the (a) versus (b) and (c) panels.

We applied the TRM attribution analysis to identify the mechanisms underlying observed differences in springtime *ET* between croplands and prairies (Fig. 7). Generally, the model reproduced the observed $\Delta\beta$, though the error is relatively higher at CMRB (Fig. 7; compare β_m and β_o bar heights). Note that negative $\Delta\beta$ values indicates higher Bowen ratio at the prairie than at the cropland (Fig. 7). However, the magnitude of Bowen ratio differences varied across locations, with the most negative $\Delta\beta$ at UMRB and least negative at KBS. In all cases, surface resistance was the dominant factor driving cropland−prairie differences in springtime Bowen ratios. At UMRB, the surface albedo and ground heat flux also played important roles. Meanwhile, at KBS, the aerodynamic resistance plays a nearly equal, but opposite role to the surface resistance. In other words, at KBS, the aerodynamic resistance over the prairie was higher than for the croplands, which negated the effects of lower surface resistance at croplands.

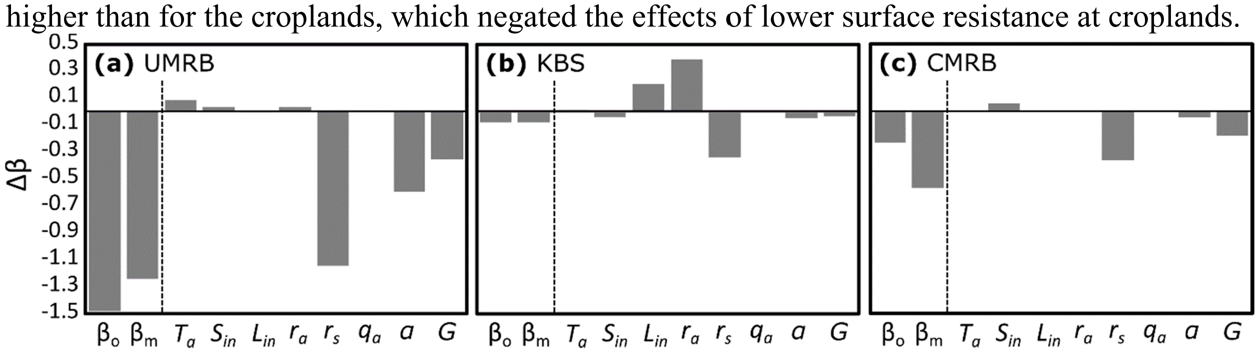

Figure 7: Attribution of the change in Bowen ratio (β) during the spring months of March–May caused by land use transition from cropland to prairie ($\Delta\beta = \beta_{crop} - \beta_{prairie}$). β_o and β_m are the observed and modeled changes in Bowen ratio, respectively. T_a, S_{in}, L_{in}, r_a, r_s, q_a, α, and G represent contributions from changes in air temperature, incoming shortwave radiation, incoming longwave radiation, specific humidity, aerodynamic resistance, surface resistance, albedo, and ground heat flux, respectively.

Springtime (March-May) r_a at KBS was slightly higher at the prairie site than at the cropland site (difference of 3 s/m), which is in contrast to the UMRB and CMRB locations (Fig. 8). The springtime r_a of the prairies at both the UMRB and CMRB locations is considerably lower than the croplands with a difference of 51 s/m and 21 s/m, respectively. An increased value of r_a decreases the H and therefore the Bowen ratio. Thus, the increased prairie r_a at KBS, relative to UMRB and CMRB, contributes to decreasing the KBS prairie Bowen ratio, relative to the KBS cropland. At the KBS location, the prairie is harvested, so the aerodynamic resistance is similar to that of the cropland throughout the year. During springtime, all locations have higher average r_s at the prairie than at the cropland, which limits prairie ET and contributes to a higher Bowen ratio at prairie sites. During the rest of the year, r_a and r_s are most stable at the KBS location with small differences between cropland and prairie in June when cropland plants are small and July-August during the peak growing season. Annual patterns of r_s are similar between cropland and prairie at the UMRB location. At the KBS and CMRB locations, differences are observed with higher r_s in croplands during June and lower r_s in croplands during July and August.

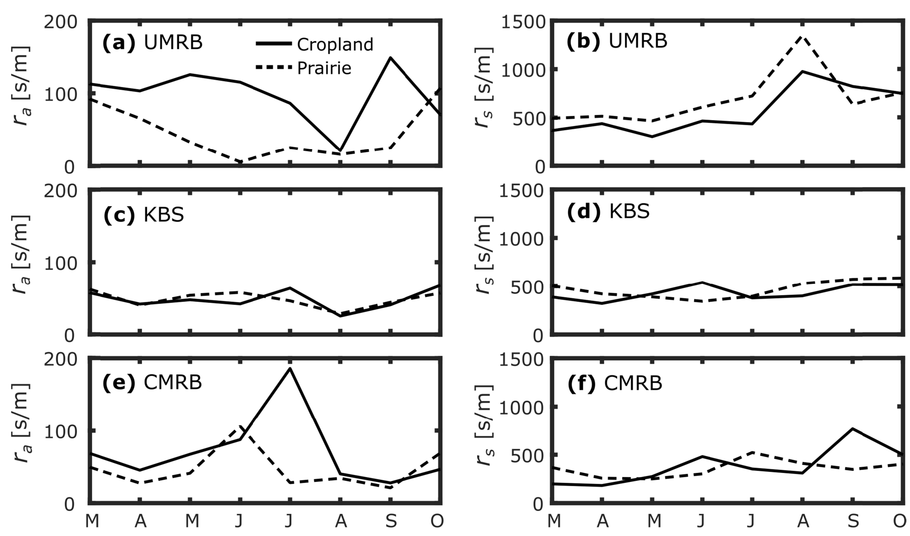

Figure 8: Monthly median value of aerodynamic resistance (r_a) and surface resistance (r_s) from cropland (solid lines) and prairie (dashed lines) sites at each location. The months of January, February, November, and December are not displayed due to high resistances during the winter dormant period.

Soil temperature differences affect surface resistance primarily through limiting evaporation from the soil surface whereas the vegetation activity controls surface resistance via plant transpiration. We present the average annual cycle of NDVI as a proxy for vegetation activity to illustrate the impacts that prairie green-up and cropland planting decisions have on the observed ET differences (Fig. 9). At the UMRB location, although there are significant differences between the cropland and prairie NDVI, the annual cycle of NDVI is very similar between the prairie and cropland sites. The magnitude of differences in the monthly NDVI are small (Fig. 9a). The KBS location also has similar annual cycles of NDVI except at the KBS prairie site vegetation activity is higher than at the croplands during May, indicating that the prairie vegetation begins activity before the cropland (Fig. 9b). At the CMRB site, this pattern is most pronounced in that the prairie has a prolonged growing season compared to the cropland, which is most evident in May and June (Fig. 9c).

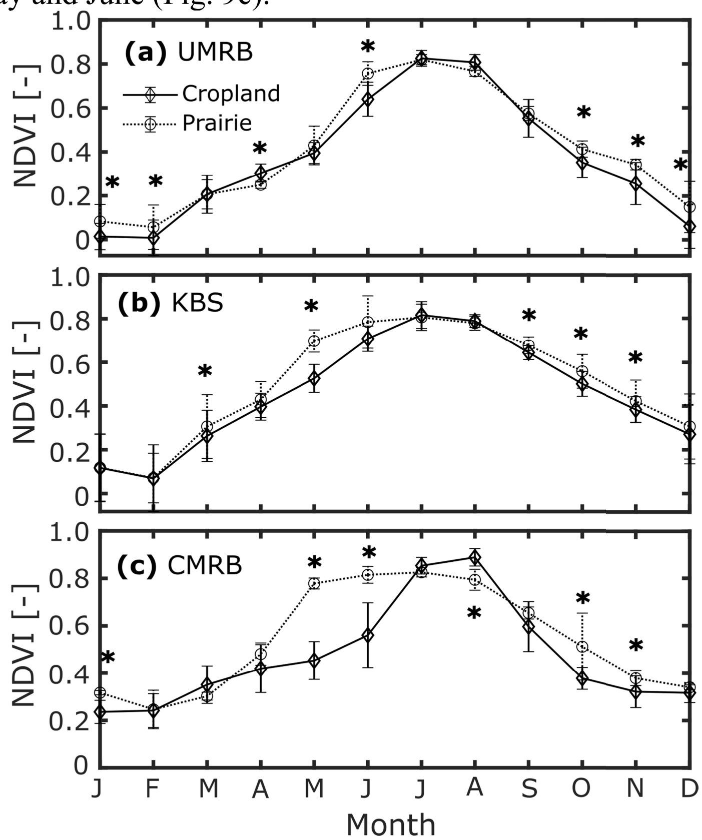

Figure 9: Mean monthly values of observed NDVI from the MOD13Q1 product for cropland (solid lines) and prairie (dashed lines) sites at the (a) UMRB, (b) KBS, and (c) CMRB locations.

4 Discussion

4.1 Land conversion and water budget

Previous attempts have been made to quantify the impact of LULCC between croplands and prairies on the water budget (Mao & Cherkauer, 2009; Schilling et al., 2008; Twine et al., 2004; Zhang & Schilling, 2006). Many studies focused on LULCC in the U.S. Midwest were framed around the question "does cropland or prairie have higher annual *ET*?" Our findings suggest the answer to this question depends on context and what factor limits *ET* at a particular location (Fig. 3). The croplands in this study have lower Bowen ratios during the springtime, which is primarily caused by lower surface resistance due to the lack of vegetation. This facilitates higher bare soil evaporation (*E*) from the croplands than the prairies. In the northern prairies (UMRB and KBS), vegetation is dormant during the spring and rates of transpiration (*T*) during this period are low, keeping the prairie *ET* low. Additionally, the surface resistance from standing vegetation in prairie can limit the transfer of sensible heat and prevents the soils from thawing. This is reflected in the importance of albedo and ground heat flux in controlling differences in springtime Bowen ratio at the UMRB location (Fig. 7). At the CMRB location, the warmer temperatures allow the prairie to green up sooner and increase *T* relative to the fallow or recently seeded cropland, particularly in May and June. The *ET* also is not as limited by soil temperature, evidenced by the lack of importance of albedo and *G* in the attribution of Bowen ratio differences (Fig. 7). Thus, the prairie has higher total *ET* than the cropland at the CMRB.

An important difference observed is that the r_a played a big role in narrowing the difference in the springtime Bowen ratio between the cropland and prairie at the KBS location (Fig. 7). This is likely a result of the prairie being harvested just like the cropland. The result is that the prairie vegetation does not insulate the soil from air temperature. As both the UMRB and CMRB locations do not harvest prairie, this is an important difference between the locations. The climate (i.e., *P*) and soil were the same between the two land covers at all locations, suggesting that vegetation and associated characteristics (e.g., transpiration, Bowen ratio, etc.) should be the key to differences in *ET* and Bowen ratio.

We believe that this mechanistic understanding of how *ET* responds to altered vegetation and soil due to land cover change in the U.S. Midwest is consistent with previous research amid some small contradictions. Previous studies investigating the effects of climate and land use change on streamflow in the Upper Mississippi River Basin (the larger basin, not the LTAR location presented in this study) had differing results. Work in Iowa, the southern portion of the basin, suggested that prairie has lower *ET*, which functions to increase streamflow, primarily baseflow (Schilling, 2016; Zhang & Schilling, 2006). In contrast, work on the river basin focused on the northern sites found that land use change from prairie to cropland did not play a major role in increasing streamflow (Frans et al., 2013). These findings are consistent with what we observed. At the southernmost location in our study (CMRB), prairie has higher *ET* than cropland, and therefore less streamflow. Whereas at the northernmost location (UMRB) cropland has more *ET* than prairie, meaning large scale conversion from prairie to cropland would lead to a decrease in streamflow. Additionally, the discussion about the water budget impacts of land cover conversion between cropland and prairie has been muddled by focus on the comparison of *ET* during growing seasons (e.g., Baeumler et al., 2019; Hamilton et al., 2015). The differences in the water budget between cropland and prairie is primarily found outside of the growing season (Fig. 4), suggesting that future research should examine the full year to draw more accurate conclusions.

There are, however, several potential limitations to the comparisons made in this study. First, *ET* at the CMRB location had an opposite response to land cover than the other two locations (i.e., prairie had higher *ET* than cropland). An important feature of the CMRB location is the shallow claypan soil, which prevents infiltration (Hofmeister et al., 2022). The prairie site has deeper topsoil that improves water holding capacity, which facilitates higher *ET* (Mudgal et al., 2010). Additionally, the CMRB prairie is a remnant prairie that has never been cultivated, so the soils and plant communities are fully developed with more than 100 plant species present (Kucera, 1956, 1958). The UMRB and KBS prairie sites, however, are restored prairie and the plant and soil communities may be underdeveloped, which may affect the *ET* rates (Chandrasoma et al., 2016). Additionally, croplands are not homogeneous and can be managed in many ways that affect *ET*. For example, planting density of crops can affect the *ET* (Jiang et al., 2014) and increases in cropland *ET* due to agricultural intensification has been documented (Mueller et al., 2016). Nitrogen management of croplands also affects *ET* and the lack of nitrogen stress in croplands has been shown to increase *ET* (Jones et al., 1986). The three cropland sites in this study have ‘conventional’ nitrogen management, but there are a variety of nitrogen management strategies in practice, which may alter the transferability of our results. Finally, although there are no tile drains in the studied fields, they are used non-uniformly across the U.S. Midwest and may alter subsurface hydrology (Kelly et al., 2017). There are many factors that influence *ET* from both prairie and cropland, while our study aims to illuminate several of the mechanisms causing different *ET*, this is by no means an exhaustive account.

4.2 Implications for agricultural management

The increased perennialization of croplands in the U.S. Midwest has been proposed as an effective strategy to promote native species, reduce stream pollution, and increase soil water holding capacity, reducing runoff and soil erosion (Ross & McKenna, 2023; Schulte et al., 2017). Of particular interest are strips of native prairie vegetation inserted into cropland that allow farming operations to continue. Previous research in Iowa has suggested that prairie strips in cropland can reduce runoff by increasing the water holding capacity in soils, but that the efficacy of prairie strips in reducing runoff is diminished when antecedent soil moisture is high (Gutierrez-Lopez et al., 2014; Hernandez-Santana et al., 2013). Thus, in the northern Corn Belt where cropland has higher *ET* than prairie, prairie strips may not reduce runoff as prairie soil water content is not depleted as rapidly by *ET*, leading to more frequently saturated soils. Model experiments in the northern Corn Belt suggested that prairie strips may reduce nitrogen inputs to streams by increasing *ET*, but our results suggest that this approach may not be successful due to reduced *ET* at the UMRB prairie site (Dalzell & Mulla, 2018). That being said, as the climate warms, the impact of frozen soils on *ET* will be lessened as sub-zero temperatures become less frequent. The results from the CMRB location may be representative of the northern locations in a future, warmer climate.

In addition to water quantity changes, the conversion to croplands typically is associated with increased nitrogen exports in the streamflow -- an effect that is primarily observed during the springtime (Gorski & Zimmer, 2021). Model simulations have suggested that nitrogen pollution can be reduced by increased perennial vegetation, which increases *ET*, especially during the spring, and reduces runoff (Dalzell & Mulla, 2018). Our estimates of *Q* demonstrate that this may not always be the case as the UMRB and KBS locations saw increased *Q* during the spring. Our approach is limited, however, because *Q* is not simply generated as the residual of [$P - ET$]. Regardless, this simple approach has proved useful, particularly when baseflow is predominant (Bales et al., 2018). At the UMRB location, conversion from cropland to prairie would likely result in increased *Q* during the spring (March-May). At the CMRB location, however, the cropland would have higher runoff than the prairie, particularly during June, a month in which observations indicate an increasing trend in precipitation. The increased runoff from croplands likely worsens soil erosion during this period (Baffaut et al., 2020).

5 Conclusions

We examined the magnitude and dynamics of *ET* at three locations with paired cropland and prairie sites across an approximately north-south gradient in the U.S. Midwest to harmonize understandings of the effects of land cover change. At the two northern locations, the UMRB and KBS LTAR sites, cropland had higher annual *ET* than prairie by 84 and 29 mm/yr, respectively. As expected, at all three locations the cropland *ET* was higher by an average of 8 mm/mon during the growing season months of July and August when extensive fertilization creates an extremely productive agro-ecosystem. The *ET* was also higher by an average of 7 mm/mon at the fallow cropland sites during the spring (March-May) period. At the southernmost location, the CMRB LTAR site, *ET* was higher at the prairie site than at the cropland by an average of 69 mm/yr. We used the two-resistance method to attribute the difference in *ET* between cropland and prairie primarily to differences in the surface resistance. Additionally, at the northern UMRB location, albedo and ground heat flux played a key role in increasing cropland *ET* during spring. The lower springtime albedo at the cropland site resulted in more energy being absorbed by the bare soil and higher soil temperature, causing increased *ET* relative to the prairie, even though the cropland field was fallow. At the CMRB location, the prairie site has a longer growing season, likely due to the warmer temperatures, and this overshadows any effect from the albedo and ground heat flux differences allowing the prairie site to have higher *ET*. Finally, at the KBS location where the prairie is harvested annually, the aerodynamic resistance between cropland and prairie was similar, which counteracts effects from surface resistance and leads to similar values of springtime *ET.* These results demonstrate that when assessing the impacts of large scale LULCC on the water budget, a mechanistic, process-based understanding is necessary. Because of the significant relationship between LULCC and the water budget, future efforts to plow or restore tallgrass prairie should consider impacts on surface resistance and therefore the hydrologic behavior of the system.

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Open Research

Data from this study can be obtained from the AmeriFlux network. The sites are: US-Mo1 (Schreiner-McGraw, 2022a), US-Mo3 (Schreiner-McGraw, 2022b), US-Ro1 (J. Baker & Griffis, 2022a), US-Ro4 (J. Baker & Griffis, 2022b), US-Ro5 (J. Baker & Griffis, 2022c), US-KL1 (G. P. Robertson & Chen, 2022a), and US-KL3 (G. P. Robertson & Chen, 2022b).

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