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RESEARCH ARTICLE

Long-term evapotranspiration rates for rainfed corn versus perennial bioenergy crops in a mesic landscape

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Abstract

Perennial cellulosic crops are promoted for their potential contributions to a sustainable energy future. However, a large-scale perennial bioenergy production requires extensive land use changes through diversion of croplands or conversion of uncultivated lands, with potential implications for local and regional hydrology. To assess the impact of such land use conversions on ecosystem water use, we converted three 22 year-old Conservation Reserve Program (CRP) grasslands and three 50+ year-old conventionally tilled corn-soybean crop fields (AGR) to either no-till continuous maize (corn) or perennial (switchgrass or restored prairie) bioenergy crops. We also maintained one CRP grassland without conversion. We measured evapotranspiration (ET) rates on all fields for 9 years using eddy covariance methods. Results show that: (a) mean growing-season ET rates for perennial crops were similar to the ET rate of the corn they replaced at the previously cultivated (AGR) field but ET rates for perennial crops at CRP fields were 5–9% higher than ET rate for corn on former CRP fields; and (b) mean nongrowing season ET rates for perennial fields were 11–15% lower than those for corn fields, regardless of land use history. On an annual basis, mean ET rates for perennial crops tended to be lower (4–7%) than ET rate of the corn that they replaced at AGR fields but ET rates for perennial crops and corn at CRP fields were similar. Over 9 years, mean ET rates for the same crop across land use histories were remarkably similar for corn, whereas for the perennial crops they were 4–10% higher at former CRP than at former AGR fields, mainly due to differences in growing season ET. Over the 9 years and across all fields, ET returned ~60% of the precipitation back to the atmosphere. These findings suggest that large-scale substitution of perennial bioenergy crops for rainfed corn in mesic landscapes would have little if any (0 to −3%) impact on terrestrial water balances.

KEYWORDS
eddy covariance, maize, perennial cellulosic bioenergy, restored prairie, seasonal evapotranspiration (ET), smooth brome grass, switchgrass

1 | INTRODUCTION

Bioenergy crops could potentially help mitigate climate change and enhance energy security by displacing conventional fossil fuel sources of liquid transportation fuel and electricity (Chu & Majumdar, 2012; Robertson et al., 2017). Globally, there has been growing interest in bioenergy crops, with policies set nationally to enhance production. Perennial bioenergy crops such as switchgrass and restored prairie are promoted as potential alternatives to fossil fuels for various reasons including: (a) their low net greenhouse gas (GHG) emissions (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Gelfand et al., 2011; Abraha, Gelfand, Hamilton, Chen, & Robertson, 2019) partially owing to their higher belowground carbon (C) storage due to high rates of soil C stabilization (e.g., West & Post, 2002) and permanent rooting systems (e.g., Glover et al., 2010; Monti & Zatta, 2009), (b) reasonable yields on marginal lands, which avoids food versus fuel conflict and indirect land use change effects (Robertson et al., 2017), (c) enhanced biodiversity (e.g., Werling et al., 2014), and (d) reduced nitrate leaching and improved water quality (e.g., Hussain, Bhardwaj, Basso, Robertson, & Hamilton, 2019; McIsaac, David, & Mitchell, 2010; Smith et al., 2013).

Substantial land area is required to meet the expected demands for perennial cellulosic bioethanol production targets (Robertson, Hamilton, Del Grosso, & Parton, 2011; U. S Department of Energy, 2016). New croplands will come either from the conversion of uncultivated lands or by replacing existing maize (*Zea mays* L.; hereafter referred to as corn) bioenergy systems—each with distinct implications for climate change mitigation (Abraha et al., 2019; Fargione et al., 2008; Gelfand et al., 2011) and potentially for local and regional hydrology (McIsaac et al., 2010; Schilling, Jha, Zhang, Gassman, & Wolter, 2008; VanLoocke, Twine, Zeri, & Bernacchi, 2012). While there is considerable evidence for the climate change benefits of such land use conversions (Abraha et al., 2019; Fargione et al., 2008; Gelfand et al., 2011; Gelfand et al., 2013), there have not been long-term empirical studies on how such conversions affect the hydrologic cycle in the face of typical interannual climate variability. Evapotranspiration (ET, water loss to the atmosphere from plant and soil surfaces)—which typically returns >60% of the annual precipitation to the atmosphere in terrestrial ecosystems (Hamilton, Hussain, Lowrie, Basso, & Robertson, 2018; Zhang et al., 2016)—determines ecosystem water balances. Changes in ET rates due to conversion to bioenergy crops would result in changes in groundwater recharge and streamflow.

Field experiments that compare water use in rainfed annual corn and perennial (e.g., switchgrass and restored prairie) bioenergy crops are few and limited to the early- to mid-establishment phases of the perennial crops; these studies have shown that crops on well-drained soils have similar ET rates (e.g., Abraha et al., 2015; Hamilton, Hussain, Bhardwaj, Basso, & Robertson, 2015; Parish, Kendall, Thompson, Stenjem, & Hyndman, 2019). On tile-drained soils with high water tables, ET rates by perennials can be higher compared with corn (e.g., Hickman, VanLoocke, Dohleman, & Bernacchi, 2010; Zeri, Hussain, Anderson-Teixeira, DeLucia, & Bernacchi, 2013). Modelling studies, largely influenced by the validation data sets used, have indicated either higher ET rates for perennial crops than for corn (e.g., Le, Kumar, & Drewry, 2011; Schilling et al., 2008; VanLoocke et al., 2012; Zhuang, Qin, & Chen, 2013) or similar ET rates (e.g., Song et al., 2016).

In this study, we measured ET using the EC method from annual (continuous corn) and perennial (switchgrass and restored prairie) bioenergy crops planted in fields of two contrasting land use histories over a 9-year period. We converted three 22 year-old Conservation Reserve Program (CRP) grasslands and three 50+ year-old conventionally tilled corn–soybean rotation agricultural (AGR) lands to no-till corn, switchgrass (*Panicum virgatum* L.), or restored prairie (19 species; see Abraha et al., 2016). A seventh site was maintained in the pre-existing CRP grassland dominated by smooth brome grass (*Bromus inermis* L.) to serve as a reference. This study builds on a previous ET study from 2009 through 2012—4 years after conversion and 3 years after planting of perennial bioenergy crops (Abraha et al., 2015)—to include the post-establishment phase and to partition the annual ET (ET_t) into contributions from the growing season (ET_{gs}) and non-growing season (ET_{ngs}). Our study thus compares three cropping systems over nearly a decade, a period that encompasses considerable climatic variability, and as well between the same crops across two contrasting land use histories (intensive row crops vs. conservation grasslands) to reveal legacy effects of prior land use.

2 | MATERIALS AND METHODS

2.1 | Study sites

The study sites are located within the northeastern part of the US Midwest Corn Belt in southwest Michigan at the Great Lakes Bioenergy Research Center of the W.K. Kellogg Biological Station's Long-term Ecological Research site (42°24′N, 85°24′W, 288 m asl). The region has a humid continental temperate climate with a mean annual air temperature of 9.9°C, ranging from −4.1°C in January to 22.8°C in July, and a mean total annual precipitation of 1,027 mm with about half falling as snow (1981–2010; Michigan State Climatologist's Office, 2013). From May to September, roughly representing the growing season for the region, the mean air temperature and the total precipitation are 19.7°C and 523 mm, respectively. Soils at the sites are moderately to slightly acidic, well-drained Typic Hapludalfs of the Kalamazoo (loam), Osthemo (sandy loam), and Boyer (loamy sand) series developed on glacial outwash (Robertson & Hamilton, 2015; Thoen, 1990) intermixed with loess (Luehmann et al., 2016).

The treatments were established on six fields (11–17 ha), three of which had been managed as CRP grasslands dominated by smooth brome grass (*Bromus inermis* L.)—an introduced cool-season C_3 grass of Eurasian origin—since 1987 and three had been managed as conventionally tilled corn–soybean rotation agricultural croplands (AGR) for 50+ years. In 2009, the fields were converted to no-till glyphosate-tolerant soybean (*Glycine max* L.). All converted fields were treated with glyphosate (*N*-(phosphonomethyl) glycine; Syngenta, Greensboro, NC, USA) at 2.9 kg ha^{-1} in May prior to soybean planting in order to kill extant vegetation and later in July during vegetative growth in order to suppress weeds. The killed vegetation was left in place. In 2010, the three fields in each set (CRP and AGR) were planted to 'Cave-in-Rock' switchgrass, mixed native prairie species (Abraha et al., 2016), or no-till continuous corn. Annual oat grass was inter-seeded along with switchgrass and restored prairie in 2010 to serve as an over-winter nurse crop. Corn was planted in early May and harvested annually in October in each year with corn stover left in place until 2014 but ~35% was, on average, removed each year afterwards. Switchgrass and restored prairie were planted only once in 2010 and harvested annually in November, following autumn senescence from 2011 onwards.

Corn fields were fertilized at ~180 kg N ha^{-1} yr^{-1} and the switchgrass fields at ~56 kg N ha^{-1} yr^{-1} while the restored prairie fields were not fertilized. The corn fields also received phosphorus (P_2O_5) and potash (K_2O) fertilizers each year before planting, and lime (~5 Mg ha^{-1}) in 2012 and 2015 and were treated with herbicides early and mid-season to suppress weeds. A seventh field (9 ha) was maintained in unharvested smooth brome grass as a reference CRP grassland (CRP-Ref; Figure 1). No agronomic management was applied to the CRP-Ref field. For details on conversion history and management practises see Abraha, Gelfand, Hamilton, Chen, and Robertson (2018).

The soils at the former CRP grasslands had significantly higher soil C and N content and lower soil bulk density (0–25 cm depth) during conversion (Abraha et al., 2016) and higher pre- and post-conversion labile soil C pools (0–10 cm depth; Abraha, Gelfand, et al., 2018) than the soils at former AGR fields.

2.2 | EC measurements

Continuous open-path EC and meteorological measurements were conducted at all seven fields over 10 years (2009–2018). Water vapour concentrations (LI-7500 IRGA, LI-COR Biosciences, Lincoln, NE, USA) and wind velocity (CSAT3 three-dimensional sonic anemometer, Campbell Scientific Inc. Logan, UT, USA) were sampled at 10 Hz frequency and the data logged using Campbell CR5000 dataloggers. The LI-7500s were calibrated every 4 to 6 months. The EC sensors were oriented towards the prevailing wind direction and placed at 1.5 to 2.0 m above the average canopy height. The EC sensors were located at the centre of each field with a fetch of at least 150 m along the prevailing wind direction.

We analyzed the raw data offline using EdiRe software (University of Edinburgh, v 1.5.0.32, 2012) to compute half-hourly ET from all fields. Data treatment during analysis included: (a) removal of out-of-range values, spikes, and time lags between the scalar (water vapour) and vertical wind speed from the raw data (McMillen, 1988); (b) alignment of the three velocity components into the mean streamline coordinate system using the planar fit coordinate rotation (Wilczak, Oncley, & Stage, 2001); (c) correction of the sonic temperature for pressure and humidity (Schotanus, Nieuwstadt, & De Bruin, 1983) and the H_2O fluxes for frequency response (Moore, 1986) and air density fluctuations (Webb, Pearman, & Leuning, 1980), and (d) removal of periods with poorly developed turbulent mixing using stationarity, flux-variance similarity, and friction velocity thresholds (Foken & Wichura, 1996). On average, ~79% of the daytime and ~49% of the nighttime ET data passed these quality checks and controls, and the rest were replaced using a standardized gap-filling algorithm of Reichstein et al. (2005) in the R package REddyProc (Wutzler et al., 2018).

We also measured incoming solar radiation, air temperature and relative humidity, and soil water content for the top 0.3 m of the soil profile at each field. Precipitation was measured at a nearby weather station (https://lter.kbs.msu.edu/datatables) located about 4 km from the nearest site.

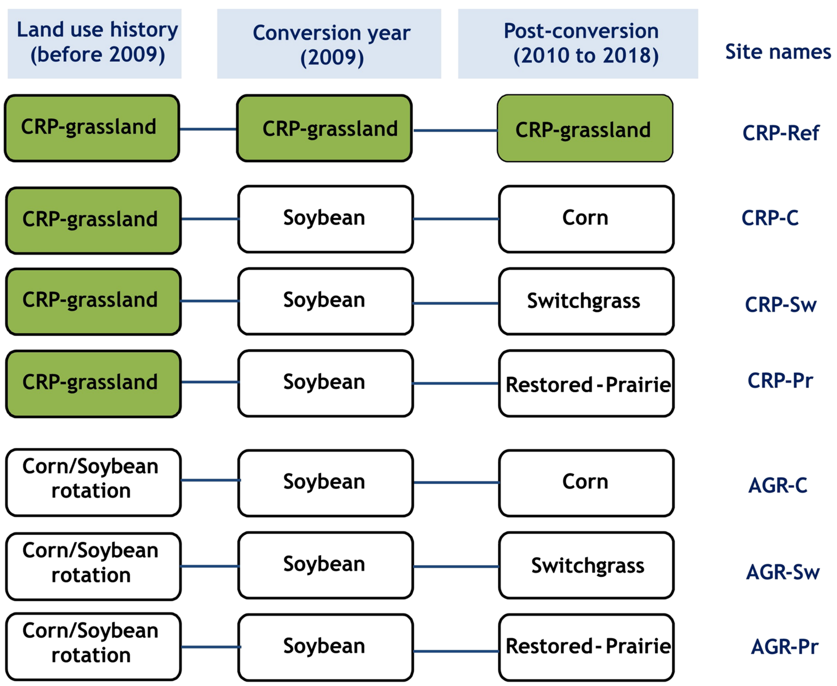

FIGURE 1 A schematic illustration of land use history and conversion at study sites. Fields were converted from Conservation Reserve Program (CRP) grasslands and conventionally tilled corn-soybean rotation agricultural (AGR) fields. The CRP grasslands were under smooth brome grass since 1987 and the AGR in row crops at least for 5 decades prior to conversion in 2009. Fields were first converted to no-till soybean in 2009, then to no-till corn (C), switchgrass (Sw) or restored prairie (Pr) from 2010 onward. The CRP-Ref was maintained in smooth brome grass that was not harvested

2.3 | Statistics

Uncertainties associated with the 30-min gap filling, friction velocity threshold selection criteria, and Monte Carlo simulations (95% confidence interval) for the half-hourly ET data were propagated into seasonal and annual uncertainties to compare ET between and within crop fields, across land use histories and years (e.g., Abraha et al., 2015; Goulden, Munger, Fan, Daube, & Wofsy, 1996; Moncrieff, Malhi, & Leuning, 1996). The upper and lower bound ranges of the differences in ET between crop fields were checked for the presence of significant differences; differences that overlap with zero indicate nonsignificant difference.

All data reported here are openly available at https://doi.org/10.5061/dryad.7m0cfxpq1.

3 | RESULTS

The 9 years of this study encompassed typical climate variability of the region. The growing season (May–September) precipitation for our sites was significantly lower in 2012 and 2017 but higher in 2015 than the historic 30-year mean of 523 mm (1981–2010; Table 1). The nongrowing season (October–April) precipitation was significantly lower in 2015 than the long-term average. The growing season mean air temperature in 2014 (18.1°C), and that of the nongrowing season in 2014 (–0.1°C) and 2015 (0.7°C) were significantly cooler than the long-term means (19.7 and 3.0°C, respectively). The mean air temperature and total precipitation for the other years and seasons were closer to the long-term averages. The growing season mean vapour pressure deficit (VPD), total solar radiation and the resulting grass reference evapotranspiration (ET_o) were also remarkably higher in 2012 compared with all other years (Table 1).

During the nongrowing seasons when actively transpiring plants were absent, the soil profile was usually recharged to its drained upper limit of soil water content (Figure S1). A progressive decline in soil water content was observed during the growing seasons as plants grew in size and coverage, although near-surface soil water was occasionally increased by rain events. Dry spells, characterized by marked decreases in soil water content because plant water uptake exceeded rainfall for weeks, were observed during most of the growing seasons, although these dry spells were sharper and lasted longer in 2012 and 2017. The drought in 2012, which coincided with high temperatures, had unusually severe impacts on local and regional crop production.

Annual ET consumed 60%, growing season ET consumed 100%, and nongrowing season ET consumed 34% of the respective total precipitation over 9 years across all fields (Table 1). The highest ET as a percentage of precipitation occurred in the years or seasons with low precipitation; in the dry years of 2012 and 2017 for the annual (~71%) and growing season (~161%) ET and in 2015 for the nongrowing season ET (56%; Table 1). Growing season ET was well correlated with the aboveground net primary productivity for each field, except CRP-Ref, over the years (Figure 2).

TABLE 1 Growing season (May–Sept), nongrowing season (Oct–Apr), and annual total precipitation, mean air temperature (T_{air}) and vapour pressure deficit (VPD), total incoming solar radiation, and total evapotranspiration (ET; averaged across all fields) and grass reference crop evapotranspiration (ET_o, in brackets) for all fields from 2010 through 2018. Long-term means (1981–2010) are from Michigan State Climatologist's Office (http://climate.geo.msu.edu/climate_mi/stations/3504/)

Year	Precipitation (mm)			T_{air} (°C)			VPD (kPa)			Solar radiation (MJ m^{-2})			ET (ET_o, mm)		
	May–Sept	Oct–Apr	Oct–Sept	May–Sept	Oct–Apr	Oct–Sept	May–Sept	Oct–Apr	Oct–Sept	May–Sept	Oct–Apr	Oct–Sept	May–Sept	Oct–Apr	Oct–Sept
2010	568	368	936	19.8	3.0	10.0	0.67	0.25	0.42	2955	1941	4897	411(609)	151(296)	562(906)
2011	510	465	975	19.2	1.7	9.0	0.66	0.24	0.42	2843	1879	4722	411(586)	143(262)	555(848)
2012	227	569	796	20.1	4.9	11.3	0.99	0.29	0.58	3366	2028	5394	367(745)	188(333)	554(1078)
2013	446	694	1139	18.9	2.0	9.1	0.67	0.21	0.40	3079	1764	4843	445(616)	169(249)	614(865)
2014	473	499	971	18.1	-0.1	7.5	0.57	0.21	0.36	3010	2017	5027	478(561)	148(260)	626(821)
2015	726	246	972	18.9	0.7	8.4	0.57	0.22	0.36	2882	1929	4811	439(541)	139(252)	577(793)
2016	500	448	948	19.8	4.2	10.7	0.69	0.26	0.44	3114	1776	4890	434(608)	174(270)	609(878)
2017	262	582	844	18.7	4.4	10.4	0.69	0.23	0.42	2953	1666	4619	419(587)	184(248)	603(835)
2018	541	774	1315	20.3	1.7	9.4	0.67	0.22	0.41	2739	1809	4548	444(548)	146(248)	590(799)
1981–2010 means	523	504	1027	19.7	3.0	9.9	-	-	-	-	-	-	-	-	-

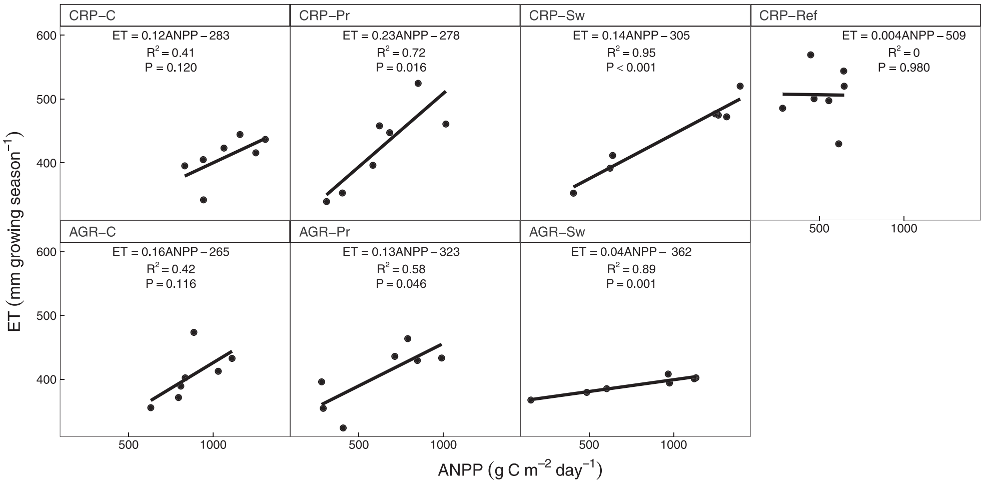

FIGURE 2 Mean aboveground net primary productivity (ANPP, *n* = 10) versus growing season (May–Sept) evapotranspiration (ET_{gs}) for all fields from 2010 through 2016. ANPP for the corn fields does not include seeds. See Figure 1 for land use history and field names

ET rates during the conversion year in 2009 were higher at the AGR than at the CRP fields when soybean was planted in all converted fields (data not shown here; see Abraha et al., 2015). However, ET rates were similar within each land use history, except for a somewhat higher ET rate at AGR-C than at AGR-Sw field. ET rate comparisons between the annual (corn) and perennial bioenergy crops (switchgrass and restored prairie) from 2010—the year when the continuous corn and perennials were planted—through 2018 are presented below.

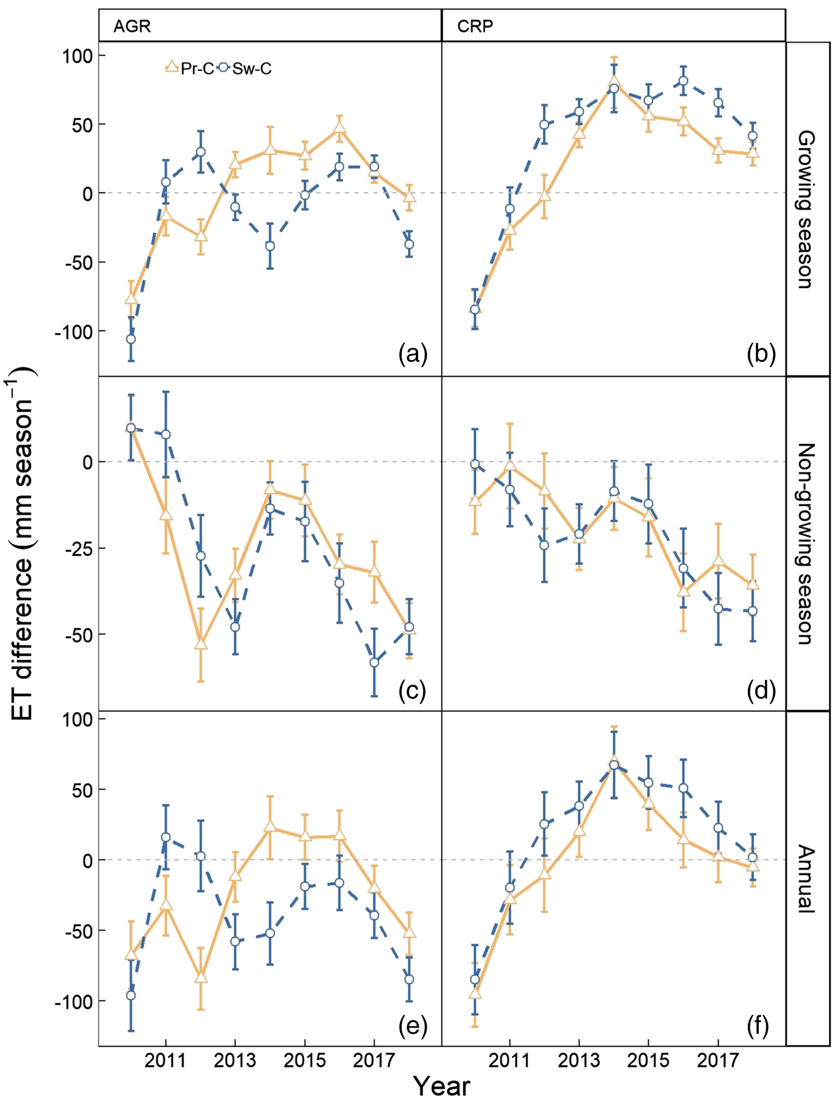

FIGURE 3 Growing season, nongrowing season and annual evapotranspiration (ET) differences between the perennial (restored prairie and switchgrass) crops and corn from 2010 through 2018. The legend Pr-C refers to restored prairie ET less corn ET, and Sw-C refers to switchgrass ET less corn ET. The growing season is from May to September, the nongrowing season is from October of previous year to April of current year, and annual spans from October of previous year to September of current year. Error bars—representing uncertainty—that lie along the broken horizontal line indicate similar ET between the perennials and corn, points above the line indicate ET rates for perennials higher than those for corn; whereas those below the line indicate ET rates for perennials less than those for corn. See Figure 1 for land use conversion details

3.1 | ET between crops within the same land use history

The growing season ET (ET_{gs}) rates of the perennial crops (switchgrass and restored prairie) were lower than those for corn at both the AGR and CRP fields in 2010, the year when the perennials were planted (Figure. 3a,b). In 2011, ET_{gs} rate for restored prairie was lower than that for corn but the ET_{gs} rate for switchgrass was similar to that for corn at the respective land use histories (Figure 3a,b). From 2012 onwards, there was no consistent pattern in ET_{gs} differences between the perennials and corn at AGR fields with ET_{gs} rates of the perennials being either less than, similar to, or higher than those for corn over the years (Figure 3a). On average over the 9 years, restored prairie and switchgrass ET_{gs} rates (expressed as mm gs^{-1}) were similar to corn ET_{gs} rate, with differences (mean ± uncertainty) of 1 ± 11 mm gs^{-1} (0%) and −13 ± 12 mm gs^{-1} (3%), respectively, at the AGR fields (Table 2).

At the CRP fields, ET_{gs} rates for perennial crops were higher than those for corn from 2012 onwards, except for similar ET_{gs} rates between restored prairie and corn in 2012 (Figure 3b). On average over the 9 years, restored prairie and switchgrass ET_{gs} rates were higher than ET_{gs} rate for corn by 20 ± 12 mm gs^{-1} (5%) and 38 ± 12 mm gs^{-1} (9%), respectively, at the CRP fields (Table 2).

The nongrowing season ET (ET_{ngs}) rates for the switchgrass fields were similar to those for the corn fields in 2010 and 2011 at both the AGR and CRP fields (Figure 3c,d). The ET_{ngs} rates for the restored prairie fields were also similar to those for the corn fields in 2010 and 2014 at the AGR fields and from 2010 to 2012 at the CRP fields (Figure 3c,d). The ET_{ngs} rates for the perennial fields were lower than those for the corn fields in all the other years at both the AGR and CRP fields (Figure 3c,d). On average over the 9 years, the restored prairie and switchgrass field ET_{ngs} rates were lower than ET_{ngs} rate for the corn field by 25 ± 9 mm ngs^{-1} (14%) and 26 ± 10 mm ngs^{-1} (15%) at AGR and by 19 ± 10 mm ngs^{-1} and (11%) 21 ± 11 mm ngs^{-1} (12%) at CRP fields, respectively (Table 2).

The annual ET (ET_t) rates of the perennials were lower than those for corn at both the AGR and CRP fields in 2010, the year when the perennials were planted (Figure 3e,f). From 2011 onwards, there was no consistent pattern in ET_t differences between the perennials and corn at the AGR fields (Figure 3e). On average over the 9 years, restored prairie and switchgrass ET_t rates were lower than ET_t rate for corn by 24 ± 19 mm yr^{-1} (4%) and 39 ± 20 mm yr^{-1} (7%), respectively, at the AGR fields (Table 2).

At the CRP fields, switchgrass ET_t rates were higher than those for corn from 2012 to 2017, but similar in 2011 and 2018 (Figure 3f). Restored prairie ET_t rates were higher than those for corn in 2014 and 2015 only, with similar ET_t rates in the other years (Figure 3f). On average over the 9 years, restored prairie and switchgrass ET_t rates were similar to ET_t rate for corn, with mean differences of 1 ± 21 mm yr^{-1} (0%) and 17 ± 21 mm yr^{-1} (3%), respectively, at the CRP field (Table 2).

Growing season ET rates at the CRP-Ref field were higher than at all converted fields in all the years except in 2016 and 2017 when they were lower than or similar to those at the CRP perennial fields (Figure 4). On average over the 9 years, the CRP-Ref ET_{gs} rate was higher than ET_{gs} rates for corn, restored prairie and switchgrass at the CRP fields by 87 ± 13 mm gs^{-1} (21%), 67 ± 12 mm gs^{-1} (16%) and 48 ± 12 mm gs^{-1} (11%), respectively. The ET_{ngs} rates for the CRP-Ref were similar to those for corn with mean difference of −1 ± 11 mm ngs^{-1} over the 9 years. However, ET_{ngs} rates for CRP-Ref were higher than those for the perennials at CRP fields in half of the study years, with similar ET_{ngs} rates for the rest of the years (Figure 5). On average over the 9 years, the CRP-Ref ET_{ngs} rate was higher than ET_{ngs} rates for restored prairie and switchgrass at the CRP fields by 18 ± 10 mm ngs^{-1} (12%) and 20 ± 12 mm ngs^{-1} (13%), respectively. Annual ET rates at the CRP-Ref field were higher than at all converted fields in all the years except for similar ET_t rates to those for switchgrass at the CRP field in 2016 and 2017 (Figure 6). On average over the 9 years, the CRP-Ref ET_t rate was higher than ET_t rates for corn, restored prairie and switchgrass at the CRP fields by 86 ± 23 mm yr^{-1} (15%), 85 ± 21 mm yr^{-1} (15%), and 68 ± 21 mm yr^{-1} (11%), respectively.

3.2 | ET between same crops across land use histories

Growing season ET for the same crop across land use histories showed that corn ET_{gs} rates were similar at both fields from 2012 to 2017, higher at the AGR field in 2010 and 2018, but less in 2011 than at the CRP field, with overall mean difference of only 1 ± 13 mm gs^{-1} (Figure 4). Switchgrass ET_{gs} rates at the AGR field were lower than those at the CRP field in all years, except in 2010 and 2012 when they

TABLE 2 Mean total annual ET rates for all fields and differences between the perennial (restored prairie and switchgrass) and corn fields over 9 years (2010–2018)

		Mean ET_t (mm; 2010–2018)			ET difference			
Season	Land use history	Restored prairie	Switchgrass	Corn	Pr-C (mm)	Pr-C (%)	Sw-C (mm)	Sw-C (%)
Growing season	AGR	411 (7)	396 (8)	409 (9)	1 (11)	0	−13 (12)	−3
Growing season	CRP	428 (8)	446 (8)	408 (9)	20 (12)	5	38 (12)	9
Nongrowing season	AGR	150 (5)	149 (7)	175 (7)	−25 (9)	−14	−26 (10)	−15
Nongrowing season	CRP	153 (6)	151 (6)	172 (8)	−19 (10)	−11	−21 (10)	−12
Annual	AGR	560 (12)	545 (14)	584 (15)	−24 (19)	−4	−39 (20)	−7
Annual	CRP	581 (13)	597 (13)	580 (16)	1 (21)	0	17 (21)	3

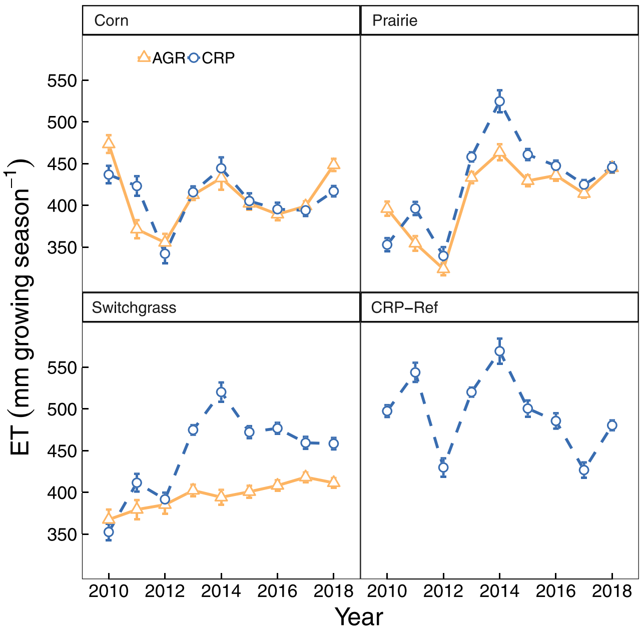

FIGURE 4 Growing season (May–Sept) evapotranspiration (ET_{gs}) rates from 2010 through 2018 for all fields. See Figure 1 for land use conversion history

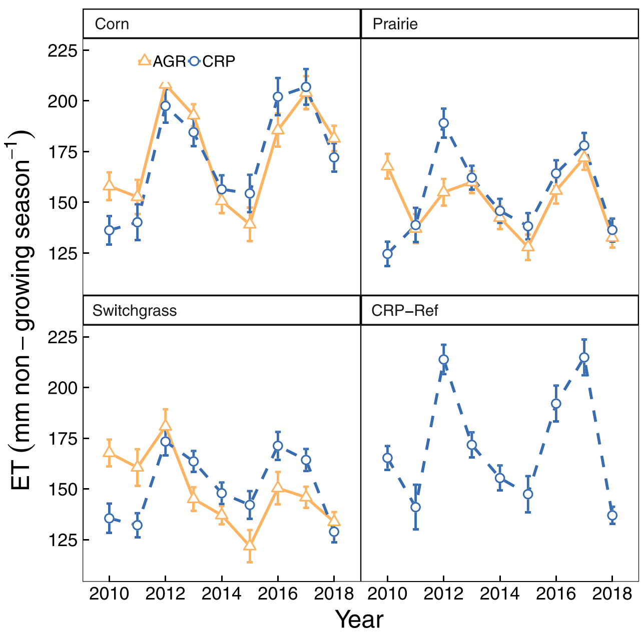

FIGURE 5 Nongrowing season evapotranspiration (ET_{ngs}) rates frm 2010 through 2018 for all fields. Nongrowing season includes ET data from October of the previous year to April of the current year. See Figure 1 for land use conversion history

were similar, with ET_{gs} rate at the AGR-Sw lower than at the CRP-Sw by 50 ± 12 mm gs^{-1} (13%) over the 9 years (Figure 4). Restored prairie ET_{gs} rates were similar at both fields in 2012, 2016–2018, higher at the AGR field in 2010, but lower in all the other years than those at the CRP field, with ET_{gs} rate at the AGR-Pr lower than at the CRP-Pr by 17 ± 11 mm gs^{-1} (4%) over the 9 years (Figure 4).

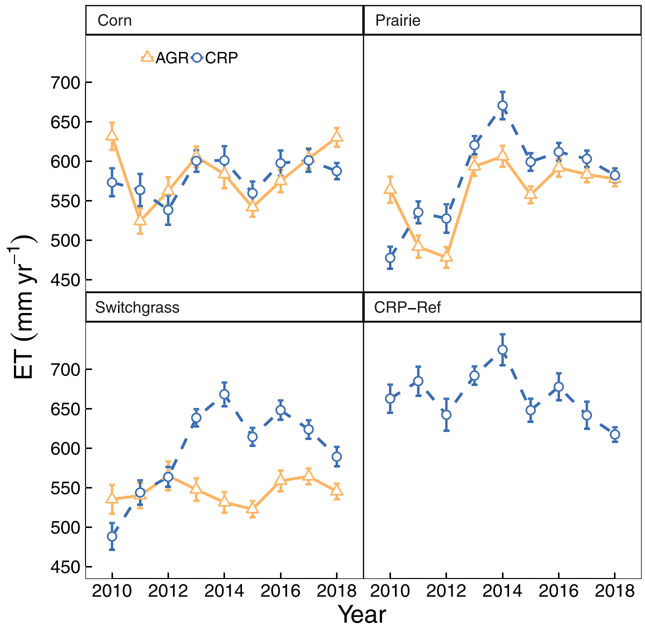

FIGURE 6 Annual evapotranspiration (ET_t) rates from 2010 through 2018 for all fields. Annual ET includes data from October of the previous year to September of the current year. See Figure 1 for land use conversion history

Nongrowing season ET rates for fields grown with the same crop across land use histories were higher at the AGR than at the CRP fields for all crops in 2010 (Figure 5). Corn ET_{ngs} rates were similar at both fields from 2011 onwards; switchgrass ET_{ngs} rates were higher at the AGR field in 2011 but were either similar to or less than those at the CRP field thereafter; restored prairie ET_{ngs} rates were similar at both fields from 2011 onward except in 2012 for lower ET_{ngs} rates at the AGR than at CRP field (Figure 5). On average ET_{ngs} rates for fields grown with the same crop across land use histories were similar between the AGR and CRP fields with overall mean differences of 2 ± 11 mm ngs^{-1} for corn, −3 ± 8 mm ngs^{-1} for restored prairie and −2 ± 9 mm ngs^{-1} for switchgrass.

Annual ET rates for the same crop across land use histories was higher at the AGR than at the CRP fields for all crops in 2010 (Figure 6). In 2011 and 2012, ET_t rates at AGR fields were either less than (e.g., restored prairie) or similar to (e.g., corn and switchgrass) those at the CRP fields (Figure 6). Corn ET_t rates at both fields were similar from 2012 onwards except in 2018; the overall mean difference was 4 ± 22 mm yr^{-1} (1%; Figure 6). For restored prairie, ET_t rates at the AGR were less than those at the CRP field from 2011 to 2015 but similar from 2016 onwards, with an overall mean difference of −20 ± 18 mm yr^{-1} (4%; Figure 6). For switchgrass fields, ET_t rates at the AGR were less than those at the CRP field from 2013 onwards, with an overall mean difference of −52 ± 19 mm yr^{-1} (10%; Figure 6).

4 | DISCUSSION

Over the 9 years of this study, annual ET rates—sum of the growing and nongrowing season rates—for perennials were 4–7% lower than for the corn they replaced at formerly cultivated (AGR) fields but the rates were similar between the perennials and corn at the former CRP fields. Over the growing season, perennials and corn ET_{gs} rates were similar at the AGR fields, but in CRP fields, the rates were 5–9% higher for perennial crops than for corn. Over the nongrowing season, ET_{ngs} rates for the perennial fields were 11–15% lower than those for corn fields for both land use histories. The unconverted CRP-Ref field had higher overall ET rates than the converted fields.

ET rates for the same crop grown at the AGR and CRP fields were remarkably similar for corn regardless of the season, but for the perennials, ET_{gs} rates were 4–13% and ET_t rates were 4–10% lower at the AGR than at the CRP fields, whereas ET_{ngs} rates were similar at both land use histories.

4.1 | Growing season ET

Growing season ET from 2010 through 2018 for all crops varied from 324 mm (at AGR-Pr in 2012 with exceptionally low precipitation and high VPD; Table 1) to 569 mm (at CRP-Ref in 2014). ET_{gs} rates generally correlated with the precipitation amount at the low end of the total precipitation range, with the dry years of 2012 and 2017 exhibiting the lowest ET_{gs} (Table 1). These years were also indicated by prolonged large drops in soil water content in early 2012 and late 2017 (Figure S1) as the plants were transpiring at faster rates than precipitation could recharge the soil water. The year 2015 had the highest growing season precipitation but not the highest ET_{gs} rate (Table 1); about 25% of the precipitation in this growing season fell in two large rain events (Figure S1) that saturated the soil profile, causing the excess water either to percolate below the root zone or flow overland without contributing to ET. In addition, 2015 had the lowest nongrowing season precipitation, which resulted in lower than the normal soil water recharge by spring (Table 1, Figure S1), limiting ET_{gs} rates early in the growing season. The 2014 growing season showed slightly higher ET_{gs} rate compared with the rest of the years, likely due to more uniform precipitation distribution (Figure S1) coupled with high incident solar radiation (Table 1). All other growing seasons had normal precipitation and similar ET_{gs} rates, the latter ranging on average between 411 and 445 mm gs^{-1} (Table 1).

The ET_{gs} rates for perennial crops were affected by the establishment phase when they were low in the first 3 years following planting but increased steadily, reaching a peak by 2014, and thereafter, varied depending on the soil water availability and climate. Consequently, ET_{gs} rates for perennial crops were less than or similar to those for corn in the first 2 or 3 years following conversion to perennials at both the AGR and CRP fields (Figure 3a,b). This was likely because the canopy size and roots of the perennials had not yet developed to their full potential, which may take up to 3 years following planting (Parrish & Fike, 2005; Abraha, Hamilton, Chen, & Robertson, 2018), and thus their peak ET rates may not have yet been realized. Following perennial establishment, there were less consistent ET_{gs} patterns at the AGR fields while the ET_{gs} rates for perennial crops were always higher than those for corn at the CRP fields. On average, the ET_{gs} rates for perennial crops at the AGR fields were similar to ET_{gs} rate for corn but 5–9% higher than ET_{gs} rate for corn at the CRP fields. These differences demonstrate how ET_{gs} is affected by the stand age of perennial crops and thus long-term experiments that span pre- and post-establishment are required for lifespan water use comparisons between annual and perennial crops.

Our observations agree with studies conducted on similar cropping systems in regions with similar climate and upland soils. For example, in nearby sites, Hamilton et al. (2015) found similar ET_{gs} rates for switchgrass, restored prairie, and corn. Parish et al. (2019) also found similar ET_{gs} rates between switchgrass and corn in the upper US Midwest. In southern Ontario, Canada, Eichelmann, Wagner-Riddle, Warland, Deen, and Voroney (2016) found lower ET_{gs} rates for switchgrass than for corn. Baeumler, Kjaersgaard, and Gupta (2019) reported similar ET_{gs} rates between native prairie grasslands and corn in west-central Minnesota. However, our observations differ from studies conducted on poorly drained soils in Illinois with high water tables and subsurface drainage, which have reported higher switchgrass ET_{gs} rates than those for corn (e.g., Hickman et al., 2010; Le et al., 2011), with the exception of McIsaac et al. (2010) who reported similar ET_{gs} rates for switchgrass and corn–soybean rotation cropping systems. The growing season lengths considered in these studies, and in Baeumler et al. (2019), were 2 to 8 weeks shorter for the annuals than for the perennials; soil–water evaporation from the annual fields during those 2–8 week periods was not considered, which could be significant and could potentially change the conclusions drawn from those studies. This emphasizes the importance of soil water loss from annual croplands during the early growing season before planting when canopies are absent or small. In soils with high water table, the perennials—with longer seasonal photosynthetic activity and nonlimiting soil water—might consume more water than corn. However, the future of bioenergy crop production likely lies in the marginal lands that are well drained rather than in soils that require subsurface drainage management (Hamilton et al., 2015; Robertson et al., 2017).

Growing season ET rates at the CRP-Ref field were higher than those for the perennial and annual bioenergy crops at the CRP fields for almost all years. The differences in ET_{gs} rates between CRP-Ref and the perennial bioenergy crops in the early years during the establishment phase of the perennial bioenergy crops were larger but diminished with time as the perennials became established. The higher ET_{gs} rates at the CRP-Ref field compared with all the bioenergy fields could be due to the earlier emergence (late-March or early April) and canopy development of the cool-season C_3 smooth brome grass, resulting in higher ET_{gs} rates in May and June (Figure 7), and also perhaps due to a second growth phase that may start in September (Figure 7; Salesman & Thomsen, 2011) when all the bioenergy crops have senesced.

Growing season ET rates for the same crop across land use histories were higher at the AGR than at the CRP fields for all crops in 2010, likely due to land use legacy differences (Figure 4). From 2011 onwards, ET_{gs} rates for perennial crops were lower at the AGR than at the CRP fields in almost all years. The differences in ET_{gs} between the same perennial crops in contrasting land use histories could be due to

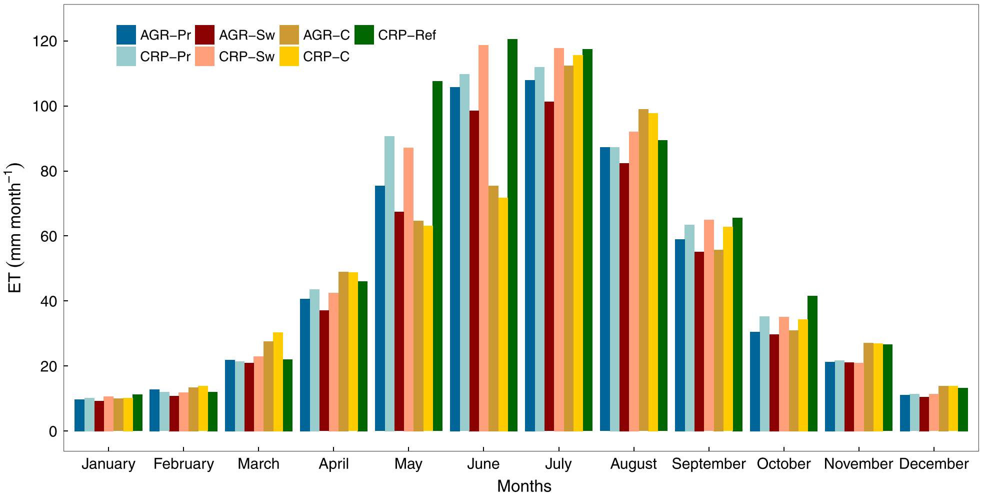

FIGURE 7 Average monthly evapotranspiration (ET) rates from 2013 to 2017 for each field. See Figure 1 for land use conversion history and site names

differences in canopy growth and development that arose due to differences in soil physical and chemical properties. For example, the soil at the CRP fields had lower bulk density, higher soil C and N content during conversion (Abraha et al., 2016) and higher pre- and post-conversion labile soil C pools (Abraha, Gelfand, et al., 2018) that likely stimulated a larger canopy growth and development (Figure S2), hence higher ET. This underscores the influence of land use legacy on the growth and development of perennial crops supplemented with little or no fertilizer. The perennials at the CRP fields also emerge a week or two earlier than those at the AGR fields, which is corroborated by a significantly higher ET rate in May at the CRP than at AGR fields of both perennial crops (Figure 7). However, corn ET_{gs} rates were similar at both the AGR and CRP fields from 2011 onwards in almost all years, suggesting that land use legacy had little influence on the corn ET_{gs} as the fields were supplemented with fertilizer to boost growth and development.

4.2 | Nongrowing season ET

Nongrowing season ET from 2010 through 2018 for all crop fields varied from 122 mm (at the AGR-Sw field in 2015, one of the coldest and wettest nongrowing seasons) to 215 mm (at the CRP-Ref field in 2017, one of the warmest and driest nongrowing seasons). The dry and warm years (2012 and 2017) had amongst the highest ET_{ngs} (but the lowest ET_{gs}) in all the fields (Table 1) demonstrating that, in this temperate, humid climate ET_{ngs} is mostly energy limited. The soil–water content in the absence of actively transpiring plants during the nongrowing season generally remains high (Figure S1).

The perennial and corn fields ET_{ngs} rates were similar in 2010 and 2011 within each land use history; however, from 2012 onwards, they were mostly lower at the perennial than at the corn fields (Figure 3c, d). With no actively growing plants, these were likely influenced by the management practises that alter the physical conditions of the soil surface and profile which in turn modify soil infiltration and heat exchange between the soil surface and the atmosphere. There was not much difference in the soil surface and physical conditions between the perennial and corn fields within each land use history in the first 2 years following conversion as the fields had been managed similarly for many years prior. However, the difference in crop types and management from 2013 onwards likely resulted in higher root biomass that add organic matter to the soil (Kong & Six, 2010; Ruess et al., 2003) improving soil structure and consequently the infiltration of precipitation (Bonin, Lal, Schmitz, & Wullschleger, 2012; Zaibon et al., 2017) into the soil through improved soil surface conditions in the perennial fields (e.g., Parish et al., 2019).

Moreover, the crop residues left on the ground could have also created a physical barrier to water vapour exchange between the soil surface and the atmosphere by shielding the soil from direct solar radiation and impeding air movement just above the surface and thus reducing soil evaporation. Although all crops except the CRP brome grass were harvested, ~35% of the stover, on average, was removed from the corn fields from 2015 onwards, exposing the ground to greater direct solar radiation and air movement that resulted in increased soil evaporation. Consequently, the differences in ET_{ngs} between the perennial and corn fields increased towards the end of the study at both AGR and CRP fields (Figure 3c, d). In agreement with our results, Suyker and Verma (2009) found increased ET_{ngs} after distributing about two thirds of the corn residues vertically along the soil profile within 0.2–0.25 m of the surface using conservation ploughing.

Most studies report ET_{gs} and disregard ET_{ngs} despite its importance in the generation of runoff and streamflow and also its impact on climate change mitigation through carbon cycling and surface energy exchange. Eichelmann et al. (2016) reported ET_{ngs} rates of 141 and 137 mm ngs^{-1} for switchgrass and continuous corn fields, respectively, in southern Ontario, Canada, with a similar climate and land use history to our AGR fields. These were similar to ET_{ngs} rates of 137 ± 5 and 151 ± 6 mm ngs^{-1} for our AGR fields for the same crop types and time period.

Nongrowing season ET rates for the CRP-Ref field were similar to those for the corn fields for most of the years, while they were higher than those for the perennial crops at the CRP fields in 4 of 9 years with similar ET_{ngs} rates in the other years. Interestingly, the years during which the CRP-Ref field had higher ET_{ngs} rates than the perennial fields were the years with the highest average nongrowing season air temperatures (Table 1; 2010, 2012, 2016 and 2017). This could be due to plants exploiting available soil water early in spring (March and April) and also during a likely second growth phase in fall (September through November; Salesman & Thomsen, 2011) under air temperatures that favour and stimulate growth of the cool-season C_3 smooth brome grass, hence increased ET, while the perennial bioenergy crops were dormant (Figure 7).

Nongrowing season ET rates for the same crop fields across land use histories were higher at the AGR than at the CRP fields in 2010 (Figure 5). This was likely because of reduced soil evaporation at the CRP fields due to the cover afforded to the ground by the partially decomposed grass residue that was left in place after killing the existing vegetation at the CRP fields during the conversion year. From 2011 onwards, the ET_{ngs} rates at the restored prairie and corn fields were remarkably similar except for a lower ET_{ngs} rates at the AGR-Pr than at the CRP-Pr field in 2012, whereas ET_{ngs} rates at the switchgrass fields were similar across land use history only in three of the years, with a lower ET_{ngs} rates at the AGR than at the CRP field in all other years except in 2011. Overall, the ET_{ngs} rates for each crop across land use histories were similar, signifying the influence of crop types and management practises in the absence of actively growing plants.

In sum, our findings demonstrate that there could be a large variation in ET_{ngs} within and between crop fields pertinent to the differences in crop type and adopted management practises, and land use history. This underscores the importance of including ET_{ngs} in ecosystem water use assessments, especially where annuals are converted to perennial systems or *vice versa*.

4.3 | Annual ET

Annual ET from 2010 through 2018 for all crops varied from 477 mm at the perennial fields during the planting year in 2010 to 725 mm at the CRP-Ref field in 2014, reflecting crop type, establishment phase of the perennial crops, and interannual climate variability in the region. There was not a clear relationship between annual precipitation and ET_t. The range in annual precipitation was wide, indicating a highly variable climate and water supply, but the range in annual ET_t was narrow in spite of the variability in annual precipitation (Table 1). Overall, ET_{ngs} contributed ~30% in corn and ~25% in the perennial fields towards ET_t.

The ET_t rates for the perennials were lower than or similar to those for corn in the first 3 years following perennial planting at both the AGR and CRP fields mainly due to lack of full establishment of the perennials. From 2013 onwards, after the perennials were established, ET_t rates for perennial crops were either less than or similar to those for corn at the AGR fields but either similar to or higher than those for corn at the CRP fields. On average, ET_t rates for perennial crops were 4–7% lower than ET_t rate for corn at the AGR fields but similar to ET_t rate for corn at the CRP fields. These results suggest that converting from large-scale corn grain to perennial bioenergy crops (or *vice versa*) in a humid temperate continental climate with well-drained soils would not strongly alter terrestrial water balances in the long term.

Field studies that directly compare ET_t for perennial and corn fields are scant. In southern Ontario, Canada, with a similar climate and land use history to our AGR fields, Eichelmann et al. (2016) found ET_t and ET_{gs} rates of 517 ± 8 mm yr^{-1} and 376 mm gs^{-1} for mature switchgrass and 611 ± 15 mm yr^{-1} and 444 mm gs^{-1} for continuous corn fields, respectively, leading them to conclude that switchgrass uses less water than corn. These were similar to ET_t and ET_{gs} rates of 531 ± 13 mm yr^{-1} and 394 ± 9 mm gs^{-1} for switchgrass and 583 ± 18 mm yr^{-1} and 433 ± 14 gs^{-1} for continuous corn, respectively, at our AGR fields for the same year. However, their comparison was based on one year of ET data and their switchgrass and corn fields were ~80 km apart albeit in similar climates. In soils with a high water table and subsurface drainage in central Illinois, Zeri et al. (2013) reported, although uncertainties were not provided, restored prairie and switchgrass ET_t rates lower than those for corn in the establishment phase (second year) but higher than those for corn in the post-establishment phase (fourth year). As ET_{gs} of the perennial crops are strongly influenced by stand age, and ET_{ngs} by crop type and management practises, ET measurements for water use comparison purposes between annual and perennial bioenergy crops should be conducted over longer time periods encompassing the pre- and post-establishment phases of the perennials, and including both the growing and nongrowing seasons.

Modelling exercises that compare ET_t of perennial and annual bioenergy crops are few but often contain conflicting findings. For example, Song et al. (2016) reported that switchgrass uses either less or similar amounts of water compared with croplands in the Upper Midwest but higher amounts of water in the Central Midwest. On the other hand, Schilling et al. (2008) for west-central Iowa and VanLoocke et al. (2012) for the Midwest US reported higher ET_t rates for switchgrass than those for corn. Findings from such modelling simulations reflect results similar to the data sets from which the model calibration and validation were performed, including sites with high water tables and subsurface drainage, indicating the need for more empirical data across the potential bioenergy growing zones to inform model simulations.

Annual ET rates at the CRP-Ref field were higher than those at the converted CRP fields (corn, restored prairie, and switchgrass) almost in all the years with patterns that are very similar to ET_{gs}. This was likely due to the longer active growth phases of smooth brome grass compared with all bioenergy crops.

Annual ET rates for the same crop across land use histories were higher at the AGR than at the CRP fields for all crops in 2010. In this year, the differences in ET_{ngs} between the AGR and CRP fields contributed 40–70% to the differences in ET_t between the AGR and CRP fields, despite ET_{ngs} being less than one third of the ET_t (Figures 4 and 5). This suggests that soil evaporation played a major role in ET_t differences between AGR and CRP fields in the early land use conversion period. From 2011 onwards, ET_t rates for the corn fields were remarkably similar at both the AGR and CRP fields. However, ET_t rates were lower at the AGR than at the CRP fields for the perennial crops for most of the study years. The differences in ET_{gs} of the perennial crops between the AGR and CRP fields contributed ~70% to the differences in ET_t of the perennial crops during this period indicating how plant water use at the AGR and CRP fields diverged as the crops continued to develop and mature.

5 | IMPLICATIONS

The substantial land area required to meet perennial cellulosic bioethanol production targets will need to come either from diversion of existing corn bioenergy systems or conversion of uncultivated lands to avoid food–fuel conflicts and indirect land use change effects (Robertson et al., 2017). Empirical evidence for the long-term impacts of such conversions on the hydrologic cycle is lacking. Our findings over 9 years of the study show that perennial bioenergy systems used 4–7% less water on an annual basis than did the corn bioenergy system they replaced (at the AGR fields); they used 14–15% less water during the nongrowing season but had similar water use during the growing season. The perennials and corn bioenergy crops grown on CRP grasslands used similar amounts of water on annual basis over the 9 years; the perennials used 5–9% more and 11–12% less water than the corn bioenergy system during the growing and nongrowing seasons, respectively. These results suggest that substituting corn grain bioenergy with perennial cellulosic bioenergy crops will not significantly alter terrestrial water balances at annual scales.

Our finding that ET_{gs}, on average over all fields, consumed ~100% of precipitation during the growing season (Table 1) shows that crops utilize all available soil water—the growing season precipitation and the soil water carried over from the previous nongrowing season. The proportion of precipitation lost as ET_{gs} was higher during drier and warmer than wetter and colder seasons. During the nongrowing season, ET_{ngs} returned, on average, ~34% of the precipitation back to the atmosphere (Table 1) suggesting that the balance recharged the groundwater and/or flowed overland (although overland flow is rarely observed at our study fields).

Our results agree with watershed water balances for the study site summarized by Hamilton et al. (2018), who estimated ET as the difference between precipitation and stream discharge and found a long-term mean of 59 ± 6% of precipitation returned to the atmosphere by ET, nearly identical to the mean of the annual data presented here in Table 1 (60%). About 78% of the streamflow in this area of well drained and highly permeable soils is baseflow generated by groundwater discharge; at the watershed scale infiltration and percolation of precipitation are significantly larger fluxes than overland flow (Hamilton et al., 2018). The balance of precipitation minus ET at our relatively level study sites can be attributed almost entirely to infiltration and percolation, as opposed to overland flow to outside the field boundaries.

The nongrowing season ET contributed 25–30% of the overall annual ET, emphasizing its importance in terrestrial water balances for effective assessment of hydrological impacts of corn versus perennial bioenergy systems. Our findings that perennial bioenergy systems during their establishment phase use less water than corn bioenergy systems, but somewhat variable to more water during the post-establishment phase, suggests that comparative studies should be conducted over multiyear periods spanning pre- and post-establishment phases of the perennials.

Our findings also show that corn and perennial bioenergy systems used 11–15% less water than the smooth brome grass fields (represented by the CRP-Ref site) they replaced. However, such conversions should be viewed from the perspective of climate change mitigation. Conversion of CRP grasslands to corn grain bioenergy systems released a large amount of GHG that are projected to take hundreds of years to repay, whereas conversion to perennial bioenergy systems provides climate benefits in fewer than 10 years after conversion (Abraha et al., 2019).

6 | CONCLUSIONS

- Annual ET rates for perennial crops were 4–7% lower than the ET rate of the corn they replaced (on former agricultural (AGR) fields) but annual ET rates of the perennials and corn on former CRP grasslands were similar over 9 years;
- Growing season ET rates for perennial crops and for the corn they replaced were similar (at AGR fields) but were 5–9% higher for the perennials than for corn at CRP fields over 9 years;
- Nongrowing season ET rates for perennial fields were 11–15% lower than those for corn fields, regardless of land use history, over 9 years;
- Annual ET rates for corn at the AGR and CRP fields were remarkably similar while annual ET rates for the perennial crops were 4–10% lower at the AGR than at the CRP fields over 9 years;
- Growing season ET rates were ~100%, and nongrowing season ET rates were ~34% of the total precipitation for the respective seasons over 9 years across all fields, with most of the nongrowing season balance likely percolating downward to recharge the groundwater;
- The nongrowing season ET accounted for 25–30% of the overall ET;
- Large-scale conversion of corn to perennial fields or *vice versa* would not significantly alter terrestrial water balances; and
- To inform decision-makers about sustainable bioenergy production, future work should focus on scaling-up land cover and land use changes (e.g., from annual to perennial crops) across a range of climatic and soil settings, integrating measurements with modelling.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available at https://doi.org/10.5061/dryad.7m0cfxpq1.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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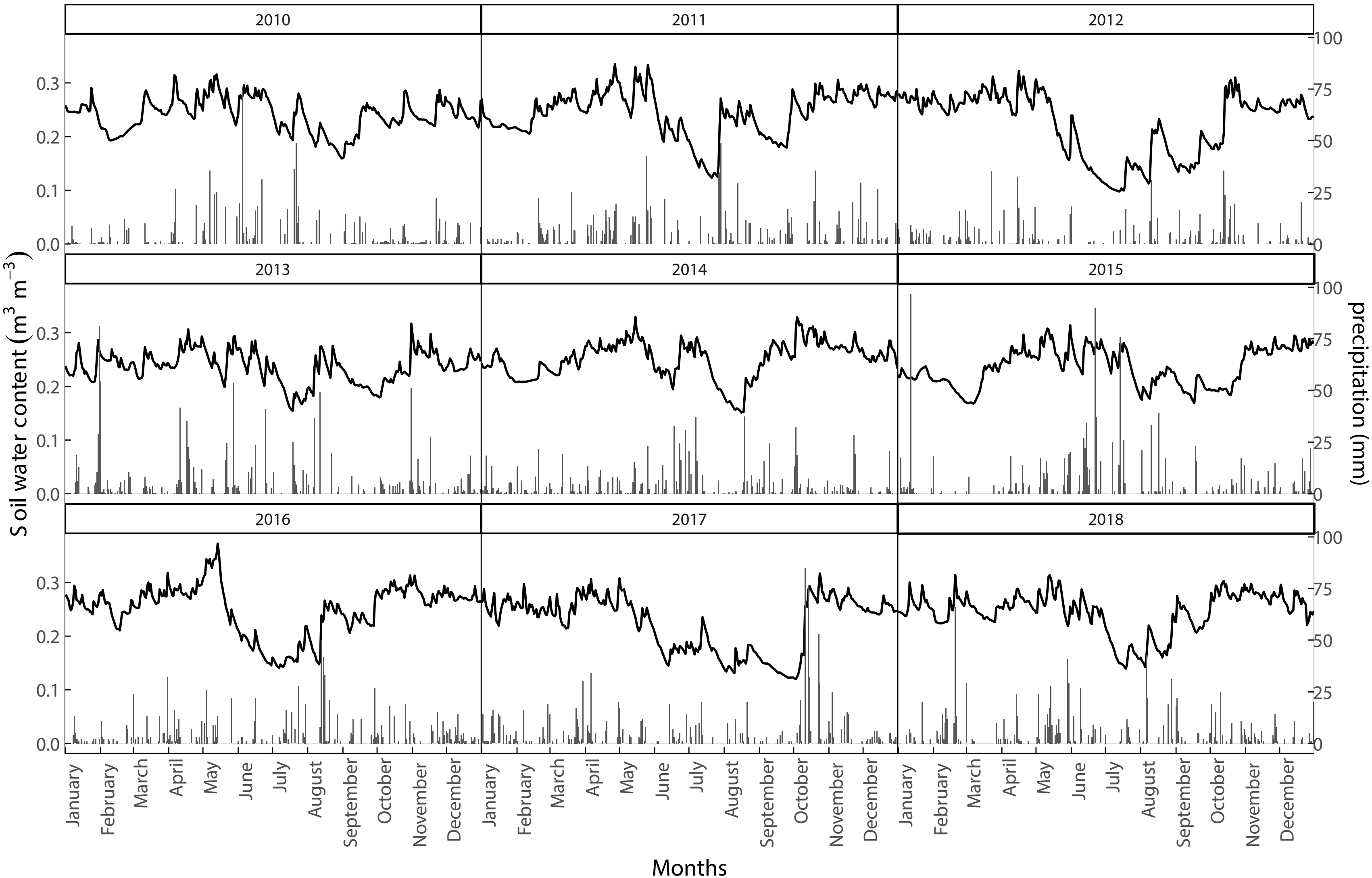
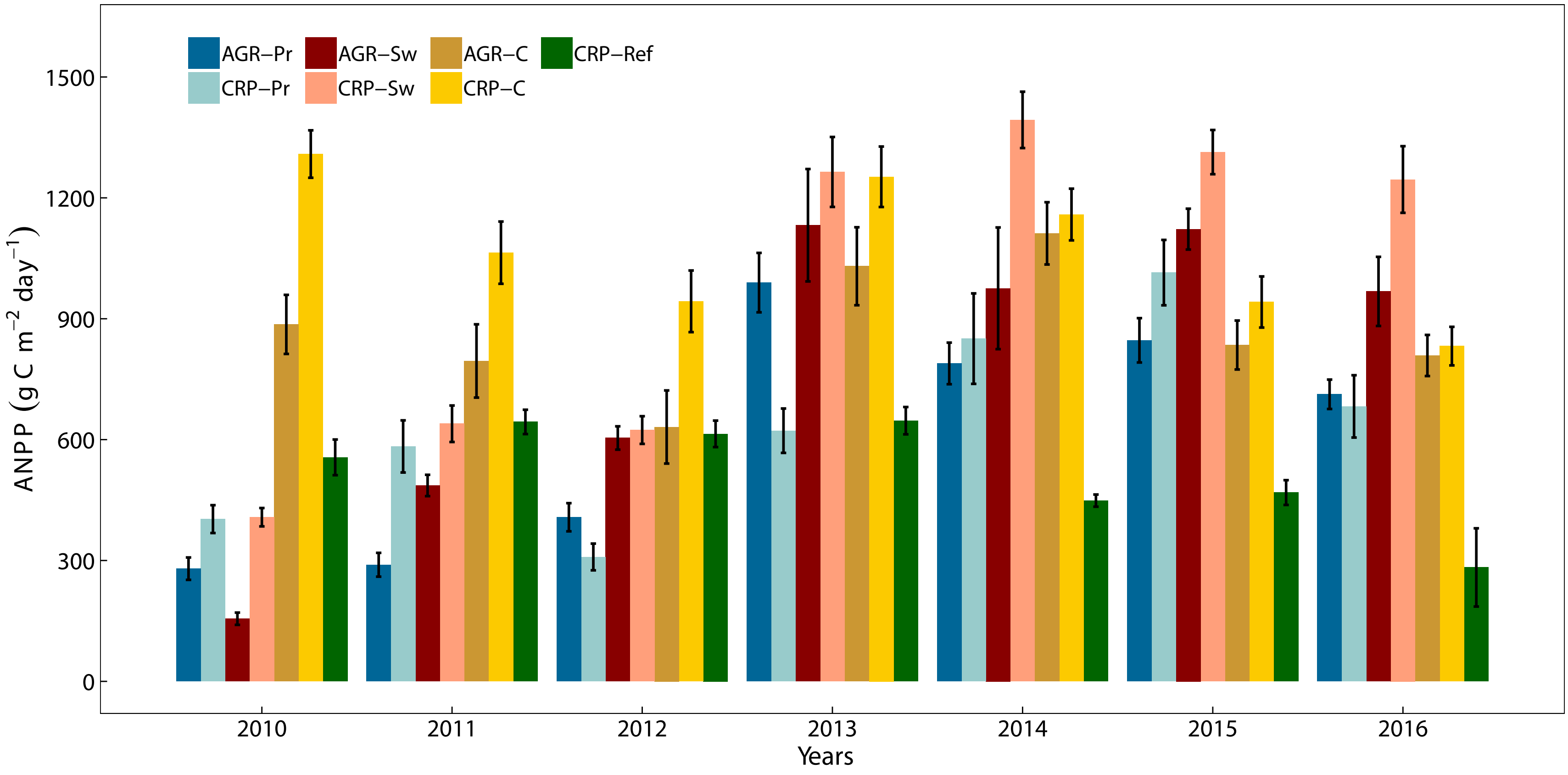


2010
2011
2012
2013
2014
2015
2016
2017
2018
Soil water content (m^3 m^{-3})
precipitation (mm)
0.0
0.1
0.2
0.3
0
25
50
75
100
January
February
March
April
May
June
July
August
September
October
November
December
Months


AGR–Pr
AGR–Sw
AGR–C
CRP–Ref
CRP–Pr
CRP–Sw
CRP–C
ANPP (g C m^{-2} day^{-1})
0
300
600
900
1200
1500
2010
2011
2012
2013
2014
2015
2016
Years