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Evapotranspiration and water use efficiency of continuous maize and maize and soybean in rotation in the upper Midwest U.S.

Mir Zaman Hussain[a,b,*], Stephen K. Hamilton[a,b,c,d], Ajay K. Bhardwaj[e], Bruno Basso[a,f], Kurt D. Thelen[b,g], G.P. Robertson[a,b,g]

[a] W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, MI, 49060, USA
[b] Great Lakes Bioenergy Research Center, Michigan State University, East Lansing, MI, 48824, USA
[c] Department of Integrative Biology, Michigan State University, East Lansing, MI, 48824, USA
[d] Cary Institute of Ecosystem Studies, Millbrook, NY, 12545,USA
[e] Central Soil Salinity Research Institute, ICAR, Karnal, 132001, India
[f] Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI, 48824, USA
[g] Department of Plant, Soil, and Microbial Sciences, Michigan State University, East Lansing, MI, 48824, USA

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ABSTRACT

This study examined evapotranspiration (ET) from no-till, rainfed maize and soybean during three growing seasons (May-Sep) of normal rainfall years (2009, 2010, 2011) and a drought year (2012) in Michigan, USA, based on daily soil water uptake measured by time-domain reflectometry at multiple depths through the root zone. During normal rainfall years, growing-season ET was similar between continuous maize (mean ± standard deviation: 471 ± 47 mm) and maize in rotation (469 ± 51 mm). During the drought year, ET decreased by only 3% for continuous maize but by 20% for maize in rotation. During the normal rainfall years, ET for soybean (453 ± 34 mm) was statistically indistinguishable from ET for maize, and was lower during the drought year (333 mm). Water use efficiency (WUE), calculated from harvest yield (grain + corn stover) and ET, was 25.3 ± 4.2 kg ha^{-1} mm^{-1} for continuous maize and 27.3 ± 3.1 kg ha^{-1} mm^{-1} for maize in rotation during the normal rainfall years, whereas WUEs for both continuous maize and maize in rotation were much lower in the 2012 drought year (14.0 and 15.5 kg ha^{-1} mm^{-1}, respectively), coincident with lower production. Soybean had a much lower WUE than maize during the three normal years (6.95 ± 0.96 kg ha^{-1} mm^{-1}) and the drought year (4.57 kg ha^{-1} mm^{-1}), also explained by lower yield. Both maize and soybean tended to use all available water in the soil profile; there was no consistent difference in ET between these crops, while yield varied markedly from year to year.

1. Introduction

The return of water to the atmosphere through evapotranspiration (ET) controls terrestrial water and energy balances (USGS, 1990; Williams et al., 2012). In vegetated landscapes, water loss by transpiration dominates annual ET (Hanson, 1991), and in temperate climates like the Midwest US, the majority of annual ET occurs during the growing season (e.g., Abraha et al., 2015). Vegetation density, species composition, and phenology are important determinants of landscape ET, yet are not well constrained for many plant communities and landscapes, and climatological models incorporating land-atmosphere interactions need more validation from ground measurements (Seneviratne et al., 2011).

The Corn Belt of the Midwest United States is the world's most expansive region of maize and soybean production with over 70 million ha of land currently under maize or soybean cultivation (USDA, 2015a). Evapotranspiration returns approximately two-thirds of precipitation to the atmosphere in this temperate climate (USGS, 1990). The ET water loss from this vast agricultural landscape strongly influences regional climate, and the surplus precipitation that is not lost to ET determines surface-groundwater exchanges, groundwater availability, and river flows.

Agricultural practices and crop varieties change over time, potentially affecting landscape ET and hence terrestrial water and energy balances in ways that are not well understood. Soybean production has become increasingly prevalent over the past five decades. In the past

* Corresponding author at: W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, MI, 49060, USA.
E-mail address: mhussai@msu.edu (M.Z. Hussain).

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decade, there has been increasing demand for ethanol production from maize grain, driving an increase in maize production in the Midwest US, including on lands formerly abandoned from agriculture (USDA, 2015b). Additionally, the fraction of cropland that is irrigated has increased to about 22 million ha in the US (Brown and Pervez, 2014), or about 18% of total US cropland of 124 million ha (NASS, 2016).

Most maize and soybean crops in the U.S. Corn Belt are grown under rainfed conditions, where soil water accumulation prior to the growing season and growing-season rainfall are the major sources of water lost through ET. Water from these sources is generally sufficient to sustain profitable crop yields, however soil water limitation reduces crop production in some years (Kucharik and Serbin, 2008; Suyker and Verma, 2009; Zeri et al., 2013), and the depletion of available soil water in occasional drought years can have devastating effects on crop yields (Lobell et al., 2014). Higher temperatures resulting from global climate change exacerbate drought stress (Kucharik and Serbin, 2008).

In this study, we investigated the ET of continuous maize and maize and soybean grown in rotations during the growing season (May-Sep) in years of normal rainfall (2009, 2010 and 2011) and a severe drought year (2012). The main objectives of the study were to determine the crop water use of maize and soybean, to examine whether water use by continuous maize is different than water use by maize in rotation with soybean or a small grain crop, and to show the influence of a severe growing-season drought on water use in these cropping systems.

2. Materials and methods

This study was conducted in southwest Michigan, USA, which is in the northeastern part of the Corn Belt region. The experimental site at the W. K. Kellogg Biological Station (KBS) (42.3956 °N, 85.3749 °W and 288 m above sea level) is part of the Great Lakes Bioenergy Research Center (www.glbrc.org) at the KBS Long Term Ecological Research site (www.lter.kbs.msu.edu). Soils are Typic Hapludalfs developed since the last glaciation under forest growing on glacial outwash (Robertson and Hamilton, 2015), and are well-drained sandy loams (Table S4). There is no significant overland flow from the study sites because of the relatively level topography and permeable soils. The water table is approximately 12–15 m below the surface. The climate of this region is humid temperate with a mean annual air temperature of 10.1 °C and annual precipitation of 1005 mm, 511 mm of which falls from May to September (1981– 2010) and about half of which falls as snow in the winter (National Climate Data Center, 2013). The controls on ET in this region tend to shift seasonally between energy limitation during the cool season and water limitation during at least part of the growing season (McVicar et al., 2012).

Soil water content was monitored between 2009 and 2012 in experimental plots (28 x 40 m) established in 2008 on land previously used for row crop agriculture for many decades. Details on experimental design are found in Hamilton et al. (2015), Sanford et al. (2016), and at http://data.sustainability.glbrc.org/. The cropping systems studied here are continuous maize and maize in rotation with either soybean or soybean and canola (Table S1). Every rotation phase was present every year. Evapotranspiration estimates for the continuous maize treatment between 2010 and 2012 were reported in Hamilton et al. (2015), who compared the ET of maize to that of adjacent perennial grasslands and poplar tree plantations.

Cropping systems over the four years of the study included continuous maize (*Zea mays* L.) and rotations of Soybean (*Glycine max* L.)-canola (*Brassica napus* L.)-Maize-Maize (ScMM), canola-Maize-Soybean-Maize (cMSM) and Maize-Soybean-canola-Soybean (MScS). Information on crop varieties and planting densities is included in Table S1. We do not analyze data for canola here because it was an experimental crop that performed poorly and is not normally grown in this region. Our experimental design allowed us to compare continuous maize to maize in rotation in each of the four years. All crops were grown without tillage (i.e., no-till) and without irrigation. In each year,

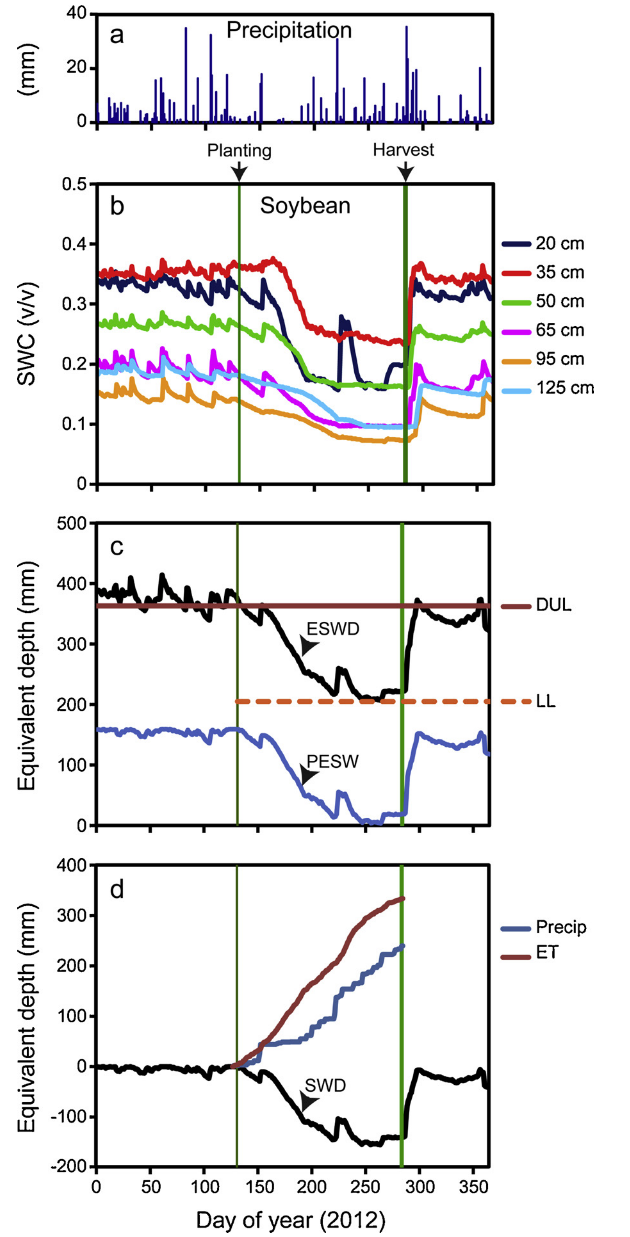

Fig. 1. Example of soil water data for soybean in the maize-soybean-canola-soybean (MScS) rotation treatment in 2012, showing (a) precipitation, (b) daily soil water content from TDR probes (0–10 cm data not shown), (c) equivalent soil water depth (ESWD) in relation to the drained upper limit (DUL) and lower limit (LL) and plant extractable soil water (PESW), and (d) the cumulative crop evapotranspiration (ET) and precipitation (Precip) in relation to the soil water deficit (SWD).

nitrogen was added to maize at 170 kg N ha^{-1} in three splits, one split prior to planting as ammonium sulphate, a second split during planting as liquid N + P fertilizer (N:P:K 19:17:0), and a third split one month after planting as urea ammonium nitrate, while soybean received no N fertilizer. Maize received 13 and 112 kg ha^{-1} of phosphate and potash fertilizers, respectively; while soybean received 45-50 kg ha^{-1} of potash and no phosphorus. As is typical of the region, maize was usually planted in the first week of May while soybean was planted in the second or third week of May. Harvest timing depended on the weather and year; maize was harvested between mid-October and mid-November, and soybean during mid-October (Table S1). The length of the growing season (planting to harvest) varied between 160 and 190 days for maize and 140 and 170 days for soybean (Table S1). Weed control was provided by glyphosate (2.5 quarts ha $^{-1}$) and 2,4-D ester (2.5 pints ha^{-1}) as per regional practice.

Soil water content was measured hourly using TDR probes installed in 2008 at depths of 20, 35, 50, 65, 90 and 125 cm (Fig. 1). Each of these probes was inserted horizontally and a seventh probe was inserted vertically from 0 to 10 cm. Measurement depths were chosen based on knowledge of soil horizons and root distributions of the cropping systems. Probes were two-wire stainless steel rods of 4 mm diameter that were 30 cm long and 4 cm apart. Prior to installation, probes were calibrated with soil of the site adjusted to a range of volumetric soil water contents from 0 to 40 percent. A polynomial calibration equation (Topp et al., 1980) was fit to the probe responses to different soil water contents; most probes were accurate to 1% before calibration. After calibration, the horizontal probes were installed from a pit dug 1.5 m into the plot from its edge and then refilled. Probes were connected to a Campbell Scientific TDR 100 and SDXM50 multiplexer. Data handling entailed initial screening of soil water content for spurious values outside reasonable ranges of 0.05 to 0.5, followed by calculation of a 13-point running mean. After screening, there were occasional gaps of not more than a few days that were filled by linear interpolation.

Crop ET was estimated based on soil water drawdown as measured by TDR during the growing season. The soil strata were delineated by the midpoints between probe measurement depths. Water use on days when there was no decrease in soil water content due to replenishment by rainfall was estimated using the SALUS model, which is well-calibrated for these soils (Basso and Ritchie, 2015); SALUS estimates ET from meteorological variables, crop phenology (including leaf area index for canopy development; see below), plot-specific soil characteristics (soil water content, texture, bulk density, organic matter, drained upper limit of soil water content, lower limit of plant-extractable soil water) and crop-specific management (nitrogen fertilization, yield, dates for planting and harvest). SALUS was run with soil strata centered around each TDR probe depth, except that 0–10 cm was subdivided into 0–2 cm and 2–10 cm depths. Approximately 20–35% of the growing-season days had no detectable daily decrease in soil water content because of infiltration of new rainfall, and hence SALUS was used to estimate ET on those days (Table S2).

For the calculation of total water content in the soil profile, the measured soil water content was first multiplied by soil stratum depth to yield the equivalent soil water depth (ESWD) for each stratum, and the sum of all strata provided total ESWD (Fig. 1). The drained upper limit (DUL) of the soil profile, which is the maximum amount of water that can be held against drainage, was estimated at each measurement site from the soil water content in the 30 days preceding the planting of the crop, when infiltration over the winter had fully replenished soil water to > 150 cm depth. Daily decreases in the ESWD when soil water content was below the DUL were ascribed to crop ET. The lower limit (LL) of plant-extractable soil water was estimated from the lowest observed soil water content over the four years. The DUL and LL were estimated separately for each stratum and summed for the 0–150 cm soil profile. Plant-extractable soil water (PESW) at any particular time was estimated as the difference between the DUL and LL, and the soil water deficit (SWD) for the soil profile was estimated as ESWD minus the DUL (thus SWD becomes more negative as water is removed from the soil).

The leaf area index (LAI), which is used in the SALUS model to indicate crop canopy development, was measured biweekly during the period of active canopy development using an LAI-2000 plant canopy analyzer (Li-COR, Nebraska, USA). Measurements (4 locations per plot) were made in diffuse light at dawn at the soil surface.

Grain was harvested using production-level agricultural equipment to estimate yield. Maize stover was collected shortly after grain harvest using a standard round-baler (2008-10) or a flail-chopper/forage-wagon combination (2011-12), leaving ~10 cm of residual stubble height. About 15% of maize residue was harvested annually. Grain and biomass yields are expressed as dry matter.

The standing biomass of each main crop was harvested within quadrats near to the seasonal maximum in late summer to estimate aboveground net primary production (ANPP). Collected biomass was separated into seed biomass and vegetative biomass and any weeds were added to the vegetative biomass. Surface litter from the previous year's crop was not included in the ANPP sampling.

Water use efficiency (WUE) was determined in two ways. WUE-Yield is based on harvest yields of grain and, in the case of maize, stover, dividing the yield as dry matter by the amount of water lost by ET from planting to the date of harvest. WUE-ANPP is based on maximum standing biomass (ANPP), dividing ANPP by growing-season ET from planting to the date of peak biomass when ANPP was measured. We present WUE in units of kg ha^{-1} mm^{-1} to facilitate comparison with precipitation and evapotranspiration, which are presented in mm. Multiplication by 0.1 converts these WUE units to kg m^{-3}.

Statistical analyses were performed in SigmaPlot 11.0 software. Variance is given as the standard deviation of the mean, and statistical comparisons are considered significant at $\alpha = 0.05$. ET rates of maize under different systems (continuous vs. rotation) and of maize vs. soybean were compared by one-way analysis of variance (ANOVA).

3. Results

3.1. Air temperature and rainfall

Air temperature during the growing season (May-September, inclusive) in the years of normal rainfall (2009–2011) averaged 19.0 °C, which was close to the long-term growing season average (1988 – 2013: 18.7 °C); however mean air temperature was warmer by 1.0 °C in the drought year (2012). Growing-season degree-day accumulations (10 °C base) were 1194, 1543, 1378, and 1465 for the years 2009, 2010, 2011 and 2012, respectively (data not shown). The lower degree-day accumulation in 2009 is due to relatively cool weather in June and July.

Rainfall totals during the growing season were near and above normal in 2010 and 2011, respectively (the long-term growing season mean measured at KBS for 1981–2010 is 511 mm), while 2009 and 2012 were lower (Fig. 2a). Some monthly rainfall totals deviated considerably from the long-term means in every year (Fig. S1). In 2011, 117 of the 555 mm fell in just four days in July. The growing-season rainfall total was 30% lower in 2009 (360 mm) than the long-term mean, due particularly to a deficit in July, and the total rainfall in 2012 was 48% of the long-term mean (Fig. S1). Because of the early season rainfall deficit in 2012, crop yields were severely reduced as compared to the other study years (2009–2011) and to the longer-term mean for the region (Sanford et al., 2016).

3.2. Soil water content and evapotranspiration

Prior to the growing season in each year, infiltration of winter and spring precipitation had recharged water in the soil profile (0–150 cm) to its DUL, as shown in the data in Figs. 1 and S2. The mean DUL observed over the four years was higher for continuous maize plot (415 mm) than for the rotational maize plots (386, 320 and 358 mm for ScMM, cMSM, and MScS rotational treatments, respectively). There are no obvious differences in soil texture among the plots that would explain these differences (data not shown). After planting, soil water drawdown by ET was observed throughout the growing season, albeit punctuated by occasional soil water recharge into part or all of the profile by rain events (e.g., Fig. 1b).

The greatest soil water drawdown observed over the four years in each plot served to indicate the lower limit (LL) of plant-extractable soil water (PESW), which for soils well beneath the surface is a function of soil texture and crop root distribution (e.g., Fig. 1c). The difference between the mean DUL and the LL (i.e., the maximum PESW once the soils are drained) over the 4 years was 186 mm for continuous maize, whereas it was 218, 135, and 155 mm for the ScMM, cMSM, and MScS

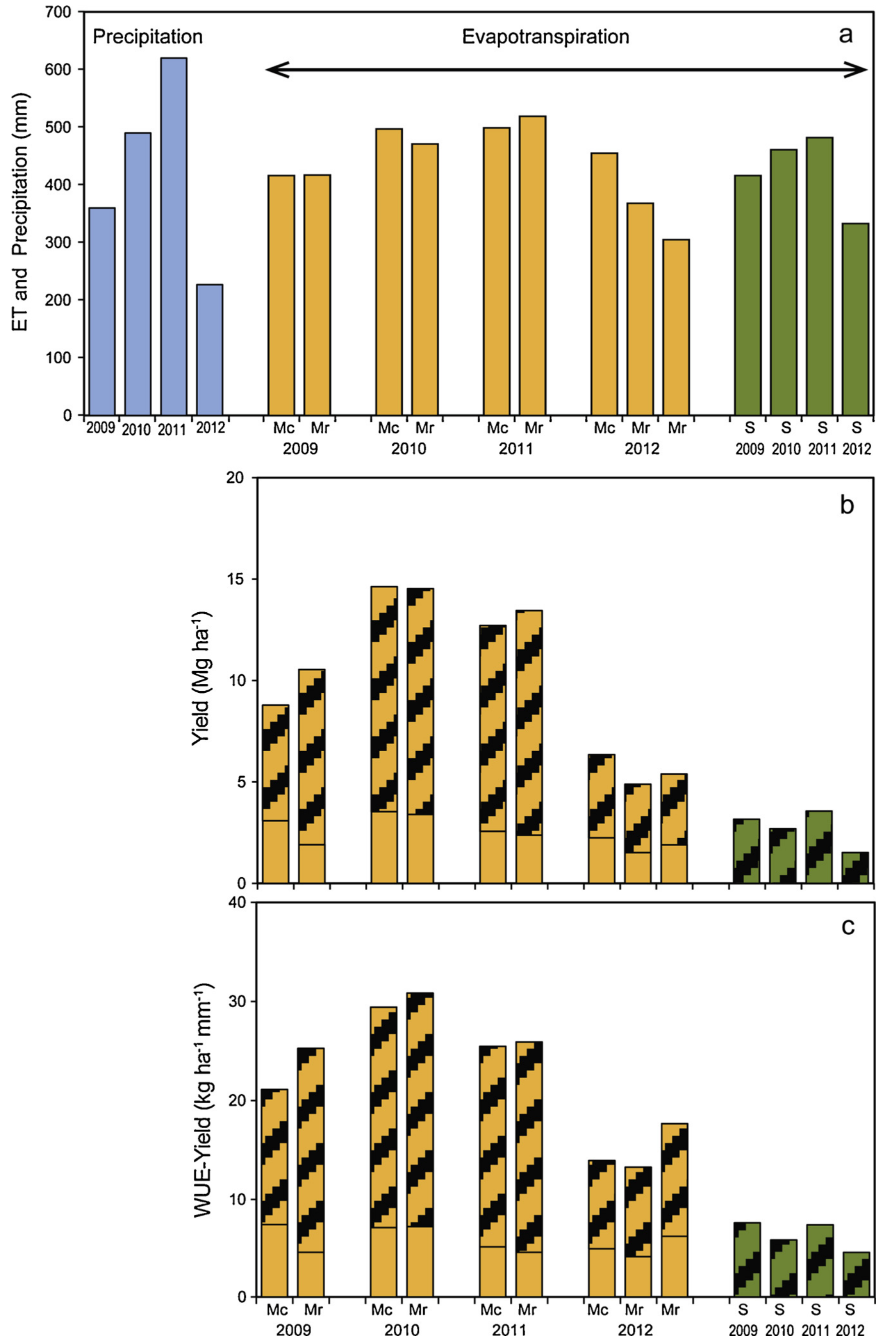

Fig. 2. (a) Precipitation (May-Sep) and crop evapotranspiration (ET) across the four years of measurement (2009–2012), (b) harvest yield of grain and stover (dry matter basis), and (c) water use efficiency based on harvest yield (WUE-Yield). M = maize (gold bars; Mc = continuous maize, Mr = maize in rotation), S = soybean (green bars). Cross-hatching shows fractions of yield and WUE attributed to grain only.

treatments, respectively (Fig. S3).

Over the 2009–2011 growing seasons, the ET of continuous maize (mean, 471 ± 47 mm) was similar to the ET of maize in rotation (mean, 469 ± 51 mm) (Figs. 2a and 3), and hence there was no detectable rotation effect on ET for maize in years of normal water availability. Over those same years, the mean ET of soybean (453 ± 34 mm) was not statistically distinguishable from that of maize ($p = 0.67$). Year-by-year comparison of maize and soybean ET also leads to the conclusion that these crops had similar ET (Fig. 4).

During the drought year of 2012 we observed only a 3% decrease in ET for continuous maize (455 mm for 2012 vs. 471 mm for 2009–2011) but a 20% mean decrease in ET for maize in the two rotations (368 and 305 mm for 2012 vs. 469 mm for 2009–2011) (Figs. 2a and 3). Soybean also had a lower ET during the drought year (333 mm for 2012 vs. 453 mm for 2009–2011) (Fig. 2a), and the 2012 soybean ET was 11% lower than the mean for maize (continuous and rotational) in 2012 (Fig. 4).

3.3. Canopy development

The maximum LAI attained during the crop growing season was variable across years, ranging from 2.2 to 4.8 for maize and 2.7–6.2 for soybean. Maximum LAI for both crops was lower in the drought year of 2012 than the other years, and the daily LAI and ET were significantly correlated ($p < 0.05$) for both cropping systems, albeit with considerable variability (Fig. S4). Continuous maize and maize in rotation

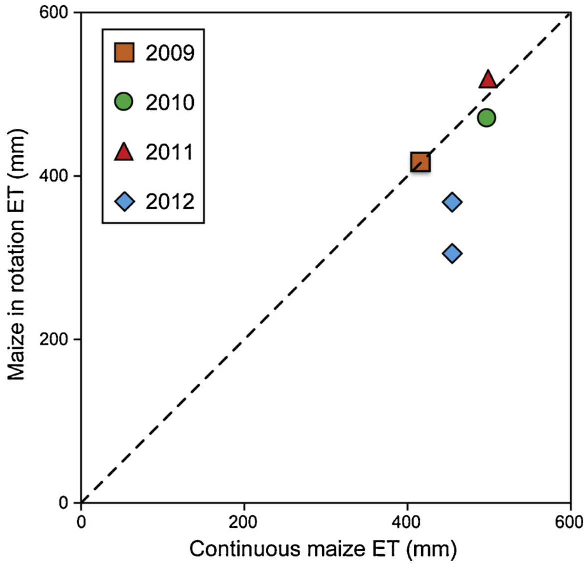

Fig. 3. Growing-season evapotranspiration (ET) compared for each year between continuous maize and maize in rotation. In 2012 maize in rotation was planted in two different plots. The dashed line is the 1:1 line.

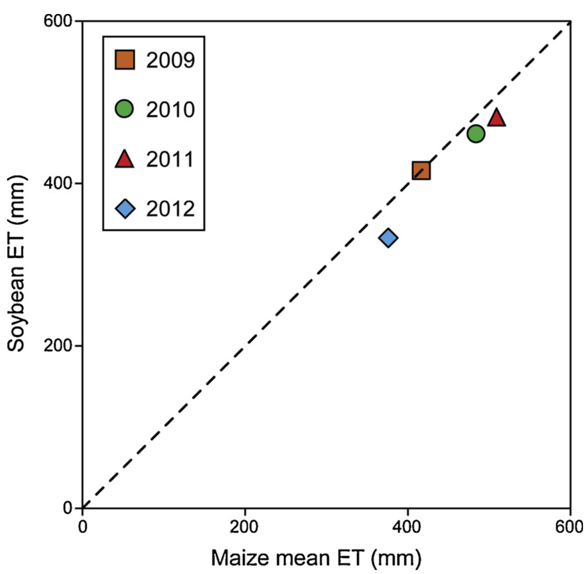

Fig. 4. Year-by-year comparison of the mean growing-season evapotranspiration (ET) of maize (continuous and rotational) and soybean.

similarly had lower LAI values in 2012. Maximum LAI generally occurred in late July or early August.

3.4. Yield and biomass production

During 2009–2011, average grain harvest yields were 9.0 ± 2.9 Mg ha^{-1} for continuous maize and 10.3 ± 1.4 Mg ha^{-1} for maize in rotation (Fig. 2b). As expected, harvested stover yield, which was ˜40% of the total aboveground biomass (Sanford et al., 2017), was almost three times lower than grain yield and was similar in both continuous maize (3.07 ± 0.49 Mg ha^{-1}) and maize in rotation (2.56 ± 0.76 Mg ha^{-1}). The 2012 drought significantly reduced grain yield in continuous maize (4.10 Mg ha^{-1}) and maize in rotation (3.43 Mg ha^{-1}) compared to normal years. Soybean grain yield was 3.14 ± 0.44 Mg ha^{-1} in 2009–2011 and 1.52 Mg ha^{-1} in 2012 (Fig. 2b).

ANPP, measured as maximum standing biomass, was not consistently different between continuous maize (mean, 22.1 ± 3.4 Mg ha^{-1}) and maize in rotation (mean, 22.2 ± 1.8 Mg ha^{-1}) during the years of normal rainfall (2009–2011) (Fig. S5a). In 2012, ANPP was substantially reduced for both continuous maize (11.2 Mg ha^{-1}) and maize in the two rotational treatments (mean, 9.51 Mg ha^{-1}). In contrast, there was a smaller (13%) reduction in soybean ANPP in 2012 (5.33 Mg ha^{-1}).

3.5. Water use efficiency

WUE-Yield, calculated as the ratio of harvested biomass to cumulative ET, differed significantly among treatments and years, with variation explained mainly by yield rather than ET (Fig. 2c). During 2009–2011, WUE-Yield (harvested grain plus stover) in continuous maize (25.3 ± 4.2 kg ha^{-1} mm^{-1}) was similar to that of maize in rotation (27.1 ± 3.1 kg ha^{-1} mm^{-1}). Compared to 2009–2011, the WUE-Yield of continuous maize and maize in rotation in the 2012 drought year was much lower (13.9 and 15.5 kg ha^{-1} mm^{-1}, respectively). The WUE-Yield of soybean (grain only) was lower than maize (grain + stover) in both normal (2009–2011: 6.95 ± 0.96 kg ha^{-1} mm^{-1}) and drought (2012: 4.57 kg ha^{-1} mm^{-1}) years.

WUE-ANPP, calculated as the ratio of ANPP to the cumulative ET up to the date of ANPP sampling, was also similar during 2009–2011 between continuous maize (50.3 ± 9.2 kg ha^{-1} mm^{-1}) and maize in rotation (50.7 ± 8.0 kg ha^{-1} mm^{-1}) (Fig. S4b). Compared to 2009–2011, WUE-ANPP of both continuous maize and maize in rotation was much lower in the 2012 drought year (29.4 and 33.6 kg ha^{-1} mm^{-1}, respectively). WUE-ANPP of soybean was much lower than that of maize and was similar for both the three normal years (mean, 18.7 ± 5.1 kg ha^{-1} mm^{-1}) and the drought year (18.3 kg ha^{-1} mm^{-1}) (Fig. S5b). As with WUE-Yield, variation in ANPP rather than ET explains most of the variation in WUE-ANPP, which was always higher than WUE-Yield because ANPP exceeded yields.

4. Discussion

4.1. Evapotranspiration under normal water availability

Maize and soybean had similar growing-season ET over the three study years of normal water availability (Figs. 2a and 4). The ET estimates in this study are comparable with those reported for rainfed maize and soybean grown elsewhere (Schneekloth et al., 1991; Bernacchi et al., 2007; Li et al., 2008; Suyker and Verma, 2009; Barbieri et al., 2012; Abraha et al., 2015; Irmak and Djaman, 2016; see Table S3), although these other studies used different methodologies to estimate ET, some had supplemental irrigation, and others had high water tables and subsurface drainage. While some other studies have reported that rainfed soybean has lower ET than rainfed maize (e.g. Suyker and Verma, 2009), we found similar ET in soybean and maize (Fig. 4). WUE-ANPP and WUE-Yield, on the other hand, were much lower for soybean than for maize because of the lower ANPP and grain yield of soybean (Figs. 2c and S5). The WUE-Yield values observed in our study are comparable to those reported by Suyker and Verma (2009) for rainfed continuous maize and maize-soybean rotations in Nebraska, USA.

4.2. Lack of evidence for a rotation effect on ET in maize

Based on comparisons of continuous maize to maize grown in rotation with soybean and canola, we found no evidence for a rotation effect on maize ET in years of normal rainfall (Figs. 2 and 3). These results contrast with the positive effect on yield and water use that has often been reported in maize-soybean crop rotations compared to continuous crops (Copeland et al., 1993). Enhanced water acquisition (maize) or water use efficiency (soybean) are but two of a wide variety of hypotheses suggested to explain the rotation effect, which exists in many cropping systems, and it is possible that different combinations of mechanisms explain the effect in different settings (Anderson, 2005).

The cropping systems we studied, which were established in 2008, may not have been in place long enough to create a continuous maize yield penalty (Anderson, 2005) or we may simply lack the statistical power to detect a difference in the face of spatial and inter-annual variation.

4.3. Effects of a strong growing-season drought

Drought conditions in 2012, with growing season rainfall 44% of normal, resulted in the drawdown of soil water content to approach the lower limit of plant-extractable soil water (e.g. Fig. 1). However, despite reaching the point of severe water limitation early in the growing season, the growing-season ET for continuous maize was somewhat similar to that over the preceding three years of normal water availability (Fig. 2a). In contrast, maize in rotation and soybean displayed markedly lower ET in the drought year. This difference between ET for continuous maize vs. maize in rotation in the drought year was not apparent in the maximum LAI values attained by these crops, which were very similar and lower than in previous years (Fig. S4). It is possible that maize in rotation with soybeans had a reduced amount of crop residues on the soil surface from the previous crop (soybeans have less persistent residue), leaving the surficial soil more directly exposed to soil evaporation early in the year. Another explanation could be the lower DUL of this treatment compared to the DUL of continuous maize plots (Fig. S3), which corresponds with a lower soil water availability for evapotranspiration that became important in the drought year.

5. Conclusion and implications

Our results show that during years of normal water availability continuous maize, maize in rotation, and soybean crops have similar ET over the growing season. Thus, changes in the proportions of cropland area devoted to these three crops should not greatly affect landscape water balances. During the drought year (2012), ET was lower in soybean and in maize in rotation, but not lower in continuous maize.

The ET results reported here for annual crops resemble those reported earlier by Hamilton et al. (2015), who compared the same continuous maize treatment reported in this study with nearby perennial biofuel cropping systems over 2009-12 and found no consistent differences. Over the four years in that study, which included the 2012 drought year, the mean growing-season ET of the perennial cropping systems investigated—including switchgrass, Miscanthus, mixed grasses, a restored prairie, a fallow field, and a hybrid poplar plantation—ranged from 458 to 573 mm while ET for continuous maize was 496 mm.

Maximum crop biomass (ANPP) and harvest yields were more variable, resulting in different water use efficiencies. As found in our previous studies of perennial biofuel crops (Hamilton et al., 2015; Abraha et al., 2015), in this setting annual maize and soybean crops tend to use all available soil water during their growing seasons, and that water originates from the combination of soil water storage in the profile at the start of the growing season plus new rainfall afterwards. Growth and yield were not closely coupled to total water use except in the 2012 drought year when water availability was severely limiting. Nonetheless, water limitation was likely at least during some point in the growing season, and the timing of water limitation can be important with respect to crop phenology.

Our findings should apply to much of the US Corn Belt, and perhaps to other humid regions where these crops are grown. Maize and soybean represent most of the cropland acreage in the US Corn Belt, where crops are predominantly rainfed. No-till or strip-till management is practiced at least in some years on at least half of the cropland in this region (Horowitz et al., 2010), and adoption of these practices is expected to grow (Wade et al., 2015). Brazil, Canada, Australia, and Argentina also have large amounts of cropland managed with no-till (UNEP, 2013).

The soils in this study represent well-drained loams with the water table far below the soil surface, and thus they are not representative of fields that are so poorly drained that they require subsurface tile drainage; although drainage is common in parts of the US Corn Belt, the majority of cropland is not drained (Sugg, 2007). In spite of their tile drainage, drained farmland often has high water tables that might provide crops with more access to water. The results of this study suggest that in well-drained soils without access to water from irrigation or high water tables, ET is remarkably similar among crops during years of normal water availability.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2019.02.049.

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Supplementary figures

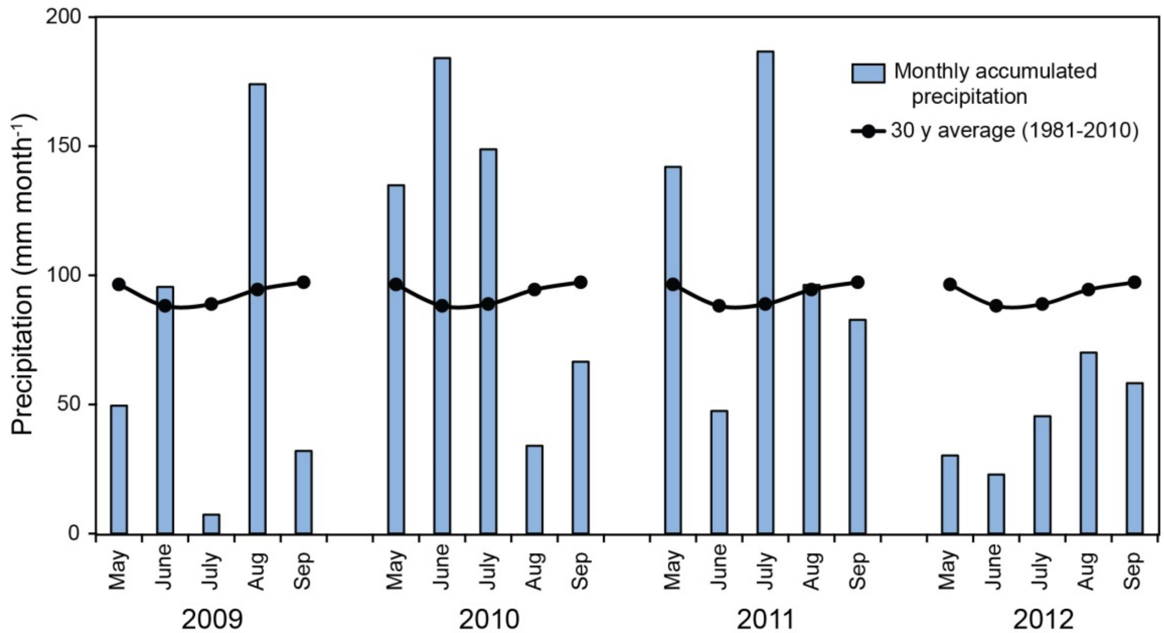

Fig. S1 Monthly precipitation measured at KBS over the four growing seasons (May-Sep) compared with 30-year precipitation averages (1981-2010) for the KBS region (Climate Division 8 from the National Climate Data Center 2013).

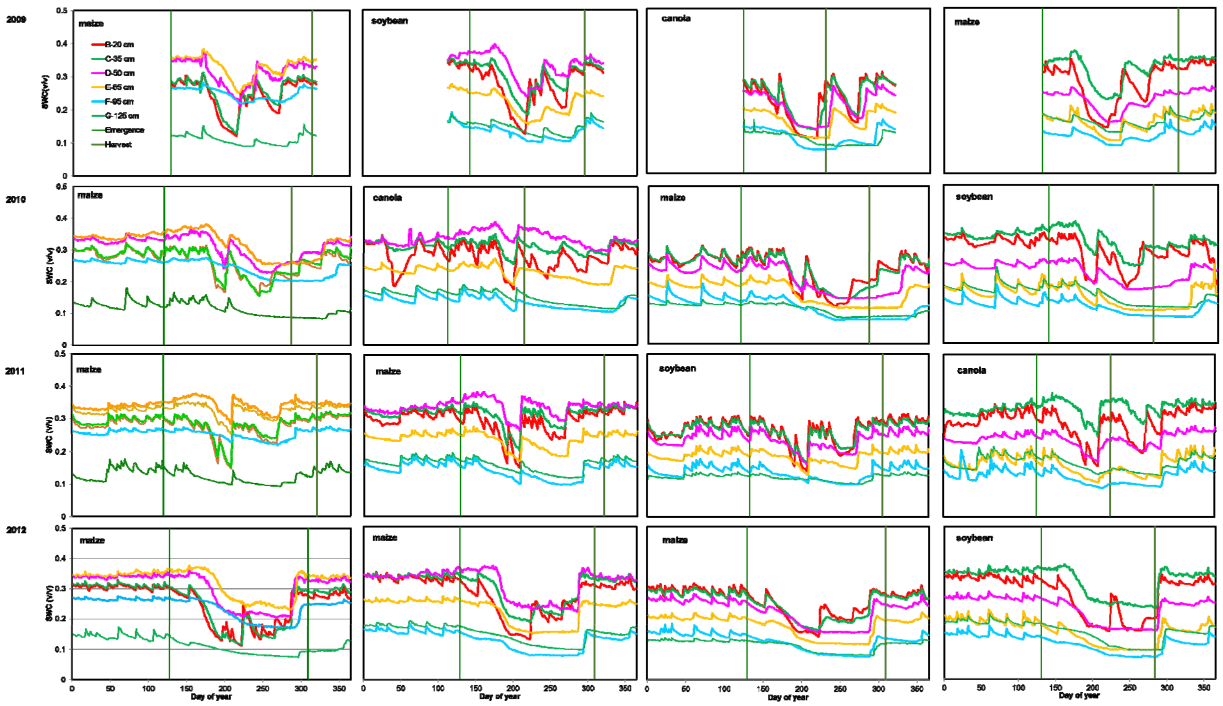

Fig. S2 Soil moisture content (v/v) of each cropping system across the four growing seasons, which are delineated by the vertical green lines. Data for canola were not analyzed in this study.

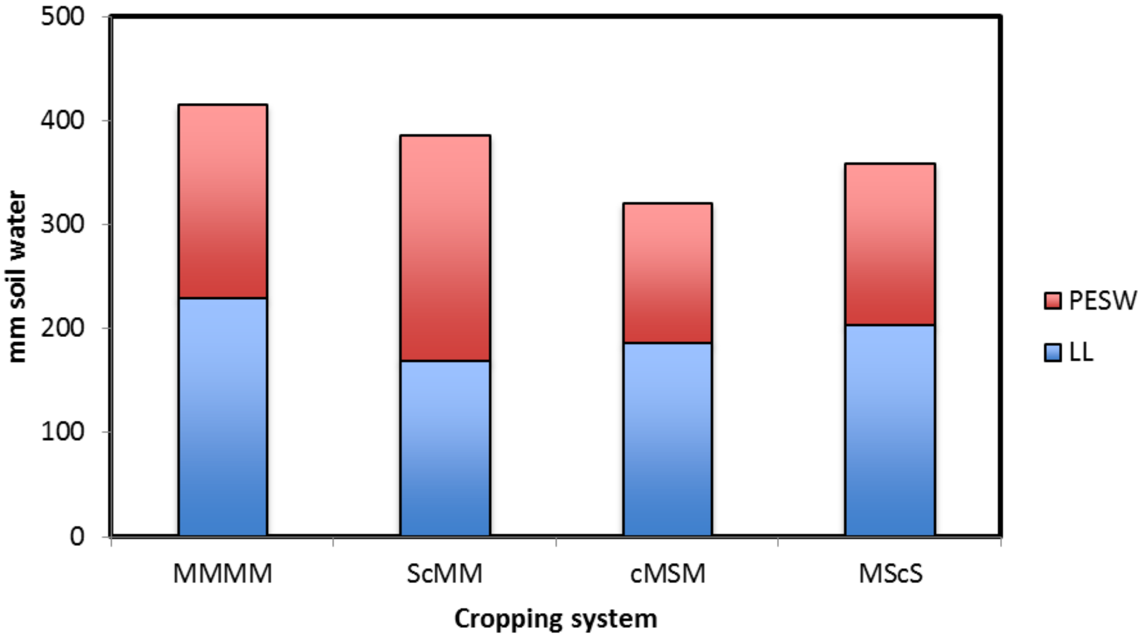

Fig. S3 Drained upper limit (DUL; means for 2009-2012) partitioned into the lower limit of plant-extractable soil water (LL; based on the lowest soil water content observed over the four years) and the plant-extractable soil water (PESW; estimated as DUL – LL) for each of the four plots in which soil water content was measured. The cropping systems in each plot were MMMM = continuous maize, ScMM = Soybean-canola-Maize-Maize, cMSM = canola-Maize-Soybean-Maize, and MScS = Maize-Soybean-canola-Soybean. Maize and soybean years were included in the calculation of means but canola years were not.

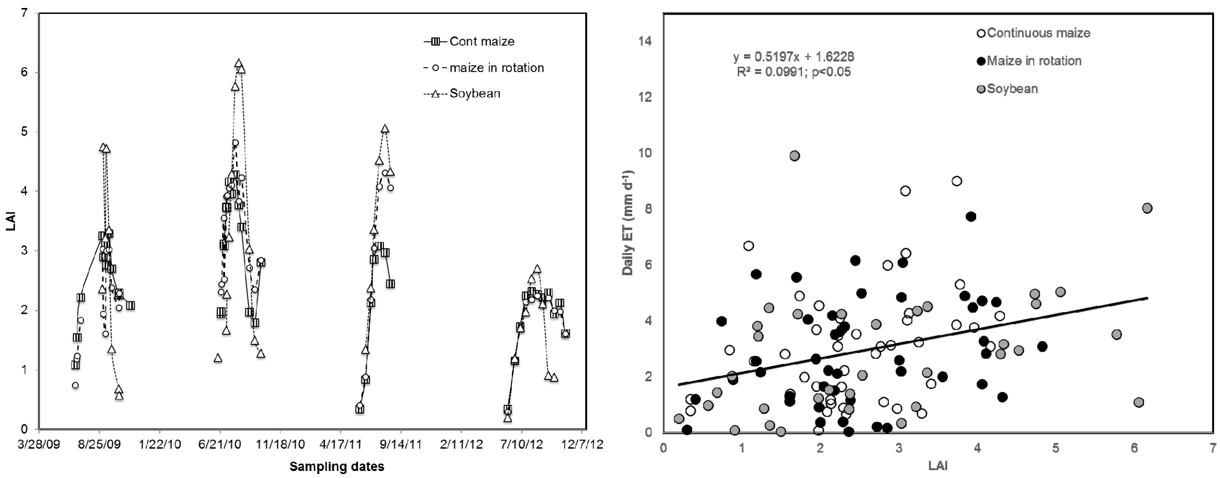

Fig. S4 Daily leaf area index (LAI) of continuous maize, maize in rotation and soybean during each growing season (left panel), and the correlation between daily LAI and the corresponding daily ET of these crops (right panel).

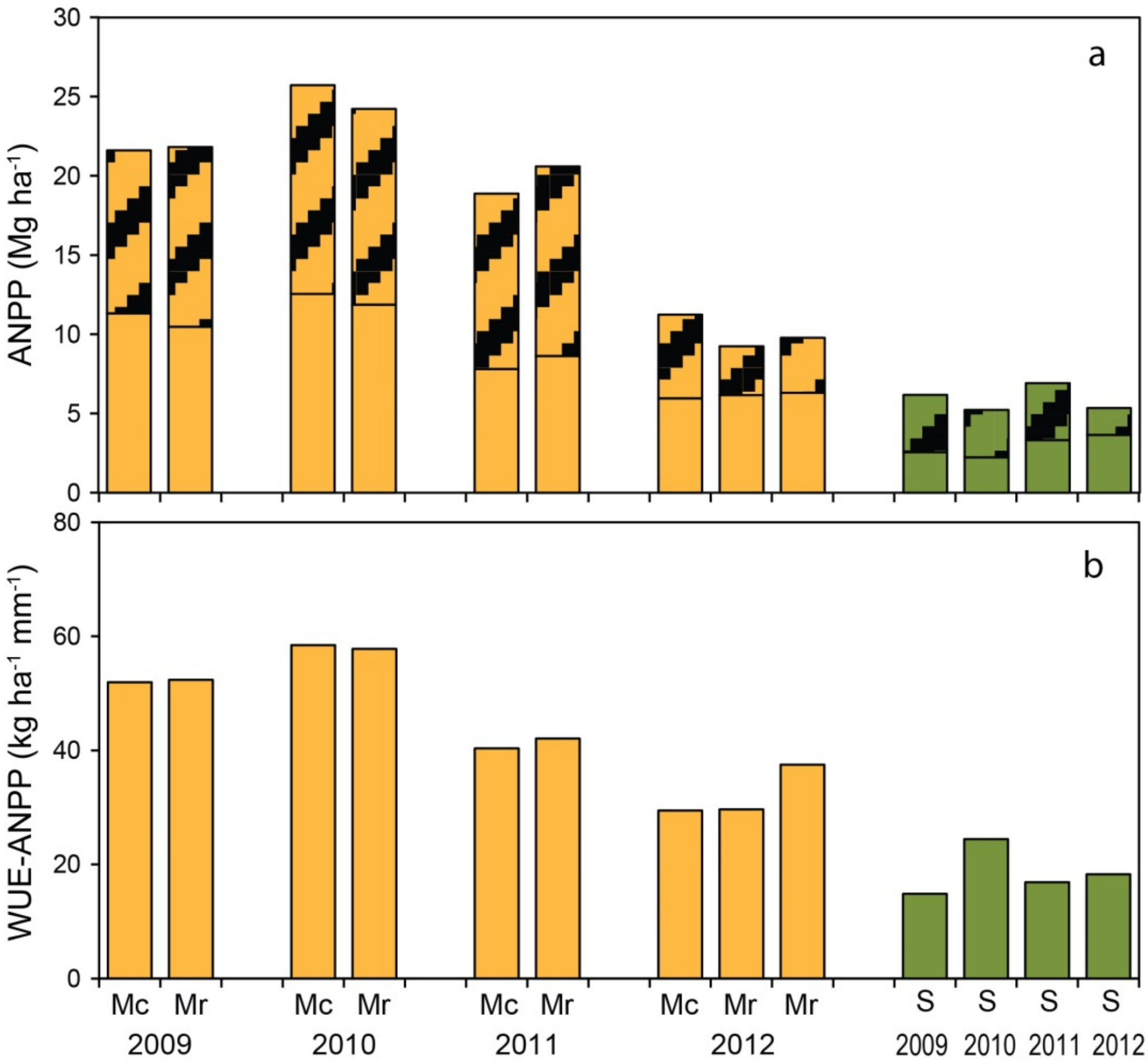

Fig. S5 (a) Aboveground net primary production (ANPP) (cross-hatching shows fraction in grain biomass) and (b) water use efficiency based on total ANPP (WUE-ANPP) for each cropping system across the four years of measurement (2009-2012). M = maize (gold bars; Mc = continuous maize, Mr = maize in rotation), S = soybean (green bars).

Supplementary tables

Table S1 Planting and harvest dates (in days of year) and growing-season lengths (days) for each cropping system. Crop varieties and planting densities were Pioneer 92Y30 (72,843 seeds ha^{-1}) for soybean and Dekalb DKC52-59 (11,735 seeds ha^{-1}) for most of the maize plantings, except that the Dekalb DKC48-12RIB corn hybrid (12,221 seeds ha^{-1}) was planted in the ScMM and cMSM treatments in 2012.

Year	Cropping system	Crops	Planting	Harvest	Days
	Continuous maize				
2009		Maize	129	315	186
2010		Maize	120	287	167
2011		Maize	129	321	192
2012		Maize	128	309	181
	Soybean-canola-maize-maize rotation (ScMM)				
2009		Soybean	142	295	153
2010		Canola	--	--	--
2011		Maize	129	321	192
2012		Maize	129	309	180
	Canola-maize-soybean-maize rotation (cMSM)				
2009		Canola	--	--	--
2010		Maize	120	287	167
2011		Soybean	133	306	173
2012		Maize	129	309	180
	Maize-soybean-canola-soybean rotation (MScS)				
2009		Maize	132	315	183
2010		Soybean	140	279	139
2011		Canola	--	--	--
2012		Soybean	131	284	153

Table S2 Percent of growing-season days when the SALUS model was used to estimate evapotranspiration because rainfall precluded the use of soil water drawdown as measured by TDR.

Year	Cropping system	Crops	% Days
	Continuous maize		
2009		Maize	34
2010		Maize	24
2011		Maize	34
2012		Maize	26
	Soybean-canola-maize-maize rotation (ScMM)		
2009		Soybean	29
2010		Canola	--
2011		Maize	27
2012		Maize	26
	Canola-maize-soybean-maize rotation (cMSM)		
2009		Canola	--
2010		Maize	23
2011		Soybean	32
2012		Maize	29
	Maize-soybean-canola-soybean rotation (MScS)		
2009		Maize	35
2010		Soybean	28
2011		Canola	--
2012		Soybean	25

Table S3 Compilation of published evapotranspiration (ET) estimates from maize and soybean cropping systems.

Location	Country	Crop	ET, mm	Reference
Hickory Corners, MI	USA	Rain-fed maize	460	This study
Hickory Corners, MI	USA	Rain-fed soybean	450	This study
Mead, NE	USA	Rain-fed maize	480	Suyker and Verma, 2009
Mead, NE	USA	Rain-fed Soybean	430	Suyker and Verma, 2009
Balcarce	Argentina	Irrigated maize	460-490	Barbieri *et al.* 2012
Balcarce	Argentina	Rain-fed maize	390-390	Barbieri *et al.* 2012
North Platter, NE	USA	Continuous maize	390-640	Schneekloth *et al.* 1991
North Platter, NE	USA	Wheat-maize-soybean	470-670	Schneekloth *et al.* 1991
Hickory Corners, MI	USA	Rain-fed maize	400	Abraha *et al.* 2015
Urbana, IL	USA	Rain-fed soybean	320-400	Bernacchi *et al.* 2007
Urbana, IL	USA	Rain-fed maize	520-800	Zeri *et al*. 2013
Urbana, IL	USA	Rain-fed soybean	700	Zeri *et al*. 2013
Wuwei, Gansu	China	Maize	487	Li *et al.* 2008
Lincoln, NE	USA	Maize	355-500	Irmak and Djaman 2016

Table S4. Soil profile characteristics at the W.K. Kellogg Biological Station Biofuel Cropping System Experiment. The dominant soil series is Kalamazoo series, which are sandy loams, semiactive, mixed and mesic Typic Hapludalfs.

Soil depth (cm)	Texture (%)			Bulk density (g cm^{-3})	Soil organic carbon (%)	Soil nitrogen (%)
	Sand	Silt	Clay			
10	61	32	8	1.62	0.77	0.07
20	61	32	8	1.62	0.81	0.07
35	71	17	12	1.74	0.26	0.03
50	71	17	12	1.74	0.26	0.03
65	90	4	6	1.43	0.14	0.02
95	90	4	6	1.43	0.14	0.02
125	90	4	6	1.43	0.14	0.02