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Comparison of Cellulosic Ethanol Yields from Midwestern Maize and Reconstructed Tallgrass Prairie Systems Managed for Bioenergy

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Keywords

Tallgrass prairie, Cellulosic ethanol, Grassland, Iowa, Dietary, Detergent

Disciplines

Agriculture | Agronomy and Crop Sciences | Oil, Gas, and Energy

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Abstract Maize- and prairie-based systems were investigated as cellulosic feedstocks by conducting a 9 ha side-by-side comparison on fertile soils in the Midwestern United States. Maize was grown continuously with adequate fertilization over years both with and without a winter rye cover crop, and the 31-species reconstructed prairie was grown with and without spring nitrogen fertilization. Both maize stover and prairie biomass were harvested in the fall. We compared amounts of cellulosic biomass produced and harvested, carbohydrate contents as measured by both dietary and detergent methods, and estimated cellulosic ethanol yields per hectare. From 2009–2013, the cropping system with the largest non-grain biomass yield was fertilized prairie, averaging 10.4 Mg ha^{-1} year^{-1} aboveground biomass with average harvest removals of 7.8 Mg ha^{-1} year^{-1}. The unfertilized prairie produced 7.4 Mg ha^{-1} year^{-1} aboveground biomass, with average harvests of 5.3 Mg ha^{-1} year^{-1}. Lowest cellulosic (non-grain) biomass harvests were obtained from continuous maize systems, averaging 3.5 Mg ha^{-1} year^{-1} when grown with, and 3.7 Mg ha^{-1} year^{-1} when grown without a winter rye cover crop, respectively. Unfertilized prairie biomass and maize stover had equivalent dietary-determined potential biomass ethanol yields at 330 g ethanol kg^{-1} dry biomass, but fertilized prairie was lower at 315. The detergent method did not accurately capture these differences. Over the five-year period of the experiment, unfertilized and fertilized prairie systems averaged 810 and 1,790 L potential cellulosic ethanol ha^{-1} year^{-1} more than the maize systems, respectively. Differences in harvested biomass accounted for >90 % of ethanol yield variation.

Keywords Tallgrass prairie · Cellulosic ethanol · Grassland · Iowa · Dietary · Detergent

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Abbreviations

US	United States
Mg	mega-gram, 1,000 kg
Ha	hectare, 10,000 m^2
Yr	year
N	nitrogen
STRIPS	Science-based Trials of Rowcrops Integrated with Prairies
DTG	Detergent
NREL	National Renewable Energy Laboratory
LCAs	Life cycle assessments
UAN	Urea ammonium nitrate
CC	Continuous maize cropping system
CCW	Continuous maize grown with a winter rye cover crop cropping system
P	Un-fertilized prairie system
PF	N-fertilized prairie system
°C	Degrees Celsius
BEY	Biomass ethanol yield

Introduction

In the US, commercial-scale cellulosic biofuel facilities are projected to have combined operating capacities of 950 million liters by 2015 [1]. The feedstock demand of these facilities will likely be met using a combination of agricultural waste and dedicated biomass crops [2]. As the US has seen with grain ethanol, biofuel feedstock demand has the potential to significantly impact on-farm economics and therefore land-use decision making [3–5], as well as the environment [6, 7]. In order for the cellulosic biofuel industry to proceed in a sustainable manner, potential feedstocks must be carefully evaluated and policy proactively written. In light of the documented environmental services provided by both restored and remnant prairies [8–14], prairie biomass could offer an environmentally sustainable feedstock of cellulosic biofuels.

Biomass systems need to be compared using ethanol yield upon a land area basis (e.g., liters per hectare). Cellulosic ethanol yield is determined by the amount of biomass harvested, the carbohydrate content of the biomass, and the efficiency with which those carbohydrates are extracted and fermented to ethanol. This study examines the first two factors, whereby, ethanol yield is estimated based upon the carbohydrate contents.

Present estimates of Midwestern tallgrass prairie biomass production are limited to low-input systems, often grown on degraded land that is unsuited for arable crop production. In the most recently updated US Billion Ton Report, low input reconstructed prairies were estimated to produce 3.9 Mg ha^{-1} $year^{-1}$, and managed prairies 5.6 Mg ha^{-1} $year^{-1}$ [2]. Studies performed on agricultural-grade land have found prairie biomass productions ranging from 3.1–7.7 Mg ha^{-1} $year^{-1}$ [15–17]. Some studies have shown prairies increase biomass production in response to nitrogen (N) fertilization [18, 16, 19], suggesting that the full production potential of prairie biomass has not been fully investigated. Field-scale estimates of prairie productivity when managed explicitly for biomass production on agricultural land are needed to accurately estimate potential contributions of prairie biomass to fuel production goals.

In the Midwest maize (*Zea mays* L.) stover is projected to be the dominant cellulosic ethanol feedstock as it is the dominant crop [20, 2], but there is rapidly increasing interest in incorporating prairies into maize production systems. The STRIPS project (Science-based Trials of Rowcrops Integrated with Prairies) proposes strategically converting 10 % of a row-crop field into prairie to gain a large suite of benefits such as a 95 % reduction in sediment loss, a 90 % reduction in phosphorus loss, an 85 % reduction in N loss, a four-fold increase in plant diversity, and twice as many bird species [21]. While these environmental impacts are significant, financial incentive will also play an important role in the decision to convert row-cropped land to prairie. Early prairie strip adopters are gaining prairie value through grazing and baling prairie strips for livestock bedding, but cellulosic ethanol may offer another income source. Evaluations of how prairie systems perform relative to maize stover systems on the same soil are needed.

A reliable yearly supply of feedstock is critical for development of a cellulosic ethanol industry, but the supply should also be of a consistent quality. Therefore, when considering potential biomass feedstocks, it is important to identify the range of carbohydrate contents that can be expected from that feedstock. There are several laboratory-scale methods available which estimate carbohydrate contents; we chose to use the detergent (DTG) system because it is a widely applied standard method, as well as a National Renewable Energy Laboratory (NREL) procedure based on the dietary fiber method because it is recognized as being more accurate for this application than the detergent system [22].

Both genotype and variation in environmental growing conditions have been shown to alter biomass biochemical composition [23, 24]. Previous studies have analyzed individual prairie plants as well as mixtures with respect to biofuel conversion potential, but with two or less growing seasons of data or using less accurate methods [25–27]. It is therefore unclear whether the range of prairie composition will be comparable to that of a monoculture of maize across diverse growth environments. This comparison is particularly pertinent in Iowa, considering the first generation of cellulosic ethanol plants is being designed to accept maize stover [28]. If prairies exhibit similar composition ranges, it is feasible that these industries could accept prairie biomass as feedstock with minimal process alterations.

Expected ethanol yields per unit land area are an important metric when evaluating feasibility of a production system. Currently, cellulosic fuel facilities are not being constructed as duel-operation grain and cellulosic ethanol producers. Therefore, the cellulosic industry would be concerned with potential *cellulosic* ethanol yields only, and new plants will eventually face the decision of what kind of feedstock to purchase—maize stover or an alternative such as prairie biomass. We calculated the potential cellulosic ethanol yields per hectare for both the maize and prairie systems utilizing carbohydrate content as estimated via the NREL method. Jarchow and colleagues [29] present an in-depth analysis of the energy balances, including estimated cellulosic and grain ethanol yields from the same study site. Both energy studies will be important in creating life cycle assessments (LCAs) that compare the ultimate profitability of the two systems.

In summary, the goals of this study were to address the following three questions:

1. How do prairie biomass and maize stover production compare on high quality Midwestern agricultural land?
2. Do maize stover and prairie biomass exhibit similar theoretical ethanol yields per unit biomass, and is this sensitive to the method of measurement?
3. How do the theoretical cellulosic ethanol yields per unit land area of maize and prairie compare?

Materials and Methods

Experimental Site and Design

The experimental site was located at Iowa State University's South Reynoldson Farm in Boone County, IA (41°55 N 93°45 W). The predominant soil types are Webster silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) and Nicollet loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) [30]. Subsurface drainage was installed under each of the plots in spring of 2008, after which all cropping systems for this experiment were established. The site has been managed without tillage since establishment.

Four cropping systems were investigated in this study: continuous maize (CC) grown for both grain and stover, continuous maize grown with a winter rye (*Secale cereale* L.) cover crop (CCW) also grown for grain and stover, a 31 species-seeded reconstructed tallgrass prairie (P), and a spring nitrogen-fertilized (84 kg N ha^{-1}) prairie seeded with the same seed mix (PF), both grown for biomass. Plots were 27×61 m, arranged as a randomized complete block design with four replicates. A meteorological station located at the research site collected air temperature, solar radiation, wind speed, humidity, and precipitation data. The 2009–2013 planting, harvesting, and fertilization details of the four cropping systems are presented in Table 1.

A 104 day maturity hybrid was used for all maize treatments and was planted in 76 cm rows. Both maize treatments (CC and CCW) received 84–90 kg N ha^{-1} (32 % urea ammonium nitrate (UAN) injected at 7.6 cm depth) at planting. Based on results from a late spring soil nitrate test [31] conducted each year when plants were 15 to 30 cm tall, maize plots were side-dressed with 22–157 kg N ha^{-1} in the form of 32 % UAN injected to a depth of 7.6 cm. The large range is due to 2013, the year following a severe drought year, when two of the field replications showed very high levels of soil nitrate, and thus required very low post-emergence application of nitrogen fertilizer. Lime, phosphorus and potassium were applied to the maize plots as needed based on soil tests. Glyphosate was used for weed control in the maize plots. Maize grain was harvested after physiological maturity. After grain harvest, stover from the CC and CCW plots was shredded using a flail chopper, then wind-rowed. Approximately, 1 kg of biomass (cobs, stems, and leaves) was collected by hand from windrows for moisture determination and subsequent biomass analysis. Stover from the entire plot was then baled, weighed, and removed from the site; this stover was considered harvested cellulosic biomass. Estimation of the amount of cellulosic biomass produced is described in detail in Jarchow et al. 2014. Briefly, six randomly chosen maize plants from each plot were harvested, separated into grain, cob, and stover. Each component was weighed, dried at 60° Celsius (°C) for at least 48 h, and reweighed for moisture determination. These values were used to estimate harvest index and grain to ear ratio, which in conjunction with grain harvests produced estimates of cellulosic biomass production. Following stover harvest, "Rymin" winter rye (*S. cereale* L., cv. Rymin) was planted in CCW plots as a winter cover crop. Rye was terminated the following spring using glyphosate.

The prairie seed mix contained 31 species (Prairie Moon Nursery, Winona, MN; see [32] for a complete species list). The seed mix was comprised of, by weight, 12 % C_3 grasses, 56 % C_4 grasses, 8 % legumes, and 24 % non-leguminous forbs. The fertilized prairie (PF) received 84 kg N ha^{-1} $year^{-1}$ (broadcast ammonium nitrate or 28–32 % UAN) in late March or early April. Biomass from both prairies was harvested after a killing frost, usually in mid-October. The prairies were mowed at a height of 7–20 cm with all loose biomass being removed, leaving only stubble. The biomass removed from the entire 27×61 m plot was reported as harvested biomass. The fresh biomass was weighed, and subsamples from each plot were collected for moisture determination and biomass analysis. Residue was measured by sampling 0.28 m^2 areas within each prairie plot. The stubble was clipped to ground level, and all dry matter within the sampling area was removed. From 2009 and 2010, two sampling areas were taken per plot. From 2011–2013, four areas were sampled: one from each quadrant of the plot. The amount of biomass produced was estimated as the sum of biomass removed and remaining residue.

Biomass Analyses

All hand collected biomass samples were weighed, dried at 60 °C for at least 48 h, ground to 2 mm using a Wiley Mill (Thomas Scientific), then stored in air tight containers at room temperature and humidity.

Detergent System of Analysis

Ground biomass samples were analyzed for cellulose, hemicellulose, lignin, and ash via ANKOM's sequential filter bag method using an ANKOM-200 Fiber Analyzer (ANKOM Technology, Macedon, NY). The 2009–2011 seasons' biomass was further ground to 1 mm using an UDY Mill (UDY Corporation, Ft. Collins, CO) and was analyzed in duplicate. In 2012, preliminary analyses indicated that a 1 mm grind was too fine for the filter bags; the 2012 biomass was analyzed using the Wiley Mill 2 mm grind and run in triplicate through the ANKOM fiber analyzer. Following terminology recommended by Udén and colleagues [33], hemicellulose was estimated as the difference between aNDF (amylase-neutral detergent fiber) and ADF (acid detergent fiber), and cellulose as the difference between lignin and ADF.

Table 1 Planting, harvesting, and nitrogen fertilization details of maize (CC and CCW) and prairie (P and PF) systems from 2009–2013

Year	System	CCW cover crop termination	Maize hybrid, seeding rate	Planting date, emergence, harvest	CCW cover crop planting[a]	Nitrogen fertilization
2009	CC, CCW	May 6	Agrigold 6325 VT3 (104-d), 82,670 sds ha^{-1}	May 7, May 10, Oct 2	Nov 6	May 7, 84 (CC,CCW) kg N ha^{-1b} June 17, 84 (CC) or 134 (CCW) kg N ha^{-1c}
	P, PF	NA	NA	NA, NA, Oct 19	NA	(PF only) April 17, 84 kg N ha^{-1} 32 % ammonium nitrate broadcast
2010	CC, CCW	May 5	Agrigold 6325 VT3 (104-d), 82,670 sds ha^{-1}	May 6, May 21, Sept 29	Oct 4	May 6, 87 (CC, CCW) kg N ha^{-1b} June 17, 36 (CC) or 82 (CCW) kg N ha^{-1c}
	P, PF	NA	NA	NA, NA, Oct 21	NA	(PF only) March 29, 84 kg N ha^{-1} 32 % ammonium nitrate broadcast
2011	CC, CCW	May 10	Agrigold 6325 VT3 (104-d), 82,670 sds ha^{-1}	May 11, May 21, Oct 3	Oct 10	May 11, 87 (CC, CCW) kg N ha^{-1b} June 29, 36 (CC) or 82 (CCW) kg N ha^{-1c}
	P, PF	NA	NA	NA, NA, Oct 20	NA	(PF only) April 11, 84 kg N ha^{-1} 32 % UAN broadcast
2012	CC, CCW	April 18	Pioneer P0448XR (104-d), 80,200 sds ha^{-1}	May 11, May 18, Sept 25	Oct 1	May 11, 87 (CC, CCW) kg N ha^{-1b} June 12, 134 (CC) or 134 (CCW) kg N ha^{-1c}
	P/PF	NA	NA	NA, NA, Oct 10	NA	(PF only) March 28, 84 kg N ha^{-1} 28 % UAN broadcast
2013	CC, CCW	May 7	Pioneer P0448XR (104-d), 80,200 sds ha^{-1}	May 17, May 24, Oct 9	Oct 21	May 17, 90 (CC, CCW) kg N ha^{-1b} June 12, 67 /157 (CC) or 22/157 (CCW) kg N ha^{-1c}
	P, PF	NA	NA	NA, NA, Oct 28	NA	(PF only) April 26, 84 kg N ha^{-1} 28 % UAN broadcast

[a] 101 kg seed ha^{-1} , 19.1 cm rows

[b] 32 % urea ammonium nitrate (UAN) injected every row

[c] 32 % UAN injected every *other* row

Dietary Fiber (NREL) Method of Analysis

In 2013, samples from 2009–2012 were analyzed using a modified procedure developed by the NREL for determination of structural carbohydrates and lignin in biomass [34]. The 1 mm (2009–2011 samples) or 2 mm (2012 samples) ground biomass samples were used for these analyses. Our interest was to estimate the potential ethanol yield from sugars and carbohydrates—no analyses were performed to determine water or ethanol extractives, lignin or uronic acid. Briefly, samples were treated with 72 % sulfuric acid, heated, diluted to 4 % acid concentration, heated at 121 °C for one hour, then analyzed for sugars using High-Performance Anion Exchange Chromatography with Pulsed Amperometric Detection (HPLC-PAD, Thermo Scientific Dionex). Due to time and equipment constraints, only 2009 and 2012 samples were run in duplicate through the HPLC.

Calculating Biomass Ethanol Yields

Theoretical biomass ethanol yields were estimated from the cellulose and hemicellulose fractions assuming anhydrous sugar-to-ethanol stoichiometric yields of 0.567 and 0.580 for hemicelluloses and celluloses, respectively [35]. While expecting 100 % conversion efficiency is unrealistic, theoretical ethanol production is a useful basis for comparing various systems. Theoretical ethanol yields per unit biomass were calculated as presented in Eqs. 1–3. The result from Eq. 3 represents maximum theoretical ethanol yields per unit biomass (BEY).

Calculation of hemicellulose-derived ethanol yield.

$$\frac{\text{g C5 ethanol}}{\text{g biomass}} = \left(\frac{\text{g hemicellulose}}{\text{g dry biomass}}\right) \times \left(\frac{0.567\text{ g ethanol}}{\text{g hemicellulose}}\right) \tag{1}$$

Calculation of cellulose-derived ethanol yield.

$$\frac{\text{g C6 ethanol}}{\text{g biomass}} = \left(\frac{\text{g cellulose}}{\text{g dry biomass}}\right) \times \left(\frac{0.580\text{ g ethanol}}{\text{g cellulose}}\right) \tag{2}$$

Calculation of maximum biomass ethanol yield using results from Eqs. 1 and 2.

$$\frac{\text{g ethanol}}{\text{g biomass}} = \frac{\text{g C5 ethanol}}{\text{g biomass}} + \frac{\text{g C6 ethanol}}{\text{g biomass}} \tag{3}$$

Theoretical Cellulosic Ethanol Yield per Unit Land Area

The maximum BEY (grams of ethanol per gram dry biomass, Eq. 3) was multiplied by the amount of dry biomass harvested on a per hectare basis, yielding a theoretical amount of ethanol produced per hectare of land (Eq. 4).

Theoretical ethanol yield per hectare

$$\frac{\text{L ethanol}}{\text{hectare}} = \left(\frac{\text{kg ethanol}}{\text{kg biomass}}\right) \times \left(\frac{\text{kg harvested cellulosic biomass}}{\text{hectare}}\right) \times \left(\frac{1\text{ L ethanol}}{0.789\text{ kg}}\right)^{*} \tag{4}$$

* Density of ethanol at 20 °C.

Statistical Analyses

All dependent variables were analyzed using a linear mixed model and the MIXED procedure of SAS [36]. For the dependent variables "cellulosic biomass produced" and "cellulosic biomass removed" block and its interactions were considered random effects, while year, crop, and their interaction were considered fixed. The assumption of equal variances for each year was tested using the REPEATED statement. We found the mixed model that accommodated unequal variances for each year provided the better fit based on Akaike's Information Criteria (AIC). For both "maximum BEY" and "ethanol yield per hectare" block and its interactions were considered random effects, while year, crop, method of estimation (DTG or NREL) and their 2- and 3-way interactions were considered fixed effects. Pairwise comparisons were performed using the PDIFF and ESTIMATE statements. Unless otherwise specified, differences were considered significant at $p<0.05$.

Results and Discussion

Cumulative daily precipitation for each year, along with 30-year means taken from a site 15 miles from this experiment is presented in Fig. 1a. Cumulative stress degree days are presented in Fig. 1b along with 30-year means. Stress degree days were calculated using the daily high air temperature with a base temperature of 30 °C, meaning if the maximum air temperature exceeded 30 °C, one stress-degree-day was accumulated for each degree >30. We chose 30 °C because it is the temperature threshold above which maize development is negatively impacted and the plant is likely to suffer from water stress [37]. This data set encompasses varied growing season environments, ranging from warm to cool, and flooding to drought. In general, the years were characterized as follows (30-year mean annual precipitation is 846 mm): in 2009, there was spring flooding (938 mm) with very cool growing season temperatures; in 2010, there was summer flooding (1443 mm) again with cooler temperatures; in 2011, there was average precipitation (805 mm) with slightly warmer than average temperatures; in 2012, there was an extreme drought (566 mm) with equally extreme warm temperatures; in 2013, there was spring flooding followed by late season

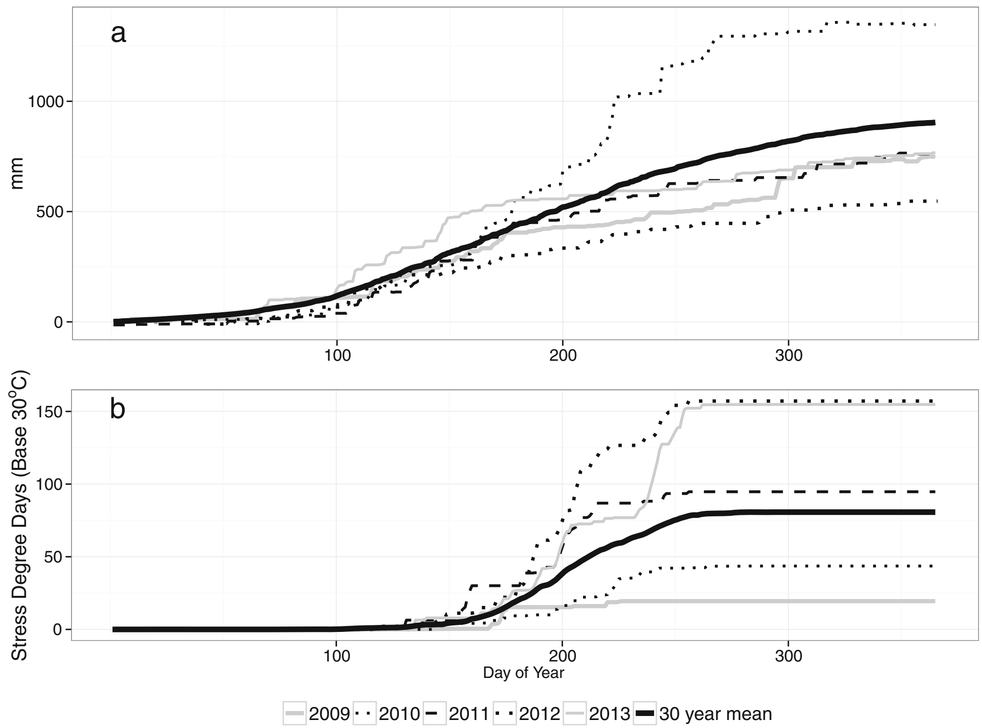

Fig. 1 Weather summaries for 2009–2013. **a**. Cumulative precipitation **b**. Cumulative stress degree days at a base temperature of 30 °C

drought (866 mm) with cool early season temperatures but warm late season temperatures.

How Do Prairie Biomass and Maize Stover Production Compare on High Quality Midwestern Agricultural Land?

Maize grain yields on a dry matter basis are presented in Table 2, and cellulosic (non-grain) biomass yields in Fig. 2.

There was a significant interaction between crop and year, with the prairies having lowest biomass production in the drought years of 2012 and 2013, while both maize systems had highest stover productions in 2012 and 2013. Within the maize systems, in all years except 2009, the CCW system produced less grain than the CC system (Table 2). In all years, CCW produced equal or lower amounts of stover compared to the CC system (Fig. 2). Within the prairie systems, the N-fertilized prairie (PF) produced significantly more biomass than the un-fertilized (P) in every year of this study (Fig. 2).

Table 2 Maize grain yields (2009–2013) for continuous maize (CC) and continuous maize with a winter rye cover-crop (CCW) along with yearly Boone County IA averages [38] for comparison

	2009 Mg ha^{-1}	2010	2011	2012	2013
County average	(*9.7*)	(*9.0*)	(*10.2*)	(*8.1*)	(*8.6*)
CC	10.7	8.7	8.6	8.0	9.0
CCW	10.9	8.6	8.3	5.2	7.1

There are two considerations regarding the amount of biomass in a biofuel system—the amount of biomass produced, which represents a maximum, and the amount of biomass that is harvested, which depends on management. Five year averages of the amount of cellulosic (non-grain) biomass produced and harvested are presented in Fig. 3.

Over a span of diverse weather years, the maize systems produced an average of 7.3 Mg cellulosic (non-grain) biomass ha^{-1} year^{-1}. The prairie showed a strong response to N fertilization, increasing average production from 7.4 Mg ha^{-1} year^{-1} (P) to 10.4 Mg ha^{-1} year^{-1} (PF). The maize stover production values are consistent with other studies from central Iowa [39, 40]. Both the P and PF biomass production values are substantially higher than the 0.5–6 and 6–8 Mg ha^{-1} year^{-1} production rates previously reported for un-fertilized and fertilized prairies in the Midwest [16, 41, 17] as well as the 5.6 Mg ha^{-1} year^{-1} production rate assumed for “managed prairie” in the US Billion Ton Update [2, 42]. In 2009, PF exceeded the “break-even” production rate of 13.4 Mg ha^{-1} year^{-1}, which is the amount of biomass required (at $60 per Mg) to compete economically with maize systems [43], although harvest losses and the cost of fertilization are not considered in those calculations.

In our study, the maize and prairie systems responded to drought years differently. In 2012, the most severe drought year, both maize systems (CC, CCW) produced the lowest grain yields of this five year study (Table 2), but produced the highest amount of cellulosic biomass (Fig. 2). This is likely due to the timing of the drought—the maize experienced favorable growing conditions during vegetative growth, but water-limiting conditions during tasseling, pollination, and

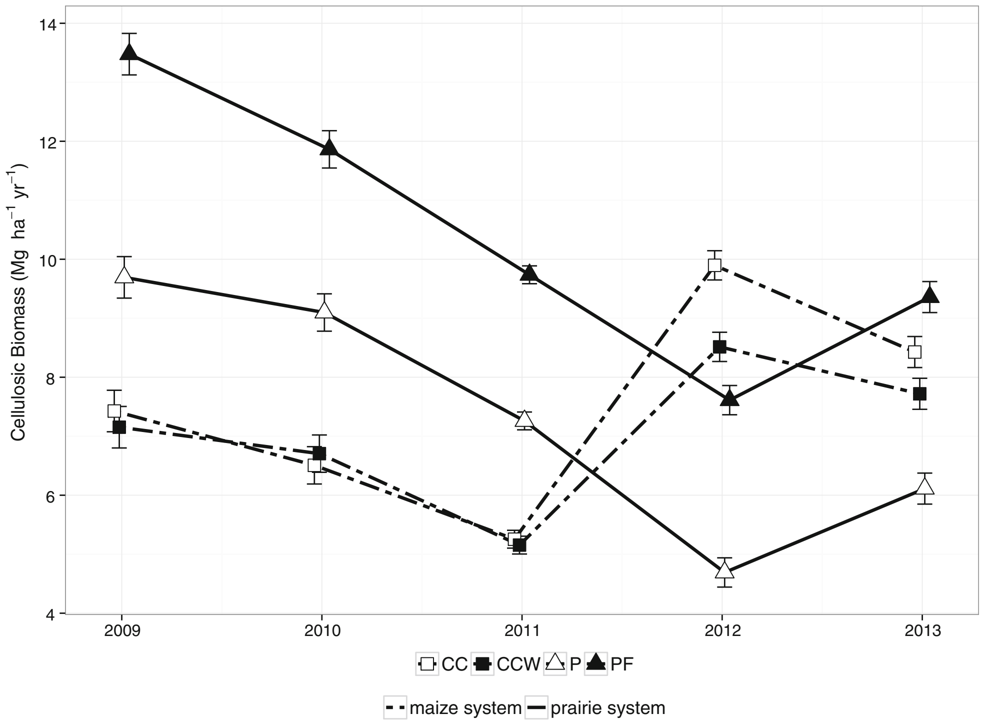

Fig. 2 Aboveground cellulosic dry biomass produced (2009–2013) for continuous maize (CC), continuous maize with a winter rye cover-crop (CCW), un-fertilized prairie (P), and N-fertilized prairie (PF) with 95 % confidence intervals; point-joining provided to aid in interpretation

grain fill [44]. In 2012, the P and PF treatments' production dropped to 48 and 56 % of their maximum production, respectively. These results are consistent with the results from a study conducted by Tilman and Haddi [45], which found a 47 % decrease in un-fertilized prairie production during a drought in Minnesota in 1988. Drought also affected the efficacy of prairie fertilization, increasing prairie production by 2.9 Mg ha^{-1} in 2012 compared to the 3.9 Mg ha^{-1} increase observed in the most responsive year, 2009. The early summer timing of the 2012 drought may have allowed for early spring fertilization to be effective before the systems became water-limited.

The amount of cellulosic biomass produced versus harvested is not necessarily proportional, as harvesting regimes vary

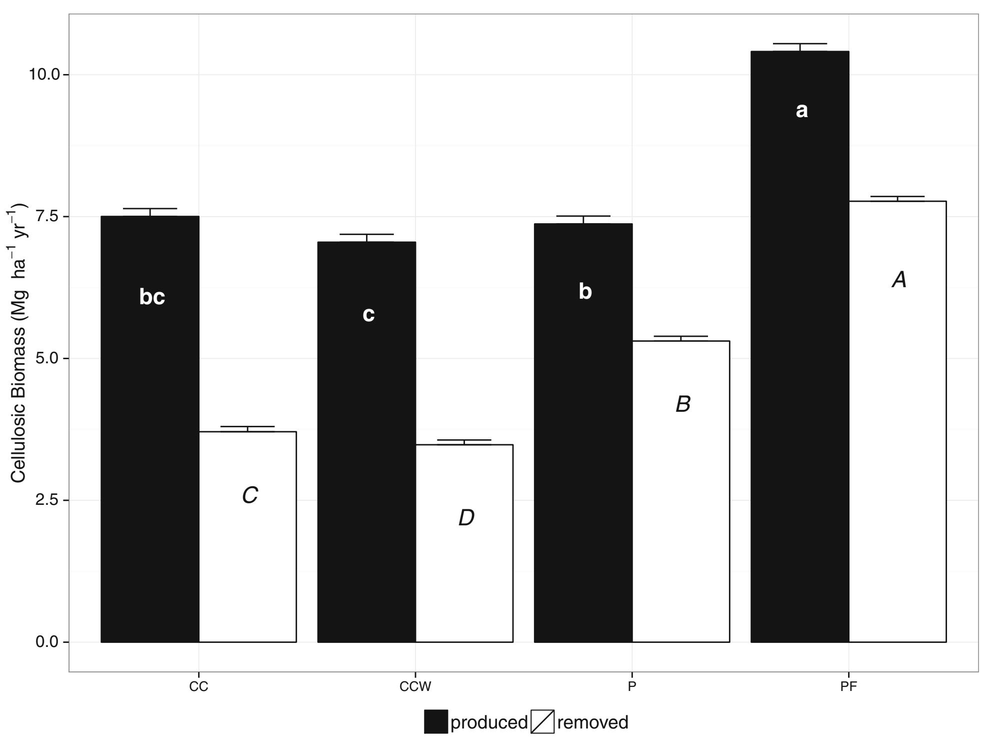

Fig. 3 Mean annual cellulosic biomass produced and removed averaged over 2009–2013. *Lowercase letters* indicate significant ($p<0.05$) differences in produced biomass; *uppercase letters* indicate significant ($p<0.05$) differences in harvested biomass amounts; *error bars* represent standard errors of the means

for different systems. For maize stover harvesting, it has been shown that soil erosion can remain "tolerable" for removal rates up to 70 % [46], but harvest rates should remain under 20 % to maintain soil carbon [47]. Our study utilized a rake and bale system, which has been shown to collect approximately 55 % of the stover [48]. During the five years of our study, we removed between 38–61 % of the maize stover. Under this harvesting regime, in 4 of the 5 years, the CC and CCW maize systems did not produce sufficient biomass to provide the 4.5 Mg ha^{-1} year^{-1} harvests (2 t acre^{-1} year^{-1}) desired by Iowan industries [49, 50].

As an ecosystem, prairies require periodic disturbance such as mowing, grazing, or fire in order to suppress growth of woody shrubs and trees [51, 52]. Studies on perennial prairie grasses indicate nutrient cycling is altered not only by the amount of biomass removed, but also the timing of removal [53, 54]. In our study, we harvested biomass in the fall after a hard frost, usually late October. For a detailed investigation of the system's nutrient dynamics, the reader is referred to Jarchow and collegues [29]. Due to variable mowing heights, the amount of above-ground material harvested from the prairie systems varied from 52 to nearly 100 % removal. In all 5 years of this study, the PF system provided more than 4.5 Mg ha^{-1} of harvested biomass, while the P system provided more than 4.5 Mg ha^{-1} in 3 of the 5 years. This indicates that on a per area basis, prairies could provide cellulosic biomass in sufficient amounts to satisfy the requests of the cellulosic biofuel industry (e.g., DuPont, POET).

Do Maize Stover and Prairie Biomass Exhibit Similar Theoretical Ethanol Yields per kg of Biomass, and is this Answer Sensitive to the Method of Measurement?

The biomass ethanol yield (BEY) as predicted via the NREL and DTG methods are presented in Fig. 4.

The DTG and NREL methods predicted significantly different BEY for every crop in every year, except for CC in 2012. An analysis within prairie systems showed no significant interaction between year and method. In other words, in the prairies, the difference between the DTG and NREL estimates was consistent across years. Conversely, in the maize systems, there was a significant interaction between year and method; in 2009, the difference between methods was large (102 g kg^{-1}, p<0.0001), but in 2012, it was small (3 g kg^{-1}, p=0.72).

It is generally recognized that the NREL method is the more accurate method for this application because carbohydrates are directly measured [22]. Therefore, averaged over the 4 years, the DTG overestimated BEY by 63 g kg^{-1} in the maize systems and 44 g kg^{-1} in the prairie systems, or by roughly 15 %. Although small, this difference was significant.

When averaged over the 4 years, the NREL-based BEY values for CC, CCW, and P were not significantly different, predicting 330 g kg^{-1}. Fertilization significantly reduced the prairie's NREL-based BEY, estimating 315 g kg^{-1} from PF. The ranges in NREL-based BEY observed in the P and PF systems were within the range observed in the maize systems.

Total carbohydrate contents and, therefore, theoretical biomass ethanol yields were similar for maize stover and prairie biomass according to the NREL method. 2009–2012 covered a wide scope of growing conditions (Fig. 1) with 2013 biomass productions falling within the range established by the previous 4 years (Fig. 2). This indicates the 2009–2012 average NREL-based BEY of each system is robust. In some scenarios, it may be appropriate to use the NREL conversion estimates found in this study of 330 g kg^{-1} for both maize stover and C_4-grass dominated prairie biomass, and 315 for N-fertilized prairie biomass, which contains a diverse mixture of C_3- and C_4-grasses and forbs [32]. These values are within the ranges reported for these types of feedstocks [55], and are consistent with other studies that show lower conversion values for mixtures as compared to C_4 grasses [27].

That the DTG system and NREL method gave varying results is not unexpected given their procedural differences. The DTG system works based on cell wall solubility under neutral and acidic conditions. Because plants vary in their exact cell wall composition and arrangement, different plants will exhibit differential responses to this method. The NREL method, on the other hand, has been shown to be accurate in its estimations of cellulose and hemicellulose across feedstocks [22]. As has previously been found, the DTG system overestimated both the cellulose and hemicellulose contents as compared to the NREL method, with the amount of overestimation depending on the plant source and year [22, 56]. However, the DTG system's differential interaction with year for maize stover as compared to the prairie biomass was surprising. The DTG procedure begins with a neutral detergent wash, which removes all water soluble components from the biomass. From 2009–2012, we observed an increasing amount of water soluble components in the maize stover, which correlated to a decrease in grain yield. The majority of the water solubles in stover are monomeric or short-chain sugars such as glucose [57]. It is likely, that due to the lack of "sink" strength by low grain yields, stover sugars did not mobilize from stover to grain during grain fill [58, 59]. The DTG's neutral detergent step removed these non-structural sugars and therefore precluded their inclusion in the theoretical ethanol yields. We did not perform water nor ethanol extractions [60] prior to NREL analyses. Therefore, our NREL estimates include both non-structural (water-soluble) and structural sugars. These observations only add to the uncertainty associated with the DTG system's estimates of ethanol conversion.

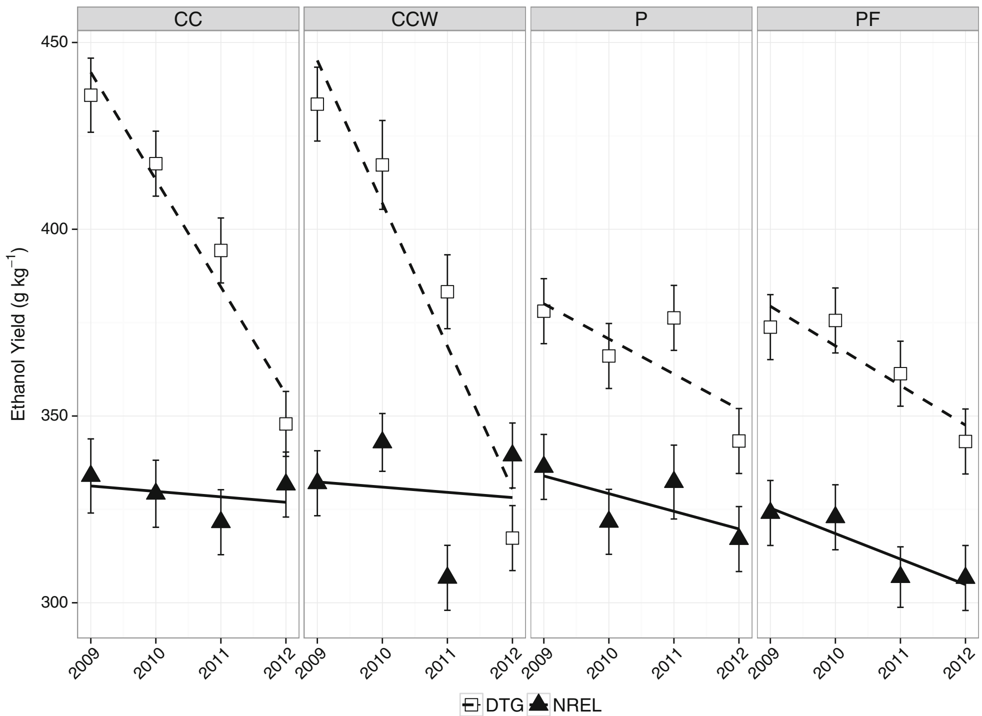

Fig. 4 Maximum grams of ethanol expected per kilogram of biomass as measured by the detergent system (DTG) and NREL method (NREL) for 2009–2012 contin. maize (CC), contin. maize grown with a winter rye cover-crop (CCW), un-fertilized prairie (P), and N-fertilized prairie (PF) with standard errors of the means; linear fits are provided to aid in interpretation; to change units to L of ethanol per Mg of biomass multiply values by 1.27

How Do The Theoretical Cellulosic Ethanol Yield per Hectare of Maize and Prairie Compare?

The maximum theoretical ethanol yields per unit land were calculated for 2009–2013 biomass harvests based on the 4-year (2009–2012) average NREL-based BEY for the CC, CCW, and P (330 g kg^{-1}), and PF (315 g kg^{-1}) systems. Ethanol yields were calculated using Eq. 4, results are presented in Fig. 5.

When averaged across years, the P and PF system produced 809 and 1790 L cellulosic ethanol ha^{-1} year^{-1} more than the maize systems, respectively. Differences in the amounts of biomass harvested accounted for 90 % of the variability in ethanol yield per hectare.

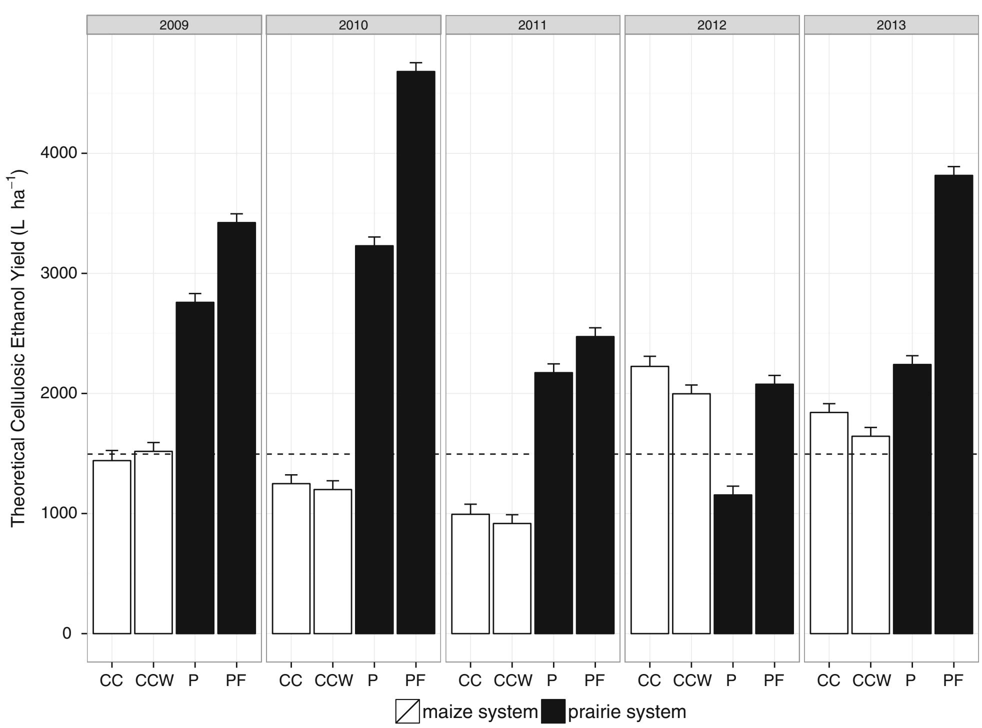

Fig. 5 2009–2013 theoretical ethanol yields per hectare for contin. maize (CC), contin. maize grown with a winter rye cover-crop (CCW), un-fertilized prairie (P), and N-fertilized prairie (PF) with standard errors of the mean; the *dashed line* represents the 1500 L ha^{-1} year^{-1} yields expected by Iowa cellulosic fuel industries [49, 50]

Our results are consistent with other studies that have found that the amount of biomass rather than carbohydrate content is the dominant variable dictating ethanol yields per unit of land area [27, 17]. For example, at a constant biomass harvest of 3 Mg ha^{-1} $year^{-1}$, if the maize stover BEY were to drop from 345 to 310 g kg^{-1}, which is the approximate range of NREL-based values observed in this study, the ethanol yield per hectare would drop ~100 L, or about 10 %. Thus, while total carbohydrate content of biomass is an important consideration in biofeedstock evaluation, we found that a system's ethanol output was strongly dictated by its biomass production.

The focus of this study was to investigate *cellulosic* aspects of these systems, including biomass productions and harvests, harvested biomass ethanol yields, as well as potential cellulosic ethanol yields per hectare. While prairie systems produce only cellulosic biomass, maize systems produce both grain and stover. Grain may be converted to ethanol, which would add to the fuel yield of those systems, as well as the profitability. For ethanol yield estimations which include both grain and cellulosic biomass, along with a detailed study of the overall energy balances of these systems, the reader is directed to Jarchow and colleagues [29].

Conclusions

When grown on high quality land suitable for rain-fed row crop production, prairie systems have the potential to produce significantly more biomass than previously reported. Prairie biomass production is further improved with modest amounts of spring N-fertilization. Our study indicates that the most productive management strategies of reconstructed prairie systems have not yet been exploited; with further research, it is feasible that reconstructed prairies could be managed to optimize biomass production as well as other ecosystem services. Although the exact botanical make-up of prairies may vary, we found that as a biofuel feedstock, the range in carbohydrate content, and therefore potential biomass ethanol yields fell within the range expected from maize stover. We found that the method used to determine biochemical composition significantly affected the estimated biomass ethanol yield, but that the dominating variable in ethanol yields per unit area was the amount of harvestable biomass. If the interest of a study lies in comparing ethanol yields per unit land area, utilizing available detergent data or assuming constant conversion rates may be sufficient.

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