Long-term Biomass and Potential Ethanol Yields of Annual and Perennial Biofuel Crops

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ABSTRACT

Although energy crops could eventually supply a growing portion of cellulosic biofuel feedstocks, long-term comparisons of annual and perennial crops are rare. An experiment was established in 2007 near Manhattan, KS, to compare biomass productivity and ethanol yield of perennial and annual crops. Perennial crops included three C4 grasses: switchgrass (*Panicum virgatum* L.), big bluestem (*Andropogon gerardii* Vitman), and miscanthus (*Miscanthus sacchariflorus*). Annual C4 crops were corn (*Zea mays* L.) in two rotations: continuous and rotated with soybean [*Glycine max* (L.) Merr.]; and five types of sorghum [*Sorghum bicolor* (L.) Moench]: photoperiod sensitive, sweet, dual purpose (grain and biomass), brown mid-rib, and grain; all rotated with soybean. Annual crops produced 7 Mg ha^{-1} yr^{-1} more biomass than perennial crops throughout 11 yr, with sweet sorghum exceeding 22 Mg ha^{-1} yr^{-1}, and 12 m^3 ha^{-1} yr^{-1} of ethanol. Biomass yield of miscanthus approached 14 Mg ha^{-1} yr^{-1}, essentially the same as for several annual crops but with half as much fertilizer nitrogen. Annual ethanol production from miscanthus and switchgrass was 3.6 m^3 ha^{-1} yr^{-1}, half as much as that of several annual crops that produced similar biomass yields. Big bluestem consistently produced the least biomass and ethanol, less than 7 Mg ha^{-1} yr^{-1} and 1.7 m^3 ha^{-1} yr^{-1}, respectively. Rotated corn averaged 7.1 m^3 ha^{-1} yr^{-1} of ethanol. Eleven years of results indicate that annual corn and sorghum crops as well as perennial grasses such as miscanthus and switchgrass could play a role as potential bioenergy feedstocks in diversified production systems.

Core Ideas

- Annual crops produced a third more biomass and three times as much ethanol as perennials.
- Perennial crops used half as much nitrogen fertilizer as annual crops.
- Grain from most annual crops enhanced ethanol production per unit of biomass.
- Sweet sorghum produced substantially more ethanol than all other crops.
- Sorghum yielded more biomass and potential ethanol than corn in hot, dry years.

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IDENTIFYING AND characterizing sources of renewable energy have become increasingly important as consumption of renewable energy continues to grow (USDOE, 2016). The fossil energy ratio $\left(FER = \frac{\text{energy available to consumers}}{\text{fossil energy used to generate that energy}}\right)$ for renewable energy from cellulosic feedstocks is four- to seven-fold greater than for ethanol produced from corn (*Zea mays* L.) grain (Farrell et al., 2006; USDOE, 2016). The USDOE has identified sustainable production of regionally adapted feedstocks as a research priority for developing the cellulosic bioenergy industry (USDOE, 2015). Although crop residues will supply the bulk of potential cellulosic bioenergy feedstocks in the near future, energy crops are predicted to supply a growing portion of the supply beginning in the 2020's, potentially surpassing crop residues by 2030 (USDOE, 2016).

With corn occupying a large land area in the United States (USDA–NASS, 2014), corn residues have been identified as a primary source of cellulosic feedstock (Dhugga, 2007; USDOE, 2016). Karlen et al. (2014) reported that removing half to all corn residue resulted in stover yields of 4 to 7 Mg ha^{-1} in a meta-analysis of results from 239 site–yr. Karlen et al. (2014) indicated that residue removal improved yields in no-till situations in the central Corn Belt, but Varvel et al. (2008) documented a reduction in corn yield with 50% residue removal in eastern Nebraska. Johnson et al. (2014) estimated that roughly 6 Mg ha^{-1} of residue needed to be returned to the soil to maintain soil organic carbon levels. Karlen et al. (2014) and Propheter and Staggenborg (2010) documented that any amount of residue removal increased nutrient export from the field, implying a greater fertilization requirement in situations where the residue is harvested for bioenergy production.

The various types of sorghums [*Sorghum bicolor* (L.) Moench] have several potential advantages over corn relative to biomass production (Mathur et al., 2017; Nghiem et al., 2016). Forage and sweet sorghums maximize biomass yield at N fertilizer rates less than those required to maximize biomass

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Abbreviations: BMR, brown mid-rib; Cont, continuous; DP, dual purpose; GDU, growing degree unit; PTS, photoperiod sensitive; R, rotated; UAN, urea ammonium nitrate.

yields for corn (Han et al., 2012; Thivierge et al., 2015). Forage and photoperiod-sensitive sorghums have been documented to produce more biomass per unit of irrigation water (Rooney et al., 2007). Dry biomass production of several potential bioenergy sorghum crops can be impressive: 18 to 32 Mg ha^{-1} for sweet sorghum, 16 to 24 Mg ha^{-1} for forage sorghum, and 32 Mg ha^{-1} for photoperiod-sensitive sorghum (Rooney et al., 2007). The potential exists to further develop sorghum as a bioenergy crop because it possesses an array of traits such as brown midrib, sweet stalks, staygreen, and high biomass that can be combined via plant breeding and genetic manipulation to maximize the conversion of biomass to ethanol (Vermerris et al., 2007). Sorghum also has a vast, relatively untapped reservoir of genetic diversity that could enhance biomass production and ethanol conversion potential (Brenton et al., 2016).

Perennial crops have several potential advantages over annual crops. These include less annual input cost, nutrient recycling, longer annual duration of photosynthesis leading to greater annual solar energy conversion efficiency, reduced environmental footprint resulting from less water runoff and soil erosion, and greater potential for production on marginal or contaminated lands (Arundale et al., 2013a; Pidlisnyuk et al., 2014; Pogrzeba et al., 2017; USDOE, 2006; Yost et al., 2017). Miscanthus (*Miscanthus* × *giganteus*) has been documented to be particularly well suited to the temperate regions (Köppen Climate Classification System: Cfa, Cfb, Dfa, Dfb) of the United States (Kottek et al., 2006; Lee et al., 2014) and Europe, with recent reports proposing an expanded area of potential production based on current climatic conditions and genetics (Clifton-Brown et al., 2017). Reports from both the United States and Europe have demonstrated that *M.* × *giganteus* responds to N fertilization, but suggest that fertilization strategies should be tailored to specific site and within-site conditions (Arundale et al., 2013b; Stępień et al., 2014; Yost et al., 2017), including the possibility that N fertilization may increase the mobility of heavy metal contaminants in the soil (Pogrzeba et al., 2017). Lee et al. (2014) summarized results from several miscanthus trials and reported dry biomass yields of 6 to 30 Mg ha^{-1}, with the least production from second-yr stands in the southeastern United States and the greatest from 3- to 5-yr stands in central and southern Illinois. Yost et al. (2017) reported yields from >5-yr stands of up to 25 Mg ha^{-1} on eroded sites in Missouri. Long-term research has documented a decline in yield after the fifth year of stand age, with average yields of 23 Mg ha^{-1} from mature stands in Illinois (Arundale et al., 2013a). Clifton-Brown et al. (2017) suggested that miscanthus yields in Europe could range from 10 to 41 Mg ha^{-1} depending on location, but Stefanovska et al. (2017) documented potential insect pests in Ukraine where commercial use of miscanthus as a biofuel feedstock has been increasing. Switchgrass (*Panicum virgatum* L.) is native to the Great Plains of the United States and has received significant attention as a potential perennial bioenergy crop with yields reported of 4 to 15 Mg ha^{-1} (Arundale et al., 2013a, 2013b; Hong et al., 2013; Lee et al., 2009; Rooney et al., 2007; USDOE, 2006). Big bluestem (*Andropogon gerardii* Vitman), another native perennial species that has been historically important for rangeland cattle production, has been documented to produce roughly 3 to 4 Mg ha^{-1} in the US Northern Plains when managed for dry biomass production (Hong et al., 2013; Lee et al., 2009).

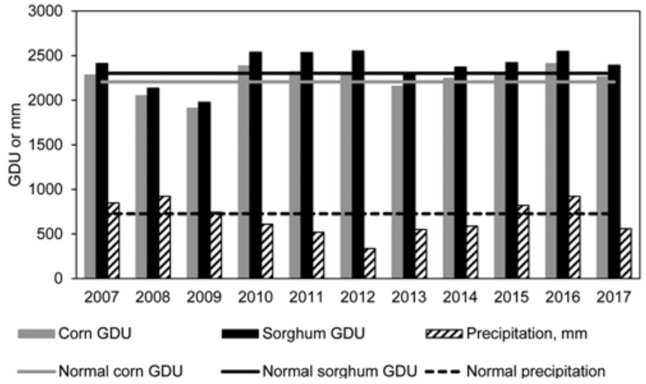

Fig. 1. Cumulative growing-season (1 April to 31 October) growing degree units (GDU) and precipitation at Manhattan, KS, 2007 to 2017. Calculations of GDU used maximum temperatures of 30 and 38°C for corn and sorghum, respectively, and minimum and base temperatures of 10°C for both crops. Weather data collected from a station located ≈625 m from the study site, 1981 to 2010 Normals (Weather Data Library, 2018).

Direct, long-term comparisons of annual with perennial biomass crops or comparisons of corn with various types of sorghum for biomass production are rare (Rooney et al., 2007; Varvel et al., 2008, Wortmann et al., 2010). The objective of this study was to compare long-term biomass production and to estimate potential ethanol yield for annual and perennial biofuel crops.

MATERIALS AND METHODS

An experiment was established in 2007 at the Kansas State University (KSU) Agronomy Research Farm in Manhattan, KS (39°11′ N, 96°35′ W), on Ivan, Kennebec, and Kahola silt-loam soils (fine-silty, mixed, superactive, mesic Cumulic Hapludolls). The site has a hot, humid continental climate (Köppen Climate Classification System:Dfa) with annual precipitation of 904 mm and annual mean temperature of 12.7°C (1981–2010 Normals). Cumulative growing-season growing degree units (GDU) and precipitation (Fig. 1) were calculated from data collected by a weather station located approximately 625 m from the experimental site (Weather Data Library, 2018).

The experiment was designed to compare long-term productivity of perennial and annual cropping systems. Perennial crops included three C4 grasses: switchgrass, big bluestem, and miscanthus (obtained in 2007 as *Miscanthus* × *giganteus*, but likely tetraploid *Miscanthus sacchariflorus* based on genetic analysis of source material by Głowacka et al. [2015] as well as in-house genetic analysis and observations of rhizome structure and growth habit of plants in this study). Annual C4 crops were corn in two rotations: Continuous (Cont) corn and corn rotated (R) with soybean [*Glycine max* (L.) Merr.] and five types of sorghum: photoperiod sensitive (PTS), sweet, dual purpose (DP), brown mid-rib (BMR), and grain, all rotated with soybean. Specific cultivars varied with year depending on seed availability (Table 1). In 2007 and 2008, the experiment included two cultivars of dual-purpose sorghum (Propheter et al., 2010), but beginning in 2009, one of the dual-purpose cultivars was replaced with a full-maturity grain sorghum hybrid cultivar to better represent typical grain sorghum production in the region.

Planting, weed control, harvest, sampling, and residue removal operations were as described by Propheter et al. (2010) with yearly variations in fertilizer applications and seeding rates

Table 1. Cultivars planted as biofuel feedstock crops at Manhattan, KS, 2007 to 2017.

	Year										
Crop†	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Corn	Pioneer 33K40	Pioneer 33K44	— Pioneer 33T57 —		DeKalb DKC63–49	DeKalb DKC63–46	DeKalb DKC63–49	— DeKalb DKC64–69 —			
PTS sorghum	— Sorghum Partners 1990CA —									Sorghum Partners SP1615	
Sweet sorghum	— Mississippi State M81E —										
BMR sorghum	— Crosbyton — GW8528		BMR PS440	Crosbyton GW8528	— BMR PS440 — (photoperiod sensitive)			— Sorghum Partners BMR SP3909BD — (brachytic dwarf)			
DP sorghum	— Sorghum Partners NK300 —										
Grain sorghum	DeKalb DKS59–09 (dual purpose)		— Pioneer 84G62 grain sorghum —							Sorghum Partners SP78M30	Pioneer 84G62
Soybeans	— KSU Foundation Seed KS3406RR —							Asgrow 4033RR	Asgrow 3701RR	Asgrow 4033RR	Pioneer P41T79L
Miscanthus	— Miscanthus (likely *M. sacchariflorus*‡)§ —										
Switchgrass	— Kanlow§ —										
Big bluestem	— Kaw§ —										

† BMR, brown midrib; DP, dual purpose; PTS, photoperiod-sensitive.

‡ Obtained as *Miscanthus* × *giganteus* in 2007, but source later identified as tetraploid *M. sacchariflorus* by Głowacka et al. (2015). Subsequent in-house genetic analysis and observations of rhizome structure and growth habit of plants in this study agree with descriptions of *M. sacchariflorus*.

§ Perennial grasses planted in 2007 and regrowth harvested in subsequent years.

Table 2. Seeding and fertilizer rates and planting and harvest dates for biofuel feedstock crops at Manhattan, KS, 2007 to 2017.

	Year										
Crop	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
	Seed rate (seeds ha^{-1})										
Corn	68,000	68,000	68,000	74,000	68,000	68,000	68,000	64,000	68,000	68,000	68,000
Sorghums	143,000	191,000	158,000	160,000†	173,000	173,000	175,000	186,000	186,000	198,000	183,000
Soybeans	250,000	296,000	346,000	346,000	346,000	346,000	346,000	395,000	296,000	395,000	395,000
Grasses	‡										
	Fertilizer rate (kg N–P_2O_5–K_2O ha^{-1})										
Corn	180–0–0	168–66–279	179–0–0	179–0–0	167–99–0	168–0–0	168–20–0	168–0–0	168–0–0	168–0–0	197–99–0
Sorghums	180–0–0	168–66–279	179–0–0	179–0–0	167–99–0	112–99–0	112–20–0	134–0–0	168–0–0	168–0–0	197–99–0
Soybeans	0–0–0	0–66–279	0–0–0	0–0–0	89–99–0	0–0–0	10–20–0	0–0–0	0–0–0	0–0–0	29–99–0
Miscanthus	§	45–66–279	112–0–0	112–0–0	167–99–0	84–0–0	84–20–0	84–0–0	84–0–0	84–0–0	113–99–0
Other grasses	0–0–0	45–66–279	56–0–0	56–0–0	167–99–0	84–0–0	84–20–0	84–0–0	84–0–0	84–0–0	113–99–0
	Planting date										
Corn	14 May	22 Apr.	22 Apr.	15 Apr.	6 May	11 May	30 Apr.	14 Apr.	10 Apr.	7 Apr.	18 Apr.
Sorghums	21 May	21 May	29 May	24 May	6 June	6 June	24 May	16 May	19 May	14 May	5 May
Soybeans	21 May	21 May	29 May	24 May	6 June	6 June	26 May	9 May	30 Apr.	14 May	5 May
	Harvest date										
Corn	29 Sept.	27 Sept.	1 Oct.	1 Oct.	6 Sept.	10 Oct.	30 Sept.	4 Sept.	24 Sept.	20 Sept.	13 Sept.
Sorghums	24 Oct.	27 Sept.	10 Oct.	1 Oct.	21 Oct.	4 Nov.	17 Oct.	6 Oct.	7 Oct.	13 Oct.	17 Oct.
Soybeans	18 Nov.	27 Oct.	21 Oct.	15 Oct.	10 Oct.	18 Oct.	8 Oct.	30 Oct.	28 Oct.	2 Nov.	17 Oct.
Grasses	28 Nov.	23 Nov.	2 Dec.	2 Dec.	6 Nov.	10 Nov.	8 Nov.	18 Nov.	11 Nov.	22 Nov.	21 Nov.

† Sweet sorghum: 123,000 seeds ha^{-1}.

‡ Miscanthus planted at 6148 live plants ha^{-1}, switchgrass and big bluestem at 4.0 and 6.3 kg live seed ha^{-1}, respectively.

§ 2.5 g N, 0.8 g P_2O_5, and 1.7 g K_2O applied in 3.76 L of water solution to each miscanthus plant when transplanted into the field.

determined by soil test results and growing conditions (Table 2). All crops were managed without tillage in all years of the experiment. Non-selective herbicides were applied to annual crop plots in early spring to control winter annual and early-emerging summer annual weed species. Pre-emergence herbicides were applied to annual crop plots at planting to control dominant weed species, and post-emergence herbicides were applied as needed to control weeds that emerged during the growing season. Specific herbicide products and timings were updated periodically to reflect changes in availability and efficacy as well as to better control changing weed populations. Hand weeding was used as needed to maintain weed-free conditions. Beginning in 2014, liquid fertilizer products (28% urea ammonium nitrate [UAN] and ammonium poly-phosphate [10–34–0]) were used instead of dry materials to facilitate accurate, uniform distribution using either sprayer-mounted streamer bars (Chafer Machinery Ltd, Gainsborough, Lincolnshire, UK) or a disk-coulter applicator to facilitate injection below the crop residue layer. Annual crops were planted in 0.76-m row spacing as close to recommend times as soil conditions permitted in April and May for corn and sorghums, respectively. Residue managers (Yetter Farm Equipment, Colchester, IL) mounted on planter row units facilitated accurate seed depth and placement without tillage. Corn was harvested after physiological maturity when grain had dried sufficiently for shelling (<200 mg kg^{-1} grain moisture content), typically mid-September (Table 2). Sorghums were harvested at physiological maturity for grain-producing types (grain and dual purpose) or when growth had essentially ceased due to cooling fall temperatures for those that did not produce grain (PTS) and for sweet sorghum. Perennial grasses were harvested after frost when plants were completely dormant. Damage from an accidental application of the non-selective herbicide, glyphosate [N-(Phosphonomethyl) glycine], to the perennial grasses in the spring of 2012 was minimized by mowing the top growth (<0.5 m in height) within 24 h of the application. Subsequent regrowth of miscanthus and switchgrass revealed minimal loss of plant density, but yields were not recorded in that year. Big bluestem took longer to recover, and yields were not recorded in either 2012 or 2013. Biomass yields of all crops were estimated by harvesting all above-ground material from a bordered, minimum harvest area of 9.3 m^2 within each 65-m^2 experimental unit. Biomass was separated into grain and stover for corn and sorghums. Stover subsamples were dried at 65°C until they reached constant mass to determine dry matter concentration for calculation of dry stover yield. Grain yields were converted to dry biomass using moisture contents determined with a GAC2000 Grain Analysis Computer (DICKEY-john Corp., Auburn, IL).

Ethanol yields were estimated as the sum of potential ethanol yields derived from grain, stover, and fermentable sugars in stover. Ethanol from grain and stover were estimated as liters of ethanol produced from each megagram of dry plant mass by multiplying dry mass of each fraction by conversion factors for each fraction of each crop listed in Table 3. Ethanol yield from sweet sorghum stalks included conversion of cellulosic biomass plus free sugars assuming 1.76 kg fermentable carbohydrates L^{-1} of ethanol (Putnam et al., 1991).

The experimental design was a randomized complete block where crops rotated with soybeans were duplicated within replication so each phase of the 2-yr rotation was present every year. Analysis of variance (ANOVA) was conducted using PROC GLIMMIX (SAS 9.4, SAS Institute Inc., Cary, NC) with crops and years as fixed effects and replications as random effects. With 11 yr of yield data, biomass and ethanol yields also were summarized over years with year as a random factor based on the assumption that the changing environmental conditions and slight changes in management from year to year represented a random sample of possible combinations of weather and management for the experimental location.

RESULTS AND DISCUSSION

Weather Conditions

Weather from 2007 through 2017 provided a wide range of growing conditions for the biofuel feedstock crops. Below-Normal temperatures characterized 2008 and 2009 as illustrated by cumulative growing-season GDU (Fig. 1). The subsequent 3 yr, 2010 through 2012, plus 2016 had above Normal temperatures, but the remaining years were not far from Normal. Growing-season precipitation was below Normal in 6 out of the 11 yr, with record-breaking drought in 2012 (Hoerling et al., 2014). Three years (2007, 2008, and 2016) had growing-season precipitation that exceeded Normal by more than 100 mm. These annual variations in temperature and precipitation likely influenced relative performance of the crops in specific years based on their developmental and growth responses to environmental conditions (Abendroth et al., 2011; Roozeboom and Prasad, 2016) and as reflected in previous research (Wilhelm and Wortmann, 2004). Analysis of variance over years indicated highly significant interactions (probability of a greater $F < 0.0001$) of crop with year for all response variables. Therefore, all response variables were subjected to analysis of variance for each year, and treatment means were separated using pairwise t tests at $\alpha = 0.05$.

Table 3. Conversion factors used to estimate potential ethanol yields from biofuel feedstock crops grown at Manhattan, KS, 2007 to 2017.

	Fraction		
Crop	Grain	Stover	Source
	— L dry Mg^{-1} —		
Corn	495	330	Wang et al., 2005; Humbird et al., 2011
Sorghums	480	270	Wu et al., 2007; Xu et al., 2011
BMR sorghum	480	291	Rivera-Burgos, 2015
Sweet sorghum	480	560†	Cifuentes et al., 2014; Rivera-Burgos, 2015
Miscanthus	–	256	Zhang et al., 2015
Switchgrass	–	334	Mitchell et al., 2012
Big bluestem	–	332	Zhang et al., 2015

† Sweet sorghum stover conversion includes conversion of cellulosic biomass plus free sugars.

Grain Production

Grain yield varied by year and by crop (Table 4). Rotated corn usually produced the most grain, followed by continuous corn, and both surpassed grain production of sorghum, agreeing with comparisons of corn and grain sorghum in Nebraska that documented greater grain production from corn (Wortmann et al., 2010). Notable exceptions were 2011 and 2012, when temperatures were substantially warmer than normal, precipitation was substantially less, and both corn crops produced less grain than one or more of the sorghum crops. A meta-analysis of yield data from the region by Assefa et al. (2014) showed that sorghum typically produced more grain than corn when April to September precipitation was less than 432 mm. Sorghum grain yield has historically been more stable than corn grain yield in non-irrigated production scenarios in the semiarid Great Plains (Assefa et al., 2014). The yield advantage for corn rotated with soybeans compared to continuous corn has been well documented, with an even greater advantage for rotation in no-till systems (Triplett and Dick, 2008; Wilhelm and Wortmann, 2004). Grain yields of dual purpose and grain sorghum were similar in most years, with dual purpose sorghum producing more grain in 3 of the 11 yr (Table 4). Dual purpose sorghum averaged 76 cm taller than grain sorghum (data not shown) and may have intercepted light more efficiently, translating to a yield benefit in some years. Graham and Lessman (1966) documented the positive influence of plant height on grain yield, possibly due to less intra-plant shading. Grain sorghum yielded more than dual purpose sorghum only in 2012 when an early-season

Table 4. Dry grain yields of biofuel feedstock crops grown at Manhattan, KS, 2007 to 2017.

	Year											LS‡
Crop†	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Mean
						$\mathrm{Mg\ ha^{-1}}$						
Cont-corn	8.7b§	9.1b	6.5b	3.4c	3.5b	2.3c	6.5a	8.8b	8.4b	9.2a	9.5b	6.8b
R-corn	10.0a	11.0a	9.4a	6.1a	4.2b	3.1bc	7.0a	11.6a	9.3a	10.6a	11.2a	8.3a
Sweet sorghum	1.5f	2.1d	< 0.1d	1.7d	0.5c	—	—	4.2d	2.0d	3.6c	3.9e	1.9d
DP sorghum	6.7c	5.0c	3.9c	4.5b	6.5a	3.9b	6.4a	7.2c	6.1c	5.4b	7.3cd	6.0c
BMR sorghum	3.9e	2.7d	—	1.5d	—	—	—	—	1.9d	3.4c	5.7d	—
Grain sorghum	5.6d	5.3c	4.8c	4.2bc	3.6b	6.8a	4.9b	7.2c	6.9c	5.2b	7.6c	5.7c

† Cont, continuous; R, rotated; DP, dual purpose; BMR, brown midrib.

‡ Least square means.

§ Values followed by the same letter within a column are not significantly different ($\alpha = 0.05$).

Table 5. Dry stover yields of biofuel feedstock crops grown at Manhattan, KS, 2007 to 2017.

	Year											LS‡
Crop†	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Mean
						$\mathrm{Mg\ ha^{-1}}$						
Cont-corn	11.8bc§	10.3de	8.8de	5.1ef	5.0e	2.5e	8.2c	9.8f	6.9ef	6.5f	11.4cde	7.6 ef
R-corn	11.3bc	11.2cde	11.7abc	6.5ef	6.9de	3.6e	8.7c	13.4e	8.8d	8.0ef	13.3cd	9.2 d
PTS sorghum	26.8a	22.2b	11.3abcd	20.8a	18.8a	19.0a	18.2a	25.4b	20.2a	24.2a	21.3ab	20.6 a
Sweet sorghum	26.1a	29.8a	10.3bcde	21.5a	16.9ab	18.7ab	20.8a	27.9ab	12.8b	21.7b	24.5ab	20.7 a
DP sorghum	13.1b	15.5c	11.0abcd	15.7b	13.1c	10.1c	5.1d	19.9cd	8.6d	12.3d	18.6b	13.0 b
BMR sorghum	11.0c	11.0de	13.5a	13.3bc	12.9c	16.1b	10.6c	29.9a	7.3e	11.8d	10.2def	13.4 b
Grain sorghum	8.2d	13.7cd	8.1e	10.6cd	7.9d	7.5d	4.2d	17.8d	5.9fg	9.1e	9.5ef	9.2 de
Miscanthus	2.7e	11.8cd	12.1ab	9.7d	17.8a	—	19.1a	20.9c	11.9bc	17.5c	11.9cde	13.8 b
Switchgrass	3.6e	7.2e	9.1cde	7.9de	14.4bc	—	14.3b	17.6d	10.9c	13.0d	14.3c	11.4 c
Big bluestem	3.8e	7.7e	4.7f	3.8f	8.0d	—	—	11.6ef	5.1g	8.0ef	6.1f	6.5 f

† Cont, continuous; R, rotated, BMR, brown midrib; DP, dual purpose; PTS, photoperiod-sensitive.

‡ Least square means.

§ Values followed by the same letter within a column are not significantly different ($\alpha = 0.05$).

infestation of chinch bugs (*Blissus leucopterus*) affected the dual-purpose sorghum more than the grain sorghum. In the drought years of 2011 and 2012, dual-purpose sorghum or grain sorghum produced more grain than either corn crop. No grain was produced by BMR sorghum in several years (Table 4) because the cultivar in those years was also photoperiod sensitive (Table 1). When a grain-producing cultivar was planted, grain yield of BMR sorghum was typically less than that of grain or dual-purpose sorghum (Table 4). Grain yield of sweet sorghum ranged from zero to more than 4 Mg ha^{-1} and typically ranked at or near the bottom, averaging less than 2 Mg ha^{-1} over 11 yr.

Stover Production

Although the amount of stover produced by the different sorghum crops changed with year, their relative rankings were consistent in most years (Table 5). Photoperiod-sensitive sorghum and sweet sorghum usually ranked first or second, often by a significant margin. Stover yields for the two crops were not different from each other in 8 of 11 yr. In the 3 yrs when stover yields of the two crops differed significantly, sweet sorghum produced 34% more stover than photoperiod-sensitive sorghum in 2008, but 58% less in 2015 and 12% less in 2016. The depressed sweet sorghum stover yield in 2015 was likely due to delayed emergence of plants replanted in gaps formed because of surface soil crusting after intense rain events that occurred on the first and fourth days after planting that year (Weather Data Library, 2018). Averaged across 11 yr, stover yields of the two crops were within 0.1 Mg ha^{-1} of each other at more than 20 Mg ha^{-1} (Table 5). Sweet sorghum stover yields in all years of the current study fell within the range reported by Wortmann et al. (2010) from a study conducted at four locations in Nebraska in 2007 and 2008. Stover yields of dual-purpose sorghum and BMR sorghum typically varied between 40 and 75% of the stover yields of photoperiod-sensitive and sweet sorghum. Both dual-purpose sorghum and BMR sorghum matched the top stover yields in 2009, and BMR sorghum stover yield exceeded that of photoperiod-sensitive sorghum in 2014. Although the 11-yr mean stover yields for BMR and dual-purpose sorghum were both close to 13 Mg ha^{-1}, their stover yields differed in 7 of 11 yr, with dual-purpose sorghum stover yield significantly less than that of BMR sorghum in 3 yr and significantly more in 4 yr. Relatively frequent changes in the BMR cultivar likely contributed to this inconsistent ranking (Table 1). Grain sorghum produced less than 10 Mg ha^{-1} of stover, ranking less than the other sorghums in most years and when averaged over years (Table 5). Although the 11-yr mean stover yield of grain sorghum was similar to both continuous and rotated corn, it was less than that of rotated corn in 5 yr when temperatures were near Normal and nearly twice that of either corn crop in 3 yr when growing season precipitation was below Normal (Fig. 1).

Corn stover yields tended to be 30 to 50% of the stover yields of photoperiod-sensitive and sweet sorghum and often were similar to one or more of the other sorghums (Table 5). Exceptions were in 2009, a relatively cool year (Fig. 1) when stover yield of rotated corn was similar to that of the top-yielding crops and in 2010, 2012, and 2014 when corn stover yields were significantly less

Table 6. Total dry biomass yields of biofuel feedstock crops grown at Manhattan, KS, 2007 to 2017.

Crop†	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	LS‡ Mean
						Mg ha^{-1}						
Cont-corn	20.6b§	19.4b	15.3b	8.5d	8.5de	4.8c	14.7c	18.6de	15.2c	15.7cd	20.9cd	14.4d
R-corn	21.3b	22.2b	21.2a	12.6bc	11.1cd	6.7c	15.7bc	25.0c	18.1b	18.7b	24.6bc	17.4c
PTS sorghum	26.8a	22.2b	11.3def	20.8a	18.8a	19.0a	18.2ab	25.4c	20.2a	24.2a	21.3c	20.7b
Sweet sorghum	27.6a	32.0a	10.3ef	23.2a	17.3a	18.7a	20.8a	32.1a	14.8c	25.3a	28.4a	22.4a
DP sorghum	19.7b	20.5b	14.9bc	20.2a	19.6a	14.0b	11.5de	27.1bc	14.7c	17.7bc	25.9ab	18.9c
BMR sorghum	14.9c	13.7c	13.5bcd	14.8b	12.9bc	16.1ab	10.6e	29.9ab	9.2f	15.1d	15.9e	15.1d
Grain sorghum	13.7c	19.0b	12.9bcde	14.8b	10.8cd	14.3b	9.1e	25.0c	12.8d	14.3de	17.2de	14.6d
Miscanthus	2.7d	11.8cd	12.1cdef	9.7cd	17.8a	—	19.1a	20.9d	11.9de	17.5bc	11.9f	13.7d
Switchgrass	3.6d	7.2e	9.1f	7.9d	14.4b	—	14.3cd	17.6e	10.9e	13.0e	14.3ef	11.3e
Big bluestem	3.8d	7.7de	4.7g	3.8e	8.0e	—	—	11.6f	5.1g	8.0f	6.1g	6.5f

† Cont, continuous; R, rotated; PTS, photoperiod-sensitive; DP, dual purpose; BMR, brown midrib.

‡ Least squares means.

§ Values followed by the same letter within a column are not significantly different (α = 0.05).

than stover yields of all sorghum crops. Although continuous and rotated corn stover yields were similar in 8 of 11 yr, stover yield of continuous corn was significantly less than that of rotated corn in the remaining 3 yr as well as for the 11-yr mean (Table 5), coinciding with the grain yield pattern for the two corn crops (Table 4). The 11-yr mean stover yields of 7 to 9 Mg ha^{-1} for continuous and rotated corn are greater than the 7 Mg ha^{-1} reported by Karlen et al. (2014) in the Corn Belt. This difference may reflect the direct harvest of standing residue in the current study compared to post-grain harvest removal of stover reported by Karlen et al. (2014).

Although all three perennial grasses had production in all years of the experiment, yields were not recorded for any perennials in 2012 or for big bluestem in 2013 because of the misapplication of herbicide to these crops in the spring of 2012 (Table 5). As with most perennial grass crops, it took a year or two for the stands fill in and become established. Even so, miscanthus yield was similar to the stover yield of some of the sorghum crops already in 2008. In 2009, 2011, and 2013, miscanthus yield was similar to the stover yield of top-ranked annual crops and was within 30% of those crops in 2014 to 2016. Peak miscanthus yields were close to 20 Mg ha^{-1} in 2013 and 2014 and were not far from that in 2016. Switchgrass yield was similar to that of miscanthus in three of the nine post-establishment years when yields were recorded, with both crops averaging 11 Mg ha^{-1} in those years. In the remaining six post-establishment years, switchgrass yield was significantly less than that of miscanthus and averaged 2.4 Mg ha^{-1} less over 11 yr. Big bluestem yield ranked less than all crops in most years, but was similar to the stover yield of continuous and/or rotated corn in five of eight post-establishment years when yields were recorded. In 2011, big bluestem produced significantly more than continuous corn stover. In most years and averaged over 11 yr, big bluestem yield was roughly half that of miscanthus and switchgrass, following a similar trend reported in 2 yr of yields from established big bluestem and switchgrass in South Dakota (Lee et al., 2009).

Total Biomass Production

Total biomass yield was the sum of stover and grain yield and was the same as stover yield for crops that did not produce grain: all three perennial grasses, photoperiod-sensitive sorghum, BMR sorghum in the years when a photoperiod-sensitive cultivar was planted, and sweet sorghum in 2012 and 2013 when it failed to produce grain (Tables 5 and 6; Fig. 2A). Even though sweet sorghum produced relatively little grain in most years (Table 4), it produced the most biomass or was similar to the top biomass yield in 9 of 11 yr, exceeding 30 Mg ha^{-1} in 2008 and 2014. The 11-yr average of more than 22 Mg ha^{-1} (Table 6) was similar to the average of yields from 7 site–yrs reported by Wortmann et al. (2010) in Nebraska. Cool temperatures in 2009 (Fig. 1) and emergence issues in 2015 were the likely causes of sweet sorghum biomass yields less than 15 Mg ha^{-1} in those years. Photoperiod-sensitive sorghum often had biomass yield similar to that of sweet sorghum, but produced less biomass than sweet sorghum in 2008, 2014, and 2017 and more in 2015. Biomass yields of photoperiod-sensitive sorghum were less variable than those of sweet sorghum and averaged only 1.7 Mg ha^{-1} less over the 11-yr experiment (Table 6). Of the remaining sorghum crops, relatively consistent grain production by dual-purpose sorghum (Table 4) resulted in total biomass production that often was within 25% of sweet sorghum biomass production and was superior to biomass production by BMR sorghum and grain sorghum, averaging nearly 19 Mg ha^{-1} (Table 6; Fig. 2A). Total biomass production by BMR sorghum and grain sorghum often was similar, averaging close to 15 Mg ha^{-1}, and tended to be less variable than for the other crops evaluated.

Rotated corn biomass yield averaged 17.4 Mg ha^{-1} (Table 6), similar to past reports for corn biomass yield (Dhugga, 2007; Karlen et al., 2014; Rooney et al., 2007). Although rotated corn biomass yields were only 1.5 Mg ha^{-1} less than that of dual purpose sorghum and 5 Mg ha^{-1} less than that of sweet sorghum, a greater fraction was in the form of grain (Fig. 2A). Biomass yield of rotated corn exceeded that of continuous corn in 6 of 11 yr and was 3 Mg ha^{-1} greater averaged over 11 yr (Table 6), largely due to greater grain yield of rotated corn (Table 4; Fig. 2A). Continuous corn biomass yield was similar to that of BMR sorghum and grain sorghum in several years (Table 6). Biomass yield of rotated corn was superior to that of all other crops in 2009 when temperatures were below Normal, and precipitation was near Normal (Fig. 1). In 2012, biomass yield of both corn crops averaged 5.8 Mg ha^{-1}, which was significantly less than biomass yield of all sorghum crops, likely due to warm temperatures and severe drought (Hoerling et al., 2014). Several of the sorghum crops yielded more than both continuous and rotated corn in years that had above-average temperatures and/or below

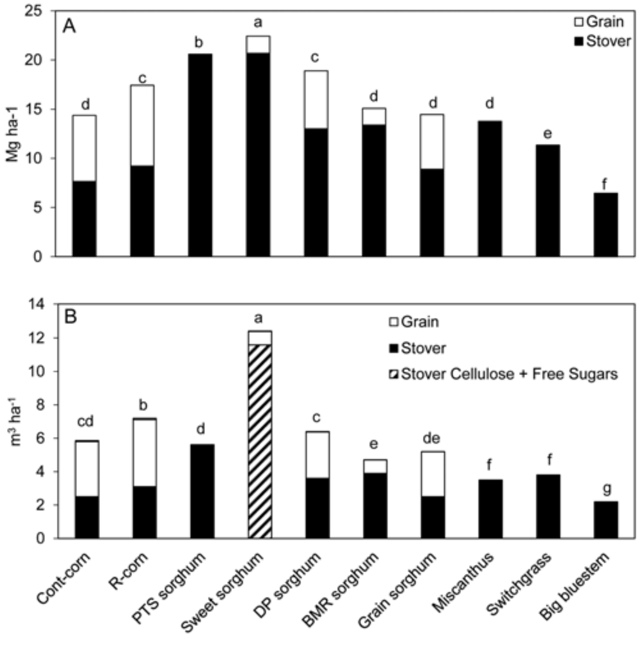

Fig. 2. Average annual total dry biomass (A) and estimated annual total ethanol (B) yields of biofuel feedstock crops grown at Manhattan, KS, 2007 to 2017. Cont, continuous; R, rotated, BMR, brown midrib; DP, dual purpose; PTS, photoperiod-sensitive.

normal precipitation. Rotated corn was competitive with several of the sorghum crops in years that were more favorable but seldom exceeded them all in biomass production.

Miscanthus was the only perennial grass with biomass yields similar to annual crops in most years and averaged over years (Table 6). After the establishment year, miscanthus biomass yield was similar to one of the sorghum or corn crops in 8 of 10 yr when yields were recorded. The multi-yr mean was similar to that of continuous corn, BMR sorghum, and grain sorghum, averaging 14.4 Mg ha^{-1} across the four crops (Fig. 2A). Switchgrass biomass yields were similar to or less than those of miscanthus in every year, and the 11-yr mean was 2.4 Mg ha^{-1} less. Yields of miscanthus and switchgrass appeared to peak 7 or 8 yr after planting, 2 or 3 yr later than the 5 or 6 yr identified by Arundale et al. (2013a), but this delay in peak yields could have been related to the accidental herbicide application to the perennial grasses in 2012. Big bluestem biomass yields were roughly half those of switchgrass in most years and averaged 4.8 Mg ha^{-1} less than switchgrass. Morris et al. (2016) documented a yield reduction for a mixture of switchgrass and big bluestem compared to a mixture of switchgrasses in 2 yr and a yield increase in 1 yr of 5 production yr in Illinois. Hong et al. (2013) also reported consistently less yield for big bluestem compared to switchgrass in 9 site–yrs of yield data from the northern Great Plains.

Potential Ethanol Production

Total potential ethanol yields (Table 7) were determined by summing ethanol contributions estimated from all biomass fractions using crop-specific and fraction-specific conversion factors (Table 3). Sweet sorghum produced the most ethanol in 10 of 11 yr, often surpassing 10 m^3 ha^{-1}. Not only did sweet sorghum often have the most production of biomass of all crops evaluated (Table 6), it also had potential ethanol production from free sugars contained in the stalks as well as a nominal amount of potential ethanol production from grain (Fig. 2B). Photoperiod-sensitive sorghum produced the same amount of stover biomass as sweet sorghum (Table 5), but with less than half as much potential ethanol production because of the lack of grain or fermentable sugars contained in juice (Fig. 2).

Rotated corn most often followed sweet sorghum in total ethanol production and was the only crop to surpass sweet sorghum, which occurred in 2009 (Table 7). Rotated corn produced 3 Mg ha^{-1} yr^{-1} more biomass and 1.2 m^3 ha^{-1} yr^{-1} more ethanol than continuous corn. Dual purpose sorghum combined relatively substantial production of both grain and stover (Fig. 2), which resulted in estimated ethanol yields that trailed only rotated corn and sweet sorghum in most years, substantiating previous claims that greater plant height should result in greater biomass and ethanol yield (Salas Fernandez et al., 2009). Dual-purpose sorghum estimated ethanol production surpassed both corn crops in 2011 and 2012. Both rotated corn and dual-purpose sorghum had a greater proportion of their biomass yield in the form of grain, which has a greater ethanol conversion rate than stover (Table 3). The estimated ethanol yields from the grain fraction ranged from 2.7 m^3 ha^{-1} for grain sorghum to 4 m^3 ha^{-1} for rotated corn. Photoperiod-sensitive sorghum, continuous corn, and grain sorghum had similar 11-yr mean estimated ethanol production, but their ranks changed from year to year. Estimated ethanol production from BMR sorghum was similar to that of grain sorghum but lagged behind the other sorghum crops (Fig. 2B).

The perennial grasses were estimated to have roughly half the potential annual ethanol production of most of the annual crops (Table 7). Previous comparisons of corn and switchgrass in Nebraska in 2000 to 2004 indicated that ethanol production from the two crops was roughly equal (Varvel et al., 2008). Varvel et al. (2008) conducted those comparisons on less productive soils, with only half of the corn stover harvested, with both crops receiving the same amount of N fertilizer, and using the same conversion factor for both crops, but the current study was on highly productive soils, removed all corn stover, and used conversion factors specific to each crop (Table 3). Estimated ethanol production from miscanthus and switchgrass was similar to that of several of the sorghums and ranked better than some of them in 2011 and 2013 (Table 7). Estimated ethanol production from big bluestem was only two-thirds that of the other perennial grasses. Although the accidental application of a nonselective herbicide in 2012 may have contributed to its relatively poor performance, estimated ethanol yields of big bluestem had already begun to lag behind that of miscanthus and switchgrass in 2009 through 2011. Stand reduction of this species over time (data not shown) may indicate that it is unsuited to the management imposed in this study.

Although long-term biomass production and estimated ethanol yield for annual and perennial biofuel crops varied with year depending on weather conditions, the different crops demonstrated specific attributes that could allow them to contribute to the overall feedstock supply. Corn, grain producing sorghums, and sweet sorghum were documented to produce significant quantities of both first- and second-generation biofuel feedstocks, potentially important during the development and adoption of cellulosic ethanol conversion processes (Xu et al., 2018). As cellulosic conversion processes become more cost and energy competitive, perennial crops could form the basis

Table 7. Estimated total ethanol yields of biofuel feedstock crops grown at Manhattan, KS, 2007 to 2017.

	Year											LS‡
Crop†	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Mean
						m^3 ha^{-1}						
Cont-corn	8.2b§	7.9bc	6.1b	3.4d	3.4fg	2.0c	5.9b	7.6de	6.4c	6.7c	8.5c	5.9cd
R-corn	8.7b	9.1b	8.5a	5.2c	4.4cdef	2.7c	6.3b	10.2b	7.5b	7.9b	10.0b	7.1b
PTS sorghum	7.2c	6.0d	3.1e	5.6bc	5.1cd	5.1b	4.9c	6.9ef	5.5d	6.5c	5.7de	5.6d
Sweet sorghum	15.3a	17.7a	5.9bc	12.9a	10.5a	10.5a	11.7a	17.6a	8.1a	13.9a	15.6a	12.4a
DP sorghum	6.7c	6.6cd	4.8cd	6.4b	6.6b	4.6b	4.4cd	8.8c	5.2de	5.9c	8.5c	6.4c
BMR sorghum	5.1d	4.5e	3.9de	4.6d	3.7ef	4.7b	3.1e	8.7cd	3.0g	5.0d	5.7de	4.7e
Grain sorghum	4.9d	6.2d	4.5d	4.9c	3.9def	5.3b	3.7de	8.3cd	4.9e	5.0d	6.2d	5.2de
Miscanthus	0.7e	3.0ef	3.1e	2.5d	4.6cde	—	4.9c	5.4g	3.0g	4.5d	3.1f	3.5f
Switchgrass	1.2e	2.4f	3.0e	2.6d	4.8cd	—	4.8c	5.9fg	3.6f	4.3d	4.8e	3.8f
Big bluestem	1.3e	2.6f	1.5f	1.3e	2.7g	—	—	3.8h	1.7h	2.7e	2.1f	2.2g

† Cont, continuous; R, rotated; PTS, photoperiod-sensitive; DP, dual purpose; BMR, brown midrib.

‡ Least square means.

§ Values followed by the same letter within a column are not significantly different ($\alpha = 0.05$).

of a supply chain where annual crops are inserted for 2 or 3 yr between multi-year cycles of perennial crop stands. Given that perennial crops did not maximize production until 3 to 5 yr into the production cycle, annual crops may be required to maintain feedstock supplies during establishment of perennials. The consistent yields of large quantities of biomass by photoperiod sensitive sorghum documented in the current study illustrate its potential as an annual cellulosic feedstock that could be inserted between cycles of perennial crops or in rotation with soil-building legumes (Fontes et al., 2017). Systems that include both annual and perennial crops could maintain stable feedstock supplies within close proximity to processing facilities, an important consideration for bulky cellulosic feedstocks (Mitchell et al., 2012) and also sustain or possibly enhance long-term soil quality (McGowan et al., 2018). Retiring a set percentage of declining perennial stands each year and producing annual crops for a set number of years would maintain a consistent supply of the various types of feedstocks, which are likely to have unique processing optima (Xu et al., 2011). Although they produced roughly half as much ethanol yield potential as annual crops, perennial crops are uniquely adapted for marginal or contaminated land, providing opportunities for economic return as well as phytostabilization or phytoremediation of such sites (Pidlisnyuk et al., 2014; Pogrzeba et al., 2017; Varvel et al., 2008; Yost et al., 2017).

SUMMARY

Averaged over the 11-yr study, annual crops produced 7 Mg ha^{-1} more biomass each year than perennial crops. Rotated corn combined first and second generation biofuel feedstocks to average more than 7 m^3 ha^{-1} yr^{-1} of estimated ethanol production, second only to sweet sorghum. Sweet sorghum biomass production exceeded 22 Mg ha^{-1} yr^{-1}, outstripping all annual and perennial crops. The additional ethanol production from sugars contained in the stalks plus a small amount of ethanol potentially available from grain resulted in sweet sorghum averaging more than 12 m^3 ha^{-1} yr^{-1} of potential ethanol yield over the 11-yr study. Average potential ethanol yields from grain sorghum, dual purpose sorghum, and photoperiod-sensitive sorghum compared favorably with corn and surpassed corn in hot, dry years.

Perennial crop biomass and potential ethanol yields lagged behind that of annual crops in the establishment years, but eventually matched several of the annual crops in some years. Mean biomass yield of miscanthus was nearly 14 Mg ha^{-1} yr^{-1}, essentially the same as for several annual crops (continuous corn, rotated BMR sorghum, and grain sorghum) but with roughly half as much fertilizer N input. However, less efficient conversion of that biomass to ethanol resulted in 3.6 m^3 ha^{-1} yr^{-1} in average estimated ethanol yield for miscanthus and switchgrass, roughly half as much as that of annual crops that produced a similar amount of biomass and less than a third of the estimated annual ethanol yield of sweet sorghum. After the first 2 yr when the perennial stands were becoming established, big bluestem consistently produced the least amount of biomass and the least estimated ethanol yield in most years, averaging less than 7 Mg ha^{-1} and 1.7 m^3 ha^{-1}, respectively.

CONCLUSIONS

Eleven years of yield results indicate that several of the annual and perennial crops evaluated in this study could play a role as potential bioenergy feedstocks. Corn, dual-purpose sorghum, and grain sorghum produced significant grain yields, providing feedstocks for the mature starch-based ethanol industry. Annual variations in corn and sorghum response to weather conditions in the current study illustrate the importance of targeting these crops to areas and production systems that match their production requirements (Assefa et al., 2014). Although potential ethanol production from sweet sorghum surpassed that of all other annual or perennial crops in the current study, logistical and ethanol conversion challenges remain (Cifuentes et al., 2014). Ethanol production from perennial species via cellulosic conversion pathways also faces substantial challenges (Humbird et al., 2011; USDOE, 2015) in addition to being potentially less productive than annual crops as documented in the current study. However, perennial systems possess potentially substantial benefits in terms of energy inputs, carbon balance, and greenhouse gas emissions (Farrell et al., 2006; Mitchell et al., 2012), and research is underway to address roadblocks to adoption (Clifton-Brown et al., 2017). Balancing the biofuel feedstock supply among these crops could be used to manage the ratio of first and second-generation biofuels as well as the mix of cropping system practices that influence greenhouse gas emissions and soil carbon balance of the biofuel production cycle.

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