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Impact of warm-season grass management on feedstock production on marginal farmland in Central Illinois

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Abstract

The production of dedicated energy crops on marginally productive cropland is projected to play an important role in reaching the US Billion Ton goal. This study aimed to evaluate warm-season grasses for biomass production potential under different harvest timings (summer [H1], after killing frost [H2], or alternating between two [H3]) and nitrogen (N) fertilizer rates (0, 56, and 112 kg N/ha) on a wet marginal land across multiple production years. Six feedstocks were evaluated including *Miscanthus x giganteus*, two switchgrass cultivars (*Panicum virgatum L.*), prairie cordgrass (*Spartina pectinata* Link), and two polycultures including a mixture of big bluestem (*Andropogon gerardii* Vitman), indiangrass (*Sorghastrum nutans*), and sideoats grama (*Bouteloua curtipendula* [Michx.] Torr.), and a mixture of big bluestem and prairie cordgrass. Across four production years, harvest timing and feedstock type played an important role in biomass production. *Miscanthus x giganteus* produced the greatest biomass (18.7 Mg/ha), followed by the switchgrass cultivar "Liberty" (14.7 Mg/ha). Harvest in H1 tended to increase yield irrespective of feedstock; the exception being *M. x giganteus* that had significantly lower biomass when harvested in H1 when compared to H2 and H3. The advantage H1 harvest had over H2 for all feedstocks declined over time, suggesting H2 or H3 would provide greater and more sustainable biomass production for the observed feedstocks. The N application rate played an important role mainly for *M. x giganteus* where 112 kg N/ha yielded more biomass than no N. Other feedstocks occasionally showed a slight, but statistically insignificant increase in biomass yield with increasing N rate. This study showed the potential of producing feedstocks for bioenergy on wet marginal land; however, more research on tissue and soil nutrient dynamics under different N rates and harvest regimes will be important in understanding stand longevity for feedstocks grown under these conditions.

KEYWORDS

bioenergy feedstock, harvest and fertility management, marginal land, mixture, warm-season grass

1 | INTRODUCTION

The production of bioenergy is forecasted to play an important role, particularly as a source of liquid transportation fuel, as the US transitions toward greater energy independence. The U.S. Department of Energy (USDOE) has set a goal to produce 1 billion tons of dry biomass annually to offset the use of petroleum-based fuels and products by 30% (based on consumption in 2005) by 2040 (Johnson, Efroymson, & Langholtz, 2016). Additionally, DOE projected that biomass production would have multiple benefits including stimulating the US economy, increasing the productivity of land resources, as well as improving environmental benefits (US. DOE BETO, 2013). However, even with these multiple benefits, the increased use of biofuels and bio-based products requires feedstock production and conversion to be cost competitive with their current production from fossil fuels (U.S. DOE, 2011). A large component influencing the economics of feedstock production is yield potential. Yield potential is influenced by a number of factors including crop and cultivar, production environment including climate, weather and soil conditions, and soil fertility and harvest management (Lee & Boe, 2005; Mulkey, Owens, & Lee, 2006, 2008; Waramit, 2010). Many of these factors can be controlled by the farmer through management practices; yet, more research is needed to understand how these factors either individually or combined affect biomass productivity, especially on marginal land. Targeting marginal land for bioenergy feedstock production alleviates some competition with food crop production along with providing potential environmental benefits including soil health, water quality, and wildlife habitat (Johnson et al., 2016). Further research will be important to provide recommendations to farmers for future production of bioenergy feedstocks with increased biomass yield and economic benefits on marginal land.

Previous research has already led to the design of best management practices for many warm-season grasses (Mitchell, 2013) where many of those studies, either field-based or modeling, have looked at crop comparisons across locations, years, and/or fertilizer regimes (Lee, Mitchell, Heaton, Zumpf, & Lee, 2018; Song, Jain, Landuyt, Kheshgi, & Khanna, 2014; Wang, Lebaauer, & Dietze, 2010). The review of Wullschleger, Davis, Borsuk, Gunderson, and Lynd (2010), for example, suggested that 100 kg N/ha could be considered an optimum for both upland and lowland switchgrass ecotypes. However, Mitchell, Lee, and Casler (2014) note that optimum fertilizer rates are dependent on field productivity, management practices, and yield potential of cultivars. Variation in these factors helps to explain why yield responses are not always seen in switchgrass (Wullschleger et al., 2010) or even *Miscanthus x giganteus* (referred to as *M. x giganteus*) (Davis, David, Voigt, & Mitchell, 2014; Shield, Barraclough, Riche, & Yates, 2014; Yost, Randall, Kitchen, Heaton, & Myers, 2017). Fertilizer application rates have been recommended to replace, at a minimum, the nutrients removed as a result of annual biomass harvesting. Lee, Parrish, and Voigt (2014) suggested calculating the rate based on tissue N concentration and biomass yield (e.g., 50 kg N/ha should be applied the following spring from an after killing frost harvest of switchgrass yielding 10 Mg/ha with an average tissue N concentration of 0.5%), adjusted for soil N and N-mineralization rates. For *M. x giganteus*, Yost et al. (2017) note that removal can range between 20 and 116 kg N ha^{-1} $year^{-1}$, depending on biomass yield in the United States. Lee, Aberle, et al. (2018) in a multistate study note that fertilizer management is site and species specific, and fertilizer management should be tailored for each situation to reduce input costs and environmental risks.

Harvest timing and frequency of biomass influence yield and nutrient removal. For biomass production, a single harvest is generally recommended for practicality, economics, stand persistence, and environmental sustainability including fossil fuel use and greenhouse gas emissions, where multiple harvests tend to show little to no yield benefits over a single annual harvest (Lee et al., 2014; Mitchell, 2013; Pennington, 2015; Waramit, 2010). With regard to harvest timing, postponing harvest until after a killing frost or post-physiological maturity has also been recommended for perennial grasses used for bioenergy production because it allows time for the plants to senesce or translocate nutrients and water from their aboveground tissues to belowground structures including the crown, rhizomes, and roots (Mitchell, 2013; Mitchell, Vogel, & Uden, 2012; Sarath, Baird, & Mitchell, 2014). For switchgrass, harvesting after a killing frost or physiological maturity can reduce the N requirements needed the following year by one third (Mitchell et al., 2012). However, waiting to harvest after this point (compared to harvesting at peak biomass production around anthesis/flowering), tends to result in yield losses due to senescence, increased litter fall, and greater lodging. For switchgrass, yield losses ranged from 10% to 20% when harvest was delayed until after a killing frost (Pennington, 2015; Waramit, 2010) and greater than 40% when harvest was delayed until the following spring (Pennington, 2015). In contrast, from a feedstock composition perspective, later harvested biomass tends to have lower concentrations of minerals and protein and higher structural carbohydrates and lignin, resulting in higher quality biomass feedstock (Mitchell, 2013).

However, the majority of the previous studies referenced above have assessed biomass production and the impact of management practices on land deemed suitable for row crop production. Less is understood on how warm-season perennial grasses will perform across a variety of landscape conditions including marginal land. The definition of marginal land varies across publications; however, it is based on crop production potential and economic return (underproductive, inaccessible, barren, or set aside land), as well as the environmental risk or degradation associated with crop production or other activities (Baxter & Calvert, 2017; Gopalakrishnan, Negri, & Snyder, 2011; Peterson & Galbraith, 1932; Ssegane et al., 2016). Many studies have discussed the importance and potential of warm-season grass production on marginal land for bioenergy (Gopalakrishnan et al., 2011; Kludze et al., 2013; Quinn et al., 2015) but few studies have actually assessed their production potential on marginal land (Boe et al., 2009; Gelfand et al., 2013). Because marginal land can be underproductive for row crops, yield potential for bioenergy crops on these lands also comes into question. In addition, due to the range of environmental factors that result in the classification of these lands as marginal, yield response across marginal lands is also expected to vary. Site-specific conditions including temperature, soil moisture, soil fertility, and water holding capacity, to name a few, can influence crop establishment and performance. As a result, these site-specific conditions will ultimately influence the selection of crops by farmers for production across different environmental and geographical locations. Many perennial grass species targeted for feedstock production typically have wide production ranges and environmental tolerances that aid in their attractiveness for production (Parish, Dale, English, Jackson, & Tyler, 2016; Yost et al., 2017). Schröder et al. (2018) also argue that with targeted management practices that are soil specific, the yield potential of crops produced on marginal lands can be improved. This suggests that much of the previous research on management practices such as N fertilizer use and harvest timing with warm-season perennial grasses may not directly apply to feedstock production on marginal land.

As a result, this study attempted to assess the potential interactions between management practices, crop selection, and their influence on biomass production on marginal land in Central Illinois. It included the comparison of different warm-season grass species that have the potential to be used for feedstock production in the Midwest including native tallgrass prairie species [big bluestem (*Andropogon gerardii* Vitman), indiangrass (*Sorghastrum nutans*), prairie cordgrass-(*Spartina pectinata* L.), sideoats grama (*Bouteloua curtipendula* [Michx.] Torr.), and switchgrass (*Panicum virgatum* L.)] along with non-native *M. x giganteus*. For switchgrass, a new high-yielding biomass cultivar, "Liberty", developed for biomass feedstock production, was included in the study and compared to "Shawnee" a switchgrass cultivar designed for forage production, selected from "Cave-in-Rock" (Mitchell, 2013). Two polyculture mixtures were also included to assess impact of site-specific shifts in species adaptation on biomass production. The objective of this study was to understand interactions among fertilizer rate, harvest regime, and species and/or mixture that optimized biomass productivity for Central Illinois. This information can be used to develop decision-support tools for crop producers, improve calibrations/validations for biophysical and economic biomass models, and provide additional field-based data to support development strategies for bioenergy production on wet marginal land.

2 | MATERIALS AND METHODS

A field experiment, consisting of two plantings at the same location, was carried out from 2012 to 2017 in Urbana, Illinois (40°07′20.4″N, 88°22′09.0″W) on Drummer silty clay loam soils (fine-silty, mixed, superactive, mesic Typic Endoaquolls) with 0%–3% slope. The experimental area located in a footslope landscape position is categorized as land capability class (LCC) 5W due to frequent spring flooding that prevents the normal production of row crops (USDA NRCS, 2001). Prior to the start of the study, no crop was planted on this area since 2007 due to seasonal spring ponding up to 10 cm deep that extended, in some cases up to 2 weeks. Spring ponding tended to occur prior to timing of emergence for warm-season grasses and extended until the early stage of growth, four-leaf stage, depending on the year. Soil samples were collected prior to planting to determine soil nutrient characteristics (soil organic matter: 5%, pH: 6.7, NH_4-N: 6.0 mg/kg, NO_3-N: 1.0 mg/kg, K: 157 mg/kg, and P: 72 mg/kg).

The first planting, denoted henceforth as the 2012 planting, was done on May 17, 2012 (for all seeded cultivars and mixtures) and on June 6, 2012 (for plug planting of *M. x giganteus*). Drought conditions in 2012 resulted in poorer stand establishment and loss of much of the *M. x giganteus* transplants. It was decided that only the *M. x giganteus* required replanting in the spring of 2013 (June 4) based on frequency counts in the summer and fall of 2012 (Vogel & Masters, 2001). Although, harvest was initially expected to begin for the second season in 2013, due to the poor establishment in the first season, all plots were allowed a second year to establish without harvest. In the spring of 2013 (May 15), the experiment was repeated in a second area adjacent to the 2012 planting including all treatments except for one due to seed limitation (henceforth denoted as the 2013 planting).

The experimental design for both plantings was arranged as a split-split plot within a randomized complete block design with four replications. Harvest timing was treated as the whole plot which included three harvest regimes (annual summer harvest: H1; annual harvest after a killing frost: H2; and an alternate year harvest of H1 and H2: H3). Harvest for both plantings started in 2014. Within each harvest timing, six feedstocks (subplot) were evaluated in the 2012 planting, whereas only five of those feedstocks were evaluated in the 2013 planting. Two switchgrass cultivars ("Liberty" and "Shawnee"), "Savoy" prairie cordgrass, and *M. x giganteus* Greef et Deu (collected from University of Illinois Horticulture Research Center) (Lee, Mitchell, et al., 2018) were assessed as monocultures. Two polycultures were also evaluated, where the first polyculture consisted of a broad Midwest-adapted mixture of "Goldmine" big bluestem, "Warrior" indiangrass, and "Butte" sideoats grama (denoted as BBxINxSOG), and the second polyculture (included only in the 2012 planting) was an Illinois-adapted mixture of "IL ecotype" big bluestem and "Savoy" prairie cordgrass (denoted as "Savoy" × IL BB). Feedstock subplots were subdivided into three nitrogen (N) fertilizer rates (sub-subplot: 1.5 m × 4.6 m), including 0, 56, and 112 kg N/ha. Based on the N rate for each treatment, N fertilizer was hand applied annually in the spring at emergence as preweighed urea (46-0-0).

Planting preparation for both plantings included tilling and packing of the soil to control pre-existing weeds and to create a firm seed bed for planting. Grass cultivars and mixtures except for *M. x giganteus* were seeded at a rate of 325 pure live seeds (PLS) per m^2 by drilling preweighed seeds with 19 cm row spacing and 1.3 cm depth using a no-till drill (Great Plains Plot planter, Salina, KS). *Miscanthus x giganteus* was planted by plug with 60 cm row spacing and 90 cm spacing between plants. For pre-emergent weed control, experimental plots containing switchgrass and prairie cordgrass were sprayed with atrazine (2-chloro-4-ethylamine-6-isopropylamino-s-triazine) at 2 kg a.i./ha and quinclorac (3,7-dichloro-8-quinolinecarboxylic acid) at a rate of 0.5 kg a.i./ha immediately after planting. Imazapic (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-methyl-3-pyridinecarboxylic acid) was applied in plots containing big bluestem, indiangrass, and sideoats grama at a rate of 70 g a.i./ha.

Aboveground biomass from a 1.2 m × 4.0 m area in each sub-subplot was annually harvested from 2014 to 2017 (Table 1), using a biomass plot harvester (Cibus S, Wintersteiger, Salt Lake City, UT). All feedstocks were harvested at a cutting height of 10 cm. Fresh plot biomass weight was measured and a subsample was taken for dry matter (DM) calculation. Subsamples were placed in a forced-air oven at 60°C for 5 days to measure moisture content and to report yields on a DM basis.

Biomass data from each planting were analyzed as a linear mixed model using the lme4 and lmerTest packages in the R statistical software version 3.4.3 (R Core Team, 2017). To avoid any carryover effect of surviving 2012 *M. x giganteus* plants or any benefits of a second establishment year for seeded grasses and mixtures, the two plantings were analyzed separately.

Harvest year (4 years), harvest timing (3 timings), feedstock (5 or 6 species/mixtures), and N fertilizer rate (3 rates) and their interactions were included as fixed factors. The randomized arrangement of N rate, feedstock, and harvest timing within each harvest year (as a repeated measure design) was included as the random effect along with replication as a second random factor. Residuals of the model were assessed for normality. Table 2 shows the ANOVA table, where all statistical significance was determined at $\alpha = 0.05$. The lsmeans package in R was used for pairwise mean comparisons using the Tukey method for *p*-value adjustments.

TABLE 1 Harvest dates of warm-season grasses planted on wet marginal land in Urbana, IL. A drought in 2012 (first planting year) led to the planting of a new area adjacent to the first in 2013. Both planting years were harvested at the same time starting in 2014, resulting in the 2012 planting year having 2 years for establishment compared to the 2013 planting year which had one establishment year prior to the first harvest

	Harvest timing[a]		
Year	**H1**	**H2**	**H3**
2014	August 28	December 1	December 1
2015	September 15	December 18	September 15
2016	September 18	November 18	November 18
2017	September 21	November 28	September 21

[a]H1, Summer harvest; H2, Harvest after the first killing frost; H3, Alternate H2 and H1 harvests.

TABLE 2 ANOVA for biomass yields of warm-season grass feedstocks showing main effects and interactions, with significant effects indicated by a *p*-value with an asterisk. Analysis was conducted at $\alpha = 0.05$

	Planting year, $p > F$	
Source of variance	**2012[a]**	**2013[b]**
Harvest year	<0.001*	<0.001*
Feedstock	<0.001*	<0.001*
Harvest timing	<0.001*	<0.001*
N rate	<0.001*	<0.001*
Harvest year × feedstock	<0.001*	<0.001*
Harvest year × harvest timing	<0.001*	<0.001*
Feedstock × harvest timing	<0.001*	<0.001*
Harvest year × N rate	0.138	0.690
Feedstock × N rate	0.036*	0.029*
Harvest timing × N rate	0.360	0.036*
Harvest year × feedstock × harvest timing	<0.001*	<0.001*
Harvest year × feedstock × N rate	0.296	0.863
Harvest year × harvest timing × N rate	0.675	0.970
Feedstock × harvest timing × N rate	0.988	0.003*
Harvest year × feedstock × harvest timing × N rate	0.986	0.917

[a]Planting was initially done in the spring of 2012. Due to drought conditions, *Miscanthus x giganteus* plots were replanted in 2013. All other feedstocks were not replanted but allowed a second year for establishment before starting harvest in 2014.

[b]The 2013 planting was harvested a year after establishment. Due to seed limitation, one of the feedstocks was not replicated in 2013 planting.

3 | RESULTS

3.1 | Weather

Monthly temperature, precipitation, and their 30 year average (1981–2010) for Urbana, IL are shown in Figure 1, where drought conditions were experienced in 2012 with an annual precipitation of 733 mm compared to the 30 year average of 1,009 mm. Annual precipitation in both 2013 (830 mm) and 2017 (814 mm) were also low compared to the other three study years (1,008 mm in 2014; 1,113 mm in 2015; and 935 mm in 2016). In 2017, especially, precipitation during June and July was much lower than the other study years and the 30 year average.

3.2 | Harvest timing

Analysis of variance (ANOVA) found that the four-way interaction for biomass yield between the fixed factors (harvest year, feedstock, harvest timing, and N rate) was not significant (Table 2). However, for both planting years, the three-way interaction of harvest year, feedstock, and harvest timing was significant (Table 2). The influence of these three factors on biomass yield is shown in Figure 2.

The impact of harvest timing on biomass yield for each feedstock was assessed by looking at biomass yield trends across harvest years (2014–2017) (Figure 2). Annual biomass yield by feedstock did not show, in many cases, a significant decline over time under the H1 (summer) harvest regime. Biomass yields were similar between H1 and H2 (after a killing frost) harvest regimes. However, comparison of the difference between harvestable annual yields between H1 and H2 showed the advantage of an annual summer harvest declined over time in both planting years (Figure 3). This was especially true for *M. x giganteus*, which produced significantly less biomass by 2015 and/or 2016 under the H1 than under the H2 harvest regime for both planting years. *Miscanthus x giganteus* was also the only feedstock that had lower yields under the H1 harvest regime than under the H2 for all harvest years in both planting years with the exception of the 2014 harvest in the 2012 planting year.

"Savoy" and "Savoy" × IL BB also had faster rates of decline in the difference between yield with the H1 harvest and the H2 harvest (Figure 3), particularly in the 2012 planting year. However, only the 2017 yield for "Savoy" in the 2013 planting was significantly higher under H2 than under H1. In the 2012 planting, the BBxINxSOG mixture, "Liberty" and "Shawnee" still had greater biomass yield (numerically) under H1 than H2 across all harvest years. However, in the 2013 planting, all five feedstocks in 2017 had lower biomass under H1 than under H2.

For all feedstocks, there was no consistent difference in biomass yield between H2 and H3 (alternate year harvest between H1 and H2) harvest regimes although differences in biomass yields between H2 and H3 depended on the H3 harvest regime (Figures 2 and 4). In general, biomass yields of H2 were greater in years 2014 and 2016, in which the H3 plots were harvested after a killing frost and biomass yields of H3 were greater in years 2015 and 2017, in which the H3 plots were harvested in summer (Figure 4). An H3 harvest regime resulted in a fluctuating (up and down) annual trend in biomass yield for BBxINxSOG, "Shawnee," and "Liberty" resulting from alternating between an after killing frost harvest and a summer harvest. However, "Shawnee" in the 2012 planting and "Liberty" in the 2013 planting were the only two feedstocks across all production years that had greater biomass production with an H3 harvest regime than an H2.

3.3 | Nitrogen rate

The three-way interaction of N rate, harvest timing, and feedstock for biomass yield was significant (Table 2); however, only for the 2013 planting year, N rate effect on

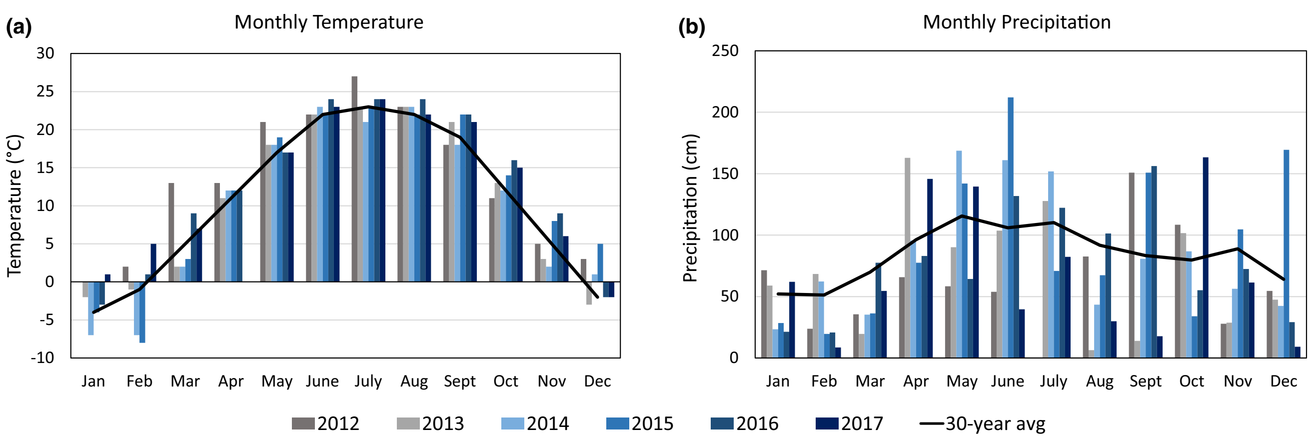

FIGURE 1 Local weather conditions in Urbana, IL (Willard airport: collected from Weather Underground 2012) across the 4 years of study including (a) monthly average temperature and (b) monthly precipitation and the 30-year monthly average (1981–2010) (data: Angel, n.d.)

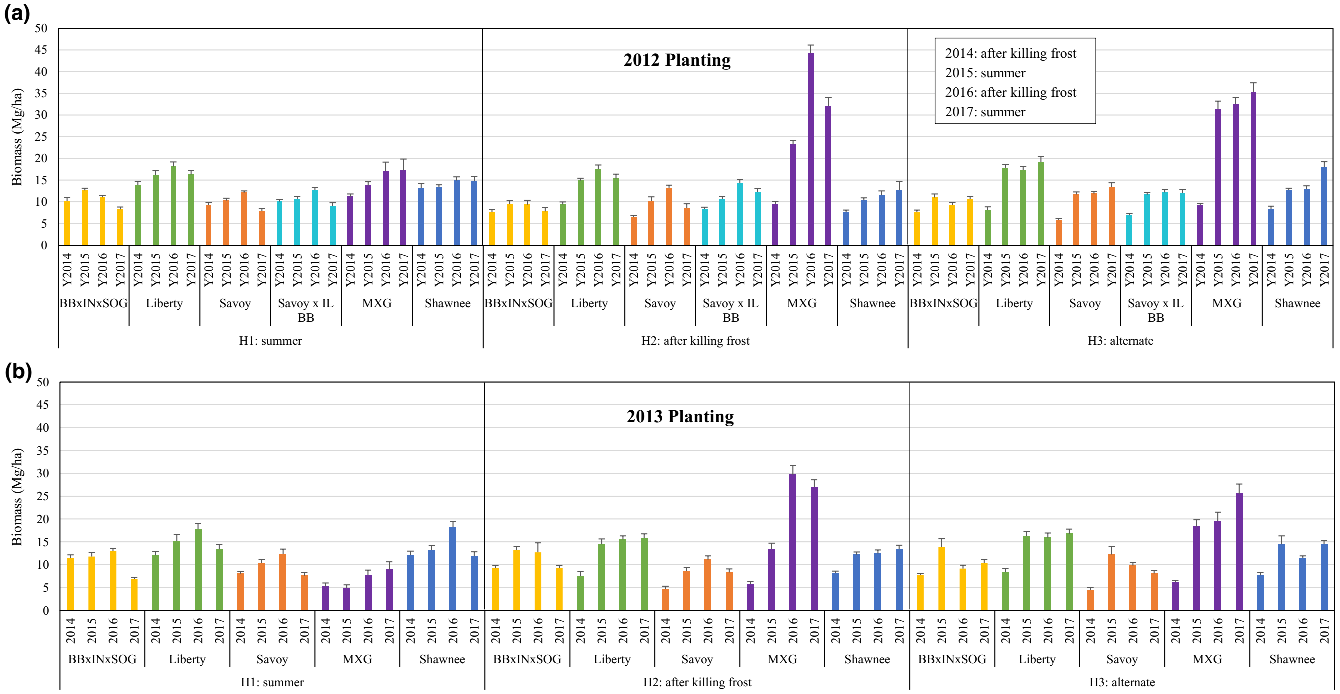

FIGURE 2 The significant three-way interaction between harvest timing, feedstock, and harvest year and their influence on annual biomass yields of warm-season grass feedstocks for (a) 2012 planting and (b) 2013 planting years. Feedstocks evaluated included a mixture of big bluestem (BB, "Goldmine"), indiangrass (IN, "Warrior"), and sideoats grama (SOG, "Butte"), a mixture of local adapted big bluestem (IL BB) and prairie cordgrass ("Savoy"), two switchgrass cultivars ("Liberty" and "Shawnee"), and *Miscanthus x giganteus* (MXG). Feedstocks were harvested under three harvest regimes including a summer harvest (H1), after a killing frost (H2), and alternate year harvest between H2 and H1 (H3), with 2014 being harvested after a killing frost. Mean values were averaged across N rates. Bars represent sample means and errors bars are the standard error of the means

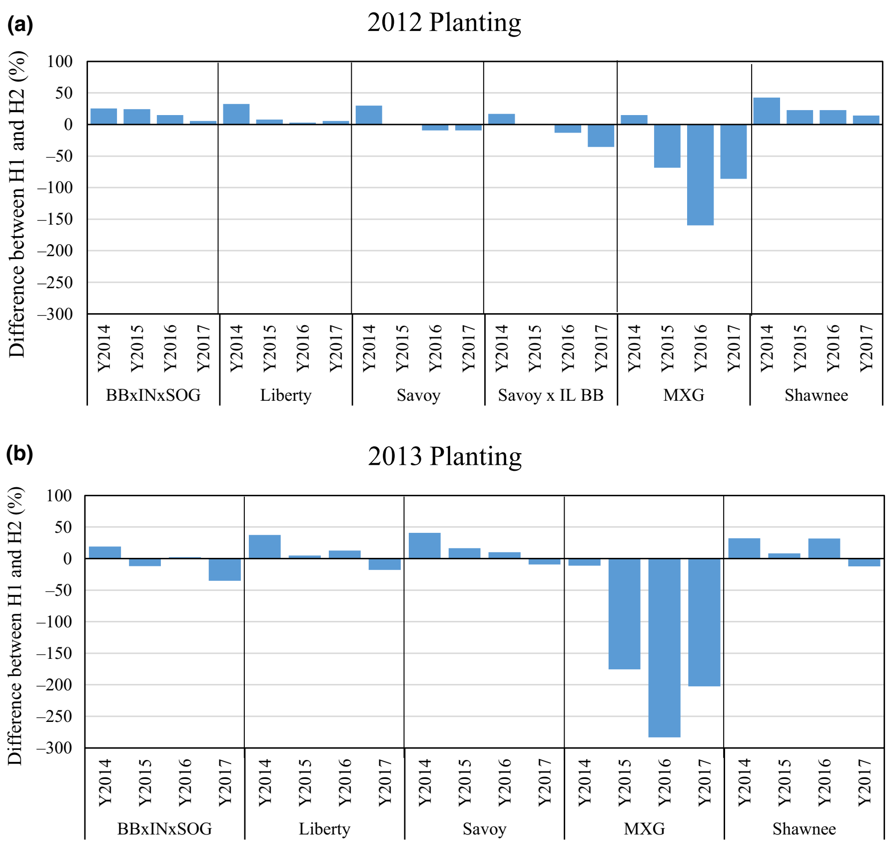

FIGURE 3 Postponing harvest from summer (H1) until after a killing frost (H2) for the 2012 (a) and 2013 (b) planting years. Values are the percent difference between summer harvest and after killing frost using the equation: $((H1 - H2)/H1) \times 100$. Feedstocks evaluated included a mixture of big bluestem (BB, "Goldmine"), indiangrass (IN, "Warrior"), and sideoats grama (SOG, "Butte"), a mixture of local adapted big bluestem (IL BB) and prairie cordgrass ("Savoy"), two switchgrass cultivars ("Liberty" and "Shawnee"), and *Miscanthus x giganteus* (MXG). Positive percent differences represent years when the H1 harvest regime results in greater biomass yields and negative percent differences represent years when H2 harvest results in greater biomass yields

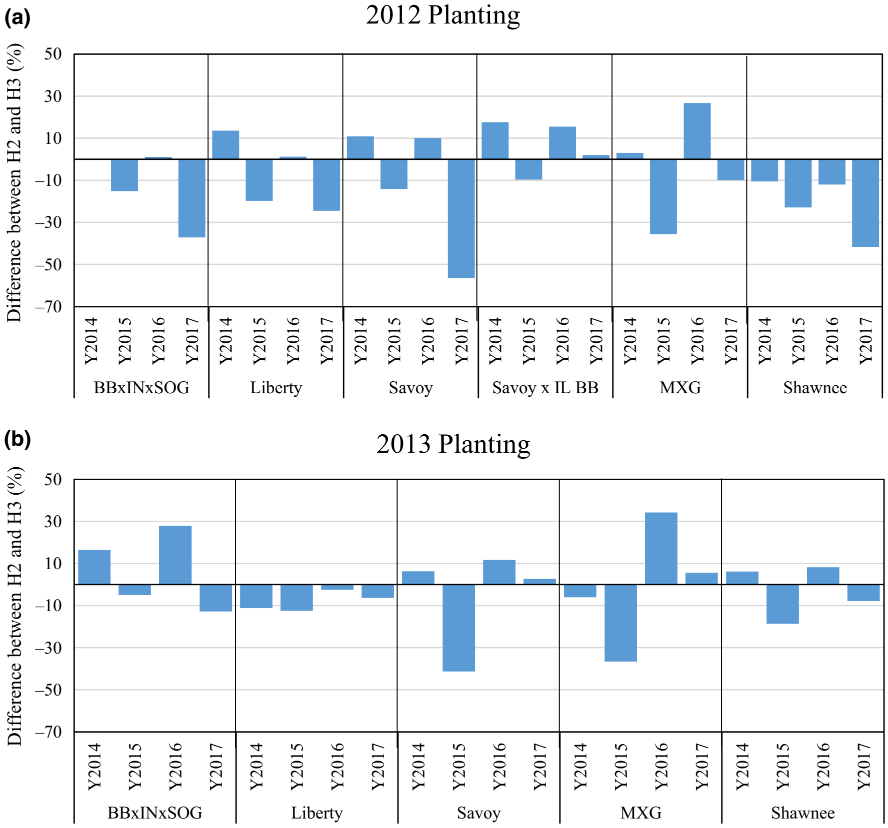

FIGURE 4 Percent difference in biomass production between an after killing frost harvest (H2) and an alternate year harvest between H2 and H1 (H3), with the 2014 harvest being harvested after a killing frost, for the 2012 (a) and 2013 (b) planting years, using the equation: ((H2-H3)/H2) × 100. Feedstocks evaluated included a mixture of big bluestem (BB, "Goldmine"), indiangrass (IN, "Warrior"), and sideoats grama (SOG, "Butte"), a mixture of local adapted big bluestem (IL BB) and prairie cordgrass ("Savoy"), two switchgrass cultivars ("Liberty" and "Shawnee"), and *Miscanthus x giganteus* (MXG). Positive percent differences represent years when the H2 harvest regime results in greater biomass yields and negative percent differences represent years when H3 harvest results in greater biomass yields

M. x giganteus biomass yield was different among harvest regimes. *Miscanthus x giganteus* produced significantly greater biomass with a fertilizer application of 112 kg N/ha than without fertilizer application or with 56 kg N/ha ($p = 0.004$) under the H2 harvest regime. However, at all three fertilizer rates, biomass production was statistically greater under both the H2 and H3 harvest regimes than under H1 ($p < 0.002$). All other feedstocks were not found to have a significant interaction between N rate and harvest timing.

The two-way interaction between feedstock and N rate for biomass yield was significant for both planting years (Table 2). Figure 5 shows the effect of N rate on biomass production by each feedstock. Across all N rates, *M. x. giganteus* produced the most biomass, followed by switchgrass, "Liberty," and "Shawnee" for both planting years, and N application increased biomass yields of some species, *M x. giganteus* (significantly when 112 kg N was applied compared to 0 kg N), and "Liberty," "Savoy," "Savoy" × IL BB, and BBxINxSOG (numerically for at least one of the planting years). The 2012 planting had greater differences in feedstock by N rate comparisons for biomass yield, where generally the application of N did not change the ranking of the species in terms of their biomass production. For example, *M. x giganteus* produced significantly greater biomass than all other feedstocks at all N rate comparisons.

"Liberty" also produced significantly greater biomass than "Savoy" and the "Savoy" × IL BB mixture at all N rate comparisons, while "Liberty" only produced significantly greater biomass than "Shawnee" when both had no fertilization or 112 kg N applied. "Shawnee" also produced significantly greater biomass without fertilizer application than "Savoy" with or without fertilizer application. However, in the 2013 planting, although *M. x giganteus* still produced greater biomass, numerically, than all other feedstocks with the exception of "Liberty" when both had no fertilizer applied, biomass yields were not always significantly greater. "Savoy" and the BBxINxSOG mixture were both the lowest yielding, with many comparisons yielding significantly lower biomass than *M. x giganteus* and "Liberty." The application of N aided in increasing biomass yield for both BBxINxSOG and "Savoy" numerically, however. "Liberty" and "Shawnee" also did not produce significantly different biomass yields regardless of N application. The same was true for *M. x giganteus* and "Liberty."

3.4 | Feedstock

The greatest yielding feedstock across both planting years was *M. x giganteus*, however, only under the H2 and H3 harvest regimes, as previously mentioned. The next highest producing feedstocks included "Liberty" and "Shawnee" switchgrass. Table 3 shows the average biomass production across all harvest regimes, harvest years, and fertilizer rates. Biomass production by *M. x giganteus* was significantly greater (under either H2 or

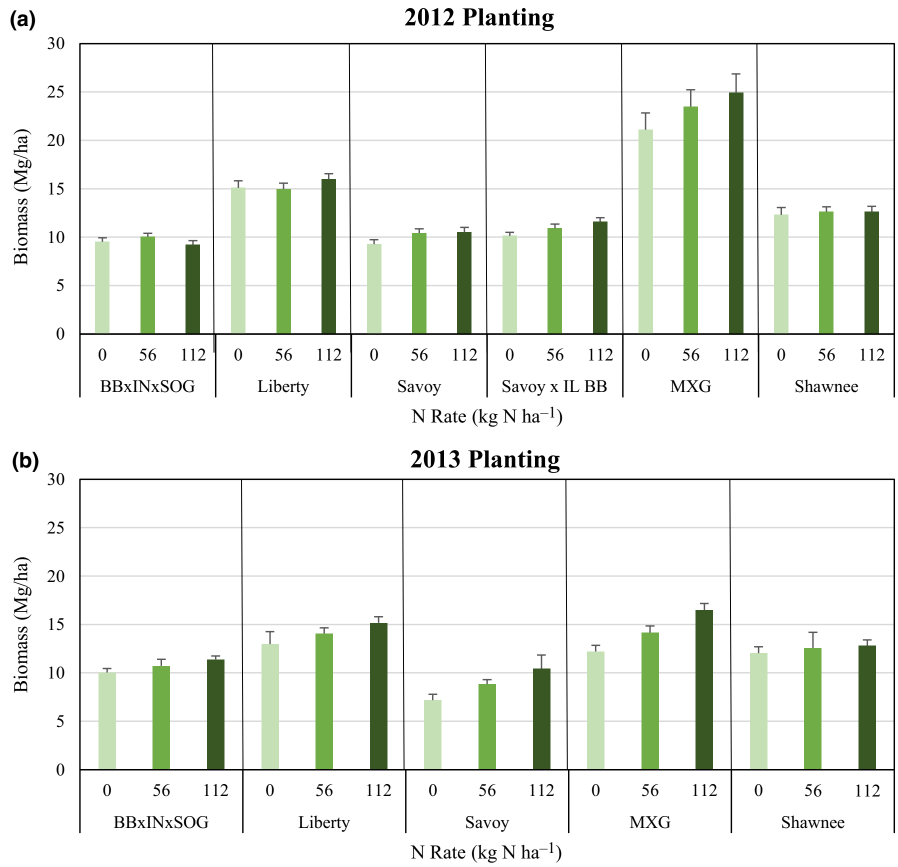

FIGURE 5 Biomass production by N rate and feedstock type: (a) 2012 planting and (b) 2013 planting years. Biomass yields were averaged across harvest timing and year. Feedstocks evaluated included a mixture of big bluestem (BB, "Goldmine"), indiangrass (IN, "Warrior"), and sideoats grama (SOG, "Butte"), a mixture of local adapted big bluestem (IL BB) and prairie cordgrass ("Savoy"), two switchgrass cultivars ("Liberty" and "Shawnee"), and *Miscanthus x giganteus* (MXG). Feedstocks were harvested under three harvest regimes including a summer harvest (H1), after a killing frost (H2), and alternate year harvest between H2 and H1 (H3), with 2014 being harvested after a killing frost. Both planting years were harvested annually from 2014 to 2017. Subplots were fertilized with urea (46-0-0)

H3 harvest regimes) than all other feedstocks for at least two of the production years for both planting years. *Miscanthus x giganteus*, as Table 4 shows, has a later flowering period relative to the other feedstocks. *Miscanthus x giganteus* also was the only feedstock to significantly increase biomass yield between harvest years in the 2012 planting, with the exception of 2017 when biomass significantly declined like some of the other feedstocks. "Liberty," as the second greatest yielding feedstock, also significantly produced greater biomass than other feedstocks including BBxINxSOG and "Savoy" prairie cordgrass after 2015 in the 2012 planting for all harvest regimes.

3.5 | Moisture content

Moisture content of the harvested biomass was also assessed between summer and after killing frost harvests of each harvest year (Table 5). *Miscanthus x giganteus*, BBxINxSOG, and "Liberty" switchgrass had the greatest biomass moisture content during the summer harvest, whereas after a killing frost, *M. x giganteus* maintained a higher moisture content at harvest as did "Savoy" prairie cordgrass and "Savoy" × IL BB. "Liberty" and the BBxINxSOG mixture had the largest loss in biomass moisture between the two harvest periods. In contrast, "Savoy" and the "Savoy" × IL BB mixture had the smallest change in moisture content. Although both had the lowest average moisture content during a summer harvest, other than *M. x giganteus*, both had the highest average moisture content after a killing frost harvest.

4 | DISCUSSION

4.1 | Weather

Precipitation seemed to play a role in biomass yield in 2017. Both the H1 and H2 harvest regimes across many of the species had lower biomass yield in 2017. Although only in a few cases was the difference in biomass yield in 2017 significantly lower than in 2016, such as for the BBxINxSOG mixture and *M. x giganteus* but for only one of the planting years and one of the harvest regimes. Spring precipitation, however, in 2017 was still comparable to the other growing seasons and may be the reason biomass yield was not as significantly impacted. Previous work by Lee, Mitchell, et al. (2018) emphasized the importance of spring (April–July) precipitation for sustainable bioenergy feedstock production in the Midwest.

4.2 | Harvest timing effects on yield, N use, and moisture content

Harvest timing can play an important role in stand persistence and plant nutrient requirements. Switchgrass, for

TABLE 3 Annual biomass yield (Mg/ha) of six feedstocks grown on wet marginal land during the first four production years. Feedstocks evaluated included a mixture of big bluestem (BB, "Goldmine"), indiangrass (IN, "Warrior"), and sideoats grama (SOG, "Butte"), a mixture of local adapted big bluestem (IL BB) and prairie cordgrass ("Savoy"), two switchgrass cultivars ("Liberty" and "Shawnee"), and *Miscanthus x giganteus* (MXG). Feedstocks were harvested under three harvest regimes including a summer harvest (H1), after a killing frost (H2), and alternate year harvest between H2 and H1 (H3), with 2014 being harvested after a killing frost. Both planting years were harvested annually from 2014 to 2017. Subplots were fertilized with urea (46-0-0) at a rate of 0, 56, or 112 kg N/ha. Biomass yields were averaged across all N rates, harvest timings, and production years with the maximum and minimum average production, which were averaged across two planting years, also noted, regardless of harvest year, harvest timing, or N rate

	Biomass (Mg/ha)		
Feedstock	2012 planting	2013 planting	Maximum (minimum) yield
BBxINxSOG	9.6	10.7	18.1 (5.9)
"Liberty" switchgrass	15.3	14.1	20.9 (5.7)
"Savoy" prairie cordgrass	10.1	8.8	17.0 (3.9)
"Savoy" × IL BB	10.9	–	15.5 (6.3)
MXG	23.2	14.3	48.5 (3.7)
"Shawnee" switchgrass	12.5	12.5	20.7 (6.7)

example, reaches maximum annual biomass at or around anthesis (McIssac, David, & Mitchell, 2010; Pennington, 2015; Serapiglia, Boateng, Lee, & Casler, 2016). If the harvest objective is to maximize annual biomass, then harvesting either at or after anthesis would achieve that goal, which was also supported by the results of this study. In general, summer harvests (whether a part of the H1 harvest regime or the H3 harvest regime) yielded the greatest amount of biomass; however, the difference between a summer harvest and an after a killing frost harvest was not generally significant across feedstocks for either planting year. A continual summer harvest (H1) was found detrimental to *M. x giganteus*'s biomass production potential. Although many of the feedstocks evaluated have wide flowering periods, *M. x giganteus* has the latest flowering period (Table 4). *Miscanthus x giganteus* flowers after summer harvest occurs, as compared to the other feedstocks in which summer harvest occurs after flowering. Timing of flowering for *M. x giganteus*, relative to the summer harvest period and other feedstocks, may aid in explaining harvest timing effect. The summer harvest may occur before *M. x giganteus* reaches peak maturity and therefore late harvests allow for additional time for vegetative growth and reproductive tiller growth, resulting in greater biomass harvests after a killing frost than during the summer. All feedstocks also showed a general declining trend in biomass production when biomass was harvested annually in the summer (H1) as compared to harvesting annually after a killing frost (H2). This is important from a long-term production

TABLE 4 Flowering periods for each feedstock in Urbana, IL. Individual flowering times for mixed species: Feedstocks evaluated included a mixture of big bluestem (BB, "Goldmine"—July flowering), indiangrass (IN, "Warrior"—July to early August flowering), and sideoats grama (SOG, "Butte"—July flowering), a mixture of local adapted big bluestem (IL BB—beginning of July to mid-August flowering) and prairie cordgrass ("Savoy"), two switchgrass cultivars ("Liberty" and "Shawnee"), and *Miscanthus x giganteus* (MXG). Feedstocks were harvested under three harvest regimes including a summer harvest (H1), after a killing frost (H2), and alternate year harvest between H2 and H1 (H3), with 2014 being harvested after a killing frost. Both planting years were harvested annually from 2014 to 2017. Subplots were fertilized with urea (46-0-0) at a rate of 0, 56, or 112 kg N/ha

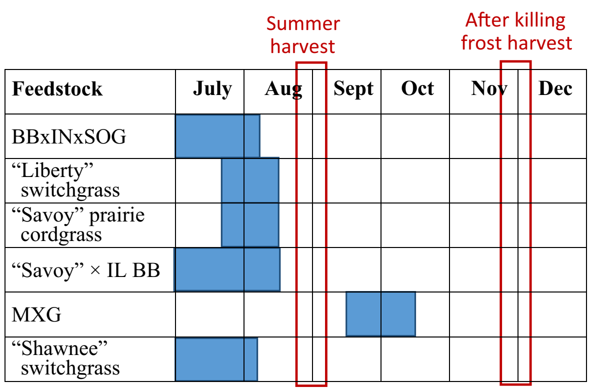

TABLE 5 Moisture content at harvest (% moisture) averaged across location, harvest year, fertilizer rate and harvest timing. Feedstocks evaluated included a mixture of big bluestem (BB, "Goldmine"), indiangrass (IN, "Warrior"), and sideoats grama (SOG, "Butte"), a mixture of local adapted big bluestem (IL BB) and prairie cordgrass ("Savoy"), two switchgrass cultivars ("Liberty" and "Shawnee"), and *Miscanthus x giganteus* (MXG). Feedstocks were harvested under three harvest regimes including a summer harvest (H1), after a killing frost (H2), and alternate year harvest between H2 and H1 (H3), with 2014 being harvested after a killing frost. Both planting years were harvested annually from 2014 to 2017. Subplots were fertilized with urea (46-0-0) at a rate of 0, 56, or 112 kg N/ha

Feedstock	Summer harvest moisture %	After killing frost harvest moisture %
"Liberty" switchgrass	54.0	20.7
"Savoy" prairie cordgrass	46.0	31.6
"Savoy" × IL BB	48.6	29.3
"Shawnee" switchgrass	51.2	23.9
BBxINxSOG	55.8	23.2
MXG	57.0	30.1

standpoint, where a continual summer harvest may reduce the stand longevity for the feedstocks assessed. Harvest at anthesis results in the removal of aboveground tissue that is still actively photosynthesizing. If the stand is harvested early enough to leave time before a killing frost, the plants may be able to regrow a portion of the aboveground tissue to replenish lost organic reserves thereby reducing the impact of an early harvest (Hall, 1994). Delaying harvest until after a killing frost has generally been accepted to improve stand sustainability as the plants will naturally senesce at the end of the season and translocate nutrients to perennial tissues that can be recycled and reused the following year (Lee et al., 2014; Mitchell et al., 2014; Pennington, 2015). Under the H3 harvest regime, however, there were some years where a summer harvest produced greater biomass than after a killing frost. This was true across all the feedstocks evaluated (Figure 4). Both "Shawnee" (in the 2012 planting year) and "Liberty" switchgrass (in the 2013 planting year) had greater biomass production across all harvest years under the H3 harvest regime as compared to H2. This suggests there is some benefit to utilizing an alternate year harvest regime. For *M. x giganteus*, the H1 harvest regime is not recommended, but the potential benefits of a H3 harvest (that include a summer harvest) may still allow for high biomass yields. The application of N fertilizer did not mitigate the effect of an early harvest on biomass yield and stand longevity in this study, as only *M. x giganteus* was found to significantly respond to increasing fertilizer application (112 kg N/ha vs. 0 kg N/ha). Other feedstocks as shown in Figure 4, did respond to fertilizer application but did not produce significantly greater biomass with fertilizer application (56 or 112 kg N/ha). Therefore, the results of this study suggest that 112 kg N/ha would be recommended for *M. x giganteus* production on wet marginal soils; however, the application of fertilizer for the other feedstocks, including "Savoy" prairie cordgrass, the two switchgrass cultivars "Liberty" and "Shawnee" and the two mixtures "Savoy" × IL BB and BBxINxSOG, would not be recommended from a yield increase standpoint. However, two concepts should be kept in mind. This study focuses on biomass only and does not include nutrient dynamics in plant tissue (which will be discussed in a later paper) or soil over time; both of which will be important in more fully understanding the impacts of fertility management on stand health and longevity under these environmental conditions. The other important aspect to consider is initial soil fertility. The production location was on a footslope which is generally characterized as having greater fertility than other landscape positions (Brubaker, Jones, Lewis, & Frank, 1993). Higher initial soil fertility may have offset the impacts of added nutrients on biomass production. As a result, harvest timing played a larger role in biomass production than fertility management, other than for *M. x giganteus*.

An alternate year harvest regime may provide feedstock producers with greater flexibility to adjust to markets/biomass demand or time constraints that may arise from other fall crop harvests such as corn and soybean (Ogden, Ileleji, Johnson, & Wang, 2010). However, it should be noted that an alternative year harvest can result in more variability in harvestable biomass over time for some feedstocks such as the BBxINxSOG mix and "Shawnee," because of the summer (greater biomass) and after a killing frost (lower biomass) harvest alternation. Part of this high-low trend is a result of lower harvestable biomass with senescence and litter loss with a delayed harvest. Although, for some feedstocks such as "Liberty" and "Shawnee," the high-low trend is either very slight or not existent which may also be a factor of the actual timing of summer harvest relative to their physiological maturity. For the switchgrass, the summer harvest may have been too late, where water and nutrients may have already begun to be translocated. This potentially resulted in summer and after killing frost harvestable biomass being more similar, resulting in more of a stable biomass production over time. Previous studies including Fike et al. (2006) and Waramit, Moore, and Heaton (2014) highlight the importance of matching harvest timing with morphological development to improve biomass yield. Fike et al. (2006) note that differences in maturity relative to harvest timing can also impact biomass yield comparisons between species or species' ecotypes. Therefore, in some cases, it could be argued that if the timing of the summer harvest is taken into account relative to the species' physiological maturity, an alternate year harvest could still provide some flexibility in harvest timing across years while prolonging stand longevity, although additional research may be needed to verify this, particularly across much longer term periods.

Another concern with the inclusion of a summer harvest, however, is moisture content. Moisture content in summer harvests is higher than after a killing frost due to the desiccation that occurs in preparation for winter. From a feedstock quality perspective, lower moisture content in the biomass at harvest is more desired (Tanger, Field, Jahn, DeFoort, & Leach, 2013). However, summer harvests in the Midwest are less of a concern. Especially in Illinois, where high air temperatures are still typical throughout the state during late August and early September, high moisture containing biomass is still expected to dry quickly on the field after cutting. Producers tend to leave the biomass dry on the field for a short period of time prior to raking and bailing (Ogden et al., 2010). However, biomass field-drying could be problematic on soils that are marginally productive due to standing water.

4.3 | Feedstock comparison

Regardless of harvest timing and moisture content, one of the largest driving factors for biomass production is yield. When the six feedstocks were compared, *M. x giganteus* had the greatest yield, followed by "Liberty" switchgrass. Yields for both of these feedstocks were significantly greater, especially in the last years of the study, than many of the other feedstocks. Additionally, *M. x giganteus* was the only feedstock that produced annual biomass above 22.4 Mg/ha (10 US ton ac^{-1}) on wetness-prone marginal land, the targeted yield for dedicated bioenergy crop production to meet the US Billion Ton Study's goal of producing 1 billion tons of dry biomass annually to displace 30% of petroleum use (Perlack et al., 2005). Both switchgrass cultivars had average maximum yields (regardless of harvest timing, harvest year, or N rate) that were close to 21 Mg/ha, but their average yields across treatments were lower. In general, *M. x giganteus* also had the greatest magnitude of biomass yield increase between production years than the other species under the H2 and H3 harvest regimes. In fact, under the H2 harvest regime, for both planting years, *M. x giganteus* significantly increased harvestable biomass from 2014 to 2015 and from 2015 to 2016.

Although "Liberty" is a bioenergy selected cultivar as compared to "Shawnee" which was initially targeted for forage quality (Mitchell, 2013; Vogel, Hopkins, Moore, Johnson, & Carlson, 1996), there was only one comparison (H2 harvest in 2016 for the 2012 planting) in which "Liberty" significantly produced more biomass than "Shawnee." All other comparisons were not significant; however, on average, "Liberty" produced about 2.2 Mg/ha more biomass than "Shawnee" across all harvest years, harvest timings, and fertilizer rates. There was only one comparison (H1 harvest in 2016 in the 2013 planting) in which "Shawnee" yielded greater biomass than "Liberty." "Liberty" also had more stable biomass production on average than "Shawnee" across production years (less variation between years). Mitchell (2013) reported "Liberty" yields in Nebraska around 18.1 Mg/ha as a 3 year harvest average, which is about 2.8 Mg/ha greater than the average yield for "Liberty" across treatments in this study.

Comparison of the two polycultures, one locally adapted ("Savoy" × IL BB) and one more regionally adapted (BBxINxSOG), revealed that biomass yields were generally similar. Under the H1 harvest regime, both polycultures produced similar biomass quantities. Under the H2 harvest regime, the local adapted "Savoy" × IL BB mixture produced greater biomass from 2015 to 2017 than the BBxINxSOG mixture. The same was true for the H3 harvest, with the local adapted "Savoy" × IL BB mixture having more of a stable biomass production from 2015 to 2017 than the BBxINxSOG mixture. Averaged between the H2 and H3 harvest regimes, "Savoy" × IL BB produced 2.6 Mg/ha more biomass than BBxINxSOG across the harvest years and fertilizer rates. Mixtures also produced lower biomass yields than monocultures. The major exception to this was the "Savoy" monoculture which produced similar biomass to the two mixtures. These results support previous work (Hong, Owens, Lee, & Boe, 2012; Lee, Mitchell, et al., 2018) that monocultures can outperform mixtures potentially due to species competition; however, it also highlights the importance of species selection for monoculture production.

In summary, this study found that *M. x giganteus* produced the greatest amount of biomass relative to the other feedstocks on wet marginal land, in which frequent spring flooding limits row crop production in Central Illinois. However, individual plot yields suggest that the other feedstocks have the potential to produce a significant amount of biomass, but more breeding or site management may be needed to improve their overall production potential. Harvest timing of these feedstocks also plays a very important role. Summer harvests tend to produce the largest amount of biomass. However, there is a certain cost associated that may impact biomass production over time. Fertilizer was not found to significantly reduce this cost and N fertilization was not a limiting factor for biomass yield during the first 4 years of production on wet marginal land located in a footslope landscape position. Overall, the importance of harvest timing for biomass yield was a larger factor than fertilizer and species in this specific study. An alternative year harvest may provide a compromise to address nutrient and biomass management; however, more research is needed to assess this across multiple locations. This study demonstrated the potential of wet marginal land for bioenergy feedstock production using perennial warm-season grasses.

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