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Harvest Date Effects on Biomass Yield, Moisture Content, Mineral Concentration, and Mineral Export in Switchgrass and Native Polycultures Managed for Bioenergy

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Abstract Various local factors influence the decision of when to harvest grassland biomass for renewable energy including climate, plant composition, and phenological stage. However, research on biomass yield and quality related to a wide range of harvest timing from multiple environments and years is lacking. Our objective was to determine the effect of harvest timing on yield, moisture, and mineral concentration of switchgrass (*Panicum virgatum* L.) and native polyculture biomass. Biomass was harvested on 56 unique days ranging from late summer (2 September) to late spring (20 May) spanning 3 years (2009 to 2011) and seven sites in Minnesota, USA. Biomass yield varied considerably by location and year (range=0.7–11.7 Mg ha^{-1}) and was lowest during the winter. On average, there was no difference in biomass yield harvested in early fall compared to late spring. Biomass moisture content was lowest in late spring, averaging 156 g kg^{-1} across all locations and years when harvested after 1 April. Biomass N concentration did not change across harvest dates; however, P and K concentrations declined dramatically from late summer to late spring. Considering the economic costs of replacing exported minerals and changes in revenues from biomass yield through time, biomass harvest should be conducted in late summer–early fall or late spring and avoided in winter. However, biomass managed for gasification should be harvested in spring to reduce concentrations of minerals that lead to slagging and fouling. Changes in biomass yield and quality through time were similar for switchgrass and native polyculture biomass. These biomass harvest recommendations are made from data spanning multiple years and locations and should be applicable to various growing conditions across the Upper Midwest.

Keywords Switchgrass · Native polyculture · Biomass quality · Harvest date · Bioenergy

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Introduction

About 500,000 ha of US Conservation Reserve Program (CRP) land has been converted from perennial grassland to corn/soybean production since 2006 [1]. Conversion of perennial cover to annual crops results in increased soil erosion, nutrient leaching, and carbon emissions and also fragments wildlife habitat and reduces biodiversity [2–4]. Maintaining low-input grasslands in the CRP for perennial biomass feedstock production could preserve many of the ecosystem benefits accrued during the CRP contract period while also increasing farm profit and supporting development of local bioeconomies. Methods that integrate biomass operations within the schedule of row crop agriculture should increase adoption so that the environmental and economic benefits can be realized. For instance, a typical fall biomass harvest may result in competition for labor or equipment with grain harvest operations, while winter and early spring harvests would extend the harvest window and potentially increase return on equipment investment by increasing hours of operation [5]. Delaying harvest could also expand the temporal availability of feedstocks and reduce the need for feedstock storage, which could help reduce costs. However, access to fields can be challenging in winter or spring in Minnesota and other areas in the Upper Midwest. Johnson and Gresham noted mechanical harvest was only possible prior to April 15 in one of 4 years of their study in Minnesota because of snow cover or muddy conditions [5]. Beyond this date, harvest would compete with spring field operations for grain crops and potentially disturb early nesting activities of grassland birds [6, 7].

To evaluate the potential of alternative harvest dates for conservation grasslands as sources of biomass, it is important to consider yield potential and chemical and physical properties that influence their use in renewable energy systems. A few studies have compared biomass yields of energy crops across harvest seasons. For summer harvest of switchgrass monocultures, maximum biomass yields were achieved when harvested at anthesis, which occurs sometime around early August in the Midwest [8]. Another Midwest study found that delaying harvest from anthesis to senescence increased yield of mixed-species grasslands (hereafter referred to as polycultures) [9]. Biomass yields were not different for stands harvested after a killing frost in autumn compared to stands that overwintered and were harvested in spring [5]. However, yield reductions in overwintered biomass have been observed and attributed to lodging, shattering, leaf loss, and reduced tiller mass from reallocation of C to belowground structures [10–12] Comparing biomass yield across seasons may be misleading unless biomass was harvested at multiple dates within a season to capture intra-seasonal variability. Likewise, the effect of a season on biomass yield can vary across locations and years due to variation in growing conditions.

Although biomass yields are a primary concern for producers, biomass quality should also be considered. Thermo- and biochemical conversion processes require feedstocks with low moisture, mineral, and N content [13]. For thermochemical processes, high moisture and inorganic mineral concentrations reduce the energy density of the feedstock and also combustion efficiency, which reduces overall energy output [14, 15]. The extent of boiler fouling, slagging, and corrosion, as well as the amount of regulated emissions, is dependent on the amount of ashes and minerals released during combustion, which largely depends on biomass mineral characteristics [16]. High mineral concentrations in harvested biomass also increase nutrient export from soils, which increases the need for fertilizers and associated costs [4].

Harvest timing has been shown to affect biomass mineral concentrations and associated moisture content [10, 17]. The concentration of nitrogen and other minerals decreases in aboveground plant tissues as warm-season grasses mature [17–19]. As switchgrass and other perennial warm-season grasses senesce, minerals are translocated from aboveground tissues to roots [20, 21]. Thus, mineral concentrations in harvested biomass should decline with progressively later harvest dates. Biomass moisture content also decreases from summer to winter in switchgrass [22]. Therefore, postponing harvest until late winter–early spring improves storage characteristics and combustion potential of grassland biomass [22] and may reduce the cost of transporting the biomass to the end-use facility [23]. However, as with biomass yield, comparing biomass moisture content and mineral concentration across only a few harvest dates during each season ignores intra-seasonal variability. Understanding how harvest timing influences biomass yield and quality is important if existing conservation grasslands are to be included in the portfolio of feedstocks for the emerging bioeconomy. Currently available literature on the subject takes a discrete “fall-versus-spring” approach with regard to harvest timing. However, treating biomass quantity and quality factors as continuous through time may provide insights as how to balance yield, quality, and logistical components. The current literature lacks a comprehensive analysis on the effect of harvest timing on biomass yield and quality while accounting for spatial and temporal variation. Our study addresses this knowledge gap and interprets results in the context of bioenergy production. Our objective was to examine various biomass quality and quantity metrics in response to harvest timing while accounting for random variation across multiple locations and growing seasons. We focused on two perennial herbaceous feedstocks, switchgrass and native polycultures, and harvest dates ranging from late summer to a late spring harvest just prior to emergence.

Materials and Methods

Experimental Design

The study was conducted over 3 years (year 1=2009–2010, year 2=2010–2011, and year 3=2011–2012) at seven Minnesota sites spanning a variety of soil and climate conditions (Table 1). Three sites had native polycultures (Austin, Chisago, Vermillion), three sites had switchgrass (Lamberton, Waseca, Rosemount), and one site had both types of bioenergy crops (Becker). Austin and Vermillion native polycultures were established in 2005 and 2006 and are managed by the Minnesota Department of Natural Resources as Schottler and Vermillion Highlands Wildlife Management Areas, respectively. The native polyculture at Chisago was established in 2005 and managed by a private landowner while all other vegetation was established in 2006 for previous studies at the University of Minnesota Agricultural Experiment Stations and Research and Outreach Centers [24]. All sites were managed without fertilizer inputs.

The study was established as a completely randomized block design with four replicates at each of seven sites. Treatments were harvest dates, with vegetation type (switchgrass or native polyculture) as a covariate. At each site, biomass harvests were conducted on four occasions throughout the

Table 1 Location, soils, vegetation, and selected climate data for seven Minnesota sites

Site name	Location	Soil type	Vegetation	1981–2010 Climatological mean			
				Annual temp. (°C)	Annual precip. (cm)	Last spring frost[a]	First fall frost[a]
Austin	43° 36′ 43″ N −92° 55′ 23″ W	Sargeant silt loam (fine-loamy, mixed, superactive, mesic Aquic Glossudalfs)	Native polyculture	11.9 max 6.2 mean 0.6 min	81.2	14 May	18 Sept
Becker	45° 23′ 18″ N −93° 52′ 55″ W	Hubbard loamy sand (sandy, mixed, frigid Entic Hapludolls)	Native polyculture, switchgrass	12.8 max 6.2 mean 1.8 min	77.0	18 May	22 Sept
Chisago	45° 29′ 27″ N −92° 45′ 31″ W	Nebish loam (fine-loamy, mixed, superactive, frigid Typic Hapludalfs)	Native polyculture	12.9 max 7.2 mean 1.4 min	80.7	21 May	20 Sept
Lamberton	44° 14′ 15″ N −95° 19′ 3″ W	Normania-Ves complex loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls)	Switchgrass	12.9 max 6.8 mean 0.8 min	66.7	17 May	17 Sept
Rosemount	44° 41′ 16″ N −93° 4′ 30″ W	Waukegan silt loam (fine-silty over sandy, mixed Typic Hapludoll).	Switchgrass	12.0 max 6.4 mean 0.7 min	87.9	17 May	22 Sept
Vermillion	44° 40′ 24″ N −93° 5′ 39″ W	Mayer silt loam (fine-loamy over sandy or sandy-skeletal, mixed, superactive, calcareous, mesic Typic Endoaquolls)	Native polyculture	12.0 max 6.4 mean 0.7 min	87.9	17 May	22 Sept
Waseca	44° 3′ 52″ N −93° 31′ 30″ W	Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls)	Switchgrass	12.2 max 6.6 mean 1.0 min	88.2	15 May	19 Sept

[a] Probability of observing a temperature as cold or colder than 0 °C later in the spring or earlier in the fall than the indicated date is 0.1

dormant season following a killing frost (0 °C) or plant senescence. The first harvest, "late summer–early fall," was conducted between 2 September and 5 October of each year and was meant to represent a typical harvest scenario for grassland biomass. The second harvest, "late fall–winter," was conducted between 10 November and 11 January of each year. The third harvest, "early spring," was conducted between 14 March and 16 April of each year. The fourth harvest, "late spring," was conducted between 1 May and 20 May of each year. Harvest dates varied over locations and years because of variation in weather events such as rainfall and snowfall.

Percent vegetative cover by functional group was visually estimated using six cover classes [25] in two randomly selected 0.25-m^2 quadrats in each plot at the beginning of the experiment. The cover class midpoints of each observation were then averaged by vegetation type (where applicable) and by site. Vegetative cover in switchgrass fields at Waseca, Lamberton, Rosemount, and Becker ranged from 90 to 96 % switchgrass and 4–10 % weeds at the beginning of the experiment. At Austin, 11 species were identified in the native polyculture at the beginning of the study. Ground cover at this time was 67 % warm-season grasses, 2 % cool-season grasses, 29 % forbs, and 2 % leguminous forbs. In the Vermillion polyculture field, 12 species were identified with ground cover being 23 % warm-season grasses, 36 % cool-season grasses, 27 % forbs, and 14 % leguminous forbs. At Becker, ground cover in the polyculture was 75 % warm-season grasses, 6 % cool-season grasses, 18 % forbs, and less than 1 % leguminous forbs, while at Chisago ground cover was 30 % warm-season grasses, 35 % cool-season grasses, 26 % forbs, and 9 % leguminous forbs.

Field and Laboratory Methods

In years 1 and 2, all vegetation in one randomly selected 1-m^2 quadrat was hand harvested to a 10-cm stubble height in each of four replicates on each harvest date at each site. In year 3, all vegetation in two randomly selected 0.25-m^2 quadrats was hand harvested to a 10-cm stubble height in each of four replicates on each harvest date at each site. Samples were weighed wet in the field following harvest. The samples were then dried in a 60-°C oven to a constant weight and weighed again to obtain biomass dry matter yield (hereafter referred to as "biomass yield") and moisture content. If snow cover was greater than the cutting height (i.e., >10 cm deep), samples were collected, but only vegetation above the snow cover was used to determine moisture content. Randomly collected subsamples were ground with a Wiley mill (Thomas-Wiley Mill Co., Philadelphia, PA, USA) to pass a 1-mm screen and then reground with a cyclone mill. Biomass mineral concentrations (P, K, S, Ca, Mg) were determined with inductively coupled plasma (ICP) mass spectroscopy following digestion with HNO_3 and H_2O_2 [26] except for N, which was determined via dry combustion and a Perkin-Elmer 2400 CHNS Analyzer (Perkin-Elmer Inc., Waltham, MA, USA) by Agvise Laboratories (Benson, MN, USA).

Mineral Export, Revenue Differences, and Gasification Quality Index

Biomass yield was multiplied by the concentration of N, P, and K for each sampling date to determine mineral export rates. The economic result of harvest date effects on biomass yield and mineral export (hereafter "revenue difference") was determined by subtracting the cost of replacing exported minerals from expected revenues from biomass sales. The price of biomass was fixed at \$66 Mg^{-1} and was multiplied by biomass yield for each sampling date. The cost of replacing exported minerals was determined as the product of N, P, and K export rates and the price of mineral N as urea fertilizer (45–0–0), P as triple super phosphate fertilizer (0–46–0), and K potassium chloride fertilizer (0–0–60), respectively. The national average fertilizer prices in 2013 [27] were adjusted for mineral content: urea at \$1.45 kg^{-1} N; triple super phosphate at \$1.68 kg^{-1} P; and potassium chloride at \$1.09 kg^{-1} K. The cost of mineral replacement was not considered as it was assumed that it would eventually occur regardless of export rate. The impact of mineral replacement (or lack thereof) on subsequent biomass yield, moisture, and mineral content was outside the scope of this analysis. All other input costs are assumed to be equal across all harvest dates and are not calculated in this analysis. Revenue difference does not accurately estimate real revenues from biomass production, but instead is used to make relative economic comparisons across harvest dates.

The gasification quality index is the ratio K/(Ca+Mg) with a threshold of 0.5 [5]. This index was developed in accordance with the University of Minnesota Morris Biomass Gasification Project. Biomass with a gasification quality index of less than 0.5 will not likely have ash sintering or fusion issues and is preferred for gasification.

Data Analysis

Harvest dates were recorded and then standardized as the number of days since 1 June (the approximate start of the growing season). This also allowed for easier interpretation for intervals that include 1 January. Harvest date was modeled as a continuous predictor variable to explain variation in biomass yield; moisture; N, P, K, S, Mg, and Ca concentrations; as well as revenue difference and the gasification quality index. We used linear mixed effects models to estimate the effect of harvest date on biomass response variables across space and time. We allowed the effect of harvest date to vary by location for each year by nesting location within year as random effects. This method accounts for spatial and temporal autocorrelation.

Initial data exploration included plotting each response variable against harvest date. Some response variables appeared to respond linearly (Ca, Mg, S), some exhibited a convex shape (biomass yield, N, P, K, gasification quality index), while others exhibited a concave shape (moisture). Based on visual assessment of the response-harvest date plots, we determined if a nonlinear regression equation should be fit and tested against other models. For response variables with a convex pattern, we fit a nonlinear square-root polynomial function. For response variable with a concave patter, we fit a nonlinear quadratic function. We then compared nonlinear models to the linear form and a model without harvest date parameters (intercept-only) using maximum likelihood ratio tests [28]. The maximum likelihood ratio test compares two nested models by comparing the ratio of their negative log-likelihood values to a chi-squared distribution with 1 *df*. If the log-likelihood ratio is not significantly different from 0 at an alpha level of 0.05, then the models are equally supported. If two models are equally supported, the model with fewer parameters is the best-fit model. After determining the best-fit model for the effect of harvest date on each response variable, we added the categorical variable "crop type" and an interaction term with harvest date to determine if the effect of harvest date was the same for both switchgrass and native polyculture crops. We compared the best-fit model with the crop type covariate to one without for each biomass response variable using the maximum likelihood ratio test. Linear mixed effects models were fit using the "nlme" package with program R [29, 30].

Biomass yield was log_{10}-transformed before analysis to normalize residuals. All other response variables met model assumptions based on visual assessment of residual plots. To compare model-estimated responses for any two dates, we looked for overlap in the 95 % confidence intervals (CIs) for each estimate generated by the best-fit model. If there was overlap in the CIs, the two values were considered similar and if the CIs did not overlap for any two dates, they were considered significantly different.

Results

Yield

Biomass yield varied substantially across all dates and locations, with a range of 0.7–11.7 Mg ha^{-1} and an average of 3.9 Mg ha^{-1}. Accounting for random variation across years and locations, the biomass yield response curve to harvest date expressed a convex pattern; indicating biomass yield decreased from fall to winter, and then increased slightly from winter to spring (Fig. 1). A square-root polynomial model for the effect of harvest timing on biomass yield was better supported than a linear model (L ratio=8.44, P=0.004) and the intercept-only model (L ratio=9.73, P=0.008). The polynomial model was not improved by including parameters to explain variation by crop type (L ratio=4.28, P=0.232; Table 2), suggesting that the yield response to harvest timing was similar for both switchgrass and native polycultures. Although there was a significant biomass yield response to harvest date as described by the regression model, the substantial variability led to overlap of the 95 % CIs for model-based yield estimates throughout the range of dates in our study. Therefore, model-based yield estimates were similar across all harvest dates in our sampling interval.

Moisture Content

Biomass moisture content ranged from 16 to 900 g kg^{-1} and averaged 314 g kg^{-1} across all harvest dates and locations. Accounting for random variation across years and locations, the moisture content response curve to harvest date expressed a concave pattern, indicating biomass moisture content increased from fall to winter and then decreased from winter to spring (Fig. 1). A quadratic polynomial model for the effect of harvest timing on biomass moisture content was better supported than a linear model (L ratio=55.87, P<0.001) and the intercept-only model (L ratio=10.95, P<0.001). The polynomial model was significantly better than a model including parameters to explain variation by crop type (L ratio=9.57, P=0.023; Table 2), suggesting that the moisture response to harvest timing was similar for both switchgrass and native polycultures. The lower bound of the 95 % CI for the model-estimated moisture content for the earliest harvest date (2 September) was 215 g kg^{-1}, which was greater than the upper bound for all days after 2 May (Fig. 1), indicating that moisture was significantly lower in late spring compared to early fall.

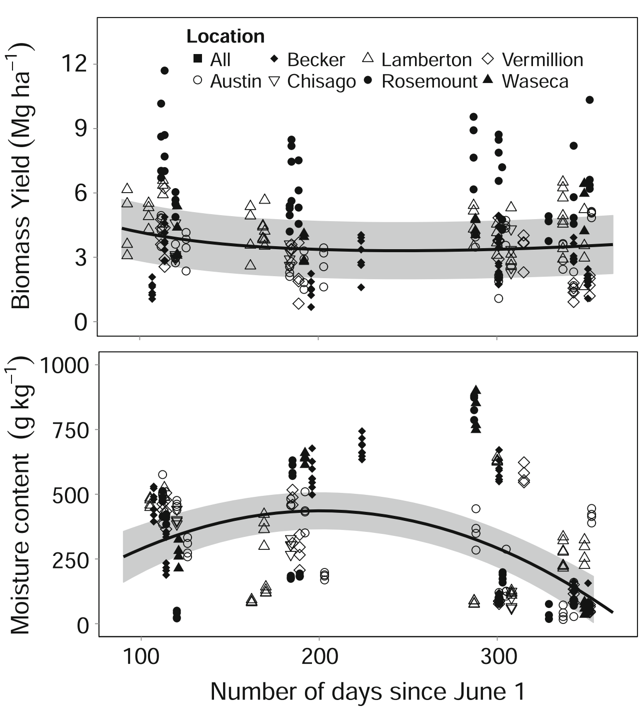

Fig. 1 Change in biomass yield and moisture content as a function of harvest date at seven locations during 3 years. *Regression lines* indicate relationship averaged across locations, years, and vegetation types with *shaded areas* representing 95 % CI of regression estimates

Biomass Mineral Concentration

Biomass N concentration ranged from 3.7 to 11.4 g kg^{-1} and averaged 6.0 g kg^{-1} across all harvest dates and locations. Accounting for random variation across years and locations, the biomass N response curve to harvest date expressed a slight convex pattern (Fig. 2). Biomass N concentration decreased from fall to winter and then increased slightly from winter to spring. A square-root polynomial model for the effect of harvest timing on biomass N concentration was better supported than a linear model (L ratio=27.7, P<0.001) and the intercept-only model (L ratio=27.9, P<0.001). The polynomial model was not improved by including parameters to explain variation by crop type (L ratio=3.7, P=0.292; Table 2), suggesting that the biomass N response to harvest timing was similar for both switchgrass and native polycultures. Although there was a significant biomass N response to harvest date as described by the regression model, the 95 % CIs for model-based biomass N concentration estimates overlapped throughout the range of dates in our study. Therefore, model-based biomass N estimates were similar across all harvest dates in our sampling interval.

Biomass P concentration ranged from 0.2 to 1.8 g kg^{-1} and averaged 0.6 g kg^{-1} across all harvest dates and locations. Accounting for random variation across years and locations, the biomass P response curve to harvest date expressed a convex pattern (Fig. 2). Biomass P concentration decreased from fall to spring and began to plateau in late spring. A square-root polynomial model for the effect of harvest timing on biomass P concentration was better supported than a linear model (L ratio=95.5, P<0.001) and the intercept-only model (L ratio=109.1, P<0.001). The polynomial model was significantly better than one including parameters to explain variation by crop type (L ratio=10.8, P=0.013; Table 2), suggesting that the biomass P response to harvest timing was similar for both switchgrass and native polycultures. Model-based estimates of biomass P were significantly lower in spring compared to values in fall.

Biomass K concentration ranged from 0.6 to 9.7 g kg^{-1} and averaged 2.8 g kg^{-1} across all harvest dates and locations. Accounting for random variation across years and locations,

Table 2 Regression equation coefficients for best-fit models determined for all response variables

Response variable	Units	Crop type	Regression equation
Biomass yield	Mg ha^{-1}	Polyculture and switchgrass	$\log_{10}(Y)=1.28+0.003\times date-0.097\times date^{0.5}$
Moisture content	g kg^{-1}	Polyculture and switchgrass	$Y=-14.89+0.583\times date-0.001\times date^2$
N	g kg^{-1}	Polyculture and switchgrass	$Y=1.63+0.005\times date-0.149\times date^{0.5}$
P	g kg^{-1}	Polyculture and switchgrass	$Y=0.42+0.001\times date-0.042\times date^{0.5}$
K	g kg^{-1}	Polyculture and switchgrass	$Y=3.09+0.010\times date-0.339\times date^{0.5}$
S	g kg^{-1}	Polyculture	$Y=0.19+0.001\times date-0.019\times date^{0.5}$
S	g kg^{-1}	Switchgrass	$Y=0.13+0.001\times date-0.010\times date^{0.5}$
Ca	g kg^{-1}	Polyculture and switchgrass	$Y=0.47-3.3\times 10^{-4}\times date$
Mg	g kg^{-1}	Polyculture	$Y=0.38-3.3\times 10^{-4}\times date$
Mg	g kg^{-1}	Switchgrass	$Y=0.38-3.4\times 10^{-4}\times date$
Revenue difference	$	Polyculture and switchgrass	Not significant
Gasification quality index	Unitless	Polyculture and switchgrass	$Y=406.4+0.964\times date-23.347\times date^{0.5}$

the biomass K response curve to harvest date expressed a convex pattern (Fig. 2). Biomass K concentration decreased from fall to spring and showed a slight increase from spring to late spring. A square-root polynomial model for the effect of harvest timing on biomass P concentration was better supported than a linear model (L ratio=110.4, P<0.001) and the intercept-only model (L ration=129.2, P<0.001). The polynomial model was significantly better than one including parameters to explain variation by crop type (L ratio=9.2, P=0.027; Table 2), suggesting that the biomass K response to harvest timing was similar for both switchgrass and native polycultures. Model-based estimates of biomass K were significantly lower in spring compared to values in fall.

Biomass S concentration ranged from 0.3 to 1.1 g kg^{-1} and averaged 0.5 g kg^{-1} across all harvest dates and locations. Accounting for random variation across years and locations, the biomass S response curve to harvest date expressed a convex pattern (Fig. 3). Biomass S concentration decreased from fall to spring and began to plateau in late spring (Fig. 3). A square-root polynomial model for the effect of harvest timing on biomass S concentration was better supported than a linear model (L ratio=22.3, P<0.001) and the intercept-only model (L ratio=29.5, P<0.001). The effect of harvest timing on biomass S varied by crop type (L ratio=12.3, P=0.006; Table 2). Biomass S decreased faster in polyculture biomass compared to switchgrass in fall (Fig. 3). From day 276 to 306 (3 March to 2 April), biomass S was significantly lower in polyculture biomass compared to switchgrass based on the 95 % CIs for model-based biomass S estimates.

Biomass Ca concentration ranged from 1.5 to 11.6 g kg^{-1} and averaged 3.9 g kg^{-1} across all harvest dates and locations. Biomass Ca concentration decreased linearly in response to harvest timing from fall to spring (Fig. 3). A linear model for the effect of harvest timing on biomass Ca was better supported than the intercept-only model (L ratio=4.20, P=0.040) and similar to square root polynomial model (L ratio=1.78, P=0.183). The linear model with an interaction term for crop type was not significant (L ratio=3.95, P=0.139; Table 2), suggesting that the biomass Ca response to harvest timing was similar for both switchgrass and native polycultures. Although there was a significant biomass Ca response to harvest date, the 95 % CIs for model-based biomass Ca concentration estimates overlapped throughout the range of dates in our study. Therefore, model-based biomass Ca estimates were similar across all harvest dates in our sampling interval.

Biomass Mg concentration ranged from 0.4 to 2.5 g kg^{-1} and averaged 1.1 g kg^{-1} across all harvest dates and locations. Biomass Mg concentration decreased linearly in response to harvest timing from fall to spring (Fig. 3). A linear model for the effect of harvest timing on biomass Mg was better supported than the intercept-only model (L ratio=12.87, P<0.001) and similar to square root polynomial model (L ratio=0.81, P=0.369). The effect of harvest timing on biomass Mg varied by crop type (L ratio=25.0, P<0.001; Table 2). Variability in biomass Mg response to harvest date resulted in overlap of the 95 % CIs for model-based biomass Mg concentration estimates throughout the range of dates in our study for both polyculture and switchgrass biomass. Therefore, model-based biomass Mg estimates were similar across all harvest dates in our sampling interval and not significantly different by crop type.

Revenue Difference and Gasification Quality Index

There was no effect of harvest date on revenue difference based on biomass yields and mineral export rates. The intercept-only model was best supported and similar to a linear model with harvest date as a predictor (L ratio <0.01,

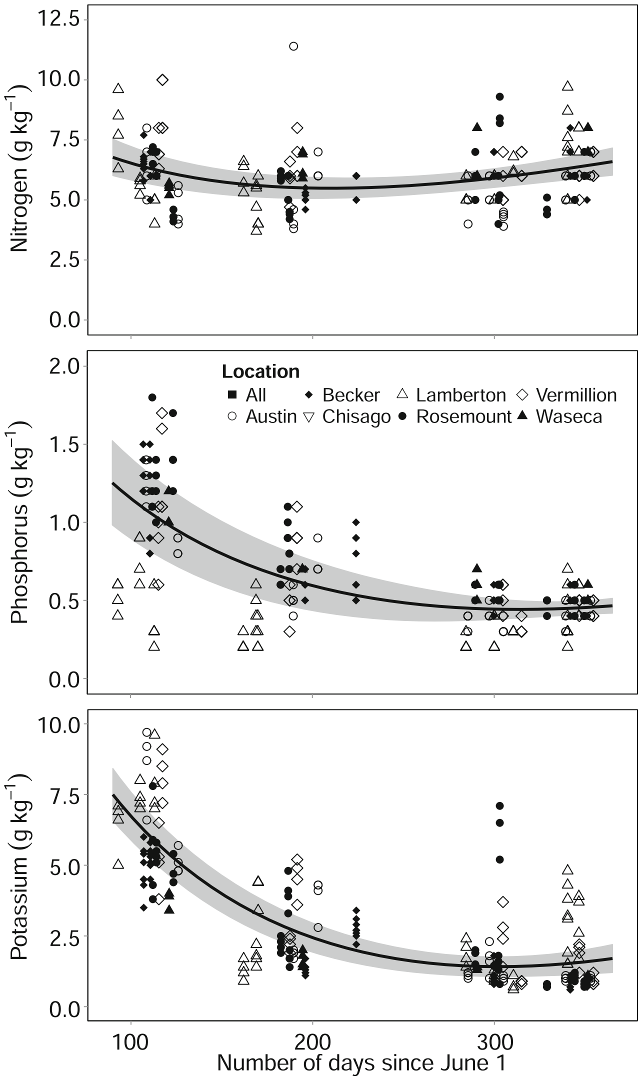

Fig. 2 Change in biomass nitrogen, phosphorus, and potassium concentrations as a function of harvest date at seven locations during 3 years. *Regression lines* indicate relationship averaged across locations, years, and vegetation types with *shaded areas* representing 95 % CI of regression estimates

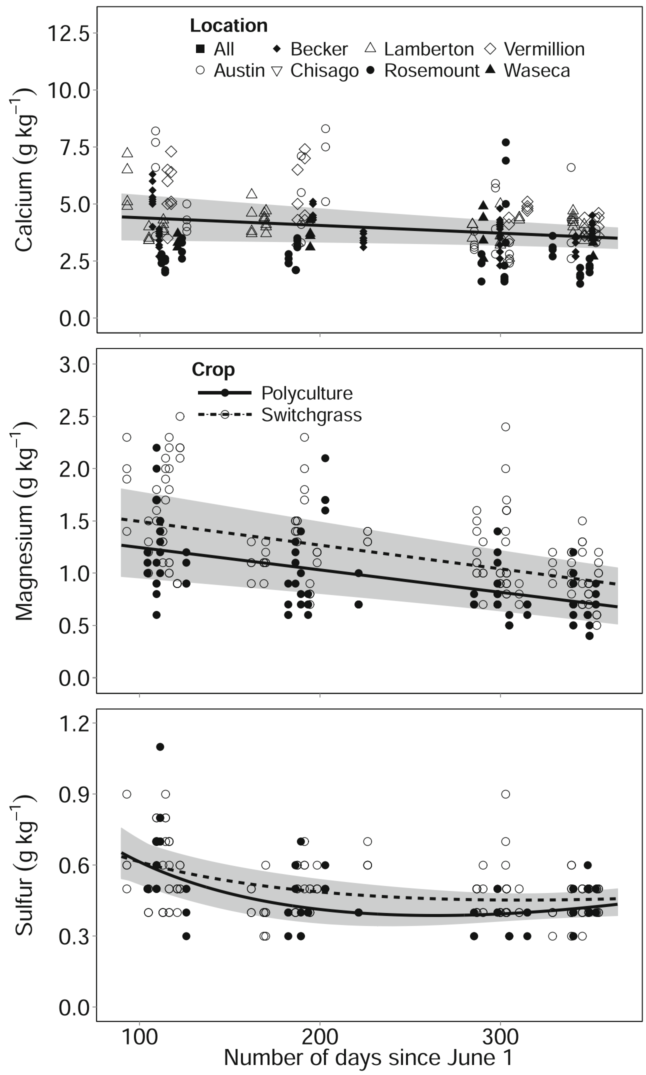

Fig. 3 Change in biomass calcium, magnesium, and sulfur concentrations as a function of harvest date at seven locations during 3 years. For Ca, the *regression line* indicates the relationship averaged across locations, years, and vegetation types with *shaded areas* representing 95 % CI of regression estimates. For Mg and S, *regression lines* indicate relationships for polyculture and switchgrass crops averaged across locations and years with *shaded areas* representing 95 % CI of regression estimates

P=0.912) and a model with harvest date varying by crop type (L ratio=2.18, P=0.535).

The gasification quality index decreased with harvest date following a convex pattern (Fig. 4). A square-root polynomial model for the effect of harvest timing on the gasification quality index was better supported than a linear model (L ratio=75.6, P<0.001) and the intercept-only model (L ratio=96.6, P<0.001). The effect of harvest date on the gasification quality index varied by crop type (L ratio=8.1, P= 0.044; Table 2). However, variability in the model-based estimates by crop type resulted in overlapping 95 % CIs; thus, the gasification quality index was similar for both crop types for all sampling dates in our study. For both polyculture and switchgrass biomass, gasification quality was lower in spring compared to autumn.

Discussion

We found that, averaged across sites and growing seasons, switchgrass and native polyculture biomass yields responded similarly to changes in harvest date. Although there was some variation across sites, in general, biomass yield declined from early fall to winter and then increased slightly from winter to late spring (Fig. 1). Based on the considerable overlap in 95 % CI for model-based estimates, there was no difference between biomass yields harvested in fall compared to spring from data spanning sites and growing seasons.

The convex shape of the yield response to harvest timing may be caused by both physical and biological factors. A

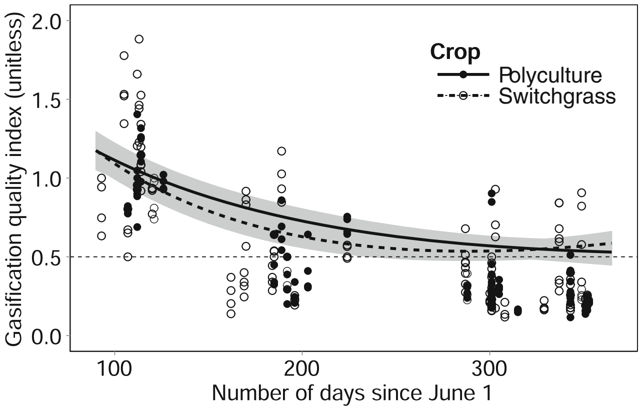

Fig. 4 Change in gasification quality index (K/(Mg+Ca)) as a function of harvest date at seven locations during 3 years. *Regression lines* indicate relationships for polyculture and switchgrass crops averaged across locations and years with *shaded areas* representing 95 % CI of regression estimates. *Dashed horizontal line* indicates maximum threshold for gasification (0.5)

decrease in biomass yield from early fall to winter (roughly day 92 to 200; Fig. 1) could be a result of leaf and stem detachment from wind, rain, and/or snow. Local weather data showed that the earliest snowfall was 2 December (day 186; Fig. 1); therefore, snowfall does not explain the decrease in yield from early fall to winter. Reduced tiller mass caused by reallocation of C to roots is another factor that may have influenced yield decline [11, 12]. The slight increase in biomass yield from winter to late spring could be caused by spring regrowth of vegetation, as harvests occurred as late as 20 May.

Other studies have reported declines in switchgrass and *Miscanthus* spp. biomass yield when harvest is delayed from fall to spring [10, 11, 17]. Lewandowski et al. compared *Miscanthus* biomass yields harvested at two dates—fall and spring—at five European locations in 1 year. They report lower mean yields during spring harvest, but this effect was not significant within or between locations [11]. Studies of switchgrass found that delaying harvest from fall senescence to the following spring resulted in yield declines from 11 to 37 % [10, 11, 17]. Switchgrass yield declines were not consistent through time or across locations [10]. We also observed some variation in the effect of harvest date on biomass yield across locations as seen in Fig. 1. However, when this variation is averaged across all locations and years, the overall change in yield from spring to fall is not statistically significant. Adler et al. found that biomass yields declined nearly 40 % when mechanical harvest was delayed from fall to spring and that this was mostly caused by biomass left behind by baling machinery. When yields were adjusted for known losses, the authors estimated that fall and spring yields were within 5 % of each other [10]. Our hand-harvest methods were likely more effective at collecting biomass in the spring compared to mechanical harvest, which would explain why we did not observe considerable yield decreases from fall to spring.

Biomass moisture content increased from early fall to winter and then decreased from winter to late spring (Fig. 1). These results contradicted our expectation that moisture content would decrease from fall to winter, as observed by others [31]. Parrish and Fike state that switchgrass can retain green tissues after experiencing multiple killing frosts (<0 °C) in the fall; thus, a full dry-down is not expected until November or December in this region [32]. However, we observed an increase in moisture content during this period. Recent precipitation or thaw events near the time of harvest could have elevated biomass moisture content for late fall samples, such as those observed around 18 December (day 200) in year 2 (Fig. 1).

Biomass moisture content did not fall below the 23 % threshold (230 g kg^{-1}) considered safe for storage [23] until 18 April (day 322). Harvesting and storing biomass with moisture content greater than 23 % increases the chance of self-ignition [11, 33] and microbial degradation of soluble and storage carbohydrates [10] and can result in reduced combustion efficiency [23]. When transporting biomass as high-density bales, the amount of biomass transported per trailer load can be limited by weight rather than space [34], and thus minimizing biomass moisture content is especially important. For instance, reducing biomass moisture content from our observed average of 310 to 210 g kg^{-1} (31 to 21 %) would allow for transport of three additional large square bales assuming a bale density of 224 kg m^{-3} and a maximum trailer load of 20.9 Mg [34]. This reduction in moisture can be achieved by delaying harvest until after 18 April, or with a typical post-senescence fall harvest, it can be achieved by allowing cut biomass to dry in windrows prior to baling [35].

We observed a slight decrease in biomass N concentration from September (day 92) through October (day 153), but the average N concentration from this interval (6.3 g N kg^{-1}) was similar to the stabilized values from previous research [18, 20, 36]. This suggests that N translocation had already occurred by the time of our first sampling dates, which we expected since plants were past senescence. In lower latitudes (Oklahoma, USA), N concentrations decreased by 20 to 60 % in switchgrass from maturity (August) to senescence (December) [19]. At sites further north (Iowa, USA), biomass N concentrations decreased curvilinearly in four native perennial grasses from the start of the growing season to about August, and then stabilized from August to the final sampling date in October [18]. Similarly, Wayman et al. observed N concentrations decrease in switchgrass stems by 77–82 % from June to August, after which time N concentrations stabilized [20].

We did not see a difference in N concentration of biomass harvested in late fall and early spring, which is similar to previous studies [17]. Our results show a slight increase in biomass N concentration in the late spring, which could be caused by the harvest of new emerging shoot material that has N concentrations of around 35 g kg^{-1} [18].

We observed dramatic declines in biomass P and K concentrations with harvest date (Fig. 2). Like N, these macronutrients are also translocated from shoots to roots in the fall [19]. Unlike N, we observed continued declines in biomass P and K concentrations after plant senescence and well into winter, after which stabilization occurred in early spring. The rate of decrease varied by location (Fig. 3). For instance, biomass P decreased from early fall to early spring by 60 % at the Vermillion location and 25 % at Lamberton in year 3, with final biomass P concentrations of 5.3 and 2.3 g P kg^{-1} for each location, respectively. This decrease is similar to that observed in switchgrass from maturity (August) to senescence (December) [19]. Winter P concentrations were less than those observed in six different perennial grasses harvested in December [37]. The decrease in biomass K concentration was generally greater than that of P, ranging from 69 to 80 % in year 3. Our average biomass P and K concentrations are similar to or slightly lower than other measured values for switchgrass [38], other bioenergy species grown in monoculture [37], and mixed-species grasslands harvested in fall [13]; however, we show that these concentrations continue to decrease throughout the winter and reach the lowest values in early spring.

We observed a nonlinear decrease in biomass S concentration with harvest date and a unique slope for polyculture and switchgrass crops. However, considerable overlap of the 95 % CIs of both regression lines suggests that the change in biomass S concentration through time is similar between crops. Also, the CIs around the predicted biomass S concentration overlap for estimates between day 130 (8 October) and day 1 (1 June), indicating little differences in biomass S concentration from fall to spring. Averaged across all harvest dates and locations, biomass S concentration was 0.48 g kg^{-1}. This was less than C_3 and C_4-dominated grasslands harvested in late fall [13] and similar to *Miscanthus* biomass S concentration grown in Europe [11].

Although we observed changes in mineral concentrations as a result of biomass harvest date, there was no economic advantage to harvesting earlier or later based on variation in biomass yield and nutrient export rates. This is evidence that, at similar low-input grassland sites, effort should be focused on increasing biomass yield to maximize economic returns from biomass production rather than focusing on biomass quality, as revenues from biomass yield can offset the added costs of mineral export. Data are needed to quantify other economic characteristics that could vary depending on harvest timing. For instance, increases in alkali metal concentration cause fouling and slagging in thermochemical conversion facilities, yet the cost of this inefficiency has not been published in terms of biomass alkali metal concentrations.

The gasification quality index decreased with harvest date from fall to spring following a square-root quadratic function (Fig. 4; Table 2). The rate of decrease was slightly greater for switchgrass, although model-estimated values for the polyculture and switchgrass plots were similar based on CI overlap for all dates within the sample period. Model estimates for the gasification quality index did not decrease below the 0.5 threshold for either crop type; however, 94 and 82 % of the measured values after 1 February were below the 0.5 threshold for polyculture and switchgrass crops, respectively. For biomass harvested prior to 1 November, the gasification quality index was less than the 0.5 threshold for 0 and 3 % of the measurements for polyculture and switchgrass crops, respectively. To prevent slagging and fouling during gasification, switchgrass and polyculture biomass should be harvested in early or late spring.

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Conflict of Interest No conflict of interests exists.

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