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Effect of Harvest Management on Biomass Yield, Forage Quality, and Nutrient Removal by Bioenergy Grasses in Mid-Central Virginia

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Abstract: The increasing cost of fossil-based energy sources has driven research in bio-based alternatives, such as perennial grasses for feedstock. The mid-Atlantic receives appreciable summer rainfall that may support a two-cut-per-year^{-1} harvest. At Virginia State University, a study on annual forage sorghum and two one-year stand perennials, miscanthus, and selected switchgrass ecotypes was carried out. The experimental design was a split-plot with harvest systems and feedstock grass species randomly assigned to the main and sub-plots, respectively. Only perennial grasses were assigned to the two-cut-per-year^{-1} system. The first cut occurred in early summer, and the second and single cut occurred after the frost-kill. Under the two-cut system, in 2022, the first-cut dry matter (DM) yield ranged from 8.9 Mg ha^{-1} in Blackwell to 14.7 Mg ha^{-1} in BoMaster. Additionally, except for BoMaster, the regrowth DM yields were within 10% of the first-cut DM yield. Under the one-cut system, the yield ranged from 10.8 Mg ha^{-1} in Blackwell to 23.2 Mg ha^{-1} in sorghum. Under the two-cut system, in 2023, miscanthus produced the greatest first-cut DM yield of 18.4 Mg ha^{-1}, while other perennials averaged 10.1 Mg ha^{-1}. Compared to the first cut, the hot and dry summer significantly reduced regrowth for all feedstock species, with the miscanthus DM yield dropping by 64%. While forage attributes differ among feedstock species, in general, both the first cut and regrowth showed greater crude protein and mineral elements, as well as lower ADF contents compared to a single cut following a killing freeze. Sorghum had better forage quality for the one-cut-per-year^{-1} feedstock material, and, along with the first cut and regrowth, it may have the potential for use as forage for maintenance energy in animal systems. For perennials, the two-cut-per-year^{-1} system removed the greatest quantities of nutrients during both years, with the first-cut harvest contributing about 65% of all removed N and K. Sorghum removed the greatest quantities of nutrients compared to the perennial under a one-cut-per-year^{-1} system. Therefore, while a two-cut-per-year^{-1} system can result in the greatest DM yields for dual-purpose use, its adoption calls for a critical analysis of economic benefits that considers feedstock bioenergy processing approaches, stand persistence, and fertilizer management strategies to address potential soil fertility depletion due to mineral element mining.

Keywords: feedstock grasses; forage; nutrient uptake; harvest system

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1. Introduction

Increases in energy costs, pollution, and continued depletion of fossil-based energy sources have led to research initiatives on bio-based alternatives. Studies on production, management, and processing technology strategies for lignocellulosic biomass feedstock are ongoing globally. A number of perennial grasses have been identified to have huge potential for biomass production at minimal input levels, and research has focused mainly on developing management strategies that may increase their productivity. While switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus* × *giganteus*) are reported to have potential as bioenergy feedstock, they may require different management strategies for successful establishment, growth, and biomass productivity. Additionally, because temperature and rainfall affect the efficiency of crop production [1], considering the adaptability of species and species eco-type to prevailing climatic conditions is crucial for successful production. For example, different switchgrass cultivars differed in their biomass productivity at the same location [2,3]. Due to their differences in climatic demands, biomass characteristics, yield potentials, and crop management aspects, optimizing productivity calls for the selection of agro-ecologically suited species [4].

Perennial grass biomass production and the associated photosynthetic removal of CO_2 and its sequestration as plant and soil C, is considered a climate risk management and mitigating strategy [5,6]. Among plant species, differences in photosynthetic activities and other physiological processes can be reflected in CO_2 fixation capacities and species contributions to amounts of sequestered C in soil and belowground plant tissues. Globally, 50% of nitrous oxide (N_2O), a more potent greenhouse gas (GHG) produced during denitrification by soil microbes [7], is released from cultivated lands [6]. While the level of N fertilization, soil structure, and water content affect the amount of N_2O released [8,9], denitrifying microbes play a very critical role. Different crops are reported to affect the quantity of ammonium oxidizing microbes in the soil in different ways [10], and thus impact the amount of N_2O released. Therefore, from an environmental standpoint, a crop whose production leads to the low release of N_2O, produces greater above- and belowground biomass, and sequesters greater quantities of CO_2 is a good bioenergy feedstock candidate. Because low N fertilizer applications reduce the amounts of N_2O released to the atmosphere, low-input perennial grasses are better bioenergy feedstock choices.

A number of studies on the production management of bioenergy grass species and their effects on yield have been reported [11–17]. Prior to frost-kill, perennial grasses relocate nutrients to belowground storage organs for re-growth following the winter dormancy [18,19], but annuals retain nutrients in dead aboveground tissues and, consequently, which lowers their bioenergy quality. Harvest timing and fertilizer management strategies have been found to affect yield, ash content, and combustion quality of bioenergy crops [17,20]. While clinker formation due to high K and Cl has been known to affect material pyrolysis, combustion, and bioenergy quality [21], low concentrations of 0.2% (K) and 0.1% (Cl) are reported to be non-problematic [22]. Because of their low water uptake, C-4 plants accumulate low amounts of mineral elements compared to C-3 plants, and harvesting late after the frost-kill allows the recycling of nutrients to belowground tissues, reducing tissue K and Cl due to leaching losses [22,23]. There are also multiple research findings suggesting that harvest management has effects on yield, tissue nutrient concentration, and nutrient removal, and that in regions with dry and hot summer months, regrowth does not add significant DM yield. Therefore, a two-cut-per-year^{-1} production system may only be appropriate for locations with appreciable summer precipitation. While in a two-cut-per-year^{-1} system the first harvest and its high mineral element content cause damage to and increase operational costs of thermal processing plants, the reduction in ash content from delayed one-cut per season's end harvest may result in low maintenance costs. Therefore, the choice of bioenergy crop species, the harvest system, and its timing could have affected the material's processing efficiency, its energy quality, the cost of machine maintenance, and, thus, the profit margins.

Despite the existence of data on switchgrass and miscanthus production in different parts of the country [19,24–28], there is limited information on how the two compare to annuals such as forage sorghum (*Sorghum bicolor* L.) under the moist conditions of southeast US. In the mid-Atlantic, unlike the feedstock-producing areas in the mid- and western US, the relatively high summer precipitations may allow for appreciable re-growth in perennial grasses after a first early summer harvest in a two-cut-per-year^{-1} harvest system and thus, a greater amount of total annual DM yield when compared to a one-cut-per-year^{-1} system. Besides the increase in DM yield, the mineral element content and forage quality characteristics of harvested material make it ideal for forage use potential, as previously reported [29], or for ameliorating soils of cadmium and arsenic contamination. Because of the multi-use operations of producer farms in the mid-Atlantic region, which include animal systems, producing perennial feedstock grasses under multiple harvests per year^{-1} in the area may provide additional income in the form of hay sales. An appropriately designed harvest system could provide forage for livestock during the summer 'slump' when cool-season forage crop performance is sub-optimal. In addition, the mid-Atlantic region, including the Commonwealth of Virginia, comprises the Chesapeake catchment area, whose water-ways are prone to chemical fertilizer pollution and, therefore, perennial grasses whose N demand is low compared to annuals will help reduce N leaching losses and the eutrophication of water bodies. This difference in a crop's N demand and fertilization level may indicate the potential for unequal contribution to environmental pollution and a need for careful assessment of feedstock species of choice. Therefore, there is a need to evaluate the productivity of bioenergy feedstock grass species in the mid-Atlantic and devise harvest strategies that allow for alternative uses, including forage. Additionally, because perennials have a lifespan of more than 10 years, there is a need to determine their performance under local climatic and soil conditions relative to the more flexible annual cropping systems.

The aim of this project was to evaluate the performance of two recognized perennial feedstock grasses: (i) miscanthus (*Miscanthus* × *giganteus*) and (ii) switchgrass (*Panicum virgatum* L.); three ecotypes, BoMaster, Cave-in-Rock, and Blackwell; and (iii) an annual, brown midrib sorghum. The specific objectives of the study were to evaluate the DM yield, tissue elemental composition, and soil nutrient removal under alternative harvest systems. The results of this research will hopefully help producers make informed choices on bio-energy crops to include in/or to replace current operations and generate information on expected pre-processed feedstock yield and quality.

2. Materials and Methods

2.1. The Site, Propagating Material, Experimental Layout, and Establishment

The experiment was conducted at Randolph Farm, the Virginia State University Research and Demonstration Farm in Chesterfield County, Virginia (37°13′43″ N; 77°26′22″ W). The soil at the site is a Bourne series fine sandy loam (mixed, semiactive, thermic Typic Fragiudults).

Switchgrass seeds for the study were obtained from Ernest Seed (Meadville, PA, USA), miscanthus rhizomes from River Marple Farms (Owosso, MI, USA), and forage sorghum seeds from Pawnee Buttes Seed Inc. (Greeley, CO, USA). The study was laid out as a split-plot design with harvest systems as the main plot. Feedstock grass species were assigned randomly into sub-plots, and the experiment had three replications. Each experimental unit (sub-plot) measured 2 m wide and 6 m long. Data for the perennial grasses were obtained during the second and third years after the stand establishment. Perennial grasses were established in 2020 from seedlings raised in the greenhouse during the 2019–2020 winter months. Prior to establishment, soil samples were obtained from 0–15 cm depth for routine soil analysis. During the study, forage sorghum was planted on the same plot every year and fertilized with 70 kg N ha^{-1} post emergence.

2.2. Crop Field Management, Biomass Sampling, and Data Collection

Production management, including fertilizer application, was handled as recommended for the annual feedstock crop. After the perennials greened up in spring, the fields were assessed for broadleaved weeds abundance, and control measures were carried out as needed. A two- or one-cut-per-year^{-1} harvest system was used to obtain biomass yield data on the perennial grasses. For the two-cut-per-year^{-1} harvest system, the first harvest was in early summer (boot stage), and regrowth was harvested in the fall. For the one-cut-per-year^{-1} system, harvest was conducted in the fall, within three weeks of the frost-kill, to coincide with the harvest of the regrowth for the two-cut-per-year^{-1} system. After the last harvest, during each production year, the remaining plant material was mowed and removed from the field.

Depending on the grass species, the number of plants sampled per plot^{-1}, used to determine the weight per plant^{-1} and the proportion of leaves in a plant, ranged from 5–10. For DM yield determination, a representative area within the plot was selected, and all aboveground plant materials were harvested by cutting manually with a pruning implement. The harvested material was oven-dried and weighed to determine the area's DM yield, which was then used to calculate biomass DM yield per ha^{-1}. A representative subsample of the dried material was ground and analyzed for elemental composition and forage quality characteristics using the near infra-red reflectance spectroscopy (NIRS) analytical methods. From the crude protein content determined, N concentration in the harvested material was calculated based on Equation (1) below. The amount of a given nutrient element removed in feedstock was calculated using the DM yield and the mineral element concentration in harvested material, as indicated in Equation (2) below.

$$\text{Nitrogen concentration } (\text{g kg}^{-1}) = \frac{\text{Crude protein } (\text{g kg}^{-1})}{6.25} \tag{1}$$

$$\text{Quantity removed } (\text{kg ha}^{-1}) = \frac{\text{Nutrient concentration}(\text{g kg}^{-1})}{1000} \times \text{Biomass yield } (\text{kg ha}^{-1}) \tag{2}$$

3. Statistical Analysis

The data were organized and subjected to analysis of variance (ANOVA), with species and harvest frequency (cuts) as fixed effects. Data processing and the analysis of variance (ANOVA) were performed using statistical software PROC GLM (SAS version 9.4: SAS Institute, Cary, NC, USA). Each year's data were analyzed independently. An analysis was performed to compare species when all are only cut once per year^{-1} to allow for a comparison between annual and perennial species. A separate ANOVA compared perennial grass species under the different harvest systems. The analysis compared biomass production and forage attributes during each production year. Means comparison used the Fisher's least significant difference test at α = 0.05.

4. Results

4.1. Soil Characteristics and Summer Precipitation at the Site

The soil at the site had a pH of 6.0 and contained 42, 77, 312, and 47 mg kg^{-1} of P, K, Ca, and Mg, respectively. Precipitation amounts and distribution were comparable between the spring of 2022 and 2023 but differed during the summer period (21 June through 21 September) of both production years (Figure 1). In 2022, 75% of the total precipitation (99 mm) in June occurred during the last week of the month, while the first week of July received 50% of the total monthly precipitation (34 mm). Except for two days of precipitation within the same week in late July that produced a total of 109 mm (75% of monthly totals), the summer of 2023 had poorly distributed precipitation compared to 2022 (Figure 1), with early July being exceptionally dry. The average temperatures were comparable for the two years, except in mid-August through mid-September of 2023, when mean temperatures were comparatively greater, with sections of the period showing the greatest differences, coinciding with a time during the month with the least precipitation (Figure 1).

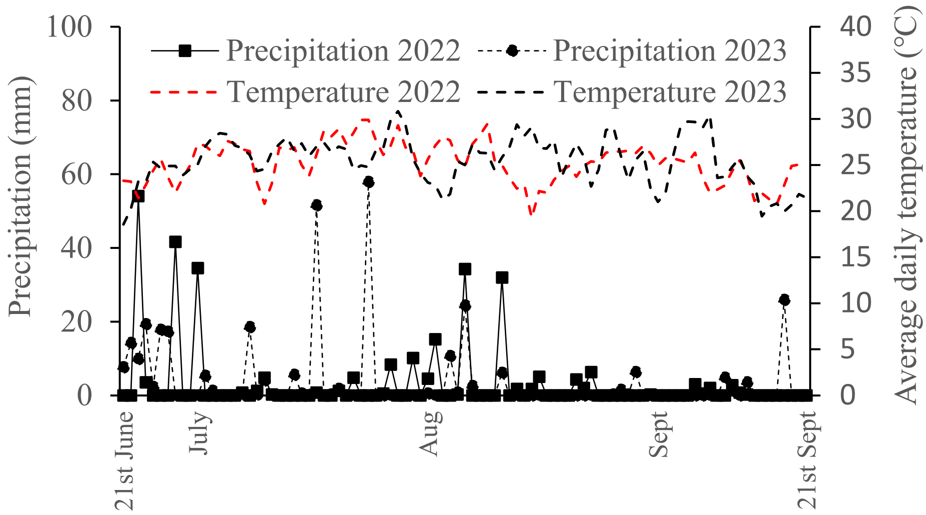

Figure 1. Amount of precipitation (lines with markers) and mean daily temperatures (lines without markers) at the experimental site during summer (21 June–21 September) during 2022 and 2023 production year.

4.2. Perennial Species Feedstock Production under Two-Cut Harvest Systems

In 2022, regrowth DM yields were comparable to the first cut for all feedstock grass species except for BoMaster, where a 34% yield reduction was observed (Figure 2). Across species, first cut registered greater DM yields, averaged at 8.7 Mg ha^{-1} compared to 6.4 Mg ha^{-1} obtained from the regrowth. Across perennial feedstock species, the two-cut-per-year^{-1} harvest system registered a 38% greater total annual DM yield compared to 16.2 Mg ha^{-1} under the one-cut-per-year^{-1} system. In miscanthus, the weight per plant^{-1} was greatest for both the first and second cuts compared to switchgrass ecotypes, averaging 19.7 and 15.5 g, respectively. The weight per plant^{-1} for the switchgrass ecotypes was similar, averaging 5.0 g for the first cut and ranging between 2.6 and 4.3 g for the regrowth harvest. Miscanthus had the lowest and greatest leaf plant^{-1} for the first cut and regrowth harvests, respectively.

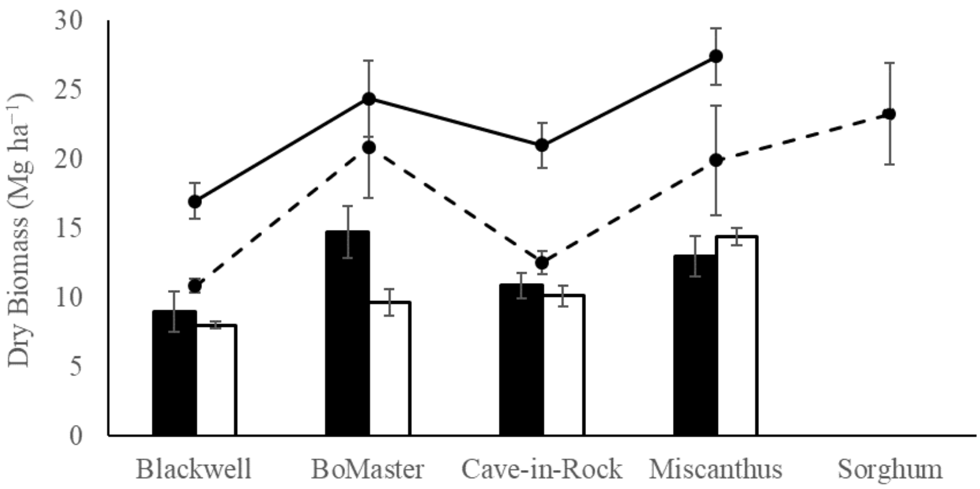

Figure 2. First cut, regrowth, and total annual DM yield of warm-season grasses under a two-cut-per-year^{-1} system in 2022. First cut (solid bar) and regrowth (open bar), two-cut totals (solid line), and single-cut total (broken line). Bars on the histogram and line charts indicate the standard error of the mean. Comparisons for one cut had an LSD of 5.6, while for two cuts, LSD was 4.7.

In 2023, the DM yield comparison showed a significant grass species × harvest date interaction. During the first cut in early July, miscanthus produced the greatest DM yields, at 18.4 Mg DM ha^{-1} (Figure 3). Both switchgrass ecotypes produced comparable yields, averaged at 10.1 Mg DM ha^{-1}. There was a reduction of between 38% and 63% in regrowth DM yield for all species, with production ranging from 5.0 Mg ha^{-1} in Cave-in-Rock to 6.7 Mg ha^{-1} in miscanthus. Across feedstock grass species, the one-cut-per-year^{-1} system produced 11% more total annual DM yield compared to the two-cuts-per-year^{-1} system. Both switchgrass ecotypes produced comparable total DM yields, averaged at 17.8 DM ha^{-1}, which was 22% lower than the total annual yield for miscanthus. The weight per plant^{-1} was greatest in miscanthus for both the first and regrowth harvests, averaging 28.3 g and 8.9 g, respectively. The weight per plant for the switchgrass ecotypes averaged 5.3 g and 2.8 g for the first cut and regrowth harvest, respectively. Miscanthus had the lowest and greatest leaf plant^{-1} count for the first-cut and regrowth harvests, respectively.

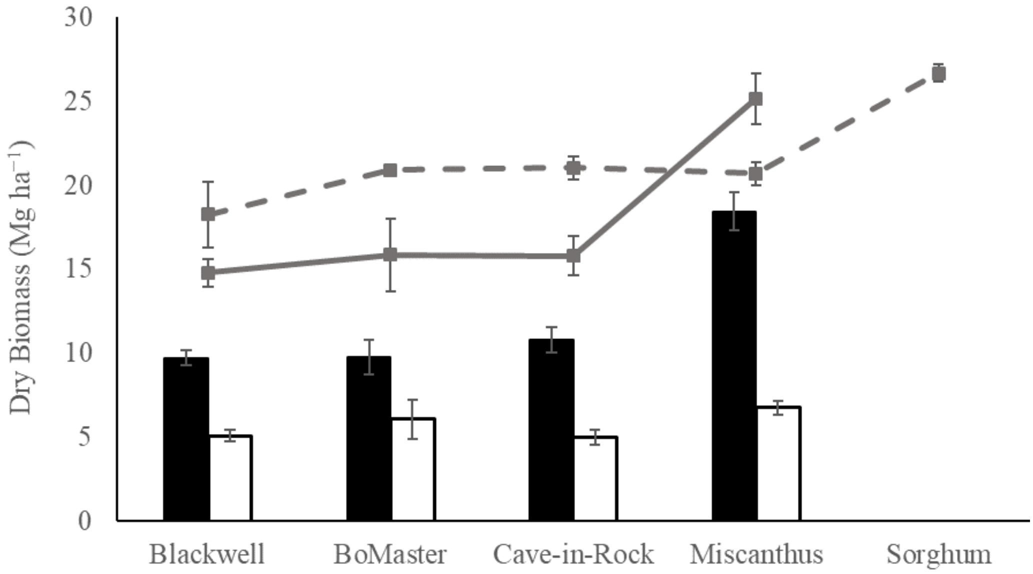

Figure 3. First cut, regrowth, and total annual DM yield of warm-season grasses under a two-cut-per-year^{-1} system in 2023. First cut (Solid bar) and regrowth (Open bar), two-cut totals (solid line), and single-cut total (broken line). Bars on the histogram and line charts indicate the standard error of the mean. Comparisons for one cut had an LSD of 3.2, while for two cuts, LSD was 2.8.

4.3. Annual DM Yield in a One-Cut Year^{-1} System

Unless otherwise stated, mean differences are significant if $p \leq 0.05$. In 2022, under the one-cut-per-year^{-1} harvest system, there was a significant difference among species ($p < 0.0303$) in total annual DM yield. Forage sorghum produced 23.2 Mg DM ha^{-1}, a greater quantity than 12.5 and 10.8 Mg ha^{-1} obtained for Cave-in-Rock and Blackwell, respectively (Figure 2). Though not significantly different, the sorghum DM yield was about 8%, being 17% greater than that of BoMaster and miscanthus, respectively. The Blackwell DM yield was comparable to that of Cave-in-Rock but significantly less than that of miscanthus. The mean weight per plant was greatest for sorghum (180.9 g), followed by miscanthus (54.1 g). Although BoMaster showed a numerically greater weight plant^{-1} value, it was not significantly different from that of Blackwell or Cave-in-Rock (Table 1). Miscanthus had a lower proportion of leaves compared to the switchgrass ecotypes.

In 2023, under the one-cut-pe-year^{-1} harvest system, sorghum produced a significantly greater DM yield (26.7 Mg ha^{-1}) compared to miscanthus and switchgrass ecotype species (Figure 3). Switchgrass ecotypes produced comparable DM yields, ranging from 18.3 Mg ha^{-1} in Blackwell to 21.0 Mg ha^{-1} in Cave-in-Rock (Table 1). The weight per plant^{-1} was greatest in sorghum, at 92.9 g, followed by miscanthus, at 48.2 g. Both switchgrass ecotypes had comparable plant weight, averaged at 9.5 g. Similar to 2022, for a one-cut-per-year^{-1} harvest system, miscanthus showed a lower proportion of leaves than the switchgrass ecotypes.

Table 1. Weight of plant and leaf proportions at harvest were compared for first cut, regrowth, and a one-cut-per-year^{-1} harvested feedstock grass species in 2022 and 2023 production years.

Species	Plant Weight (g)			Proportion of Leaves per Stem^{-1}		
	One	**First Cut**	**Regrowth**	**One**	**First Cut**	**Regrowth**
			2022			
Blackwell	5.7 ^{c}	3.7 ^{bA}	2.6 ^{cA}	0.18 ^{ab}	0.34 ^{aA}	0.26 ^{bB}
BoMaster	10.0 ^{c}	6.4 ^{bA}	4.3 ^{bB}	0.16 ^{bc}	0.34 ^{aA}	0.26 ^{bB}
Cave-in-Rock	5.7 ^{c}	4.9 ^{bA}	3.2 ^{bB}	0.19 ^{a}	0.32 ^{bA}	0.25 ^{bB}
Miscanthus	54.1 ^{b}	19.7 ^{aA}	15.5 ^{aB}	0.14 ^{c}	0.24 ^{cB}	0.35 ^{aA}
Sorghum	180.9 ^{a}	-	-	-	-	-
			2023			
Blackwell	6.5 ^{c}	4.5 ^{bA}	2.3 ^{bB}	0.16 ^{cd}	0.35 ^{aA}	0.25 ^{bB}
BoMaster	14.4 ^{c}	6.1 ^{bA}	3.6 ^{bB}	0.18 ^{bc}	0.32 ^{bcA}	0.25 ^{bB}
Cave-in-Rock	7.6 ^{c}	5.4 ^{bA}	2.6 ^{bB}	0.20 ^{a}	0.34 ^{abA}	0.25 ^{bB}
Miscanthus	42.8 ^{b}	28.3 ^{aA}	8.9 ^{aB}	0.14 ^{d}	0.26 ^{cb}	0.38 ^{aA}
Sorghum	92.9 ^{a}	-	-	-	-	-

For the same year, different small letters on a column indicate statistical a difference at $p < 0.05$. Under a two-cut-per-year^{-1} system (First cut and regrowth), different upper-case letters on the same row indicate statistical differences at $p < 0.05$.

4.4. Dry Matter Forage Characteristics and Elemental Compositions

Because of their potential as livestock feed resources, especially the first-cut and regrowth material, the forage quality attributes, including crude protein, ADF, and mineral element contents of the harvested biomass, were determined.

In 2022, a comparison of first-cut and regrowth harvested material showed no grass species × harvest time interaction on crude protein content. However, there were significant differences in the CP content between the grass species and the time of harvest (Figure 4). Across species, the CP content for the first harvest in summer, at 57.2 g kg^{-1}, was greater than the 32.4 g kg^{-1} obtained for frost-killed regrowth in the fall. Across harvest dates, Blackwell had a CP of 54.7 g kg^{-1}, which was greater than in all other grasses. The miscanthus CP content of 38.7 g kg^{-1} was the lowest, but it was comparable to the 41.4 g kg^{-1} that was found in Cave-in-Rock. The miscanthus ADF content, at 455.8 g kg^{-1}, was the greatest among all grass species. All others had lower and comparable CP amounts, averaged at 442.0 g kg^{-1}. The total digestible nutrient (TDN) content was greatest and lowest in Blackwell (483.0 g kg^{-1}) and miscanthus (460.2 g kg^{-1}), respectively. Tissue concentrations of K, Mg, and Fe were greater in summer-harvested material than in the regrowth, but the Ca content was greater in the regrowth. The regrowth material showed 50% and 19% reductions in the K and Mg contents, respectively (Table 2). Under the one-cut-per-year^{-1} system, Blackwell had the greatest CP, at 36.1 g kg^{-1}, and miscanthus had the least at 21.3 g kg^{-1} (Figure 4). Sorghum had the lowest ADF content, at 366.4 g kg^{-1}, and miscanthus the greatest, at 617.7 g kg^{-1}. In addition, the mineral element contents were low, with sorghum registering the greatest content, with 25% more K and S in the tissue compared to the other feedstock grass species (Figure 5).

In 2023, both the first cut and the one-cut-per-year^{-1} system had relatively lower CP concentrations than in 2022 (Figure 4). The first cut and regrowth material CP content differed between species. The first cut showed greater contents of CP than the regrowth material. During the first cut in July, BoMaster had a CP content of 48.4 g kg^{-1}, a content significantly greater than the lowest content of 33.7 g kg^{-1} found in miscanthus. Similarly, BoMaster exhibited the greatest CP of 40.6 g kg^{-1} in the regrowth material, while miscanthus had the lowest, with a 30% lower CP content. For the first-cut material, miscanthus had the greatest ADF content of 466.6 g kg^{-1}, while other species had less than 410 g ADF kg^{-1}. However, all species had similar and greater than 445 g ADF kg^{-1} DM in the regrowth DM. Correspondingly, the first-cut material exhibited greater TDN than the regrowth. Except for miscanthus, which had 445.5 g TDN kg^{-1} DM, the first cuts in all other species registered above 490 g TDN kg^{-1} DM. The regrowth material's TDN was comparable among species and averaged 455 g kg^{-1}. The tissue concentration of K was greatest in the early summer harvested material and least in material cut after freezing frost in the fall. Across species, the concentration of the readily mobile K in the fall-harvested material was up to 50% less (Figure 5). In addition, the S content showed low concentrations in the fall-harvested material (Figure 5). Other elements, including P, Mg, and Ca were in greater concentrations in the regrowth than in the first cut (Table 2).

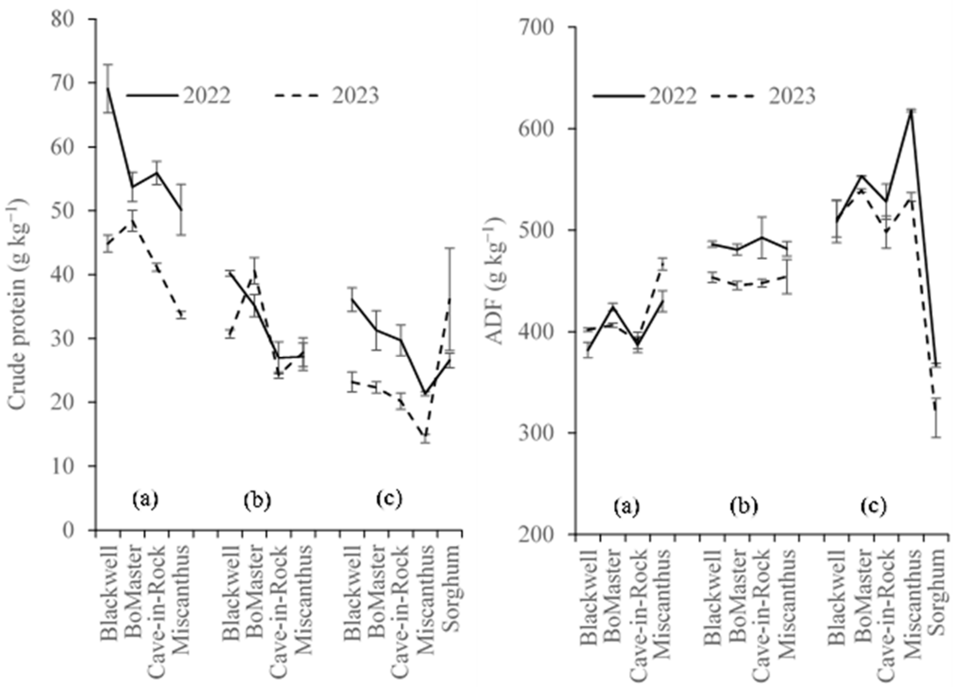

Figure 4. Crude protein content of a summer harvest (a), regrowth (b), and once-a-$year^{-1}$ harvest (c) of several warm-season grasses. Bars represent the standard error of the mean. Comparisons for one cut (crude protein, LSD; 2022 = 6.2, 2023 = 11.7: ADF; LSD; 2022 = 42.8, 2023 = 44.0) and two cuts (crude protein, LSD; 2022 = 3.9, 2023 = 2.9: ADF; LSD; 2022 = 14.4, 2023 = 15.9).

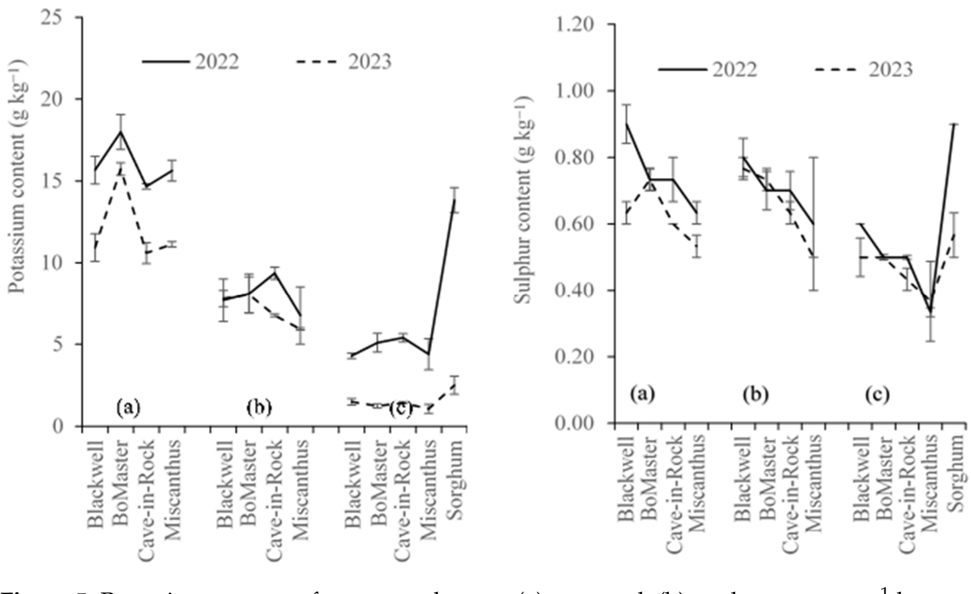

Figure 5. Potassium content of a summer harvest (a), regrowth (b), and once-a-$year^{-1}$ harvest (c) material of several warm-season grasses. Bars represent the standard error of the mean. Comparisons for one cut (potassium, LSD; 2022 = 2.1, 2023 = 2.3: sulfur; LSD; 2022 = 0.24, 2023 = 0.21) and two cuts (potassium, LSD; 2022 = 1.56, 2023 = 1.25: sulfur; LSD; 2022 = 0.02, 2023 = 0.06).

Table 2. Mean concentrations of P, Mg, and Ca in first cut, regrowth, and in one-cut-per-year^{-1} biomass material of different warm-season grasses in 2022 and 2023 production years.

Harvest System	Harvest	Species	Production Year					
			2022			2023		
			P	Mg	Ca	P	Mg	Ca
			mg kg^{-1}					
Two-cut year^{-1}	First cut	Blackwell	2.30	2.00	2.43	1.50	1.37	2.13
		BoMaster	2.20	1.70	2.23	1.90	1.70	2.53
		Cave-in-Rock	1.97	1.63	2.27	1.50	1.07	1.80
		Miscanthus	1.70	1.20	2.00	1.57	0.87	1.57
	Regrowth	Blackwell	1.60	1.30	2.60	2.40	1.63	2.93
		BoMaster	2.07	1.47	3.07	1.70	1.60	2.13
		Cave-in-Rock	2.37	1.07	1.97	2.67	1.80	2.83
		Miscanthus	1.60	1.37	2.90	2.13	1.37	3.63
		LSD (0.05) $^{+}$	0.32	0.22	0.39	0.41	0.21	0.06
One-cut year^{-1}		Blackwell	1.03	1.53	4.70	1.43	1.50	3.20
		BoMaster	1.30	1.45	2.10	1.03	1.23	2.10
		Cave-in-Rock	1.80	1.50	3.47	2.03	1.43	2.87
		Miscanthus	1.47	0.67	1.83	1.40	1.07	2.53
		Sorghum	2.60	2.83	3.53	2.13	2.50	3.07
		LSD (0.05) $^{++}$	0.77	0.91	1.94	0.80	0.93	0.73

$^{+}$ LSD compares the first and regrowth means in a two-cut-per-year^{-1} system. $^{++}$ LSD compares species means for a one-cut-per-year^{-1} system.

4.5. Nutrient Removal by Perennials under Different Harvest Management Systems

In 2022, the harvest time (first or regrowth) and species affected the amounts of nutrients removed in biomass. The first-cut material removed the greatest quantity of N per unit weight than the regrowth material (Figure 6). In fact, for all perennials, regrowth removed 40–60% of N as that of the first-cut harvest. Except for Blackwell and BoMaster regrowth, which removed less P, the others removed comparable amounts in the first-cut harvest and regrowth. The amount of K removed in regrowth was 30–60% of that removed by the first cut. A comparison of the impact of the harvest system on total nutrient removed annually showed that only the main factors, grass species and harvest system were significant, whereas their interactions were not. BoMaster removed 181.4 kg N ha^{-1}, the greatest quantity compared to those removed by other perennial feedstock grasses, which averaged 151.4 kg ha^{-1} (Figure 7). In addition, BoMaster removed 348.5 kg K ha^{-1} and 52.5 kg P ha^{-1}, the greatest quantities compared to other perennial feedstocks. Blackwell removed the least quantities of both P and K.

Similar to 2022, the harvest time (first-cut or regrowth) and species affected the quantities of nutrients removed in the biomass in 2023. The regrowth material removed 30–52% of N, 50–85% of P, and 19–38% of K compared to what was removed by the first-cut harvest (Figure 7). Across perennial feedstock species, regrowth removed 52% S, 64% Mg, and 71% Ca compared to that removed in the first-cut harvest. Unlike in 2022, the total N, P, K, and Ca removed in feedstock biomass in 2023 was significantly affected by the interaction of species and the harvest system. Magnesium removal was not affected by either the main factor or their interactions, while S differed with species. Miscanthus removed the greatest quantities and Cave-in-Rock the least quantities of N. P, K, and S. Miscanthus removed 124.5, 64.8, and 215.1 kg ha^{-1} of N, P, and K, respectively (Figure 7). The quantities removed by Cave-in-Rock were 66, 70, and 64% of that by miscanthus, respectively. BoMaster removed 112.3 kg N ha^{-1} and 190.1 kg K ha^{-1}, amounts statistically comparable to those of miscanthus. In 2023, regrowth material removed 30–52% of N, 50–85% P, and 19–38% K, in the first-cut harvests. Across perennial feedstock species, regrowth removed 52% S, 64% Mg, and 71% Ca compared to the amounts removed during the first-cut harvest (Table 3).

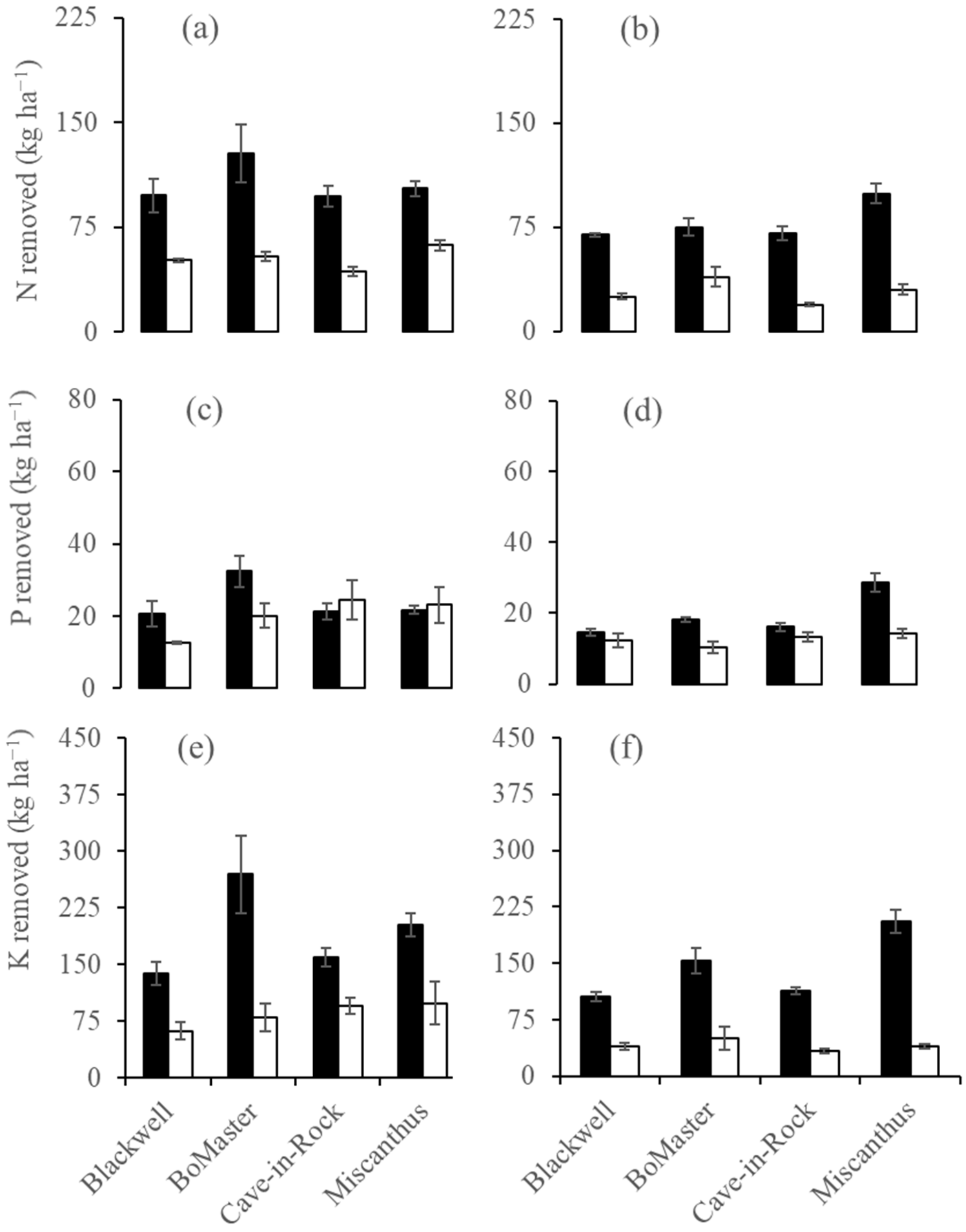

Figure 6. Amounts of N, P, and K removed during harvest by different perennial warm-season feedstock grass species in 2022 (**a**,**c**,**e**) and in 2023 (**b**,**d**,**f**). Amount removed by the first cut (black bars) and regrowth biomass (open bars). Bars represent the standard error of the mean.

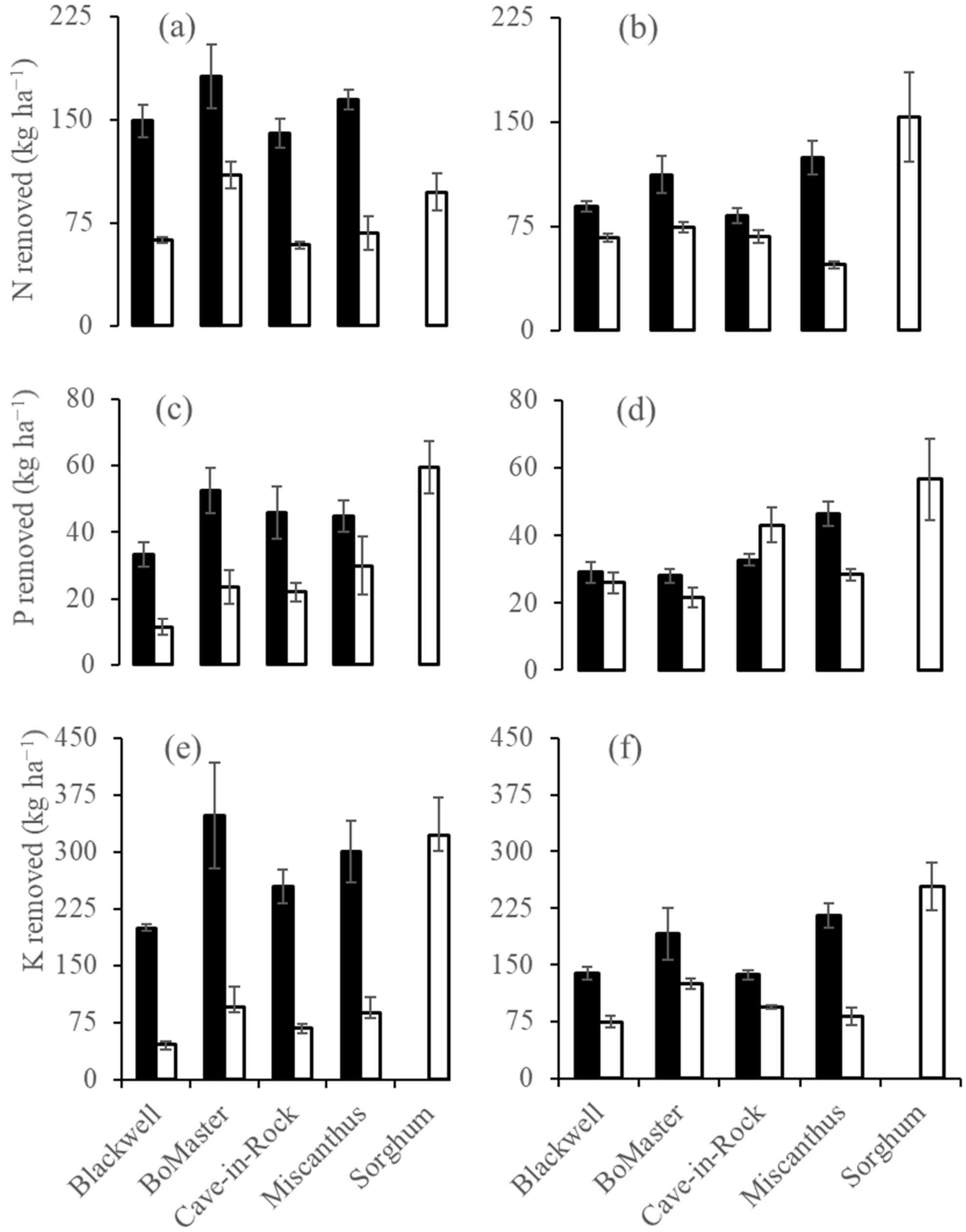

Figure 7. Total amount of N, P, and K removed annually by perennial warm-season feedstock grass species under alternative harvest management systems in 2022 (**a**,**c**,**e**) and 2023 (**b**,**d**,**f**). The amount removed by the two-cut (black bars) and one-cut (open bars) per year^{-1} system. Bars represent the standard error of the mean.

Table 3. Amounts of sulfur, magnesium, and calcium (kg ha^{-1}) removed by first cut, regrowth, and one-cut-per-year^{-1} biomass of different warm-season grasses in 2022 and 2023 production years.

Harvest System	Harvest	Species	Production Year					
			2022			2023		
			S	Mg	Ca	P	Mg	Ca
Two-cut year^{-1}	First cut	Blackwell	7.9	17.9	21.3	6.2	13.3	20.7
		BoMaster	10.9	24.7	32.9	7.1	16.5	24.7
		Cave-in-Rock	8.1	17.8	24.6	6.5	11.5	19.5
		Miscanthus	8.1	15.2	25.1	9.8	16.4	28.5
	Regrowth	Blackwell	6.4	10.3	20.7	3.9	8.3	14.8
		BoMaster	6.8	14.5	30.6	4.5	9.6	12.9
		Cave-in-Rock	7.2	10.9	19.9	3.2	9.1	14.3
		Miscanthus	8.8	19.7	41.4	3.4	9.2	24.3
		LSD (0.05) $^{+}$	2.3	3.6	5.3	1.4	2.3	3.7
One-cut year^{-1}		Blackwell	6.5	16.6	50.5	8.9	26.6	58.4
		BoMaster	7.4	21.7	34.4	10.5	25.7	43.9
		Cave-in-Rock	6.3	18.7	42.8	9.1	30.2	60.5
		Miscanthus	6.0	12.8	34.9	7.5	21.9	52.0
		Sorghum	21.0	65.4	82.1	15.1	66.3	81.7
		LSD (0.05) $^{++}$	6.9	21.0	29.7	4.2	21.6	19.4

$^{+}$ LSD compares the first and regrowth means in a two-cut-per-year^{-1} system. $^{++}$ LSD compares species means for a one-cut-per-year^{-1} system.

4.6. Nutrient Removal by Feedstock Species under the One-Cut Management System

In 2022, the potential nutrient removal in the one-cut-per-year^{-1} harvest system showed significant species differences. Forage sorghum and BoMaster removed comparable quantities of N, averaged at 103 kg ha^{-1}, which was greater than the 62.8 kg ha^{-1} average for miscanthus, Blackwell and Cave-in-Rock (Figure 7). In addition, forage sorghum removed the greatest amounts of P, K, S, Mg, and Ca, at 59.5, 322.5, 21.0, 65.4, and 82.1 kg ha^{-1}, respectively. All other feedstock species removed similar quantities of P, K, and S, averaged at 21.6, 74.9, and 6.6, respectively. They also removed 17.5 and 40.6 kg ha^{-1} of Mg and Ca, respectively (Table 3).

In 2023, and for all reported nutrients, the amounts removed differed according to the species. The annual feedstock crop, sorghum, removed 153.6 kg N ha^{-1}, a much greater quantity than that removed by perennial species, which averaged 64.2 kg ha^{-1} (Figure 7). It also removed 56.5 kg P ha^{-1}, statistically similar to the quantity removed by Cave-in Rock, but greater than that removed by other perennials, which averaged 25.4 kg ha^{-1}. Similarly, sorghum removed 254 kg K ha^{-1}, the greatest quantity. BoMaster removed the second-greatest quantity of K, at 124.8 kg ha^{-1}, which was significantly greater than the least amount of K removed by miscanthus. Sorghum also removed 81.7, 66.3, and 15.1 kg ha^{-1} of Ca, Mg, and S, respectively, whereas perennial grasses removed statistically comparable amounts of these nutrients (Table 3).

5. Discussion

The reduction in total annual DM yield in 2023 for a majority of the perennial crops under the two-cut-per-year^{-1} system can be attributed to reduced growth during the dry summer experienced during that production year, as shown in Figure 1. Compared to the first year, when the weight per plant for regrowth across species was reduced by about 25%, the weight per plant for regrowth in 2023 was reduced by about 52%, resulting in a corresponding 50% reduction in harvested DM yield. During 2023, despite a tremendous first-cut year compared to 2022, miscanthus regrowth was the most affected, with a yield reduction of 63.5% compared to the first-cut DM yield. Miscanthus is reported to yield better than other feedstock grass species in moist conditions, but it is impacted by drought stress [30]. Soil moisture stress is the single most important factor affecting miscanthus

DM yield [31,32]. Biomass increased from year one to year two, as the plant stands improved. However, the dry summer of 2023 impacted yield negatively. In 2022, a more favorable summer precipitation and distribution may explain the regrowth biomass that was comparable to that of the first harvest. The opening of the canopy arising from the harvest in summer may have allowed for a greater biomass production in the regrowth, compared to any additional growth occurring in a continuing stand where shading and reduced light penetration may have reduced the rate of accumulation of additional biomass after early summer. This could have contributed to the observed greater DM yield under the two-cut system, which experienced about a 40% increase in DM yield. Reports of greater DM yield under a two-cut-per-year^{-1} system have been reported, with DM yield increases of up to 50% under this system reported in Cave-in-Rock [33,34]. However, in some parts of the drier southern plains, a one-cut-per-year^{-1} system was reported to result in greater yields because of the low regrowth potential of switchgrass, especially if the first cut is delayed. It has also been reported that a one-cut in autumn maximizes yield and maintains stand [29]. In addition to the dry summer that reduced regrowth, the first cut was harvested about two weeks later than in 2022, which could have had a significant impact on regrowth since the delayed first cut is reported to reduce regrowth potential in switchgrass [35] and the proportion of regrowth relative to the first cut [24].

High CP contents, reduced ADF, and greater quantities of mineral elements on the plant material for the first-cut harvested material are consistent with a vibrant vegetative growth phase of the grasses at harvest time. The CP and ADF levels in the first cut and after harvest following a killing frost for switchgrass ecotypes are comparable to those reported before [19,36–38]. At this stage, elements are being moved from the soil to the shoot for growth. Similarly, for the regrowth, a resumption of growth by new tillers stimulated by the first cut leads to an uptake of mineral elements from the soil and accumulation in the growing and expanding leaves and stems. The low concentration later can be attributed to the relocation of nutrients from above- to belowground tissues. In late summer and early fall, prior to killing frost, perennial grasses usually relocate both organic and inorganic nutrients from the aboveground biomass to belowground storage material, where it is preserved for the next spring's regrowth [18,19,39]. The readily mobile and non-structural elements, such as K, are translocated to a larger degree than the structural and less mobile nutrients, and this partly explains the greater percentage reduction in K in the fall-harvested material. In addition, leaching losses from dried material can occur for K. The ability of perennials to recycle nutrients allows them to maintain an appreciable DM yield at low input levels compared to annuals. For instance, in the case of miscanthus, its demand for N was lower than that of reed canarygrass [40]. Compared to undisturbed growth (one-cut year^{-1}), remobilization of nutrients from the regrowth plants may lag behind that of the one-cut-per-year^{-1} system and may explain its relatively greater nutrient contents for harvests in the fall. The first cut and regrowth, therefore, may be more useful as livestock forage material than the full-season cut. However, sorghum, being an annual crop, retained greater material at the aboveground tissue because of a lack of nutrient recycling, as is the case for perennials. As a result, being a forage-type, sorghum retains greater forage potential than perennials at the end of the season. However, regrowth and one-cut-per-year^{-1} harvest material may offer nutrition for animal maintenance requirements during the winter months when forage supply is low.

The timing of harvests has implications for nutrient management, as well as in feedstock production systems. Similarly, because different processing strategies are in place for converting feedstock biomass into energy supply, the additional DM yield from a summer cut under a two-cut-per-year^{-1} system, can either be beneficial or detrimental. While greater mineral element content makes first-cut material good for forage use, its quality for thermal processing as a bioenergy source might be reduced because of its potential to cause clinker formation and processing plant corrosion due to high basic cation contents [21,41]. But while high cation contents may result in increased maintenance costs in thermal processing plants, the additional biomass could result in greater bioethanol yields from the low lignin first-cut material that might also contain greater quantities of easily fermentable sugars. However, the removal from the field of first-cut high-nutrient dense feedstock material can result in significant losses of mineral elements from the soil over time, a scenario that is also reported in other studies [12,36]. It is also reported that repeated biomass removal of miscanthus and switchgrass over a four-year period reduced P, K, Mg, and Ca contents in the topsoil [42]. In this study, the amount of nutrients removed in feedstock biomass is comparable to that reported elsewhere [43–45]. This continued mining of soil nutrients by a summer-harvesting strategy will call for a fertilizer management strategy to ensure continued high biomass feedstock yields. While a one-cut-per-year^{-1} system can result in low DM yield, the low cation content of the material makes it preferable for thermal processing plants. In addition, the low mineral nutrient content due to recycling reduces nutrient losses from the soil and may cut production costs associated with the rate of fertilizer supplementation and application frequency.

6. Conclusions

Despite widely reported recommendations for a one-cut-per-year^{-1} system for feedstock grass to optimize yield while sustaining stand persistence, there is potential in the moist mid-Atlantic to adopt a two-cut-per-year^{-1} harvest system. During the transition to or addition of feedstock production into farm operations, livestock production systems in the mid-Atlantic region could benefit by utilizing feedstock biomass from a two-cut-per-year^{-1} harvest strategy for forage, given that both the first cut and regrowth material have appreciable forage quality attributes. And if need be, supplemental N fertilization to promote regrowth may be performed without risking N loss in leaching because these deep-rooting perennial feedstock species trap and recycle subsoil N and reduce its potential to pollute waterways in the mid-Atlantic. Both harvest systems for perennials may be used in alternative rotational patterns to allow for species stand recovery after a few years of multiple cuts per year^{-1}. Including an annual will ensure the availability of bioenergy feedstock biomass, especially during establishment years, because productive perennials stands occur 2–3 years after establishment.

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