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The Impact of Harvest Timing on Biomass Yield from Native Warm-Season Grass Mixtures

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ABSTRACT

Interest in using native warm-season grasses (NWSG), especially switchgrass (SG) (*Panicum virgatum* L.), as a biomass crop has increased due to the focus on renewable energy sources. There is the potential to utilize the early growth of these plants as a forage crop (i.e., hay), allowing the regrowth to be harvested as a fibrous biomass crop. The three species treatments were SG, a two-way blend of big bluestem (*Andropogon gerardii* V.) and indiangrass (*Sorghastrum nutans* L.) (BB+IG), and a three-way mixture of SG, BB, and IG (SG+BB+IG). Harvest treatments were a harvest (BH) in late fall (for biomass), early-boot harvest (for forage) followed by BH (EB+BH), or early-seedhead harvest (for forage) followed by BH (ESH+BH). Delaying harvest from EB to ESH increased forage yield by 22% ($P < 0.001$). The SG and SG+BB+IG produced greater forage yield (averaged across both early harvest treatments) than BB+IG (10.1 and 9.1 vs. 5.5 Mg DM ha^{-1}, respectively; $P < 0.001$). Across all NWSG treatments, biomass yield was reduced by 51% for EB+BH and 68% for ESH+BH compared to BH ($P < 0.001$). Total yield (forage + biomass) was greatest for ESH+BH with both SG and SG+BB+IG, whereas the mixture of SG+BB+IG provided the greatest total annual yield, 20.1 Mg DM ha^{-1} ($P = 0.002$). These results suggested that NWSG, grown in the mid-South United States under a dual-harvest system, can increase harvest options for producers by supplying acceptable forage yield for both early harvests and still provide biomass production.

The development of renewable energy sources has become an issue of increasing importance and consequently has grown over the last three decades (Lynd et al., 1991; Sanderson et. al., 1996; McLaughlin and Kszos, 2005). It has been estimated that more than 21 million ha of SG might be needed annually for biomass production (English et al., 2006). If SG or other dedicated herbaceous energy crops were planted at this scale, there could be a significant portion of land currently being used for forage production being displaced by biomass crops (English et al., 2006; Graham et al., 2008; Sanderson and Adler, 2008). To address this issue, dual-harvest forage/biomass systems have been explored with interest in using SG for biomass (Sanderson et al., 1999; Guretzky et al., 2011; Mosali et al., 2013). This approach could allow producers the flexibility to divert some biomass production into forage, exploit biomass markets, select alternative harvest options, and the potential to increase profitability (Sanderson and Adler, 2008).

Where forage is a priority, growing-season harvests should occur earlier in the growing season when forage has a higher nutritive value (Mitchell et al., 2001; Guretzky et al., 2011; Richner et al., 2014). Several studies have examined dual-harvests (i.e., growing-season plus dormant-season) in SG but those harvests occurred in late June or mid-July, when plants had flowered and nutritive value had fallen below optimum levels (Grabowski et al., 2004; Thomason et al., 2005; Fike et al., 2006; Guretzky et al., 2011). In the southern Great Plains, Sanderson et al. (1999) concluded a May/dormant harvest combination was the best approach for a dual-harvest system. In another study from the southern Great Plains, Guretzky et al. (2011) recommended dual-harvest use of SG if the first harvest was taken early in the growing season and the biomass harvest was taken after the first killing frost. In the northern Great Plains, Vogel et al. (2002) recommended an early harvest

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Abbreviations: BB, big bluestem; BB+IG, two-way blend of big bluestem and indiangrass; BH, biomass harvest; EB, early-boot harvest; EB+BH, early-boot plus biomass harvest; ESH, early-seedhead harvest; ESH+BH, early-seedhead plus biomass harvest; DAP, diammonium phosphate; IG, indiangrass; NWSG, native warm-season grasses; PLS, pure live seed; SG, switchgrass; SG+BB+IG, three-way mixture of switchgrass, big bluestem, and indiangrass.

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date that corresponded to boot stage, and reported greater yield from those dual-harvest combination than from a single post-dormancy harvest. Early-season harvesting (for forage) needs to be further evaluated to examine the trade-offs between forage mass and a late-season biomass harvest. Identifying the optimum early-season harvest time is important because over the long term, multiple growing-season harvests can weaken SG stands (Parrish and Fike, 2005).

Although most research examining dual-harvest, forage-biomass systems have focused on SG, several other NWSG in mixture could combine different attributes of yield and quality for both forage and biomass production (Posler et al., 1993; Fike et al., 2006; Sanderson et al., 2006). Although BB and IG produce less biomass than SG (Hall et al., 1982), both are considered to be good-quality, leafy forages that mature later and are widely used for livestock forage (Mitchell et al., 2001; Ball et al., 2007). Compared to SG, BB and IG are generally more palatable and nutritious during early summer. They provide more consistent quality forage throughout the growing season than SG (Gillen et al., 1998; Mitchell et al., 2001) and could make an important contribution to the forage component of dual-harvest systems. In addition, higher net energy yields may be associated with BB and IG than SG due to greater levels of digestibility (Magai et al., 1994). This attribute has implications for cellulosic conversion to biofuel (Lynd et al., 1991).

There may be other benefits to using multi-species blends in dual-harvest settings. Research conducted in Minnesota reported greater yield from multi-species mixtures, but mixtures that include species with similar growth habits would likely be most favorable in the long term (Mangan et al., 2011). Mulkey et al. (2008) reported sustainable biomass production in a two-harvest system using a combination of SG, BB, and IG. Other works have reported benefits associated with more diverse plantings, including enhanced ecosystem services and system sustainability (Posler et al., 1993; Springer et al., 2001; Bonin and Tracy, 2012). Including other NWSG with SG can provide increased yield depending on the production management system (Posler et al., 1993; Fike et al., 2006; Sanderson et al., 2006). However, the literature lacks studies in the mid-South evaluating compatible species with the potential to compliment forage and biomass production and ecosystem services.

Objectives of this study were to determine: (i) the effect of two early-season harvest timings (EB and ESH) on forage yield of native grasses in monoculture and mixtures; (ii) the effect of prior harvests for forage on biomass yield in a dual-harvest system; and (iii) effects of harvest timing on total yield (forage + biomass).

MATERIALS AND METHODS

Location

This experiment was conducted from 2010 to 2012 at three locations in Tennessee. The first location was the East Tennessee Research and Education Center in Knoxville (35°54′2″ N, 83°57′36″ W; 274 m elevation) on an Etowah silt loam (fine-loamy, siliceous, semiactive, thermic Typic Paleudult) (Soil Survey Staff, 2014). The second location was the Plateau Research and Education Center near Crossville, TN (36°2′38″ N, 85°9′48″ W; 576 m elevation), on a Lily loam (fine-loamy, siliceous, semiactive, mesic Typic Hapludult) (Soil Survey Staff, 2014). The third location was the Highland Rim Research and Education Center near Springfield, TN (36°28′22″ N, 86°49′7″ W; 201 m elevation), on a Mountview silt loam (fine-silty, siliceous, semiactive, thermic Oxyaquic Paleudult) (Soil Survey Staff, 2014).

Treatments

Treatments of NWSG were: (i) 100% SG monoculture, (ii) two-way blend of 65% BB and 35% IG, and (iii) a three-way mixture of 50% SG, 35% BB, and 15% IG (50:50 ratio of treatments 1 and 2). The seeds were blended to the appropriate ratios based on mass of pure live seed (PLS). Seeding rates were: SG, 6.7 kg ha^{-1}; BB+IG, 5.4 kg BB ha^{-1} and 2.8 kg IG ha^{-1}; and SG+BB+IG, 3.4 kg SG ha^{-1}, 2.7 kg BB ha^{-1}, and 1.4 kg IG ha^{-1} (Bates et al., 2008). The cultivars Alamo SG, Rumsey BB, and OZ-70 IG were used in this study. Alamo is a lowland type SG that has been used in biomass production. Rumsey and OZ-70 are cultivars that were adapted to the southeastern growing conditions and available through Roundstone Native Seed LLC (Upton, KY).

Establishment

Plots were established in 2008 at Springfield, and 2009 at Knoxville and Crossville. In all three locations management was pasture and/or hay fields dominated by tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., formerly *Festuca arundinacea* Schreb.] with no other management or recent history of research use before this study. All sites were planted in early May. At establishment, no lime, P, and K fertilizer was applied based on soil test results indicating additional levels were not necessary (University of Tennessee Soil, Plant and Pest Center, Nashville). Plots were established by drilling into a conventionally prepared seedbed. Plot size at Knoxville was 1.8 by 7.6 m (12.9 m^2) and at Crossville and Springfield was 1.5 by 7.6 m (11.4 m^2).

Weed Control

In the fall before establishment, an application of 2.24 kg a.i. ha^{-1} glyphosate [*N*-(phosphonomethyl) glycine] was applied to the study area to eradicate existing vegetation. A second application of glyphosate at that same rate was made 2 wk before planting. At establishment, BB+IG plots were treated with an application of glyphosate (2.2 kg a.i. ha^{-1}) and imazapic (0.11 kg a.i. ha^{-1}) {2-[[(RS)-4-isopropyl-4-methyl-5-oxo-2-imidazolin-2-yl]]-5-methylnicotinic acid} to provide pre-emergence weed control. Plots containing SG were mowed twice to reduce weed competition during the establishment year. In the first year after establishment, metsulfuron (14.0 g a.i. ha^{-1}) {2-[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino]-oxomethyl]sulfamoyl]benzoic acid methyl ester} was applied to plots with only BB and IG for broadleaf weed control. No herbicide treatment was required on the plots containing SG. Once the study was in the second year after establishment, weed control was not necessary.

Fertilization

Plots were fertilized annually with 101 kg N ha^{-1} with urea 46–0–0. The BH treatment received one application N at green-up in mid-April, whereas the dual-harvest treatments received half at green-up, and the remaining half following the early-season forage harvest. Lime, P, and K were not required at Knoxville and Crossville. Springfield did receive location did require a spring application of 101 kg P ha^{-1} in the form of diammonium phosphate (DAP) at green-up, and N was adjusted for the N content of the DAP at (University of Tennessee Soil, Plant and Pest Center, Nashville).

Harvest

Harvest treatments were implemented during 2010 to 2012 and consisted of BH, EB+BH, and ESH+BH. Forage harvest timings were based on the growth stage of SG monoculture. Timing for EB was at stem swell due to the development of the seedhead and flag leaf formation. Typically this occurred from the last week in May to the first week of June, depending on location. At ESH, a seedhead was emerged and fully expanded from the sheath, which corresponded to approximately the last week of June. Average interval between EB and ESH during the course of the study was 27 d. The BH harvest took place after the first killing frost for each location. Plots were harvested at a 15-cm residual height using a flail-type small-plot harvester (Carter Mfg. Co., Inc. Brookston, IN; Swift Machine and Welding Ltd., Swift Current, SK). A 0.9 by 7.6 m harvest strip was removed from center of the plot area, resulted in a harvested area of 6.9 m^2. Harvested forage was weighed and a subsample was dried at 60°C in a forced-air oven for 72 h to determine moisture content and ultimately, yield (Murray and Cowe, 2004). Stand density estimates were taken during this study, however authors deemed data not to be included. Visual observations, of the stands for 3 yr where harvest data were taken, indicated stands maintained vigor throughout study.

Climatological Data

Rainfall and temperature data were collected by a weather station located at each study site. The 30-yr monthly average rainfall for each location [(ID: USC00404946) East Tennessee Research and Education Unit, (ID: USC00402202) Plateau Research and Education Unit, and station (ID: USC00408562) Highland Rim Research and Education Unit] indicated annual totals were higher or within 15% of the 30-yr average for the study period (Golden Gate Weather, 2014).

Statistical Methods

Dependent variables (forage, biomass, and total yields) were analyzed under a randomized complete block design with a factorial arrangement of the three NWSG and three harvest treatments replicated four times over 3 yr. Data were analyzed using SAS and the MIXED procedure with repeated measures (autoregressive variance structure) over 3 yr (SAS Institute, 2012). Random effects [replication ′ location (year)] were included in the model. Based on preliminary analysis, main effect differences in forage and biomass yield for year and location were not significant ($P > 0.05$); therefore, results were pooled over those factors in the subsequent model. With the total annual yield model (total annual yield = forage + biomass), location ($P < 0.001$) and year ($P < 0.001$) differed; however, there were no two- or three-way interactions ($P = 0.373$). Thus, results for all three models (forage, biomass, and total yield) are presented with the two-way interaction, NWSG × harvest. Normality of residuals was assessed by the Shapiro–Wilk test ($W \geq 0.90$). Mean separations were conducted using Fishers Protected LSD with $\alpha = 0.05$.

RESULTS AND DISCUSSION

Forage Yield

Forage yield is defined as the mass harvested at the EB and ESH stages of growth for hay production. Forage yield ranged from approximately 5 to 8 Mg DM ha^{-1} at EB and from 6 to 12 Mg DM ha^{-1} at ESH (Fig. 1). As expected, delaying forage harvest from EB to ESH increased forage yield for all NWSG treatments; across all treatments forage yield increased by 22% due to additional growing days ($P < 0.001$; Fig. 1). The greatest increase in forage yield from EB to ESH occurred in the three-way mixture (5.0 Mg DM ha^{-1}) followed by SG (4.4 Mg DM ha^{-1}), while the yield increase of BB+IG (1.7 Mg DM ha^{-1}) was smaller (Fig. 1). The likely explanation for the increased ESH yield for SG and the three-way mixture was the rapid growth of SG during June. The later maturing BB and IG did not show that same level of increase, however. This agreed with previous work indicating BB and IG accumulate biomass at a lower rate than SG (Springer et al., 2001). Both SG and the three-way mixture produced the greatest yields ($P < 0.001$) compared to BB+IG, regardless of harvest timing. This finding was not unexpected given the contribution made by the presence of the robust, lowland SG in these stands. Although SG produced the highest forage yield at EB, including SG with BB+IG to produce the three-way mixture increases EB yield by 2.0 Mg DM ha^{-1} (Fig. 1).

Biomass Yield

Biomass yield is the fall-harvested material typically harvested after the first frost, and which could be used cellulosic ethanol production. At BH, SG produced the greatest biomass yield (16.6 Mg DM ha^{-1}) among all treatments (Fig. 2). Taking a prior harvest for forage at EB and ESH from SG reduced biomass yield by 5.4 and 8.1 Mg DM ha^{-1}, respectively. Harvest timing of the early harvests (EB and ESH) had an impact on

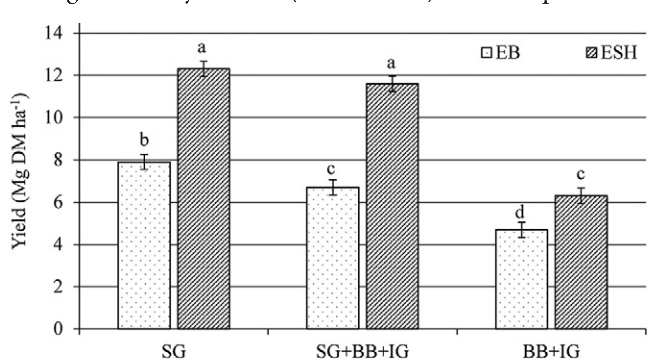

Fig. 1. Early-season forage yield at two stages of maturity averaged across three experimental locations (Knoxville, Crossville, and Springfield, TN) and 3 yr (2010–2012; $P < 0.001$). Harvests (EB, early-boot; ESH, early-seedhead). Treatments of native warm-season grasses (NWSG) (SG, switchgrass; SG+BB+IG, three-way mixture of switchgrass/big bluestem/indiangrass; BB+IG, two-way blend of big bluestem/indiangrass. Means not sharing a lowercase letter are significantly different for the harvest × NWSG interaction (Fisher's Protected LSD $\alpha = 0.05$). The error bars represent the SE mean (0.36) for the harvest × NWSG interaction.

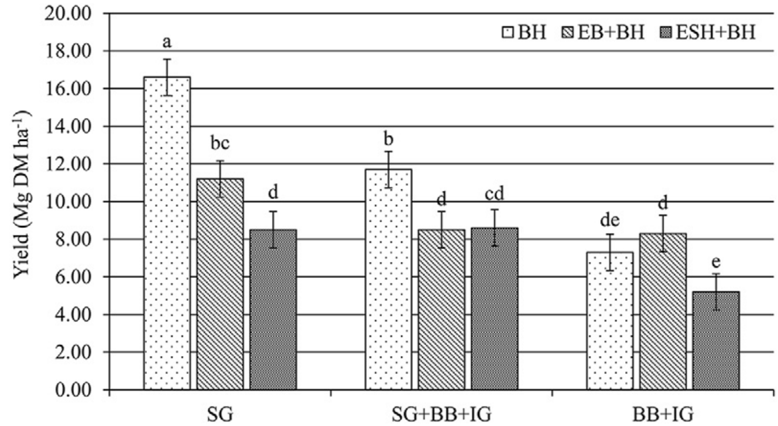

Fig. 2. Effect of early harvests for forage on biomass yield averaged across three experimental locations (Knoxville, Crossville, and Springfield, TN), and 3 yr (2010–2012; $P = 0.002$). Treatments of native warm-season grasses (NWSG) (SG, switchgrass; SG+BB+IG, three-way mixture of switchgrass/big bluestem/indiangrass; BB+IG, two-way blend of big bluestem and indiangrass). Harvest treatments (BH, biomass harvest; EB+BH, early-boot plus biomass harvest; ESH+BH, early-seedhead plus biomass harvest). Means not sharing a lowercase letter are significantly different for the harvest × NWSG interaction (Fisher's Protected LSD $\alpha = 0.05$). The error bars represent the SE mean (0.97) for the harvest × NWSG interaction.

SG biomass and was in agreement with findings reported by Vogel et al. (2002). This trend also supported the recommendation by Sanderson et al. (1999) and Guretzky et al. (2011) to remove forage early in the growing season in dual-harvest forage–biomass systems. With the three-way mixture, yield at BH was reduced compared to SG (11.7 vs. 16.6 Mg DM ha^{-1}, respectively), an outcome likely due to displacing SG with less productive BB and IG. Furthermore, SG produced more biomass with EB+BH than the three-way mixture, although biomass yields were similar at ESH+BH between SG and SG+BB+IG. As was the case with SG, taking prior harvests for forage from SG+BB+IG reduced subsequent biomass yields ($P = 0.002$) (Fig. 2). Unlike SG, however, there was no difference in biomass yield between EB+BH and ESH+BH. A plausible explanation for the similar yield at these two harvest dates for the three-way mixture is that the later maturing BB and IG made a larger contribution to the ESH yield, perhaps off-setting any lost biomass yield from SG at that time. The two-way blend of BB+IG produced the lowest BH biomass yield, 7.3 Mg DM ha^{-1} or only 44% of that produced by SG (Fig. 2). These results were in agreement with other studies that reported SG produced the highest biomass yield, in monoculture or mixture compared to BB and IG (Brejda et al., 2000; Vogel, 2004). These results support the recommendation of using SG in single-harvest systems to produce the greatest biomass yield (Springer et al., 2001; Vogel, 2004; Parrish and Fike, 2005).

Contrary to expectations for the two-harvest systems, EB did not always result in more biomass than ESH as seen with the SG+BB+IG, and the harvest for forage did not always reduce biomass yield, as seen for BB+IG. For BB+IG, early forage harvest did not affect biomass yield compared to BH (Fig. 2). These late-maturing species had not accumulated a substantial portion of their annual biomass production by the time of the EB (late May) harvest. They were still able to produce significant reproductive growth following this initial harvest, which may have off-set reductions in biomass. Biomass yield for all NWSG treatments combined was greatest for BH, while taking a prior harvest for forage at EB or ESH decreased biomass yield (11.8, 9.4, and 7.4, Mg DM ha^{-1}, respectively; $P < 0.001$). Across all NWSG treatments, biomass yield was reduced by 51% for EB+BH and 68% for ESH+BH harvest treatments compared to BH ($P < 0.001$).

Total Yield

The one-harvest system, across all NWSG, produced less total yield when compared to either two-harvest system (EB+BH and ESH+BH), except for SG for which there was no difference (Fig. 3). For SG, reduced biomass yield was offset by increased forage production at approximately equal proportions. The ESH+BH dual-harvest system was similar to that reported by Fike et al. (2006) in which they reported lowland SG produced similar yields in one- and two-harvest systems. Conversely, in the NWSG treatments with BB and IG, there was a clear yield advantage in the two-harvest systems. Thus, in both SG+BB+IG and BB+IG, forage yield increased disproportionately to the reductions in biomass yield. Put another way, for BB+IG there was almost no reduction in biomass yield as a result of removing forage in a two-harvest system. Also, SG may have contributed, especially in the ESH harvest, to this surge in production in June.

Combining forage and biomass yield to determine total annual yield for NWSG in a dual-harvest system can help determine optimal management scenarios for producers. No differences in total yield for SG suggests it offers producers the greatest flexibility among the options evaluated. If forage production is an objective, either harvest (EB or ESH) could be an option depending on the reduction in biomass production in relation to the value lost. If forage production was not an objective, biomass yield is the greatest for SG. On the other hand, for producers that intend to produce both forage and biomass, the SG+BB+IG blend may be advantageous because total yield at either EB+BH or ESH+BH did not differ from that produced by SG for those same harvests (Fig. 3). There was also a clear preference with SG+BB+IG for ESH+BH over EB+BH with respect to total yield, an outcome driven by increased forage yield at the latter date and not by changes in biomass yield (Fig. 3). The ESH forage yield for the three-way mixture did not

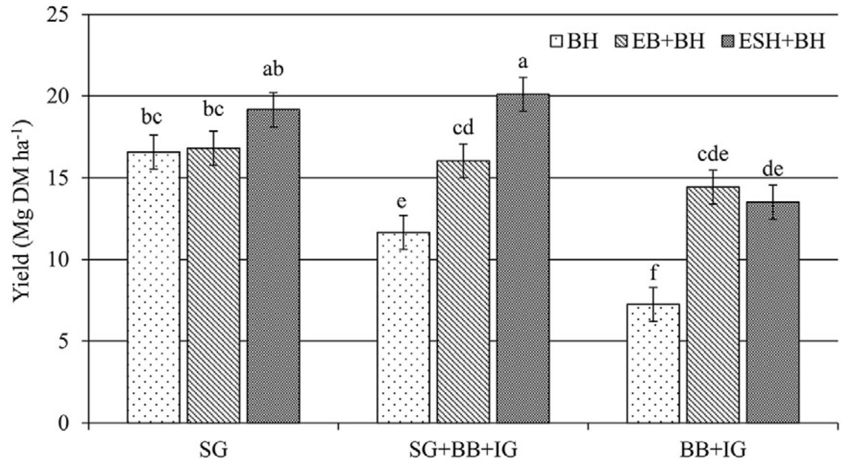

Fig. 3. Total yield (Forage + Biomass) averaged across three experimental locations (Knoxville, Crossville, and Springfield, TN), and 3 yr (2010–2012; $P = 0.002$). Treatments of native warm-season grasses (NWSG) (SG, switchgrass; SG+BB+IG, three-way mixture of switchgrass/big bluestem/indiangrass; BB+IG, two-way blend of big bluestem and indiangrass). Harvest treatments (BH, biomass harvest; EB+BH, early-boot plus biomass harvest; ESH+BH, early-seedhead plus biomass harvest). Means not sharing a lowercase letter are significantly different for the harvest × NWSG interaction (Fisher's Protected LSD $\alpha = 0.05$). The error bars represent the SE mean (1.04) for the harvest × NWSG interaction.

differ from SG with respect to yield, but because of the later maturity of BB and IG (Fig. 3).

There was no apparent yield advantage associated with combining SG with BB and IG for EB or ESH harvests, or in a single-harvest biomass system. Despite similar growth habits of the three NWSG used in the three-way mixture, there was no synergistic improvement in yield within a given harvest system as suggested by Mangan et al. (2011). Similar to the findings of Mulkey et al. (2008), the alternatives to SG offered sustainable production options, albeit with lower yield in one-harvest systems or, as was the case with BB+IG, in either one- or two-harvest systems. Indeed, the dual-harvest system for forage and biomass produced the greatest total annual yield from ESH+BH for SG and SG+BB+IG (Fig. 3).

CONCLUSIONS

When trying to produce high biomass yield, SG should be used as monoculture or in mixture with BB and IG due to the increased yield it provides. With SG in monoculture, biomass is reduced to a greater degree with later harvests for forage. On the other hand, because of SG high yield in a one-harvest system; and, the fact that the biomass yield following an EB harvest that was equal to or greater than a single BH from either mixture it provides the greatest flexibility to producers. However, the three-way mixture can provide comparable forage and biomass yield as SG, depending on harvest timing. Thus, where forage yields are an expected part of the system, there may be an advantage to the three-way mixture. No apparent synergies were captured in terms of yield through combining NWSG vs. SG in monocultures in this study.

When a producer considers planting SG for forage and/or biomass, the timing of an early-season forage harvest will be the most important management decision affecting forage and biomass yield. If the three-way mixture is used, harvest timing for forage will be less critical in terms of its impact on biomass yield, and in the case of the two-way blend, forage yield as well. If the primary consideration for both forage and biomass is yield, a SG monoculture will be the best species choice. Using BB+IG in a biomass or dual-harvest system will produce considerably lower forage and biomass yield. Considering total annual yield can inform producers' management decision making, although economic valuations of costs and outputs can help evaluate trade-offs in those decisions in the face of changing market conditions. Producers, in the mid-South, can harvest both forage and biomass from the same field offering flexibility and the potential to increase profits by providing two marketing options. To further conclusions presented here, the forage nutritive value and biomass quality data as it relates to yield will be presented in a separate work to follow.

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