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Establishing a Fall Harvest Window for Switchgrass Biomass Based on Optimum Decline of Phosphorus and Potassium Levels in Shoots

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I am submitting herewith a thesis written by Jennifer Kay Lane entitled "Establishing a Fall Harvest Window for Switchgrass Biomass Based on Optimum Decline of Phosphorus and Potassium Levels in Shoots." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

Fred L. Allen, Major Professor

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Establishing a Fall Harvest Window for Switchgrass Biomass Based on Optimum Decline of Phosphorus and Potassium Levels in Shoots

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jennifer Kay Lane
August 2011

Dedication

This thesis is dedicated to my parents, Dwight and Linda Lane, who have always been a good example, giving me support and strength throughout my entire life.

Acknowledgements

More than anything I want to thank God for blessing me so much! He has brought me peace in the midst of many storms and blessed me with irreplaceable family and friends.

"The things which are impossible with men are possible with God" Luke 18:27

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Abstract

Switchgrass *(Panicum virgatum*) is a perennial grass that remobilizes nutrients during senescence and is being used as biomass for cellulosic ethanol production. Phosphorus (P) and potassium (K) are removed in harvested biomass and replenished through additions of fertilizer. Identifying the appropriate harvest window in a one-cut system based on the remobilization of nutrients can be economically beneficial for biomass producers. The primary objective of this research was to determine if a one-cut harvest can be executed earlier in the fall based on the remobilization of P and K from stems and leaves to crown and roots of plants. Better harvesting conditions and reduced nutrient removal rates are potential benefits of earlier harvest. This project consisted of three parts, evaluating: (1) P and K levels in shoots and whole plants of Alamo and Kanlow cultivars, (2) P and K levels in shoots of upland and lowland switchgrass varieties, and (3) Effects of earlier harvest on yield. Twelve varieties, including 'Alamo' and 'Kanlow' cultivars, were planted in Knoxville, TN in 2007. Eight of these varieties were planted in Springfield, TN. Above and belowground samples were collected throughout the fall and analyzed for P and K concentrations. No significant declines of P and K were observed in stems and leaves from early October through November. Levels of P and K in leaves, stems, and panicles fluctuated during the fall season; however, final levels were similar in all tissues. Based on these changes in aboveground biomass, the harvest window could begin as early as mid-September. Data suggested that P and K in Alamo and Kanlow followed similar patterns through the fall, without significant declines in shoots. This is confirmed by data from whole plants, which showed no significant increases in P and K in crowns and roots. Levels of P and K in varieties of upland and lowland switchgrass did not differ and followed patterns observed in

Alamo and Kanlow. Yields observed in different varieties did not decline when harvested as early as mid-September. Based solely on this study, it is not necessary to delay harvest and could take place as early as September.

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Introduction

In 1985, research funded by the U.S. Department of Energy (DOE) identified herbaceous (non-woody) species for the production of fuels through the Herbaceous Energy Crops Program (HECP), which was coordinated through Oak Ridge National Laboratory (ORNL) (Parrish, 2010). Switchgrass (*Panicum virgatum*) was recognized as an ideal bioenergy crop because of its productivity on marginal land and compatibility with existing farming practices (McLaughlin and Kszos, 2005). The Energy Independence and Security Act of 2007 increased the Renewable Fuel Standard (RFS) by requiring 136 billion liters of renewable fuel by 2022 (EISA, 2007). Starting in 2016, the increase in the RFS target must be met with advanced biofuels, such as cellulosic ethanol (EISA, 2007). As of 2010, approximately 2605 hectares of switchgrass were planted were on various East Tennessee farms (UTIA, 2010). The University of Tennessee switchgrass farmer incentive program made contracts available to pay farmers $1112 per hectacre to grow switchgrass, which will be transported for use at the cellulosic ethanol pilot facility in Vonore, TN (UTIA, 2010).

Switchgrass is a perennial warm-season grass with a C4 photosynthetic system, making it broadly adaptable and yield well in warm temperatures (Vogel, 2004). Switchgrass has been identified as a good contender for biofuels, but in the upper southeastern U.S. more information on its productivity and harvest management is needed (Fike et al., 2006). “Final harvests, whether in single or double-cut systems have been found to be best applied either by mid-September to maximize yields or after the first frost to maximize retranslocation of both carbon and energy to root systems” (McLaughlin and Kszos, 2005). The current recommendation in Tennessee for a one-cut system is to harvest after a killing frost or early November, whichever comes first because nutrient removal and fertility needs of switchgrass may be reduced by harvesting after frost kills the aboveground growth (Garland, 2008).

Nutrients conserved through translocation are often beneficial for yields the following year, which implies that the most suitable and advantageous harvest time would be when the maximum amount of nutrient remobilization has occurred (McLaughlin and Kszos, 2005; Parrish et al., 2003). . Harvesting earlier in the fall would clearly be beneficial for switchgrass producers. Earlier harvest might require additional curing time, but the favorable weather conditions at an earlier date will provide ample time for curing. Identifying the appropriate time of fall harvest in a one-cut system based on the sustainable management of nutrients may be economically beneficial for the biomass producer as well as the productivity and survival of switchgrass. The primary objective of this research was to determine if fall biomass harvest of switchgrass could take place earlier than the recommended time of early November based on the optimum decline of phosphorus and potassium concentrations in shoots of different varieties and if yields would be affected by earlier harvest.

Part I

Evaluation of Phosphorus and Potassium Levels in Shoots and Whole Plants of Alamo and Kanlow Cultivars

Abstract

As the number of switchgrass producers continues to increase, so does the need for more accurate harvest information. In an effort to reduce nutrient loss, the current recommendation in Tennessee for a one-cut biomass system is to harvest switchgrass after the first killing frost or early November. The potential problem is that weather and field conditions during that time of year can be unpredictable and undesirable. The objective of this research was to determine if harvest of ‘Alamo’ and ‘Kanlow’ switchgrass cultivars can take place earlier in the fall based on the decline of phosphorus (P) and potassium (K) in the shoots of plants. As the fall progresses and switchgrass matures, nutrients can relocate from shoots to crowns and roots. This remobilization allows nutrients to be conserved for the following growing season instead of being removed from the land in the harvested biomass. Tiller samples of Alamo and Kanlow were collected from 2008-2010 at the East Tennessee Research and Education Center, Plant Sciences and Holston Units in Knoxville and the Highland Rim Research and Education Center in Springfield, TN for nutrient analyses from harvests in September, October, and November. Additionally, whole plants of Alamo and Kanlow were dug at ETREC in mid-September, late October, and early November. Tiller samples and whole plant samples from each harvest date were analyzed for nutrient concentration. The P levels in both Alamo and Kanlow were highest in panicles, while leaves and stems had similar concentrations. The K levels in both varieties were highest in stems, followed by panicles, then leaves. Potassium ranged from three to six times greater than P in different tissues. Data suggested P and K in Alamo and Kanlow varieties followed the same patterns through the harvest period and concentrations of P and K in shoots do not significantly decline from mid-September to early October. Interestingly, whole plant data

indicate that crowns and roots do not significantly increase in P and K from mid-September to mid-November. There may be other compelling reasons for later harvest, such as conversion efficiency of ethanol, but based solely on P and K levels in shoots, harvest could take place as early as mid-September without removing amounts of P and K in harvested biomass that are significantly higher than those in delayed harvests.

CHAPTER I

Introduction and Literature Review

Phosphorus (P) and potassium (K) are important for growth and development of switchgrass. During maturation and senescence, switchgrass remobilizes these nutrients and stores them in the crown and roots to aid in shoot growth the following year, making time of harvest especially important for the plant (Yang et al., 2009). Conserving and maintaining the P and K that is available within the crowns and roots may be advantageous for the longevity of switchgrass, especially if stands are harvested annually for several years. Lemus et al. (2009) defined nutrient conservation as management that can reduce the amount of nutrients removed and therefore keep them available in the system for future use. Harvesting based on optimal nutrient translocation may make conservation possible.

Because of their high productivity, lowland cultivars are more appropriate than upland cultivars for biomass production in the upper southeastern U.S. (Fike et al., 2006). ‘Alamo’ and ‘Kanlow’ are highly productive, commonly grown lowland switchgrass cultivars. Moser and Vogel (1995) identified Alamo as the top candidate for the deep South, while Kanlow is reported to be better suited for mid-latitudes in the U.S. based on yield.

Switchgrass has been reported to perform adequately on soil with low P levels (Balasko et al., 1984, Brejda, 2000, Muir et al., 2001). But it is not clear how long they can maintain productivity under fairly intense commercial production. Management strategies, such as number of harvests per growing season, will affect nutrient removal and likely stand persistence. Switchgrass grown for biomass is typically harvested annually in a one or two-cut system. Lemus et al. (2009) found that a two-cut management system significantly increased phosphorus removal, while potassium removal was comparable between the one and two-cut harvest systems. Large amounts of macronutrients, such as P and K, in harvested biomass can lead to substantial depletion of these in the soil, requiring additions of fertilizer to maintain appropriate soil fertility (Yang et al., 2009). Previous research has shown that approximately 3.5 kg of P and up to 18 kg of K can be removed per dry metric ton of corn stover harvested (Mitchell, 1999; Murdock and Schwab, 2007; Osmond and Kang, 2008; Sawyer and Mallarino, 2007). Removal of both nutrients varies depending on geographic location and yield, which averaged 10.5 t ha^{-1} (Mitchell, 1999; Murdock and Schwab, 2007; Osmond and Kang, 2008; Sawyer and Mallarino, 2007).

Fertilization is a major economical cost and environmental concern. Minimizing these costs may be possible by monitoring plant removal and ultimately adjusting harvest time accordingly for nutrient conservation. Increasing biomass yields while decreasing fertilizer needs is a positive outcome of allowing plants to senesce and remobilize nutrients, but it is important to realize that adverse weather in some areas can become a threat to harvestable material the longer it stays in the field (Heaton et al., 2009).

Continual harvest and removal of biomass without replacing nutrients can potentially mine the soil of nutrients and hinder biomass yields as stands age, with effects occurring quicker in a two-cut system than a one-cut system (Guretzky et al., 2009). Nutrients are always removed with harvested switchgrass; therefore, management of nutrients will be important for the sustainability of this bioenergy crop (Yang et al., 2009). Carefully choosing an appropriate harvest window can help sustain the future of switchgrass production (Yang et al. 2009). Thus, balancing the time of harvest with yield and nutrient removal will be an important management strategy needed by switchgrass producers.

CHAPTER II

Materials and Methods

Site Description

A field study was conducted at three sites in Tennessee. The first two sites were at the East Tennessee Research and Education Center (ETREC), Plant Sciences and Holston Units in Knoxville (35.53°N 83.57°W). Weather data were only available at the Plant Sciences Unit; however, weather conditions at the Holston Unit were comparable because these sites were located only 16 km apart. The Plant Sciences Unit had an average annual temperature of 14°C from 2008-2010. This site received 129 cm of precipitation in 2008, 173 cm in 2009, and 124 cm in 2010. The first fall freeze (0°C and below) occurred on 29 October 2008, 19 October 2009, and 7 November 2010. Soil at the Plant Sciences Unit is classified as a Sequatchie loam (fine-loamy, siliceous, semiactive, thermic Humic Hapludults). Prior to this experiment the Plant Sciences site was seeded in tall fescue (*Festuca arundinacea*). Soil at Holston is classified as a Huntington silt loam (fine-silty, mixed, active, mesic Fluventic Hapludolls). Prior to this study, the Holston site was managed for orchardgrass (*Dactylis glomerata*) hay production.

The third site in 2010 was at Highland Rim Research and Education Center (HRREC) in Springfield (36.28°N 86.51°W). This site had a mean annual temperature of 14.4°C in 2010, but received a slightly lower amount of precipitation (108 cm). The first fall freeze occurred on 29 October 2010. Soil at the HRREC is classified as a Sango silt loam (coarse-silty, siliceous, semiactive, thermic Glossic Fragiudults) or a Dickson silt loam (fine-silty, siliceous, semiactive, thermic Glossic Fragiudults). Prior to the initiation of this study, this site was cropped in winter wheat (*Triticum aestivum*).

Experimental Design

In May 2007, twelve switchgrass varieties, comprised of upland and lowland types, were planted at the ETREC Plant Sciences Unit in Knoxville, Tennessee (Table 4.1). Eight of these twelve varieties were planted on June 14, 2007 at HRREC in Springfield, TN (Table 4.1). These varieties were planted in three replications in a randomized block design at a rate of 8.9 kg ha^{-1} of pure live seed (PLS) with a Hege™ 1000 no-till plot drill. Experimental plots at ETREC were 1.4 m x 7.6 m, while the plots at HRREC measured 1.4 m x 9.1 m. An annual biomass harvest took place once in the fall of each year. Large 13.3 m x 259.1 m plots of Alamo and Kanlow were seeded at 8.9 kg ha^{-1} of PLS in May 2007 at ETREC Holston Unit in Knoxville, TN

From 2008 to 2010, P and K levels were evaluated in shoots of Alamo and Kanlow planted at the Plant Sciences and Holston Units at ETREC and in 2010 levels at HRREC were evaluated. In 2009 and 2010, P and K levels continued to be evaluated using two methods. The first method included evaluating P and K levels in leaves, stem, and panicles for each variety. The second method included evaluating P and K levels in aboveground biomass in comparison to levels in the crown and roots of belowground biomass in 2009 and 2010.

Sample Harvesting and Processing

Ten plant tillers, clipped 3-5 cm above ground level, were collected from each plot throughout the fall from each site. At ETREC Plant Sciences Unit and Holston Unit, these samples were obtained in 2008 (21 July, 22 Aug., 25 Sept., 9 Oct., 15 Oct., 24 Oct., 31 Oct., 10 Nov.), 2009 (18 Sept., 9 Oct., 28 Oct., 13 Nov.), and 2010 (15 Sept., 12 Oct., 26 Oct., 10 Nov.). Samples were obtained from HRREC only in 2010 (21 Sept., 15 Oct., 1 Nov., 22 Nov.). Fresh weight was measured on each sample and samples were dried in a batch oven (Wisconsin Oven

Corporation, East Troy, WI, USA) for a minimum of 24 hours at 49°C and dry weight was measured. Samples were further divided into panicle/seed, leaf, and stem tissue subsamples. Subsamples were ground using a Wiley Laboratory Mill (Arthur H. Thomas Company, Philadelphia, PA, USA) to pass through a 2-mm screen.

To determine the P and K ratios in above and below-ground biomass, five whole plants of Alamo and Kanlow were dug in mid-September, mid-October, late October, and early November, beginning in 2009. These were obtained in 2009 (29 Sept., 21 Oct., and 17 Nov.) and 2010 (15 Sept., 29 Oct., 8 Nov.). Whole plants were dried through the method described above. Once dried, the whole plants were divided into three subsamples composed of roots, crowns, and the above ground shoots. Subsamples were cut into smaller pieces and ground in the laboratory mill to pass through a 2-mm screen. Whole plant sampling at similar dates was repeated in 2010.

Stem:Leaf Ratio Calculation

After the shoot samples were divided into leaf, stem, and panicle subsamples, each subsample was weighed separately to calculate the ratio of stems to leaves. Once weighed, the stem:leaf ratio was calculated by dividing each sample stem weight by the corresponding leaf weight. These ratios were analyzed using PROC GLM (SAS 9.2, 2009) to identify differences.

Nutrient Analysis

Approximately 0.45-0.55 g of dried ground tissue was placed in 16x100 mm glass tubes and ashed at 450˚ C for 4-6 hours. Nitric acid was used to dissolve the ash at a rate of 10 ml HNO_3 (70%) per 0.5 g of sample. Samples were analyzed for P and K using an inductively coupled plasma mass spectrometer (ICP-MS, Model 7500ce, Agilent Technologies) at the University of Tennessee, Knoxville.

Statistical Analysis

Statistical analyses were performed using the PROC GLM procedure (SAS 9.2, 2009), Duncan’s Multiple Range Test was used to determine if treatment effects were significant at the 5% level of probability.

CHAPTER III

Results and Discussion

Shoot samples

Phosphorus

Alamo and Kanlow are typically the two standard lowland varieties grown in the southeastern U.S.; therefore a comparison of these two varieties was advantageous. Notable trends in nutrient concentrations were observed in the various tissues. The highest amounts of P were typically found in the panicles in both Alamo and Kanlow while stems and leaves consistently had similar concentrations (Tables 1.1-1.6). Much of the P is contained in the seed; however, seed were not analyzed separately from the panicle racemes. The contribution of panicles (including seed) to switchgrass biomass was minor and diminished as the fall progressed; therefore, additional discussion of panicles in these results will be minimal. Panicle data were not collected at HRREC.

Data were collected from eight harvest dates in 2008. At the ETREC Plant Sciences Unit in 2008, Alamo had the highest P concentration in leaves at late July harvest (1.4 kg t^{-1}) (Table 1.1). At the Holston Unit, P was also highest in leaves in July (2.6 kg t^{-1}) and averaged 0.9 kg t^{-1} from late August to late October (Table 1.2). Alamo stems had significantly higher P concentration in mid-November (0.9 kg t^{-1}), suggesting that earlier harvest may be more beneficial. From September to November, P levels in leaves did not vary greatly; averaging 0.9 kg t^{-1}. In stems, P averaged 0.4 kg t^{-1} from July to late October. Although overall P was slightly higher, data collected at ETREC Holston Unit in 2008 supported these findings (Table 1.2). Stem P averaged 1.0 kg t^{-1} through the harvest period with no significant changes. Observations of P in

Alamo at both locations in 2008 suggest that harvest may be executed much earlier in the fall. Based on the data obtained in 2008, the decision was made to focus on four harvest dates later in the fall, mid-September, mid-October, late October, and early November, in 2009 and 2010.

In 2009 at ETREC Plant Sciences Unit, significant increases of P in stems (1.4 kg t^{-1}) and leaves (1.8 kg t^{-1}) occurred in November, with no changes from mid-September to late October (Table 1.1). At the Holston Unit, P levels were similar through the fall, averaging 2.5 kg t^{-1} in leaves and 1.9 kg t^{-1} in stems (Table 1.2). The data obtained in Alamo in 2009 were similar to 2008, which promotes harvest before November.

At Plant Sciences Unit in 2010, no significant changes in P observed from mid-September to mid-November, with both leaves and stems of Alamo averaging 0.6 kg t^{-1} (Table 1.1). At the Holston Unit, leaves averaged 1.3 kg t^{-1} and stems averaged 0.9 kg t^{-1}, with no changes through the harvest period (Table 1.2). Alamo data were also collected from a third location (HRREC) in 2010 (Table 1.3). At HRREC, P levels were consistent from mid-September through November, averaging 0.7 kg t^{-1} in both leaves and stems. With consistent data across years and locations in both leaves and stems, these data suggest that Alamo switchgrass may be harvested as early as mid-September without removing significantly more P in harvested biomass.

As previously mentioned, Kanlow was also studied at each of the locations. In Kanlow leaves, stems, and panicles the P concentrations were present in amounts similar to those in Alamo. In 2008 at ETREC Plant Sciences, the P level in Kanlow leaves was high in July (1.6 kg t^{-1}), but averaged 0.9 kg t^{-1} from late September through November (Table 1.4). The P in leaves was steady through the fall, averaging 0.7 kg t^{-1}, which was also consistent with Alamo. At the

Holston Unit, the July 2008 P level in leaves of Kanlow were significantly higher (2.4 kg t^{-1}) than late October through November levels (0.9 kg t^{-1}), but no significant changes occurred from late August through mid-November (Table 1.5). The level of P in stems of Kanlow was also significantly higher in July (1.3 kg t^{-1}) than the latter harvests, which averaged 0.9 kg t^{-1} through the fall (Table 1.5). Based on the data collected at two locations in 2008, Kanlow harvest could occur earlier. In 2009, both stems and leaves of Kanlow at the Plant Sciences and Holston Units maintained similar P concentrations from mid-September to early November. Leaves averaged 0.6 kg t^{-1} at Plant Sciences Unit and 1.4 kg t^{-1} at Holston Unit, which supports data observed in Alamo, in which harvest could occur as early as September without significantly changing P removal. Although Holston Unit had slightly higher overall P than Plant Sciences Unit in 2010, P levels at both locations were similar across harvests in both stems and leaves (Table 1.5). As in Alamo, Kanlow data were collected from a third location (HRREC) in 2010. At HRREC, trends in P supported those observed at the ETREC locations. In both leaves and stems, P averaged 0.7 kg t^{-1} across harvest dates (Table 1.6). Once again, data observed across years and locations support harvesting Kanlow as well as Alamo as early as September.

Potassium

The amounts of K in leaves, stems, and panicles were three to six times greater than P, which supports previous studies (Lemus et al., 2009). The amount of K was generally greatest in stems, followed by panicles, and leaves. Potassium followed trends of change similar to those observed for P in Alamo and Kanlow.

In 2008 at ETREC Plant Sciences Unit, K levels in Alamo leaves were significantly higher in July (10.4 kg t^{-1}), which was the trend observed in P in the same year (Table 1.1).

There were no significant changes from late August through mid-November, averaging 3.6 kg t^{-1}. Stems of Alamo averaged 4.8 kg t^{-1} and did not change in K concentration through the harvest period (Table 1.1). At the ETREC Holston Unit, levels in leaves were highest in July (15.5 kg t^{-1}) but significantly decreased through the fall, with the lowest levels being recorded in early November (3.8 kg t^{-1}) (Table 1.2). However, K levels in stems did not change from late August through November, averaging 5.1 kg t^{-1}

At Plant Sciences in 2009, K in Alamo leaves maintained similar levels from mid-September to November, averaging 2.4 kg t^{-1}. The K levels in stems did not change until November, when the level significantly increased to 11.0 kg t^{-1} (Table 1.1). At Holston Unit in 2009, leaves had slightly higher levels in the earlier months, while stems did not change significantly from September (6.8 kg t^{-1}) to November (12.2 kg t^{-1}). Once again, these patterns of change are similar to those observed for P, only in higher amounts. At Plant Sciences in 2010, K levels were consistent with those observed in 2008 and 2009. Changes in K concentration were minimal in leaves and declined through the fall, averaging 2.4 kg t^{-1}. Stems averaged 5.6 kg t^{-1} from mid-September to late October, with no significant changes through early November. The third location in 2010, HRREC, showed similar K levels in leaves through the fall and similar stem levels. Stems had an average K concentration of 5.6 kg t^{-1} while leaves averaged 2.4 kg t^{-1} (Table 1.3). Trends of K in Alamo are similar to those in P and are consistent across years, which make a harvest prior to November a positive alternative to current recommendations.

The concentration of K in Kanlow followed trends similar to that of Alamo. At ETREC Plant Sciences in 2008, leaves had significantly high levels in July (12.3 kg t^{-1}), and decreased as the fall progressed (Table 1.4). Stems averaged 5.5 kg t^{-1} and did not significantly change until early November. At the ETREC Holston Unit in 2008, significantly higher levels were present in July in leaves (15.4 kg t^{-1}, Table 1.5). With the exception of a significantly lower level of K in November (1.8 kg t^{-1}), no other changes in stems from late August to late October or in leaves from late August through early November. In 2009, the only change was a significant decrease of K in leaves from September to early October at Plant Sciences. Stems averaged 5.5 kg t^{-1}. No changes occurred in K levels in stem or leaves through the fall at ETREC Holston Unit. In 2010, K levels in stems were similar at all three locations. Leaves in 2010 averaged 2.3 kg t^{-1} at Plant Sciences; however, stems at both Holston Unit and HRREC had significantly lower levels of K in late October (Table 1.6).

The common observation across locations and years in both varieties is that P and K did not typically decrease in significant amounts from September through November. Data were consistent in both varieties and suggests that Alamo and Kanlow switchgrass may be harvested as early as mid-September without removing significantly more P and K than when typically harvested in November.

Whole-plant samples

Phosphorus

Whole plants of Alamo and Kanlow were dug from field experiments in 2009 and 2010 and separated into shoots, crowns, and roots and analyzed for P and K in the component parts. The purpose was to test the hypothesis that switchgrass remobilizes significant amounts of these two nutrients from the shoots to crowns and roots as maturity progresses in the fall.

In Alamo and Kanlow, P concentrations in whole-plant samples were similar among shoot, crown, and root samples (Fig. 1.1). The P levels in shoots of Alamo in 2009 and 2010 averaged 1.2 kg t^{-1}. Slight changes were observed from September to November in 2009 and no significant ($P \leq 0.05$) changes in 2010. The biggest change observed was an increase of 0.7 kg t^{-1} from late October to mid-November 2009 in the crown tissue. Crown tissue in 2010 had a steady P concentration of 1.2 kg t^{-1}. The P concentrations in Alamo roots did not differ significantly from mid-September through mid-November in either 2009 or 2010 (Fig. 1.1).

The P levels in shoots, crowns, and roots of Kanlow were similar to those of Alamo (Fig. 1.2). No changes were observed in shoots of 2009 (averaging 1.1 kg t^{-1}), while only slight changes were observed in 2010 (averaging 0.9 kg t^{-1}). Kanlow crowns had P levels that tended to reach a peak in late October but were at similar levels in mid-September and mid-November in both years (Fig. 1.2). The same pattern was observed in Alamo in 2010 (Fig. 1.1). Roots had P concentrations that did not significantly differ across the three harvest dates in either year and averaged 1.4 kg t^{-1} in both years. Based on these results, no consistent declines in P levels were observed in shoots, nor were there consistent significant increases in the crowns and roots, which held true for both Alamo and Kanlow and across two years at the ETREC Holston location. These observations suggest that P is not remobilizing from shoots to crowns and roots in the fall.

Potassium

In contrast to similar levels of P in shoots, crowns, and roots of Alamo and Kanlow, K in these varieties was highest in the roots, followed by shoots then crowns (Figs. 1.1 and 1.2). As noted in the previous section regarding stems, leaves, and panicles, K levels present in shoots, crowns, and roots were up to six times higher than P levels in the same tissues. None of the Alamo tissues had significant changes in K among the three harvest periods in 2009 (Fig. 1.1). Potassium in shoots and crowns averaged 5.3 kg t^{-1}, while roots averaged 9.2 kg t^{-1}. Similarly in

2010, K concentrations in shoots and roots did not differ significantly ($P \leq 0.05$). Crowns increased in K in late October, but did not differ in November and mid-September (Figure 1.1).

Shoots, crowns, and roots of Kanlow showed no changes in K concentrations across the three harvest dates in either 2009 or 2010 (Fig. 1.2). These data reinforce the results obtained from the leaves, stems, and panicles study reported in the previous section on Alamo and Kanlow. Significant declines in P and K in the shoots of Alamo and Kanlow do not appear from mid-September into November. Crown and root data from the whole plants indicate no consistent and significant increases in P and K levels in these tissues from mid-September through mid-November. Thus, based strictly on P and K levels in shoots, harvesting earlier than late October or early November is justified, even as early as mid-September.

Stem:Leaf Ratio

Leaves and stems were separated from harvested tillers in these experiments and weighed separately. Weights were used to determine stem:leaf ratios. Based on these results there are nearly twice as many stems as leaves (ranging 1.3 to 2.2 times) in the shoots of Alamo and Kanlow switchgrass (Table 1.7-1.8). The stem:leaf ratio was found to be similar in both Alamo and Kanlow. No significant differences in ratios were observed in either variety at any of the three locations, with the exception of Kanlow at the ETREC Plant Sciences in November (Table 1.8). The stem to leaf ratios did not significantly change with harvest dates, indicating that both varieties retained the majority of their leaves through the harvest season. The stem:leaf ratio was lower at HRREC than ETREC, averaging approximately 1.5 in both varieties (Table 1.7-1.8), which is an indication that leaves and stems were more evenly balanced at HRREC and suggests that aspects of the location of switchgrass production might change the stem:leaf ratio.

Differences in the stem:leaf ratio may also affect ethanol conversion if switchgrass feedstocks that have more leaves than stems are beneficial or vice versa.

Phosphorus and Potassium Removal in Alamo

Estimated removal was calculated based on average yields of Alamo at four locations in 2010 (Part III) and the amount of P and K observed in leaves and stems in this study (Part I). The P removal was estimated at 20.4 kg ha^{-1} in late October and 22.3 kg ha^{-1} in early November (Fig. 1.3). As observed previously, K removal was more than four times greater than P removal. The K removal in late October and early November was estimated at 87.9 kg ha^{-1} and 96.7 kg ha^{-1}, respectively (Fig. 1.3). University of Tennessee Extension Service recommends that 45 kg ha^{-1} of P and 90 kg ha^{-1} of K be added to switchgrass only if the soil test reveals a low rating (Garland, 2008).

CHAPTER IV

Conclusions

The objective of this study was to determine if harvest of Alamo and Kanlow switchgrass cultivars can take place earlier in the fall based on the decline of P and K in shoots. Determining differences between Alamo and Kanlow cultivars was also of interest. Current harvest recommendations for switchgrass in a one-cut biomass system is based on the premise that that nutrient removal may be reduced when harvest is delayed until nutrients have remobilized from shoots to belowground tissues, such as crowns and roots. Harvests in this study were conducted in mid-September, mid-October, late October, and early November.

The P levels in both Alamo and Kanlow were highest in panicles, while leaves and stems had similar lower concentrations. The level of K in both varieties was highest in stems, followed by panicles, then leaves. Potassium ranged from three to six times greater than P in different tissues. Based on this study, P and K in shoots of Alamo and Kanlow do not appear to significantly decline from mid-September through mid-November. Shoot data are supported by data collected from whole plants which indicate that crowns and roots do not significantly increase in P and K from mid-September though mid-November. Implementing fall harvest as early as mid-September is justifiable based on P and K concentrations in shoots.

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Appendix A

Table 1.1 Average concentrations of P and K in leaves, stems, and panicles of Alamo switchgrass at different fall harvest dates and years at the East Tennessee Research and Education Center Plant Sciences Unit, 2008-2010.

		P			K		
Year	Harvest Time	Leaf	Stem	Panicle‡	Leaf	Stem	Panicle
		--------------------------------kg t^{-1} DM--------------------------------					
2008	Late July §	1.4 a†	0.6 b	—	10.4 a	5.1 a	—
	Late Aug.	0.8 d	0.4 bc	1.5 c	4.0 bc	3.8 a	6.9 a
	Late Sept.	1.0 bc	0.4 bc	2.4 b	5.2 bc	5.3 a	6.2 a
	Oct. week 1	1.0 bc	0.4 bc	3.1 a	3.8 bc	5.2 a	5.6 a
	Oct. week 2	0.8 cd	0.3 c	3.1 a	3.3 bc	5.1 a	6.5 a
	Oct. week 3	0.8 d	0.3 c	2.0 bc	2.1 c	4.6 a	3.6 b
	Oct. week 4	0.8 cd	0.4 bc	2.0 bc	2.9 bc	5.2 a	5.8 a
	Early Nov.	0.7 cd	0.9 a	0.8 d	3.6 bc	3.8 a	1.8 c
2009	Mid-Sept.	0.8 b	0.6 c	1.6 a	3.0 a	4.9 b	3.3 a
	Mid-Oct.	0.6 b	0.5 c	1.6 a	2.3 b	5.2 b	3.2 a
	Late Oct.	0.9 b	1.2 b	0.9 a	2.3 b	7.5 b	1.8 a
	Early Nov.	1.4 a	1.8 a	1.5 a	2.0 b	11.0 a	2.8 a
2010	Mid-Sept.	0.7 a	0.7 a	1.2 b	3.7 a	5.5 a	4.5 a
	Mid-Oct.	0.7 a	0.6 a	2.0 a	2.4 ab	5.7 a	4.0 a
	Late Oct.	0.5 a	0.5 a	1.5 b	1.8 b	5.7 a	3.7 ab
	Early Nov.	0.6 a	0.6 a	1.1 b	1.2 b	4.9 a	2.6 b

† Means within a column and year followed by a common letter are not significantly different based on Duncan's Multiple Range Test (P≤ 0.05).

‡ Includes seed

§ Dates for 2008: 21 July, 22 Aug., 25 Sept., 9 Oct., 15 Oct., 24 Oct., 31 Oct., and 10 Nov.
2009: 18 Sept., 9 Oct., 28 Oct., and 13 Nov.
2010: 15 Sept., 12 Oct., 26 Oct., and 10 Nov.

Table 1.2 Average concentrations of P and K in leaves, stems, and panicles of Alamo switchgrass at different fall harvest dates and years at the East Tennessee Research and Education Center Holston Unit, 2008-2010.

		P			K		
Year	Harvest Time	Leaf	Stem	Panicle‡	Leaf	Stem	Panicle
		-------------------------------kg t^{-1} DM			-----------------------------		
2008	Late July §	2.6 a†	1.2 a	—	15.5 a	8.5 a	—
	Late Aug.	1.9 b	1.0 a	1.3 bc	9.8 b	5.9 ab	7.7 a
	Late Sept.	2.0 b	1.1 a	2.0 ab	8.9 b	6.0 ab	7.1 ab
	Oct. week 1	2.0 b	1.0 a	2.6 a	7.5 c	5.0 b	6.6 ab
	Oct. week 2	1.9 b	1.2 a	2.5 a	7.2 cd	5.1 b	7.0 ab
	Oct. week 3	2.1 b	1.3 a	2.4 a	5.8 de	6.0 ab	5.9 ab
	Oct. week 4	1.4 c	0.9 a	1.8 ab	4.3 ef	4.5 b	5.0 ab
	Early Nov.	0.8 d	0.8 a	0.8 c	3.8 f	3.2 b	3.5 b
2009	Mid-Sept.	2.1 a	1.4 b	2.1 a	7.4 a	6.8 a	6.7 a
	Mid-Oct	3.1 a	2.4 a	3.3 a	8.2 a	9.5 a	5.8 a
	Late Oct.	2.3 a	1.4 b	2.6 a	5.7 ab	7.3 a	4.4 a
	Early Nov.	2.4 a	2.2 ab	—	4.3 b	12.2 a	—
2010	Mid-Sept.	1.3 ab	0.8 a	1.6 b	5.6 a	4.7 b	5.4 a
	Mid-Oct.	1.7 a	1.0 a	2.4 a	5.8 a	6.2 a	6.3 a
	Late Oct.	1.0 b	0.8 a	1.7 ab	3.0 a	5.6 a	4.4 a
	Early Nov.	1.0 b	0.9 a	1.9 ab	2.8 a	5.5 a	4.4 a

† Means within a column and year followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P \leq 0.05$).

‡ Includes seed

§ Dates for 2008: 21 July, 22 Aug., 25 Sept., 9 Oct., 15 Oct., 24 Oct., 31 Oct., and 10 Nov.
2009: 18 Sept., 9 Oct., 28 Oct., and 13 Nov.
2010: 15 Sept., 12 Oct., 26 Oct., and 10 Nov.

Table 1.3 Average concentrations of P and K in leaves, stems, and panicles of Alamo switchgrass at different fall harvest dates and years at the Highland Rim Research and Education Center, 2010.

	P			K		
Harvest Time	Leaf	Stem	Panicle‡	Leaf	Stem	Panicle
	--------------------------------kg t^{-1} DM-------------------------------					
Mid Sept. §	1.0 a	0.7 ab	—	3.8 a	5.0 c	—
Mid-Oct.	0.6 b	0.6 b	—	3.1 a	5.0 c	—
Late Oct.	0.8 ab	0.9 a	—	1.5 b	6.7 a	—
Mid- Nov.	0.6 b	0.7 b	—	1.3 b	5.6 b	—

† Means within a column followed by a common letter are not significantly different based on Duncan's Multiple Range Test (P≤ 0.05).

‡ Includes seed

§ Dates for 2010: 21 Sept., 15 Oct., 1 Nov., and 22 Nov.

Table 1.4 Average concentrations of P and K in leaves, stems, and panicles of Kanlow switchgrass at different fall harvest dates and years at the East Tennessee Research and Education Center Plant Sciences Unit, 2008-2010.

		P			K		
Year	Harvest Time	Leaf	Stem	Panicle‡	Leaf	Stem	Panicle
		kg t^{-1}DM					
2008	Late July §	1.6 a†	0.8 a	—	12.3 a	6.6 a	—
	Late Aug.	1.3 ab	0.7 ab	2.0 bc	7.6 bc	5.8 a	8.5 a
	Late Sept.	1.2 abc	0.8 a	2.1 bc	6.0 bc	7.1 a	6.6 ab
	Oct. week 1	1.0 bcd	0.5 ab	3.0 a	4.2 cd	6.1 a	5.1 bc
	Oct. week 2	1.0 bcd	0.6 ab	2.5 ab	4.0 cd	5.4 a	6.0 abc
	Oct. week 3	0.8 bcd	0.6 ab	2.6 ab	2.3 d	6.0 a	3.5 bc
	Oct. week 4	0.7 d	0.5 b	1.5 c	2.5 d	5.4 a	4.2 bc
	Early Nov.	0.8 cd	0.7 ab	1.0 d	4.3 cd	1.8 b	3.3 c
2009	Mid-Sept.	0.7 a	0.8 a	2.3 a	3.6 a	5.8 a	3.8 a
	Mid-Oct.	0.5 ab	0.4 a	1.2 b	1.7 b	5.4 a	2.0 b
	Late Oct.	0.5 ab	0.8 a	0.3 c	1.1 c	5.8 a	0.6 c
	Early Nov.	0.3 b	0.7 a	0.5 c	0.5 c	5.0 a	0.5 c
2010	Mid-Sept.	0.5 b	0.6 b	1.0 b	3.3 a	5.1 a	3.3 b
	Mid-Oct	0.6 a	0.8 a	2.1 a	2.7 ab	6.8 a	5.1 a
	Late Oct.	0.3 d	0.5 b	0.7 b	2.1 ab	5.2 a	2.3 bc
	Early Nov.	0.4 c	0.6 b	0.6 b	1.0 b	5.0 a	1.3 c

† Means within a column and year followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P \leq 0.05$).

‡Includes seed

§ Dates for 2008: 21 July, 22 Aug., 25 Sept., 9 Oct., 15 Oct., 24 Oct., 31 Oct., and 10 Nov.
2009: 18 Sept., 9 Oct., 28 Oct., and 13 Nov.
2010: 15 Sept., 12 Oct., 26 Oct., and 10 Nov.

Table 1.5 Average concentrations of P and K in leaves, stems, and panicles of Kanlow switchgrass at different fall harvest dates and years at the East Tennessee Research and Education Center Holston Unit, 2008-2010.

		P			K		
Year	Harvest Time	Leaf	Stem	Panicle‡	Leaf	Stem	Panicle
		---------------------------------kg t^{-1} DM---------------------------------					
2008	Late July §	2.4 a†	1.3 a	—	15.4 a	8.0 a	—
	Late Aug.	1.4 ab	0.8 b	1.6 ab	8.6 ab	5.1 b	9.1 a
	Late Sept.	1.4 ab	0.9 b	1.9 a	5.2 b	5.4 b	6.4 b
	Oct. week 1	0.9 b	0.9 b	1.6 ab	5.0 b	5.1 b	5.9 bc
	Oct. week 2	1.9 ab	0.8 b	1.8 a	9.2 ab	4.7 b	6.2 b
	Oct. week 3	0.9 b	0.7 b	1.5 abc	3.3 b	4.7 b	4.2 cd
	Oct. week 4	0.9 b	0.6 b	1.3 bc	3.4 b	4.7 b	3.8 d
	Early Nov.	1.0 b	0.9 b	1.0 c	4.4 b	1.8 c	3.0 d
2009	Mid-Sept.	—	1.2 a	—	—	6.4 a	—
	Mid-Oct	1.5 a	1.5 a	1.6 a	5.0 a	8.6 a	3.0 a
	Late Oct.	1.3 a	1.6 a	1.4 a	4.0 a	9.2 a	2.4 a
	Early Nov.	1.5 a	1.1 a	—	3.5 a	7.8 a	—
2010	Mid-Sept.	1.2 a	0.8 ab	1.2 ab	6.0 a	5.0 ab	4.2 b
	Mid-Oct	1.1 a	0.9 a	1.9 a	4.6 b	6.8 a	4.9 a
	Late Oct.	0.6 b	0.5 c	1.0 b	2.2 c	5.1 ab	2.6 c
	Early Nov.	0.6 b	0.7 bc	0.8 b	1.5 c	4.1 b	2.3 c

† Means within a column and year followed by a common letter are not significantly different based on Duncan's Multiple Range Test (P≤ 0.05).

‡Includes seed

§ Dates for 2008: 21 July, 22 Aug., 25 Sept., 9 Oct., 15 Oct., 24 Oct., 31 Oct., and 10 Nov.
2009: 18 Sept., 9 Oct., 28 Oct., and 13 Nov.
2010: 15 Sept., 12 Oct., 26 Oct., and 10 Nov.

Table 1.6 Average concentrations of P and K in leaves, stems, and panicles of Kanlow switchgrass at four fall harvest dates and years at the Highland Rim Research and Education Center, 2010.

	P			K		
Harvest Time	Leaf	Stem	Panicle‡	Leaf	Stem	Panicle
	---------------------------------kg t^{-1} DM-------------------------------					
Mid Sept. **§**	1.0 a	0.8 a	—	4.0 a	4.8 a	—
Mid-Oct.	0.8 ab	0.6 a	—	3.2 b	5.5 a	—
Late Oct.	0.6 b	0.7 a	—	1.4 c	5.6 a	—
Mid- Nov.	0.5 b	0.5 a	—	1.4 c	3.4 b	—

† Means within a column followed by a common letter are not significantly different based on Duncan's Multiple Range Test (P≤ 0.05).

‡ Includes seed

§ Dates for 2010: 21 Sept., 15 Oct., 1 Nov., and 22 Nov.

Table 1.7 Average stem to leaf ratios in tillers of Alamo switchgrass at four fall harvest dates at East Tennessee (ETREC) and Highland Rim Research (HRREC) and Education Center locations, 2010.

Location	Date	Stem: Leaf
ETREC-PS	Mid-Sept.	2.0 a†
	Mid-Oct	2.1 a
	Late Oct.	2.0 a
	Early Nov.	1.7 a
ETREC-Holston	Mid-Sept.	1.9 a
	Mid-Oct	1.9 a
	Late Oct.	2.2 a
	Early Nov.	2.1 a
HRREC	Mid-Sept.	1.6 a
	Mid-Oct	1.3 a
	Late Oct.	1.5 a
	Mid-Nov.	1.4 a

† Means within a column and location followed by a common letter are not significantly different based on Duncan's Multiple Range Test (P≤ 0.05).

Table 1.8 Average stem to leaf ratios in tillers of Kanlow switchgrass at four fall harvest dates at East Tennessee (ETREC) and Highland Rim Research (HRREC) and Education Center locations, 2010

Location	Date	Stem: Leaf
ETREC-PS	Mid-Sept.	1.9 a†
	Mid-Oct	1.8 ab
	Late Oct.	1.7 ab
	Early Nov.	1.5 b
ETREC-Holston	Mid-Sept.	1.7 a
	Mid-Oct.	1.8 a
	Late Oct.	2.2 a
	Early Nov.	1.9 a
HRREC	Mid-Sept.	1.5 a
	Mid-Oct.	1.4 a
	Late Oct.	1.4 a
	Mid-Nov.	1.4 a

† Means within a column and location followed by a common letter are not significantly different based on Duncan's Multiple Range Test (P≤ 0.05).

Table 1.9 Average estimated P and K removal in harvested Alamo switchgrass, 2010.

Harvest Time	Yield (Part III)	Observed Concentration		Estimated Removal	
		P	K	P	K
	t ha^{-1}	kg t^{-1}		kg ha^{-1}	
Late October	18.5	1.1	4.75	20.4	87.9
Early November	18.6	1.2	5.2	22.3	96.7

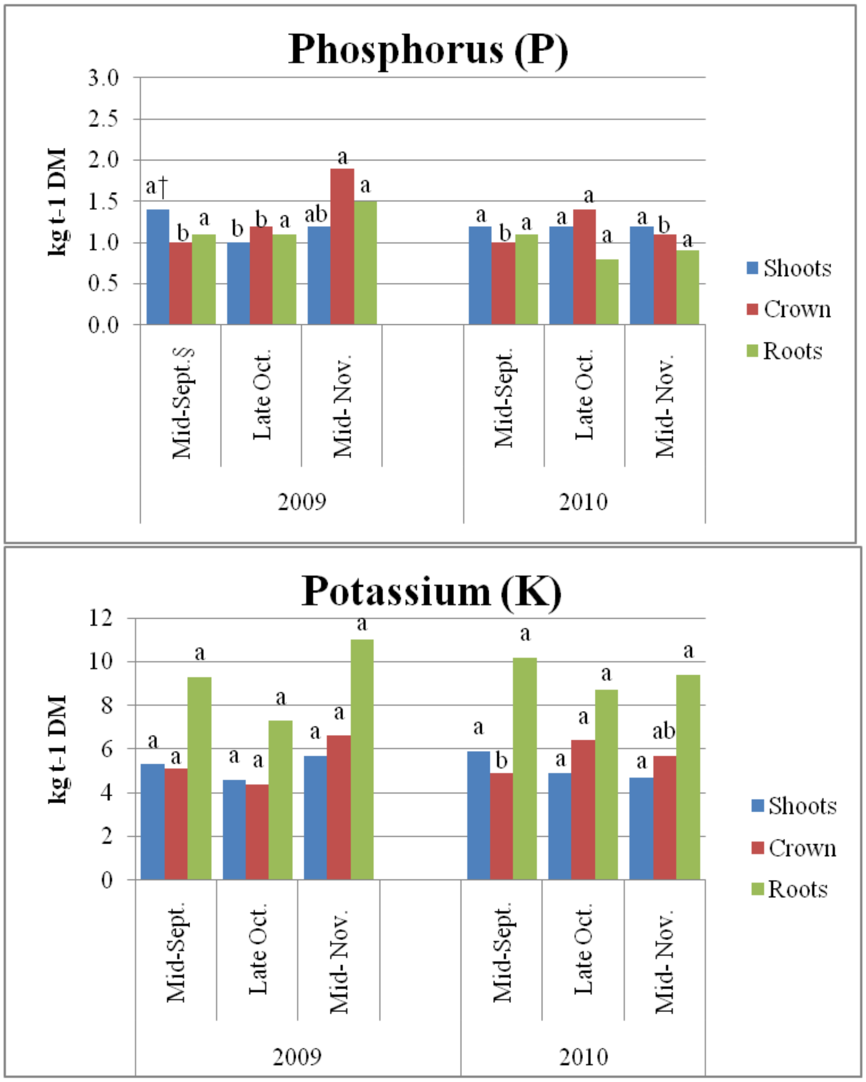

Fig. 1.1 Average concentrations of P and K in shoots, crowns, and roots of Alamo switchgrass at East Tennessee Research and Education Center Holston Unit, 2009-2010.

† Bars for the same tissue within a year followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P \leq 0.05$).

§ Dates for 2009: 29 Sept., 21 Oct., and 17 Nov.
2010: 15 Sept., 29 Oct., and 8 Nov.

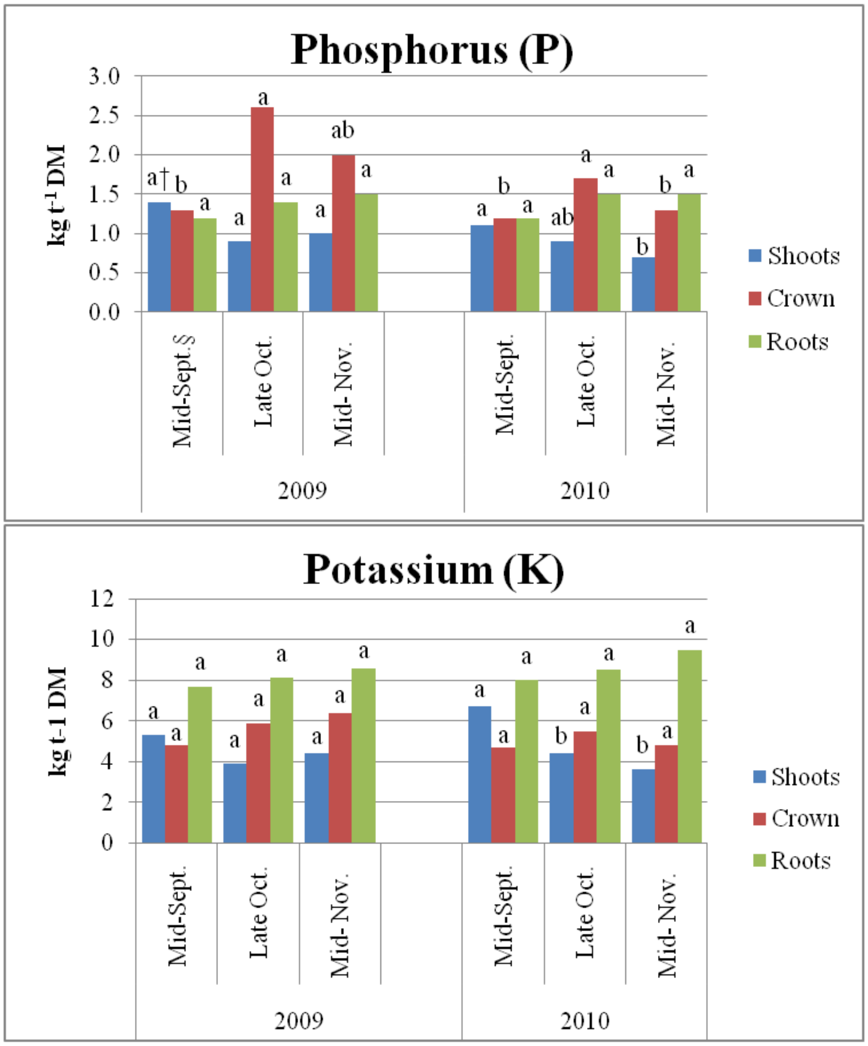

Fig. 1.2 Average concentrations of P and K in shoots, crowns, and roots of Kanlow switchgrass at East Tennessee Research and Education Center Holston Unit, 2009-2010.

† Bars for the same tissue within a year followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P \leq 0.05$)

§ Dates for 2009: 29 Sept., 21 Oct., and 17 Nov.
2010: 15 Sept., 29 Oct., and 8 Nov.

Part II

Evaluation of Phosphorus and Potassium Levels in Shoots of Different Lowland and Upland Switchgrass Varieties

Abstract

Current harvest recommendations for switchgrass are based on the premise that nutrients can be conserved and recycled within the plant if harvest is delayed until senescence. The objectives of this research were to: (1) determine if benchmark and new varieties of switchgrass harvest can take place earlier in the fall based on the decline of phosphorus (P) and potassium (K) in the shoots and (2) compare fall P and K changes in standard, newly released, and experimental varieties. Tiller samples were collected from twelve switchgrass varieties comprised of upland and lowland types. The varieties were planted in three replications at the East Tennessee Research and Education Center Plant Science Unit in Knoxville. Eight of the same varieties were planted in three replications at the Highland Rim Research and Education Center in Springfield. Leaf, stem, and panicle/seed samples were analyzed for P and K concentrations at four harvest dates in mid-September, mid-October, late October, and early November. Phosphorus was typically found in the greatest amounts in panicles, while leaves and stems had similar concentrations, whereas K tended to be highest in stems, followed by panicles then leaves. Potassium ranged from three to six times greater than P in different tissues. The P and K concentration in Alamo and Kanlow followed similar trends at the four different harvest dates, with relatively consistent concentrations through the fall. New varieties had P and K concentrations similar to those observed in benchmark varieties, such as Alamo and Kanlow. Data suggest that fall harvest as early as mid-September could be implemented without removing significant amounts of P and K from the field.

CHAPTER I

Introduction and Literature Review

Nutrients, such as phosphorus (P) and potassium (K), are important for switchgrass growth and development and are removed from the land in harvested biomass. Yang et al. (2009) suggested that a well judged choice of harvest time as well as genotype can reduce nutrient loss, meaning varieties that conservatively use nutrients may be important for sustainability and productivity.

Switchgrass for biomass is typically harvested in a one or two-cut system. Lemus et al. (2009) found that two-cut management significantly increased P removal, while K removal was comparable between the harvest systems. Harvesting biomass without replacing nutrients can mine soil of nutrients quicker in a two-cut system than a one-cut system (Guretzky et al., 2009). Although a two-cut system may result in somewhat more biomass, a one-cut system is typically used, especially in biomass production, because the yield increase would not be worth the additional cost of inputs required (Monti et al., 2008).

Varieties of switchgrass are typically classified into two types: upland and lowland, referring to the latitude of origin where each ecotype is best adapted. ‘Alamo’ and ‘Kanlow’ are popular lowland cultivars planted in the Southeast because of their high yields in moisture stressed environments, while upland cultivars such as ‘Cave-In-Rock’ and ‘Blackwell’ are more common in central and northern states because of their cold tolerance. Yang et al. (2009) found that upland and lowland types differ in elemental composition. Their study showed that Kanlow, Cave-In-Rock, and Blackwell had the least amount of nutrient loss per unit of biomass (i.e.

nutrient-use efficiency), which illustrates that genotype influences the magnitude of elements removed (Yang et al., 2009).

Switchgrass was chosen as a bioenergy feedstock for many reasons, one being its tolerance to low soil nutrient concentrations (Sanderson et al, 1999, Vogel, 1996). In several studies, switchgrass has been reported to perform well on soil with low P and K levels. Large amounts of macronutrients such as P and K in harvested biomass can lead to substantial depletion of these in the soil (Yang et al., 2009). Approximately 3.5 kg of P and up to 18 kg of K were reported to be removed per dry tonne of corn stover (Mitchell, 1999; Murdock and Schwab, 2007; Osmond and Kang, 2008; Sawyer and Mallarino, 2007).

If significant amounts of nutrients are continuously harvested with biomass, the soil can become nutrient deficient and require additions of fertilizer. Lemus et al. (2009) observed that nutrient concentrations in biomass were affected by location, management, and harvest date, while the total nutrient removal was affected by location and management. Overall, a single harvest conducted in late fall allows time for nutrients to remobilize, thus resulting in lower amounts of nutrients in biomass (Lemus et al., 2009). Conversely yield reductions have been reported when harvest is delayed until November (Sanderson et al., 1999). Earlier harvest may be possible if yields are not significantly reduced and trends in the pattern and period of remobilization can be more accurately determined.

CHAPTER II

Materials and Methods

Site Description

The field study was conducted at two sites in Tennessee. The first site was at the East Tennessee Research and Education Center, Plant Sciences Unit (ETREC) in Knoxville (35.53°N 83.57°W). From 2008 to 2010 this site had an average annual temperature of 14°C. This site received 129 cm of precipitation in 2008, 173 cm in 2009, and 124 cm in 2010. The first fall freeze (0°C and below) occurred on 29 October 2008, 19 October 2009, and 7 November 2010. Soil at the ETREC is classified as a Sequatchie loam (fine-loamy, siliceous, semiactive, thermic Humic Hapludults). Prior to this experiment the ETREC site was seeded in tall fescue (*Festuca arundinacea*).

The second site was at Highland Rim Research and Education Center (HRREC) in Springfield (36.28°N 86.51°W). This site had a mean annual temperature of 14.4°C in 2010, but received a slightly lower amount of precipitation (108 cm). The first fall freeze occurred on 29 October 2010. Soil at the HRREC is classified as a Sango silt loam (coarse-silty, siliceous, semiactive, thermic Glossic Fragiudults) to a Dickson silt loam (fine-silty, siliceous, semiactive, thermic Glossic Fragiudults). This site was previously cropped in winter wheat (*Triticum aestivum*).

Experimental Design

In May 2007, a combination of twelve lowland and upland varieties and experimental lines were evaluated at the ETREC in 2009 and 2010, which included Alamo (USDA and Bammert), Kanlow, Cimarron, Blade EG1101, Blade EG1102, OK NSL-2001-1, C75, C77, Blackwell, Hoop House, and C62. In 2010, eight of the varieties previously mentioned were evaluated at the HRREC, which were Alamo (Bammert), Kanlow, Cimarron, OK NSL-2001, C75, C77, Blackwell, and C62. The varieties were planted in a randomized complete block with three replications at a rate of 8.9 kg ha^{-1} of pure live seed (PLS) per hectare with a Hege 1000 no-till plot drill. Experimental plots at ETREC were 1.4 m x 7.6 m, while the plots at HRREC measured 1.4 m x 9.1 m. The P and K levels in leaves, stem, and seed were evaluated for each variety at ETREC from 2009-2010 and only leaves and stem were evaluated at HRREC in 2010.

Sample Harvesting and Processing

Ten plant tillers, clipped 3-5 cm above ground level, were collected from each plot of each variety throughout the fall in 2009 (18 Sept., 9 Oct., 28 Oct., and 13 Nov.) and 2010 (15 Sept., 12 Oct., 26 Oct., and 10 Nov.) at ETREC. The same number of tillers was harvested from each plot of each variety at HRREC in 2010 (21 Sept., 15 Oct., 1 Nov., and 22 Nov.). Fresh weight was measured on each sample; then dried in a batch oven (Wisconsin Oven Corporation, East Troy, WI, USA) for a minimum of 24 hours at 49˚C and dry weight was measured. Samples were further divided into panicle, leaf, and stem tissue subsamples. Panicle data were not collected at HRREC. Subsamples were cut into smaller pieces, and ground using a Wiley Laboratory Mill (Arthur H. Thomas Company, Philadelphia, PA, USA) to pass through a 2-mm screen.

Stem:Leaf Ratio Calculation

After shoot samples were divided into leaf, stem, and panicle subsamples, each subsample was weighed separately to calculate the ratio of stems to leaves. Once weighed, the stem:leaf ratio was calculated by dividing each stem sample weight by the corresponding leaf weight. These ratios were analyzed using PROC GLM (SAS 9.2, 2009) to identify differences.

Nutrient Analysis

Subsamples of the biomass were analyzed for P and K. Approximately 0.45-0.55 g of dried ground tissue was placed in a 16x100 mm glass tube and ashed at 450˚ C for 4-6 hours. Nitric acid was used to dissolve the ash at a rate of 10 ml HNO_3 (70%) per 0.5 g of sample. Samples were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS, Model 7500ce, Agilent Technologies) at the University of Tennessee, Knoxville.

Statistical Analysis

Statistical analyses were performed using the PROC GLM procedure (SAS 9.2, 2009) to identify differences caused by harvest date, variety, location, and their interactions. Treatment means were calculated and Duncan’s Multiple Range Test was used to determine if treatment effects were significant at the 5% level of probability.

CHAPTER III

Results and Discussion

Phosphorus

Lowland Varieties

Notable patterns in nutrient concentrations were observed in the separate tissues of the varieties evaluated. At both ETREC and HRREC, the highest amounts of P was typically found in the panicles of the lowland varieties; however, panicles made up only a small fraction of the switchgrass shoots and diminished as the fall progressed (Table 2.1). Stems and leaves consistently had similar concentrations of P (Fig. 2.1).

Benchmark Varieties

Alamo and Kanlow are two long-standing lowland varieties that serve as benchmarks for new and upcoming varieties. Alamo is the standard lowland variety grown in the South; therefore, Alamo is of particular interest on a commercial scale. Similar P and K concentrations were observed in the two sources of Alamo planted at ETREC in both 2009 and 2010 (Table 2.1); therefore, the Bammert source of Alamo will be discussed because it was planted at both ETREC and HRREC. In 2009, Alamo leaf and stem P was numerically similar through the fall, but significantly higher amounts were observed in early November, where P increased by approximately 0.6 kg t^{-1}(Fig. 2.1). In 2010, P levels in leaves and stems were observed in similar amounts from mid-September to mid-November, both averaging 0.6 kg t^{-1} (Fig. 2.1). Data from Alamo at HRREC followed a trend similar to that observed at ETREC because P levels remained constant throughout the fall in both stems and leaves (Fig. 2.1). Based on these data, harvest could take place as early as mid-September without removing significant amounts of P.

As previously mentioned, Kanlow is also a lowland variety that is comparable to Alamo and is also of interest in commercial switchgrass production. The P in Kanlow was present in each tissue in amounts similar to those observed in Alamo. Kanlow leaves in both 2009 and 2010 numerically decreased in P as the fall progressed, but not to levels that were significantly lower (Fig. 2.1). The P in stems averaged 0.8 kg t^{-1} in 2009 and 0.6 kg t^{-1} in 2010, which did not differ from mid-September through November (Figure 2.1). Stem and leaf data suggest that Kanlow may be harvested earlier and not remove significantly more P. The observation of Kanlow at HRREC confirmed that P in leaves and stems remained reasonably consistent through the fall, averaging 0.7 kg t^{-1} (Table 2.2, Fig. 2.1). When averaged across harvests, P in Alamo tissues was present in significantly higher amounts that Kanlow; however, both were less than 1.0 kg t^{-1} (Table 2.1). Overall, P concentration in Alamo tissues was among the highest of the lowland varieties in the study, whereas P concentration in Kanlow tissues was among the lowest. Regardless of the quantity of P, the changes of P as the fall progressed were similar in both varieties. Overall data suggest that harvest may be executed before November without removing significantly more P in biomass.

New Varieties

In the past few years, new varieties of lowland switchgrass derived from Alamo and Kanlow varieties (or crosses of these) have been developed and released. Three of the newest commercial varieties are Blade EG1101, Blade EGl102, and Cimarron. Blade EG1101 was released commercially in 2008 by Blade Energy Crops as an improved Alamo variety (Ceres, Inc., 2008). Through the first three harvests in 2009, leaf and stem P of Blade 1101 averaged 0.9 kg t^{-1} with no changes until an increase to 1.4 kg t^{-1} in November (Fig. 2.1). P averaged 0.7 kg t^{-1}

in 2010 with leaves and stems remaining constant through the season (Fig. 2.1). No significant decreases occurred from mid-September through November (0.5 to 0.9 kg t^{-1}), which encourages earlier fall harvest of Blade 1101 (Fig. 2.1).

In addition to Blade EG1101, a second variety, Blade EG1102, was also released commercially in 2008 by Blade Energy Crops as an improved Kanlow variety derived from an intercross of Alamo x Kanlow. The level of P in leaves and stems of Blade 1102 in 2009 followed a similar trend as observed for Blade 1101. One exception was an increase of P in stems in mid-October (2.1 kg t^{-1}) (Fig. 2.1), with no other changes occurring in stems through the fall of 2009. In 2010, P levels in stems and leaves of Blade 1102 did not change through November, averaging 0.6 kg t^{-1} in both tissues through the fall. When comparing both Blade varieties across harvest dates, no significant differences in the average P levels were observed in each respective tissue (Table 2.1).

The third new variety evaluated was Cimarron, which was released as a commercial variety in 2008 by the Oklahoma Agricultural Experiment Station (Oklahoma State University, 2011). It had the highest P concentration in each tissue than any other lowland variety in both years when averaged across harvest dates (Table 2.1). In 2009 and 2010, Cimarron performed similarly to Blade EG1102, with significant P increases in leaves in mid-October and steady decreases through November (Fig. 2.1). In both years, P in stems maintained similar levels through the fall with no significant changes (Fig. 2.1.). As observed at ETREC, P in tissues at HRREC revealed a steady decrease in leaves and fairly consistent levels in stems (Fig. 2.1). This data suggest that harvest of Cimarron may take place before November.

Three experimental lowland varieties were observed in this study: OK NSL-2001-1, C75, and C77. OK NSL-2001-1 is an experimental variety developed alongside Cimarron by the Oklahoma Agricultural Experiment Station. In 2009, OK NSL-2001-1 maintained P levels in leaves and stems, averaging 0.8 kg t^{-1} from mid-September through late October, but significantly increased to 1.4 kg t^{-1} in November. In 2010, P in stems and leaves remained fairly even through the season. At HRREC, the level of P in leaves and stems was steady across harvests (Fig. 2.1).

The two experimental varieties, C75 and C77, were developed by the Noble Foundation in Oklahoma. Overall, tissues of these varieties did not differ in P concentration when averaged across all harvest dates (Table 2.1). In 2009, P levels in stems and leaves averaged 0.7 kg t^{-1} from mid-September to late October, but significantly increased to an average of 1.4 kg t^{-1} in early November (Fig. 2.1). In 2010, the concentration of P remained fairly steady throughout the fall at approximately the same levels from the previous year (0.8 kg t^{-1}) with no significant changes in leaves and stems (Table 2.1). At HRREC, P in stems and leaves of C75 and C77 did not change with time (Fig. 2.1), which supported the data at ETREC. In stems of C77, P levels averaged approximately 0.8 kg t^{-1} through the fall of both years with no significant changes. The P levels in C75 at the four harvest times were similar to those observed in C77 (Table 2.2).

Upland Varieties

In 2009 and 2010, three upland varieties, Blackwell, Hoop House, C62, were evaluated at ETREC. Two of these varieties, Blackwell and C62, were also studied at HRREC in 2010. Blackwell was developed by the Plant Materials Center and the Kansas Agricultural Experiment Station from a single plant collected in 1944 (Sharp Bros. Seed Co., 2011). C62 is an experimental variety developed by the Noble Foundation in Oklahoma, which was the source of the two lowland varieties, C75 and C77. As observed in lowland varieties, P in stems of C62 and leaves was found in nearly equal concentrations regardless of year, location, and variety (Table 2.1 and 2.2).

In 2009, P in Blackwell stems and leaves significantly decreased from September to early October and, maintained low levels through November (Figure 2.2). In 2010, P in stems and leaves of Blackwell was steady through the fall, averaging 0.8 kg t^{-1}. Interestingly, overall P concentrations of Blackwell averaged across harvests in both years were significantly higher than those observed in the lowland variety, Kanlow (Table 2.1). At HRREC, P in leaves averaged 0.8 kg t^{-1}, which was consistent with levels at ETREC. P in stems at HRREC remained fairly steady through the fall, but was present at slightly higher levels at this location, where the average was 1.1 kg t^{-1} (Table 2.2).

In 2009, P in Hoop House gradually decreased in stems and leaves from mid-September to early November. In 2010, levels remained reasonably consistent, averaging 0.5 kg t^{-1}. The experimental line, C62, had consistent levels of P in leaves and stems across both years (Fig. 2.2). In leaves of C62, P averaged 0.7 kg t^{-1} from mid-September to early November. P in stems averaged slightly higher, but no significant decreases were observed. At HRREC, P was significantly lower in leaves of C62 from mid-October to early November but did not change in stems, which averaged 0.9 kg t^{-1} (Table 2.2). It is also interesting to note that overall P concentrations of C62 did not significantly differ from the levels observed in Kanlow, a lowland variety, when averaged across harvests in 2009 and 2010 (Table 2.1). In general, P in tissues of upland varieties followed patterns similar to those observed in lowland varieties and had overall

P concentrations that did not differ from that measured in most lowland varieties. Based on consistent trends of P in stems and leaves among these three varieties, fall harvest could take place earlier than the recommended time and not result in larger amounts of P removed from the soil.

Potassium

Lowland Varieties

Potassium in this group of switchgrass varieties was present in amounts three to six times greater than P, which supports previous studies. The amount of K in lowland varieties tended to be higher in stems, followed by panicles, and leaves. (Table 2.1)

Benchmark Varieties

In 2009 at ETREC, K in the benchmark variety Alamo was present in significantly higher amounts than in Kanlow; however, in 2010 no differences were detected (Table 2.1). The K levels in Alamo followed patterns similar to those of P. Leaves had K averages of 2.4 kg t^{-1} in 2009 and 2.3 kg t^{-1}in 2010, which were consistent (Figure 2.3). Although K in stems was approximately double the K in leaves, levels were fairly consistent in stems. The K concentration in stems was slightly higher in 2009 because of a significant increase in November (11.0 kg t^{-1}, Fig. 2.3). The data on Alamo at HRREC supported earlier harvest with decreases of K in stems and leaves in mid-October, which are not different from levels observed in mid-November (Fig. 2.3). Similarly to Alamo, K in Kanlow at HRREC decreased in leaves from mid-September to early November numerically but not significantly (Fig. 2.3). Also, no change in K occurred in stems, which averaged 5.5 kg t^{-1} in 2009 and 2010 (Table 2.1). As observed with P, lack of significant change ($P \leq 0.05$) in K supports earlier switchgrass harvest.

New Varieties

Blade EG1101, Blade EG1102, and Cimarron had significantly higher concentrations of K than Kanlow in 2009, but in 2010 no differences were observed among the lowland varieties (Table 2.1). Blade varieties had K levels that were similar from 2009 to 2010. In 2009, K in leaves of Blade EG1101 significantly decreased from mid-September to late October, while K in stems significantly increased by approximately two-fold in early November (14.3 kg t^{-1}, Fig. 2.3). In 2010, K in the stems and leaves remained steady throughout the harvest season (Fig. 2.3). Trends observed in both years encourage harvest prior to November. In Blade EG 1102, twice the amount of K was present in stems than leaves in both years (Table 2.1, Fig. 2.3). Although there were increases in K in both stems and leaves of Blade EG1102 in mid-October, those levels coincided with those observed in other varieties.

When averaged across harvest dates in 2009, Cimarron had significantly higher levels of K than Kanlow; however, in 2010 there were no differences (Table 2.1). Cimarron had similar levels of K in both years, which did not differ through the fall. The K levels at HRREC supported trends observed at ETREC, with K averages in stems (2.4 kg t^{-1}) and leaves (4.4 kg t^{-1}) comparable to those observed at ETREC, which averaged 2.6 kg t^{-1} in leaves and 5.6 kg t^{-1} in stems across years (Table 2.2).

The experimental variety, OK NSL-2001-1, had K levels that followed patterns observed in P, only in greater amounts. In 2009, K levels were significantly lower at each progressing harvest date, but in 2010, K in leaves did not significantly decrease as the fall progressed. The K levels corresponded with those observed in other varieties (Fig. 2.3). With the exception of a significant increase in November 2009, K in stems of OK-NSL-2001-1 in both years averaged

4.5 kg t^{-1} and did not differ significantly from mid-September through November (Table 2.1, Fig. 2.3). Observations at HRREC uphold those reported at ETREC (Table 2.2, Fig. 2.3). Although leaves had slight changes in K, stems at HRREC maintained similar levels through the fall. In stems, K levels averaged 4.8 kg t^{-1}, which was comparable to levels at ETREC (Fig. 2.3).

In 2009, K concentrations in leaves of C75 did not change, averaging 2.7 kg t^{-1} (Table 2.0), but stems actually increased through the fall, with a significant increase in November (14.0 kg t^{-1}, Fig. 2.3). The K levels in leaves in 2010 declined through the fall, while stem levels did not differ. HRREC data support patterns observed at ETREC in 2010, with significantly lower K levels in leaves later in the fall and unchanging levels of K in stems (Fig. 2.3). C75 and C77 did not differ in overall K concentration when averaged across harvest dates (Table 2.1). In 2009, C77 had the lowest K levels in stems and leaves in November. In 2010 K in leaves was lowest in late October and no significant changes were observed in stems and leaves through the fall. Data at ETREC in 2010 was mirrored by data collected at HRREC (Table 2.2).

Upland Varieties

As observed among lowland varieties, the three upland varieties, Blackwell, Hoop House, and C62, had higher levels of K in the stems than in the leaves (Fig. 2.4). Also, the K concentration in leaves tended to decline with later harvests, whereas the K levels in the stems generally did not significantly decline with later harvests (Fig. 2.4). The K concentration was measured in the panicle/seed at ETREC in both 2009 and 2010 (Fig. 2.4). Levels were lower compared to both leaves and stems but the panicles with seed do not contribute much to the overall biomass of variety. Within a variety the levels of K in stems and leaves varied somewhat between years at ETREC (e.g. Blackwell 2009 vs. 2010, Fig. 2.4); however, when considering the overall levels across harvest dates, no clear advantage of delaying harvest for the purpose expecting decline in K levels in the shoots was apparent.

Hoop House had significantly lower amounts of K in leaves in late October than in September, but did not differ from November, which was true in both 2009 and 2010 (Fig. 2.4). Stems averaged 4.9 kg t^{-1} in both years, with no changes. Hoop House differed significantly from Alamo and Kanlow in some tissues, but in 2010, there were no differences. C62 had lower levels of K in leaves in late October and early November of both years. In these later months, K decreased by nearly half the amount observed in September and mid-October. K in stems was constant from September to November. Leaves and stems at HRREC followed the same trends reported at ETREC. These data suggest that this variety may be harvested earlier than November, but not as early as other varieties.

Stem:Leaf Ratio

Overall more stems than leaves were present in the shoots of switchgrass and the extent of this difference varies among lowland and upland varieties. When averaged across the eight varieties observed at both ETREC and HRREC, there were no significant differences in stem to leaf ratios at each harvest date (Table 2.3). The average stem to leaf ratio across varieties at ETREC was 1.7, whereas the average at HRREC was 1.3 (Table 2.5). In mid-September, Blackwell had a significantly lower stem to leaf ratio than Kanlow, and Cimarron at both ETREC and HRREC (Table 2.4). All other varieties did not significantly differ ($P \leq 0.05$) from one another. At the mid-October harvest, Alamo had a significantly higher stem to leaf ratio than Hoop House and C77, while other varieties did not differ (Table 2.4). In late October, more differences began to occur. Blackwell and Blade EG1102 had the significantly lowest ratio, while Alamo had the highest ratio. HRREC was not consistent with ETREC because Blackwell had the lowest ratio and C75 had the highest of the experimental varieties. In early November, the margin between Blackwell and the other varieties at ETREC seemed to close because the ratio of Blackwell was only significantly lower than Blade EG1101 and C75. However at HRREC the stem to leaf ratio of Blackwell was significantly lower than every variety except C77 and C62. The data from ETREC reveals that although many varieties have a higher amount of stems than leaves, the overall pattern is that the ratios do not differ across varieties. At HRREC, Blackwell consistently had a significantly lower stem to leaf ratio than Alamo, Kanlow, and Cimarron, which indicated that Blackwell shoots have more leaves than stems and also that nutrients in the shoots are more evenly distributed among these tissues. When averaged across harvests, most varieties were 1.5-2.0 times more stems than leaves at ETREC (Table 2.5).

Environmental Influence on P and K Concentrations

In 2009, varieties such as Alamo, Blade EG1101, Exp. OK-NSL-2001-1, C75, and Blackwell had significant P and K increases in stems and leaves at the early November harvest (Figs. 2.1-2.4). These increases could be attributed to environmental influences, such as temperature and precipitation, which influenced some varieties more than others. Favorable temperatures and higher than average precipitation were recorded from July through October at ETREC in 2009 (Fig. 2.5). These environmental factors could have also contributed to poor yields at HRREC, where precipitation was much lower and temperatures were higher throughout the harvest season in 2010 (Fig. 2.5). Dien et al. (2006) reported P levels in switchgrass that were higher post-frost than at the pre-boot and anthesis growth stages.

CHAPTER IV

Conclusions

The objective of this research was to determine if the harvest of different varieties of upland and lowland types of switchgrass can take place earlier in the fall based on the decline of phosphorus (P) and potassium (K) in the shoots. When averaged across harvest dates, significant changes were not observed in P and K concentrations through the fall. Concentration of P and K in benchmark varieties, Alamo and Kanlow, followed similar trends at the four different harvest dates, with relatively consistent concentrations though the fall. New varieties had P and K concentrations similar to those observed in benchmark varieties, with similar patterns across harvest dates. Uplands and lowlands contained similar concentrations of P and K in the different tissues. Data from both locations support earlier harvest because P and K in shoots of different varieties in this study did not decline from mid-September through early November. This study suggests that most varieties of switchgrass grown for biomass may be harvested as early as September and October without larger amounts of P and K from the soil.

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Appendix B

Table 2.1 Average concentration of P and K in shoots of switchgrass across harvest dates in the variety test at the East Tennessee Research and Education Center, 2009-2010.

		P			K		
2009	Variety	Leaf	Stem	Panicle‡	Leaf	Stem	Panicle
		----------------------------------kg t^{-1} DM-----------------------------------					
Upland	Blackwell	0.9 bc†	1.3 a	0.8 f	1.6 ef	6.4 cde	1.2 d
	Hoop House	0.7 de	0.5 d	0.7 f	2.3 bcd	4.9 f	1.5 d
	C62	0.7 de	1.0 b	0.7 f	1.5 f	4.6 f	1.3 d
Lowland	Alamo(USDA)	0.9 bc	0.8 c	1.4 cde	2.4 bc	5.7def	2.9 bc
	Alamo(Bammert)	0.9 bc	1.0 b	1.5 cd	2.4 bc	7.1 bc	2.8 c
	Kanlow	0.5 e	0.8 c	1.1 ef	1.7 def	5.5 ef	1.7 d
	Cimarron	1.2 a	0.9 bc	1.7 bcd	2.7 ab	6.2 cde	3.5 b
	Blade EG1101	1.0 b	1.0 b	2.2 a	3.3 a	8.6 a	4.4 a
	Blade EG1102	0.9 bc	1.1 b	2.0 ab	2.6 b	6.7 cd	3.1 bc
	OK NSL-2001-1	0.9 bc	0.8 c	1.4 cde	1.8 cdef	4.9 f	2.8 c
	C75	0.9 bc	0.9 bc	1.8 abc	2.7 ab	8.1 ab	4.8 a
	C77	0.8 cd	0.7 c	1.3 de	2.2 bcde	6.2 cde	2.8 c
2010							
Upland	Blackwell	0.8 ab	0.9 a	1.3 de	2.0 b	5.1 ab	4.9 ab
	Hoop House	0.5 de	0.4 c	0.9 fg	2.2 b	4.9 ab	3.4 ab
	C62	0.7 bc	0.8 a	0.7 g	2.2 b	5.1 ab	3.4 ab
Lowland	Alamo(USDA)	0.7 abc	0.6 b	1.8 ab	2.3 ab	5.2 ab	4.4 ab
	Alamo(Bammert)	0.6 cd	0.6 bc	1.4 bcd	2.3 ab	5.5 ab	3.7 ab
	Kanlow	0.5 e	0.6 b	1.1 ef	2.3 ab	5.5 ab	3.0 b
	Cimarron	0.8 a	0.5 bc	1.4 cd	2.4 ab	5.0 ab	3.7 ab
	Blade EG1101	0.7 abc	0.6 b	1.8 a	2.5 ab	5.9 a	4.3 ab
	Blade EG1102	0.6 cde	0.6 b	1.7 abc	2.1 b	4.8 ab	5.1 a
	OK NSL-2001-1	0.8 ab	0.6 b	1.5 bcd	2.2 b	4.6 b	3.8 ab
	C75	0.7 abc	0.5 bc	1.8 a	2.4 ab	5.2 ab	4.4 ab
	C77	0.8 a	0.6 b	1.8 a	2.8 a	5.3 ab	3.9 ab

† Means within a column followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P \leq 0.05$)

‡ Includes seed

Table 2.2 Average concentration of P and K in shoots of switchgrass across harvest dates in the variety test at the Highland Rim Research and Education Center, 2010.

		P		K	
2010	Variety	Leaf	Stem	Leaf	Stem
		-----------------------kg t^{-1} DM----------------------			
Upland	Blackwell	1.2 a†	1.1 a	3.0 ab	6.6 a
	C62	0.9 b	0.9 b	3.2 a	4.9 cd
Lowland	Alamo(Bammert)	0.7 bc	0.7 bcde	2.4 c	5.6 bc
	Kanlow	0.7 c	0.7 de	2.5 c	4.8 cd
	Cimarron	0.8 bc	0.6 e	2.4 c	4.4 d
	OK NSL-2001-1	0.8 bc	0.7 de	2.9 abc	4.8 cd
	C75	0.8 bc	0.8 bc	2.6 bc	5.7 abc
	C77	0.8 bc	0.8 bcd	2.8 abc	6.1 ab

† Means within a column followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P \leq 0.05$)

Table 2.3 Ratio of stems to leaves across eight varieties of switchgrass tillers per harvest date at East Tennessee (ETREC) and Highland Rim (HRREC), 2010.

Harvest Date	ETREC	HRREC
Mid-September	1.7 a †	1.3 a
Mid-October	1.8 a	1.2 a
Late-October	1.7 a	1.3 a
Early November	1.6 a	1.3 a

† Means within a column followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P \leq 0.05$)

Table 2.4 Ratios of stems to leaves in upland and lowland switchgrass at four harvest dates at East Tennessee (ETREC) and Highland Rim (HRREC) Research and Education Center, 2010.

		Harvest Date			
Location	Variety	Mid-Sept.	Mid-Oct.	Late Oct.	Early Nov.
ETREC	Upland				
	Blackwell	1.3 b†	1.8 abc	1.2 e	1.2 c
	Hoop House	1.5 ab	1.4 c	1.4 de	1.4 bc
	C62	1.7 ab	1.6 abc	1.5 cd	1.4 abc
	Lowland				
	Alamo (Bammert)	2.0 ab	2.1 a	2.0 a	1.7 abc
	Alamo (USDA)	1.6 ab	1.6 bc	1.7 bc	1.5 abc
	Kanlow	1.9 a	1.9 abc	1.7 bc	1.5 abc
	Cimarron	1.8 a	1.7 abc	1.9 0 ab	1.8 abc
	Blade EG1101	1.9 a	1.7 abc	1.9 ab	1.8 ab
	Blade EG1102	1.8 ab	1.7 abc	1.2 e	1.2 bc
	OK NSL-2001-1	1.8 a	1.8 abc	1.8 ab	1.8 abc
	C75	1.6 ab	2.0 ab	1.8 abc	2.0 a
	C77	1.7 ab	1.6 bc	1.7 bc	1.7 abc
HRREC	Upland				
	Blackwell	0.9 b	0.6 b	0.7 c	0.8 c
	C62	1.3 ab	1.4 a	1.1 b	1.0 bc
	Lowland				
	Alamo (Bammert)	1.6 a	1.3 a	1.5 ab	1.4 ab
	Kanlow	1.5 a	1.4 a	1.4 ab	1.4 ab
	Cimarron	1.6 a	1.2 a	1.4 ab	1.2 ab
	OK NSL-2001-1	1.2 ab	1.6 a	1.4 ab	1.6 a
	C75	1.3 ab	1.3 a	1.7 a	1.3 ab
	C77	1.3 ab	1.3 a	1.1 b	1.2 abc

† Means within a column and location followed by a common letter are not significantly different based on Duncan’s Multiple Range Test (P≤ 0.05).

Table 2.5 Ratios of stems to leaves in upland and lowland switchgrass at four harvest dates at East Tennessee (ETREC) and Highland Rim (HRREC) Research and Education Center, 2010.

		Location	
Location	Variety	ETREC	HRREC
ETREC	Upland		
	Blackwell	1.4 f	0.75 c
	Hoop House	1.4 ef	—
	C62	1.6 cde	1.18 b
	Lowland		
	Alamo (Bammert)	1.9 a	1.5 a
	Alamo (USDA)	1.6 bcde	—
	Kanlow	1.8 abc†	1.4 ab
	Cimmaron	1.8 ab	1.4 ab
	Blade EG1101	1.8 ab	—
	Blade EG1102	1.5 def	—
	OK NSL-2001-1	1.8 abc	1.4 ab
	C75	1.8 ab	1.4 ab
	C77	1.7 abcd	1.22 ab

† Means within a column followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P \leq 0.05$).

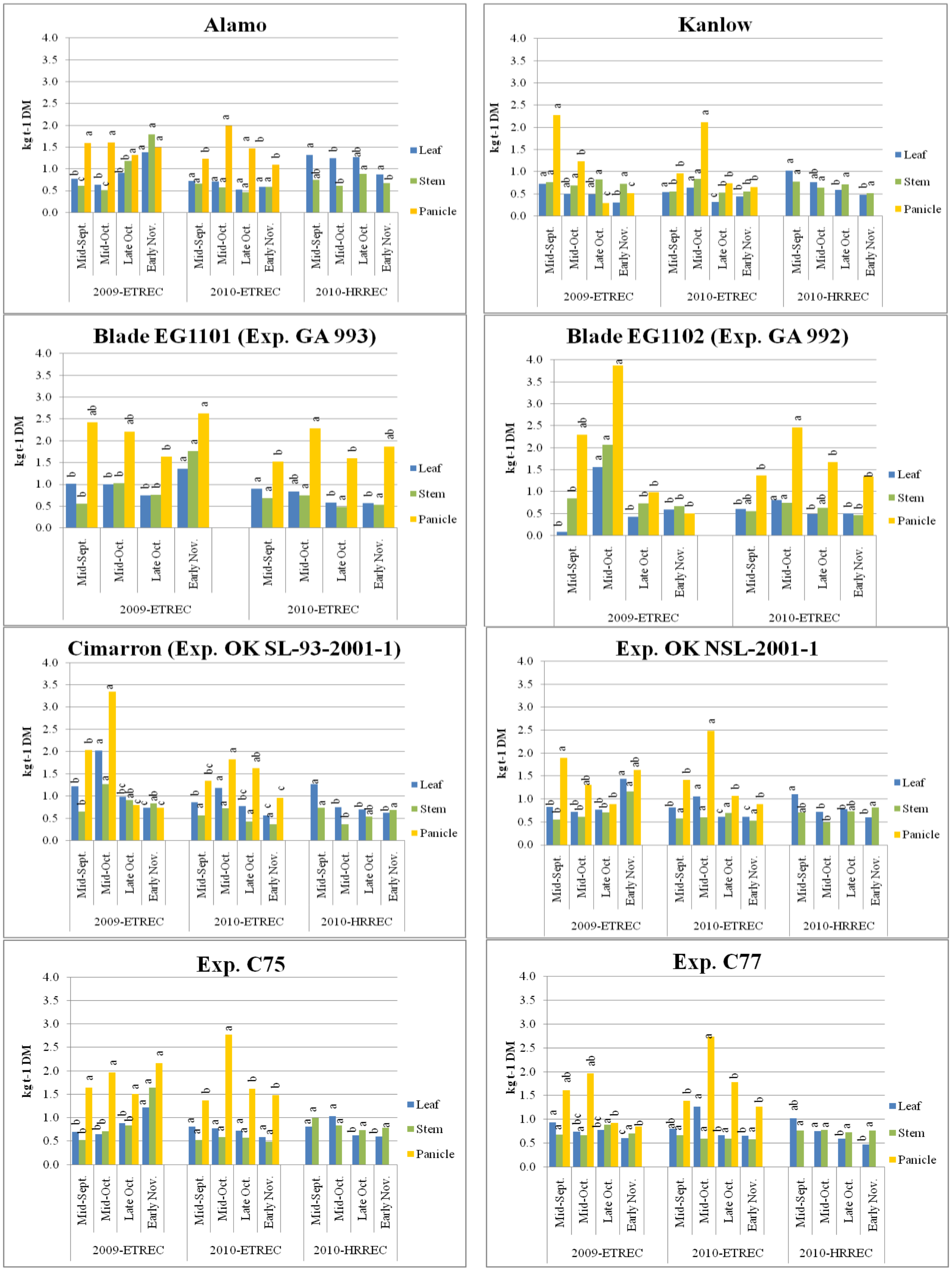


Figure 2.1 Average concentration of P in leaves, stems, and panicles of lowland varieties of switchgrass at East Tennessee (ETREC, 2009-2010) and Highland Rim (HRREC, 2010) Research and Education Centers.

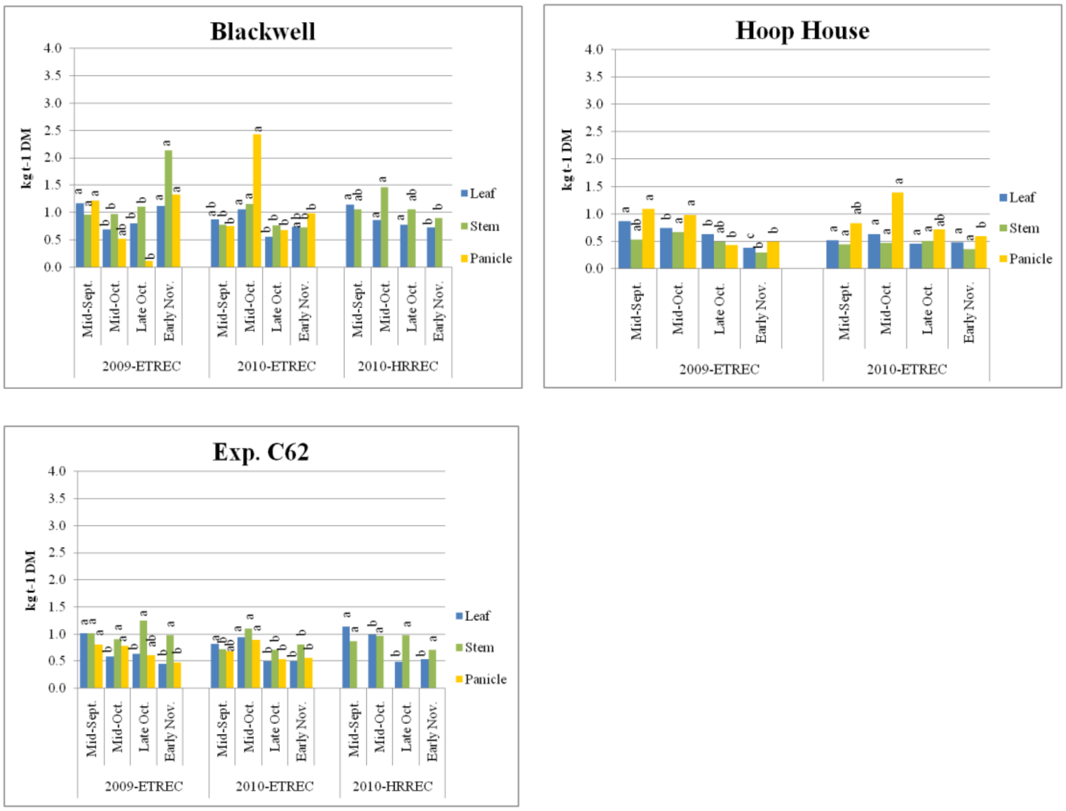


Figure 2.2 Average concentration of P in leaves, stems, and panicles of upland varieties of switchgrass at East Tennessee (ETREC, 2009-2010) and Highland Rim (HRREC, 2010) Research and Education Centers.

Figure 2.3 Average concentration of K in leaves, stems, and panicles of lowland varieties of switchgrass at East TN (ETREC, 2009-2010) and Highland Rim (HRREC, 2010) Research and Education Centers.

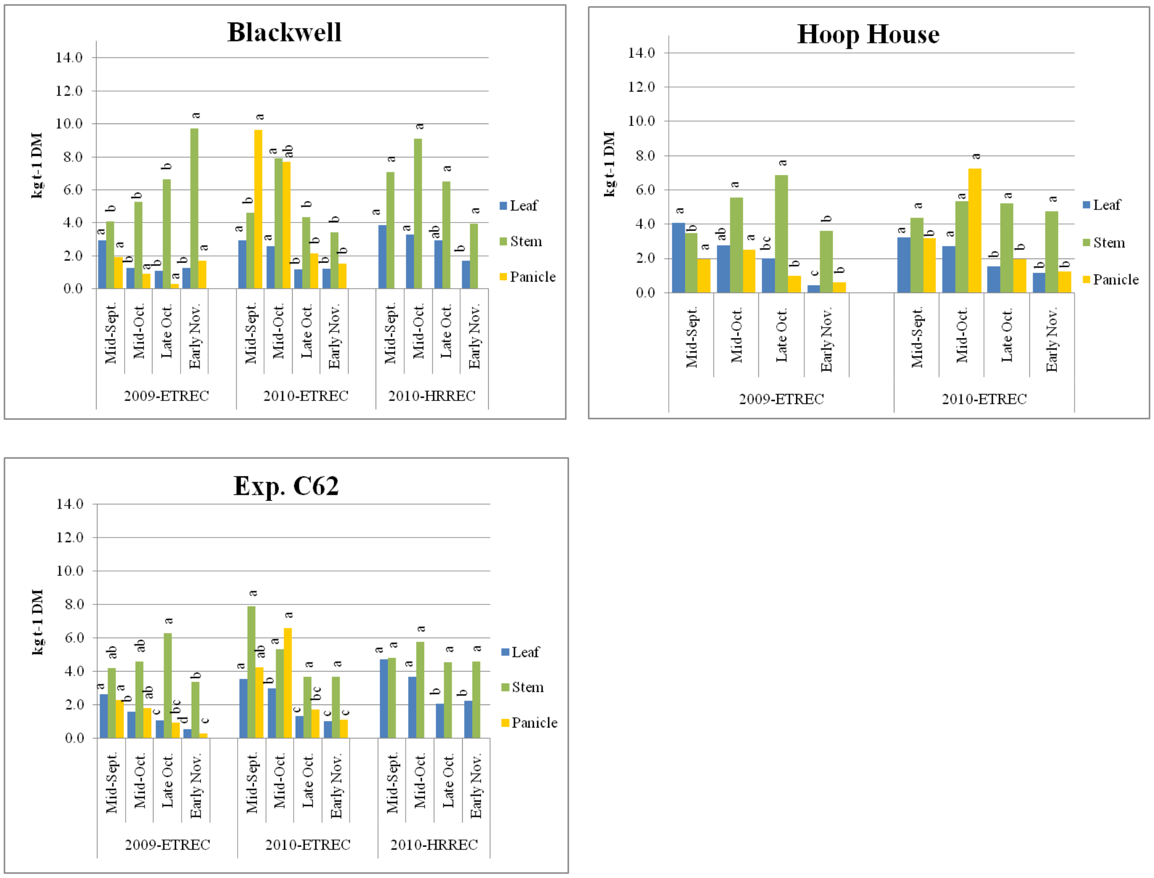
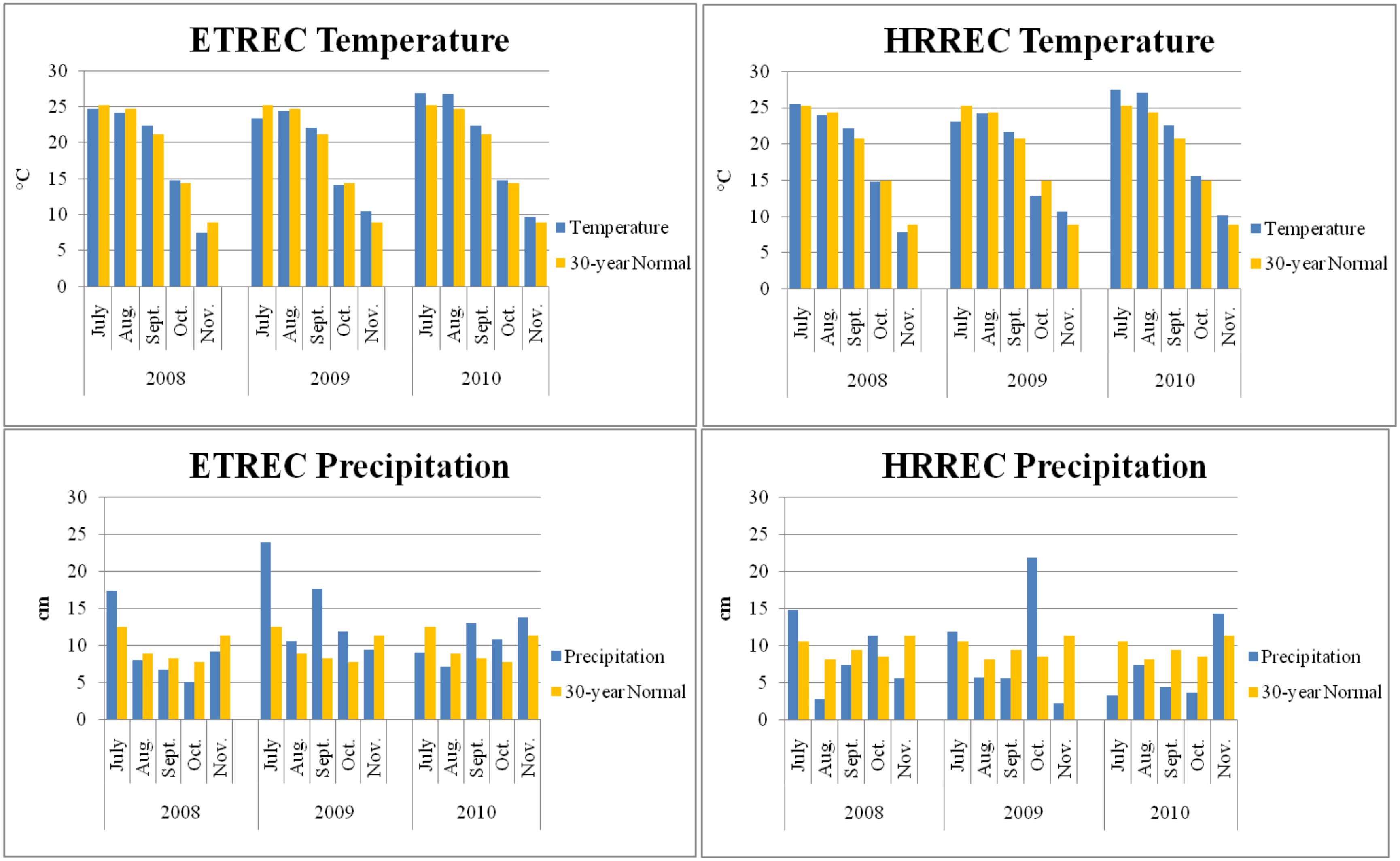


Figure 2.4 Average concentration of K in leaves, stems, and panicles of upland varieties of switchgrass at East TN (ETREC, 2009-2010) and Highland Rim (HRREC, 2010) Research and Education Centers.


ETREC Temperature

HRREC Temperature

ETREC Precipitation

HRREC Precipitation

Figure 2.5 Average temperature and precipitation at East Tennessee (ETREC) and Highland Rim (HRREC) Research and Education Centers, 2008-2010. ***(NOAA, http://cdo.ncdc.noaa.gov/ancsum/ACS)***

Part III

Effects of Earlier Fall Harvests on Biomass Yield of Switchgrass

Abstract

With the potential to harvest switchgrass earlier in the fall, effects of earlier harvest on biomass yield become a concern. A one-cut harvest system is commonly used because it is better suited to the biomass production of lowland cultivars that are grown. The objectives of this research were to determine (1) if harvesting switchgrass earlier in the fall results in a reduction of biomass yield, and (2) if standard, newly released, and experimental varieties differ in their yield response to earlier harvests. This study was composed of four experiments. In 2010, experiment one and four was conducted in Knoxville at the East Tennessee Research and Education Center (ETREC), Plant Sciences Unit and experiment three was at the ETREC Holston Unit. Experiment one consisted of four harvest dates of three upland and nine lowland varieties planted in a split plot design with three replications. Harvested plot size was 0.9 m x 1.8 m. Experiment two was conducted at the Highland Rim Research and Education Center (HRREC) in Springfield. The experiment was comprised of four fall harvest dates for eight of the twelve varieties used in experiment one (two uplands and six lowlands). Experimental design was a split plot with three replications. Harvested plot size was 1.5 m x 1.8 m. The third experiment consisted of four harvest dates of the 'Alamo' variety. Experimental design was a randomized complete block (RCB) with four replications. Harvested plot size was 3.1 m x 7.6 m. The fourth experiment consisted of four harvest dates of the 'Alamo' variety. The experimental design was a RCB with four replications. The harvested plot size was 0.9 m x 3.2 m. The four fall harvest dates in all four experiments occurred in mid-September, mid-October, late October, and mid-November. In the split plot designs, varieties were the whole plot and harvest dates were the split plot. Research was conducted in 2010 on these switchgrass stands and maintained through 2011.

Results based on one year of data reveal that new lowland varieties reflected observations in benchmark varieties, Alamo and Kanlow, with similar and consistent yields through the fall. Overall yields were relatively consistent as the fall progressed. Yields of switchgrass varieties in this study did not decline when harvested earlier in the fall, therefore harvest could be conservatively executed starting in October.

CHAPTER I

Introduction and Literature Review

Switchgrass biomass yield is affected by the time of year it is harvested (Adler et al., 2006; Madakadze et al., 1999; Sanderson et al., 1999; Vogel et al., 2002; Casler and Boe, 2003). Various studies in the U.S. have found that the maximum yield in relation to harvest date varies according to geographic location and cultivar because of genotype x environment interactions.

Switchgrass is classified by ecotype: upland and lowland. These names represent the latitude of origin in which each ecotype is best adapted. With few exceptions, most upland types are octoploids, while the lowland types are tetraploids (Parrish and Fike, 2005). Lowland types are taller and coarser than upland types, with thicker stems and larger panicles (Parrish and Fike, 2005; Casler, 2005; Porter, 1966). Upland types are less sensitive to moisture stress than lowland types because they are more adapted to drier conditions (Parrish and Fike, 2005; Porter, 1966; Stroupe et al., 2003). In an eight-year study, Parrish et al. (2003) observed that yields were comparable among upland and lowland types when managed in a two-cut harvest system; however, lowland varieties were higher yielding in a one-cut system. When cut once per season, lowland varieties produced one-third more biomass than upland varieties (Parrish et al., 2003). Wullschleger et al. (2010) reported that some of the highest yielding lowland cultivars, including ‘Alamo’ and ‘Kanlow,’ produced an average of 4.6 Mg ha $^{-1}$ more biomass annually than upland cultivars. Moser and Vogel (1995) identified Alamo as the top candidate for the deep South and Kanlow the best for mid-latitudes based on yield. Because of their productivity in a one-cut system, lowland cultivars are more appropriate for biomass production in the upper southeastern United States (Fike et al., 2006).

Alamo and Kanlow are highly productive, commonly grown lowland switchgrass cultivars. Both varieties yield similarly in response to harvest date and frequency (Parrish et al., 2003). Lemus et al. (2002) found that Alamo and Kanlow grew the tallest and produced the most biomass in a study comparing the yield of 20 switchgrass populations. In a three-year study of Alamo, Sanderson et al. (1999) found that the highest biomass yields in a one-cut system occurred in mid-September, and yields were reduced when harvest was delayed until November, which suggested that biomass yields can be maximized by implementing a single mid-September harvest. Parrish et al. (2003) observed that some yield decrease occurs between September and November harvests. They found that implementing a one-cut harvest in September rather than November lowered yields the following year. This seasonal reduction may be offset by long-term yield benefits if harvest takes place after plants mature (Parrish et al., 2003).

Nutrients are present in harvested biomass, meaning it is necessary to find a harvest window that maximizes yield while minimizing nutrient removal. When biomass is left standing in the field after senescence, the amount of harvestable material tends to decline over time, which can result in yield loss. Conversely, nutrient removal tends to be higher earlier in the season and yield may also suffer if harvest is executed too early (Heaton et al., 2009). Maximizing yield is the main goal of switchgrass producers; therefore, management strategies that help maintain high yields with lowest inputs are most desirable (Parrish and Fike, 2005)**.**

Alamo and Kanlow have been the benchmark lowland varieties for quite some time; however, recently new varieties have been released that are improvements of Alamo and Kanlow. These new varieties include Blade EG1101 and Blade EG1102, which were released commercially in 2008 by Blade Energy crops (Ceres, Inc., 2008). Cimarron is another new variety released by the Oklahoma Agricultural Experiment Station in 2008 (Oklahoma State, 2011). The purpose of this study was to compare old varieties to new varieties, as well as determine if the yield of these varieties change or differ when harvested earlier in the harvest season.

CHAPTER II

Materials and Methods

Site Description

A field study was conducted at three sites in Tennessee. The first two sites were at the East Tennessee Research and Education Center (ETREC), Plant Sciences and Holston Units in Knoxville (35.53°N 83.57°W). Weather data was only available at the Plant Sciences Unit; however, weather conditions at the Holston Unit were comparable because these sites were located only 16 km apart. From 2008-2010, Plant Sciences Unit had an average annual temperature of 14°C. This site received 129 cm of precipitation in 2008, 173 cm in 2009, and 124 cm in 2010. The first fall freeze (0°C and below) occurred on 29 October 2008, 19 October 2009, and 7 November 2010. Soil at Plant Sciences Unit is classified as a Sequatchie loam (fine-loamy, siliceous, semiactive, thermic Humic Hapludults). Prior to this experiment the Plant Sciences site was seeded in tall fescue (*Festuca arundinacea*). Soil at Holston is classified as a Huntington silt loam (fine-silty, mixed, active, mesic Fluventic Hapludolls). Prior to this study, the Holston site was managed for orchardgrass (*Dactylis glomerata*) hay production.

The third site was at Highland Rim Research and Education Center (HRREC) in Springfield (36.28°N 86.51°W). This site had a mean annual temperature of 14.4°C from in 2010, but received a slightly lower amount of precipitation (108 cm). The first fall freeze occurred on 29 October 2010. Soil at the HRREC is classified as a Sango silt loam (coarse-silty, siliceous, semiactive, thermic Glossic Fragiudults) to a Dickson silt loam (fine-silty, siliceous, semiactive, thermic Glossic Fragiudults). This site was previously cropped in winter wheat (*Triticum aestivum*).

Experimental Design

Experiment 1: ETREC Variety Trial

In May 2007, twelve switchgrass varieties comprised of three upland (Blackwell, Exp. C62, Hoop House) and nine lowland types (Alamo-Bammert, Alamo-USDA, Blade EG1101, Blade EG1102, Cimarron, OK NSL-2001-1, Exp. C75, Exp. C77, Kanlow) were planted at the ETREC Plant Sciences Unit. Harvested plot size was 0.9 m x 1.8 m. Experimental design was a split plot with three replications. Varieties were the whole plot and harvest dates were the split plot. Harvest dates were 17 September 2010, 15 October 2010, 29 October 2010, and 11 November 2010.

Experiment 2: HRREC Variety Trial

Eight of these twelve varieties (Blackwell, Exp. C62, Alamo-Bammert, Exp. C75, Exp. C77, Cimarron, OK NSL-2001-1, Kanlow) were planted on 14 June 2007 at the HRREC. These varieties were planted at a rate of 8.9 kg ha^{-1} of pure live seed (PLS) with a Hege™ 1000 no-till plot drill. Harvested plots measured 1.5 m x 1.8 m. Experimental design was a split plot with three replications. Varieties were the whole plot and harvest dates were the split plot. Harvest dates were 17 September 2010, 15 October 2010, 1 November 2010, and 22 November 2010.

Experiment 3: ETREC Holston Unit Alamo Variety

Alamo was seeded at 8.9 kg ha^{-1} PLS in May 2007 at ETREC Holston Unit. Harvested plot size was 3.1 m x 7.6 m. Experimental design was a randomized complete block with four replications. Harvest dates were 1 October 2010, 18 October 2010, 28 October 2010, and 9 November 2010.

Experiment 4: ETREC Plant Sciences Unit Alamo Variety

Alamo was seeded at 11.8 kg ha^{-1} PLS in May 2007 at ETREC Plant Sciences Unit. Harvested plot size was 0.9 m x 3.2 m. Experimental design was a randomized complete block with four replications. Harvest dates were 20 September 2010, 15 October 2010, 29 October 2010, and 11 November 2010.

Moisture Adjustment

Harvests in all experiments took place in mid-September, mid-October, late October, and mid-November. Plots in experiment one at ETREC were harvested at a height of approximately 15 cm using a flail-type forage harvester (Carter Manufacturing Co., Brookston, IN). The harvested material was weighed using a tripod and a 13.5 kg scale. Plots in experiment two at HRREC were harvested at a height of approximately 18 cm using a sickle mower. Harvested material was weighed with an electronic scale. In experiment three, plots were harvested using a 3-m rotary cutter (Bush Hog, Selma, AL). Harvested biomass from each plot was weighed with an electronic platform scale (True-Test Inc., Mineral Wells, TX). In experiment four, plot centers 0.9 m wide were cut at a height of approximately 15 cm and weighed using a self-propelled flail-type forage plot harvester (Carter Manufacturing Co., Brookston, IN).

Sub-samples were taken from each plot at harvest and fresh weights were measured. Samples were dried in a batch oven (Wisconsin Oven Corporation, East Troy, WI, USA) for a minimum of 24 hours at 49˚C and dry weight was measured. Fresh and dry weights of each sample were used to determine the percent of moisture at harvest. Yields were converted to Mg ha^{-1} on a day matter basis.

Soil Testing

Soil samples were taken in Knoxville at a depth of 15 cm to determine the residual nutrient levels per location at each harvest date and if levels changed as the harvest season progressed (Table 4.4). Examination of the results showed that experiment one and three had a P and K rating of medium across all four harvest dates. Conversely, experiment four had a low P rating and a high K rating across harvest dates, but yet had the highest yields. Soil data suggest that P and K do not vary based on harvest date, but possibly by location. The University of Tennessee Extension Service recommends the 45 kg ha^{-1} of P and 90 kg ha^{-1} of K to switchgrass only if the soil receives a low rating (Garland, 2008).

Statistical Analysis

Statistical analyses were performed using the PROC GLM procedure (SAS 9.2, 2009) to identify yield differences caused by harvest date, variety, location, and their interactions. Treatment means were calculated and Duncan's Multiple Range Test was used to test for differences among treatment means at the 5% level of probability.

CHAPTER III

Results and Discussion

ANOVA results on yield suggest that switchgrass variety was a significant source of variation in yield at both ETREC and HRREC (Table 3.1). At ETREC, harvest date was also identified a significant source of variation and is supported by yield data at ETREC, in which yield significantly increased from mid-September to mid-November (Table 3.1 and 3.3). Also, the interaction of variety and harvest date was confirmed in this study. On the other hand, at HRREC harvest and the interaction of harvest and variety were not significant, also supported by the data in which no significant changes in yield were observed in any variety through the harvest season at HRREC (Table 3.3, Figs. 3.2 and 3.3). ANOVA results on the yield of eight varieties across two locations show that location was a significant source of variation, which was confirmed by the yield differences at ETREC and HRREC as well as differences in varieties, harvest dates, and interactions with location (Table 3.2).

Lowland Varieties

Nine lowland varieties or experimental varieties were evaluated at ETREC, which included Alamo (USDA and Bammert), Kanlow, Cimarron, Blade EG1101, Blade EG1102, C75, C77, and OK NSL-2001-1. Six of the same lowland varieties were studied at HRREC, which were Alamo (Bammert), Kanlow, Cimarron, OK NSL-2001-1, C75, and C77. ETREC had higher yields, averaging 10.0 Mg ha^{-1} more than HRREC, indicating that location played a part in the performance of both upland and lowland varieties (Tables 3.3 and 3.4). When averaged across varieties, yields at ETREC were significantly lower in mid-September (19.0 Mg ha^{-1}) and significantly higher in mid-November (26.0 Mg ha^{-1}, Table 3.3). However at HRREC, no significant differences occured among harvests, averaging 12.8 Mg ha^{-1}.

Since Alamo and Kanlow are typically the two benchmark lowland varieties grown in the southeastern United States, a comparison of these was beneficial. Comparing Alamo and Kanlow at each of the four harvest dates at ETREC revealed similar yield trends with no significant differences observed in these varieties. Two seed sources of Alamo were evaluated (USDA and Bammert Seed Co.) at the ETREC location; thus the yield of each responded slightly differently to harvest date. The yield of Alamo from the USDA source did not significantly change at ETREC when harvested from mid-September to late October, with an average yield of 23.3 Mg ha^{-1}; however, yield significantly increased to 37.5 Mg ha^{-1} in November. The Bammert source of Alamo had comparable yields to those seen in the USDA source from September to October, but Bammert yielded less than the USDA in November (25.9 Mg ha^{-1}). Yields in September of the Bammert source of Alamo were significantly lower than yields in November, but the mid and late October harvests did not differ from September or November harvests, with an average yield of 23.8 Mg ha^{-1} (Table 3.5). At HRREC, only the Bammert source of Alamo was studied, which had an average yield of 14.6 Mg ha^{-1} across all four harvest dates (Table 3.4) and although the yield slightly declined as the fall progressed, no significant differences in yield were observed among harvest dates (Fig. 3.2). The data suggest that yield differences may occur in switchgrass varieties that are from different seed sources, but the differences likely will be small and furthermore yield of both sources of Alamo will not be significantly lessened by harvesting prior to early November.

Kanlow yields remained consistent throughout the fall, with no significant changes (Fig. 2.3). Yield of Kanlow averaged 22.4 Mg ha^{-1} for the season and was not significantly different from either source of Alamo (Table 3.4). Kanlow at HRREC yielded an average of 16.4 Mg ha^{-1}, which did not significantly change across time and was not significant ($P \leq 0.05$) from Alamo at this location. Based on data from one year at two locations, lowland switchgrass varieties may be harvested earlier in the fall without significant yield reduction.

Cimarron was released as a new commercial variety by the Oklahoma Agricultural Experiment Station in 2008 (Oklahoma State University, 2011). It was the highest yielding variety at ETREC, with an average yield of 27.5 Mg ha^{-1} (Table 3.4). Cimarron yield was significantly higher than that of Bammert source of Alamo and Kanlow at ETREC. September harvest yielded 9.9 Mg ha^{-1} less than the November harvest, which was a significant decrease, while October harvests did not differ from those in September and November (Fig. 3.2), as observed in Bammert Alamo (Table 3.5). At HRREC, Cimarron yielded an average of 15.2 Mg ha^{-1} (Table 3.4). Cimarron yield did not significantly differ throughout the harvest period and did not differ from the other lowland varieties (Fig. 3.1). Again, these data suggest that harvesting prior to November is warranted without a consistently significant loss in yield.

Blade EG1101 was released commercially in 2008 by Blade Energy Crops as an improved Alamo variety (Ceres Inc., 2008). Blade EG1101 did not significantly differ in yield from any other lowland variety (Table 3.4). Although yield slightly increased with each harvest, Blade EG1101 did not significantly change in yield as the fall progressed (Figure 3.2). The other variety, Blade EG1102, was also released commercially in 2008 by Blade Energy Crops as an improved Kanlow variety (Ceres Inc., 2008). It yielded similarly to C75 (Table 3.5 and Fig. 3.2).

Blade EG1102 performed similar to Blade EG1101, 25.5 Mg ha^{-1} versus 23.7 Mg ha^{-1}, and the difference was not significant (Table 3.4). The average yield of 25.5 Mg ha^{-1} was not significantly different from any of the lowland varieties (Table 3.4). As observed in Blade EG1101, increases occured at each harvest date, but no significant changes in the yield of Blade EG1102 were observed (Fig. 3.2). Based on one year of data at one location it appears that both Blade EG1101 and 1102 could be harvested earlier in the fall without having a significant yield reduction.

The experimental line OK NSL-2001-1 came from the developers of Cimarron (Oklahoma State University). Averaged across all harvest dates, OK NSL-2001-1 did not significantly differ ($P\leq 0.05$) in yield from any of the lowland varieties (Table 3.4, Fig. 3.1). OK NSL-2001-1 variety had an average yield of 26.9 Mg ha^{-1} at ETREC (Table 3.4). From September to late October the yield averaged 24.3 Mg ha^{-1}, but significantly increased to 34.5 Mg ha^{-1} in November (Fig. 3.2). The yield of OK NSL-2001-1 at ETREC in November was nearly 10 Mg ha^{-1} greater than the previous harvests, which would suggest later harvest of this variety at this location. At HRREC, OK NSL-2001-1 had an average yield of 13.9 Mg ha^{-1} (Table 3.4). It was one of the lowest yielding lowland varieties at this location, but did not change significantly through the fall or from the other lowland varieties (Fig. 3.2).

The experimental line C75 yielded an average of 25.3 Mg ha^{-1} at ETREC, which was a medial yield among the lowland varieties; however, it was not significantly different from any of the other lowland varieties (Table 3.4). No significant changes in yield were observed when harvested from September to late October, but like OK NSL-2001-1 a significant increase of 7 Mg ha^{-1} in yield occured in November at ETREC but not at HRREC (Figure 3.2). At HRREC, C75 was the lowest yielding lowland variety, averaging 13.0 Mg ha^{-1}, which was only significantly lower than Kanlow (Table 3.4). Like all other lowlands at HRREC, C75 did not significantly change in yield from mid-September through early November (Figure 3.2).

The other experimental line from Noble Foundation, C77 did not significantly differ from the other lowland varieties when yield was averaged across harvest dates (Table 3.4). C77 had an average yield of 23.4 Mg ha^{-1} at ETREC, which was nearly equal to the yield of Alamo (Bammert) and Kanlow (Table 3.4). Yield increased numerically throughout the harvest season at ETREC, but not enough to result in significant differences from September to November (Fig. 3.3). At HRREC, C77 had an average yield of 15.5 Mg ha^{-1} and did not significantly differ from any other lowland variety (Table 3.4 and Fig. 3.1). Yield remained relatively flat from September through November with no significant changes were observed (Figure 3.2). Data from both locations suggest that harvesting this variety as early as mid-September would not adversely affect yield.

Upland Varieties

The three upland varieties or experimental lines studied at ETREC were Blackwell, Hoop House, and C62. Only Blackwell and C62 were studied at HRREC. In general, uplands were lower yielding than lowlands in this study. With the exception of Hoop House, upland varieties yielded significantly less biomass than lowland varieties (Table 3.4 and Fig. 3.3). As observed in lowland varieties, the yield of the upland varieties at HRREC was much lower than upland varieties observed at ETREC (Table 3.3). The lower performance of these upland varieties could be attributed to the location where they are best adapted.

Blackwell was developed by the Plant Materials Center and the Kansas Agricultural Experiment Station from a single plant collected in 1944 (Sharp Bros. Seed Co., 2011). Blackwell was consistently the lowest yielding variety, yielding 15.7 Mg ha^{-1} (Table 3.4). This yield was significantly lower than all other varieties, except for C62, another upland variety. At ETREC, Blackwell increased significantly from 11.0 Mg ha^{-1} in September to 19.3 Mg ha^{-1} in October, maintained constant yields throughout October, and then significantly decreased in November, back down to September levels (Fig. 3.3). On the other hand, at HRREC the yields of Blackwell were relatively stable at approximately 5.0 Mg ha^{-1} across four harvest dates (Fig. 3.3).

Hoop House was the highest yielding upland variety but was only planted at the ETREC location. Hoop House averaged 25.4 Mg ha^{-1}, which was comparable to lowland variety yields Table 3.4). Hoop House yielded 9.7 Mg ha^{-1} more than Blackwell. Although Hoop House yielded numerically lower than several lowland varieties, the differences were not significant. Yield did not significantly change from September to late October, averaging 23.0 Mg ha^{-1}; however, a significant yield increase of 8.4 Mg ha^{-1} occurred in November (Fig. 3.3). Evaluation of data suggests that waiting until November to harvest would be beneficial for yield increase in this variety.

Although C62 was also one of the lowest yielding varieties, it had an average yield across four harvest dates of 18.9 Mg ha^{-1}, which did not differ from Alamo (Bammert) and Kanlow or Blackwell (Table 3.4). At ETREC, C62 significantly increased in yield from 14.4 Mg ha^{-1} in September to 21.7 Mg ha^{-1} in mid-October (Fig. 3.3). Yield was maintained through October, averaging 22.4 Mg ha^{-1}. In November, C62 yield at ETREC significantly decreased to 16.4 Mg ha^{-1}, which was a level that was not significantly different to those observed in September and mid-October. At HRREC, C62 was also among the low yielding varieties with a yield of 8.4 Mg ha^{-1}, which was significantly lower than the lowland varieties (Table 3.4). The yields of C62 did not differ across the four harvest dates (Fig. 3.3). This suggests that the recommended harvest time of early November is not appropriate for this variety because yields were lowest at this time.

Alamo Only Tests

With 2,065 ha of Alamo switchgrass planted in East Tennessse (UTIA, 2010), this variety was of particular interest because of its popularity for use in commercial production. To evaluate as much yield data as possible in one year, Alamo was evaluated in four experiments in 2010 to better establish yield changes when harvested at four different fall harvest dates, mid-September, mid-October, late-October, and early November.

Three experiments were carried out at the ETREC units and one experiment at HRREC. In two of the tests at ETREC (Plant Sciences and Holston Units; experiments 3 and 4) there were no significant changes in yield from mid-September to mid-November, even though the average yield in experiment 4 was double that of experiment 3 (25.5 versus 12.5 Mg ha^{-1}, Table 3.6). However, in the ETREC variety trial (experiment 1) Alamo had significant differences in yield among harvest dates. In that experiment, Alamo yield in mid-September (18.7 Mg ha^{-1}) was significantly lower than in mid-November (25.9 Mg ha^{-1}), but the yields in mid- and late October (23.7 and 23.8 Mg ha^{-1}, respectively) did not differ from the November yields (Table 3.6). The fourth test was at HRREC (Experiment 2). Alamo yields at HRREC were comparable to those at ETREC Holston Unit (14.6 and 12.5 Mg ha^{-1}, respectively) and did not significantly differ among the four harvest dates from September through November (Table 3.6), which supports trends observed at two of the three ETREC experiments. Overall, data from three out of four tests suggest that harvest could be executed as early as mid-September and not result in significant yield reductions in the Alamo switchgrass variety.

Processing Factors to Consider

Factors other than yield must be considered with the possibility of harvesting earlier in the fall. According to Samuel Jackson (personal communication) from the University of Tennessee, Center for Renewable Carbon, the DuPont Danisco Cellulosic Ethanol Company has determined that certain components in harvested biomass can inhibit the pretreatment and saccharification steps of the conversion process. The components of switchgrass primarily include cellulose, hemicellulose, lignin, extractives (minerals), and free sugars. Cellulose and hemicellulose are the key targets for sugars and ultimately ethanol; therefore, the key processing differences between early and late harvests are related to extractives and free sugars, which are largely leached out through rain, frosts, and drying as the material ages in the field. Extractives and free sugars in biomass can interfere with the conversion process by reducing overall sugar recovery, leading to less ethanol per ton. By having those materials leach out through the fall, inhibitors of the process are removed and thus, the later harvest material is more desirable due to the higher conversion efficiency. According to Jackson, this is currently the best knowledge available, but developing ways to address this problem from the processing aspect could remove this as a concern associated with earlier harvest. In research conducted by Dien et al. (2006) on ‘Cave-in-Rock’ switchgrass, they found that although carbohydrate levels increased as plants matured, there were not significant changes in yields of carbohydrates after pretreatment from anthesis to post-frost. They reported that as plant maturity increased, glucans were more challenging to extract.

CHAPTER IV

Conclusions

The objectives of this study were to determine if significant changes in switchgrass yield resulted from harvests occurring earlier than the recommended harvest time of early November and if yield differences occurred among standard and newly released varieties of both upland and lowland types. Harvests were implemented in mid-September, mid-October, late October, and mid-November at ETREC and HRREC in 2010. Results were based on one year of data.

Examination of the data indicates that switchgrass variety and harvest date were significant sources of variation in yields at ETREC, while only variety was significant at HRREC. This illustrated that location was also a significant source of variation as well as the interaction of location with variety and harvest date. Varieties observed at ETREC were nearly double the yield of the same varieties observed at HRREC at every harvest date. Yields at ETREC changed as the fall progressed, but there were no significant changes observed in the yield of any variety through the fall at HRREC.

Alamo and Kanlow consistently performed similarly and the average dry matter yield for both varieties did not significantly change or differ when compared at different harvest dates. Alamo compared in four tests confirmed that yield does not suffer when Alamo is harvested earlier than the recommended harvest time, therefore harvest could be executed as early as mid-September. The new lowland varieties, such as Blade EG1101, Blade EG1102, and Cimarron, reflected trends observed in Alamo and Kanlow, with similar and consistent yields through the fall. The upland variety Blackwell was consistently a low yielding variety and was surpassed by a newer variety, Hoop House. Overall lowlands were typically higher yielding than uplands.

This study suggests that most varieties of switchgrass grown for biomass may be harvested as early as September, but conservatively in October without reducing yield.

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Appendix C

Table 3.1 ANOVA results on yield of switchgrass varieties for East Tennessee (ETREC) and Highland Rim (HRREC) Research and Education Centers, 2010.

	ETREC		HRREC	
Source	DF	P>F	DF	P>F
Variety	11	0.0001	7	< .0001
Rep	2	0.0859	2	0.0015
Rep*Variety (Error A)	22	0.0752	14	0.7401
Harvest	3	< .0001	3	0.1704
Variety*Harvest	33	0.0095	21	0.5202
Residual (Error B)	72		48	

Table 3.2 ANOVA results on yield of eight switchgrass varieties at East Tennessee (ETREC) and Highland Rim (HRREC) Research and Education Centers, 2010.

Source	DF	P>F
Location	1	< .0001
Variety	7	< .0001
Variety *Location	7	0.0044
Rep (Location)	4	0.0012
Rep (Variety*Location) (Error A)	28	0.3216
Harvest	3	0.0004
Harvest *Location	3	< .0001
Variety*Harvest	21	0.0822
Variety*Harvest*Location	21	0.0061
Residual (Error B)	96	

Table 3.3 Average dry matter yield across eight varieties of switchgrass per harvest date at East Tennessee (ETREC) and Highland Rim (HRREC) Research and Education Centers, 2010.

Harvest Date	ETREC	HRREC
	----------------Mg ha^{-1}-----------------	
Mid-September	19.0 c†	13.0 a
Mid-October	22.4 b	13.5 a
Late-October	24.0 b	13.3 a
Mid- November	26.0 a	11.4 a

† Means within a column followed by a common letter are not significantly different based on Duncan's Multiple Range Test (P≤ 0.05)

Table 3.4 Average dry matter yield per variety across all harvest dates at East Tennessee (ETREC) and Highland Rim (HRREC), 2010.

	Variety Experimental Line	ETREC	HRREC
		--------Mg ha^{-1}------	
Upland	Blackwell	15.7 d†	5.1 d
	Hoop House	25.4 ab	—
	C62	18.9 cd	8.4 c
Lowland	Alamo (Bammert)	23.0 abc	14.6 ab
	Alamo (USDA)	26.8 ab	—
	Kanlow	22.4 bc	16.4 a
	Blade EG1101 (GA 993)	23.7 ab	—
	Blade EG1102 (GA 992)	25.5 ab	—
	Cimarron (OK SL-93-2001-1)	27.5 a	15.2 ab
	C75	25.3 ab	13.0 b
	C77	23.4 ab	15.5 ab
	OK NSL-2001-1	26.9 ab	13.9 ab

† Means within a column followed by a common letter are not significantly different based on Duncan's Multiple Range Test (P≤ 0.05)

Table 3.5 Average dry matter yield per variety per harvest date at East Tennessee Research and Education Center, 2010.

	Variety Experimental Line	Mid-Sept.§	Mid-Oct.	Late Oct.	Mid-Nov.
		--------------------Mg ha^{-1}--------------------			
Upland	Blackwell	11.0 c†	19.3 d	20.3 a	12.1 c
	Hoop House	20.8 a	24.0 abc	24.3 a	32.7 a
	C62	14.4 bc	21.7 bcd	23.0 a	16.4 bc
Lowland	Alamo (Bammert)	18.8 ab	20.2 cd	23.5 a	27.0 ab
	Alamo (USDA)	22.4 a	23.5 abc	23.9 a	37.5 a
	Kanlow	18.7 ab	23.7 abc	23.8 a	25.9 ab
	Blade EG1101 (GA993)	21.4 a	22.1 bcd	24.3 a	27.2 ab
	Blade EG1102 (GA 992)	23.0 a	22.2 bcd	27.3 a	29.6 a
	Cimarron (OK SL-93-2001-1)	23.4 a	26.7 a	26.5 a	33.3 a
	C75	22.5 a	20.7 bcd	25.5 a	32.5 a
	C77	20.0 ab	22.1 bcd	24.8 a	26.6 ab
	OK NSL-2001-1	23.5 a	24.9 ab	24.6 a	34.5 a

† Means within a column followed by a common letter are not significantly different based on Duncan's Multiple Range Test (P≤ 0.05).

§ 2010 dates: 17 Sept., 15 Oct., 29 Oct., and 11 Nov.

Table 3.6 Average dry matter yield of Alamo switchgrass per location, 2010.

Harvest Date	Exp. 1	Exp. 2	Exp. 3	Exp. 4
		---Mg ha^{-1}---		
Mid-Sept §	18.7 b†	16.9 a	11.7 a	24.7 a
Mid-Oct	23.7 ab	15.0 a	12.8 a	29.5 a
Late Oct	23.8 ab	14.0 a	13.4 a	22.9 a
Mid-Nov	25.9 a	12.6 a	12.1 a	23.9 a

† Means within a column followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P\leq 0.05$)

§ 2010 harvest dates for Exp. 1 (ETREC, Variety Trial): 17 Sept., 15 Oct., 29 Oct., and 11 Nov.
Exp. 2 (HRREC, Variety Trial): 17 Sept., 15 Oct., 1 Nov., and 22 Nov.
Exp. 3 (ETREC, Holston Unit): 1 Oct., 18 Oct., 28 Oct., and 9 Nov.
Exp. 4 (ETREC, Plant Sciences Unit): 20 Sept., 15 Oct., 29 Oct., and 11 Nov.

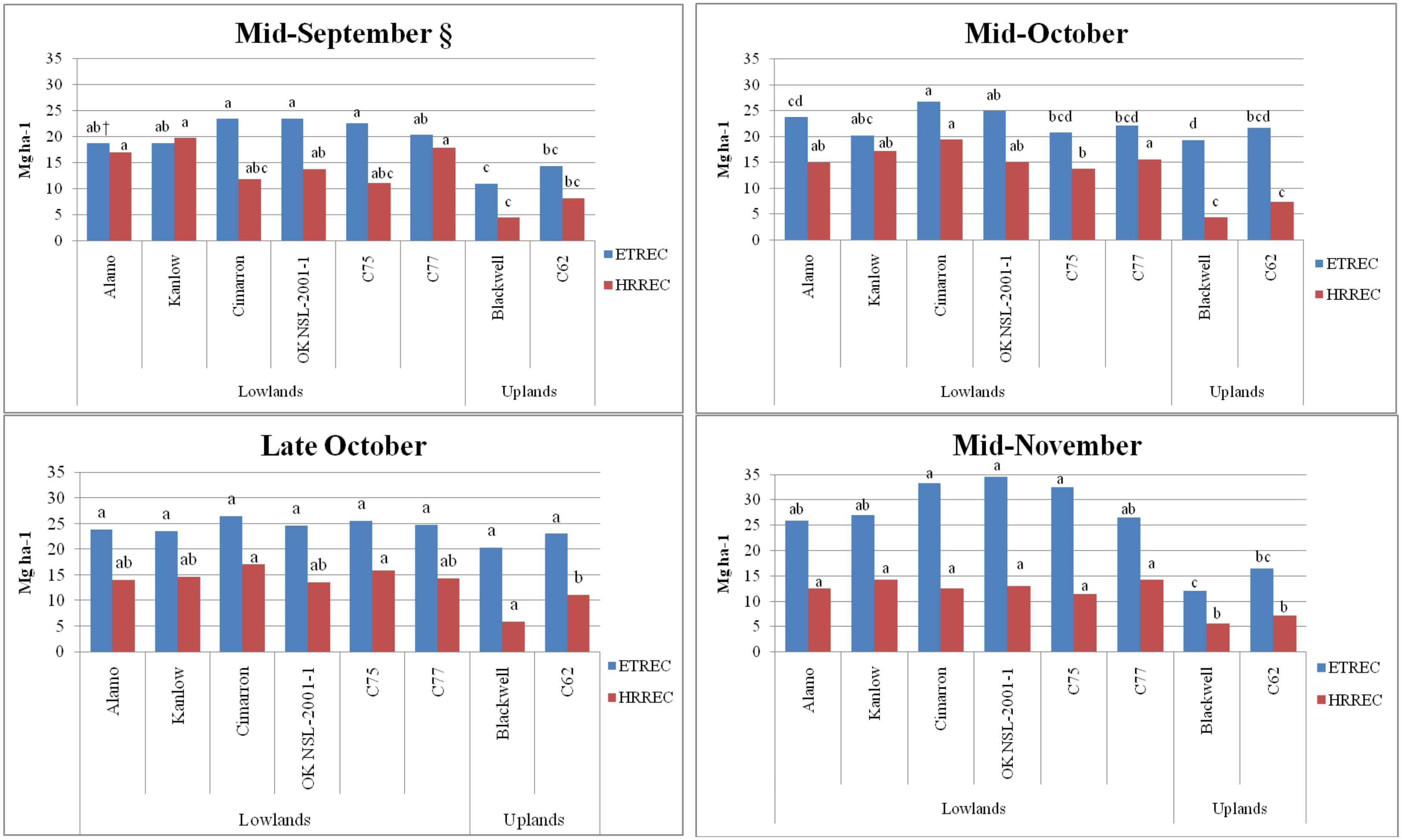

Figure 3.1 Average dry matter yield per variety per harvest date at East Tennessee (ETREC) and Highland Rim (HRREC) Research and Education Centers, 2010.

† Means within a location followed by a common letter are not significantly different based on Duncan's Multiple Range Test (P≤ 0.05)

§ 2010 dates for ETREC: 17 Sept., 15 Oct., 29 Oct., and 11 Nov.
HRREC: 17 Sept., 15 Oct., 1 Nov., and 22 Nov.

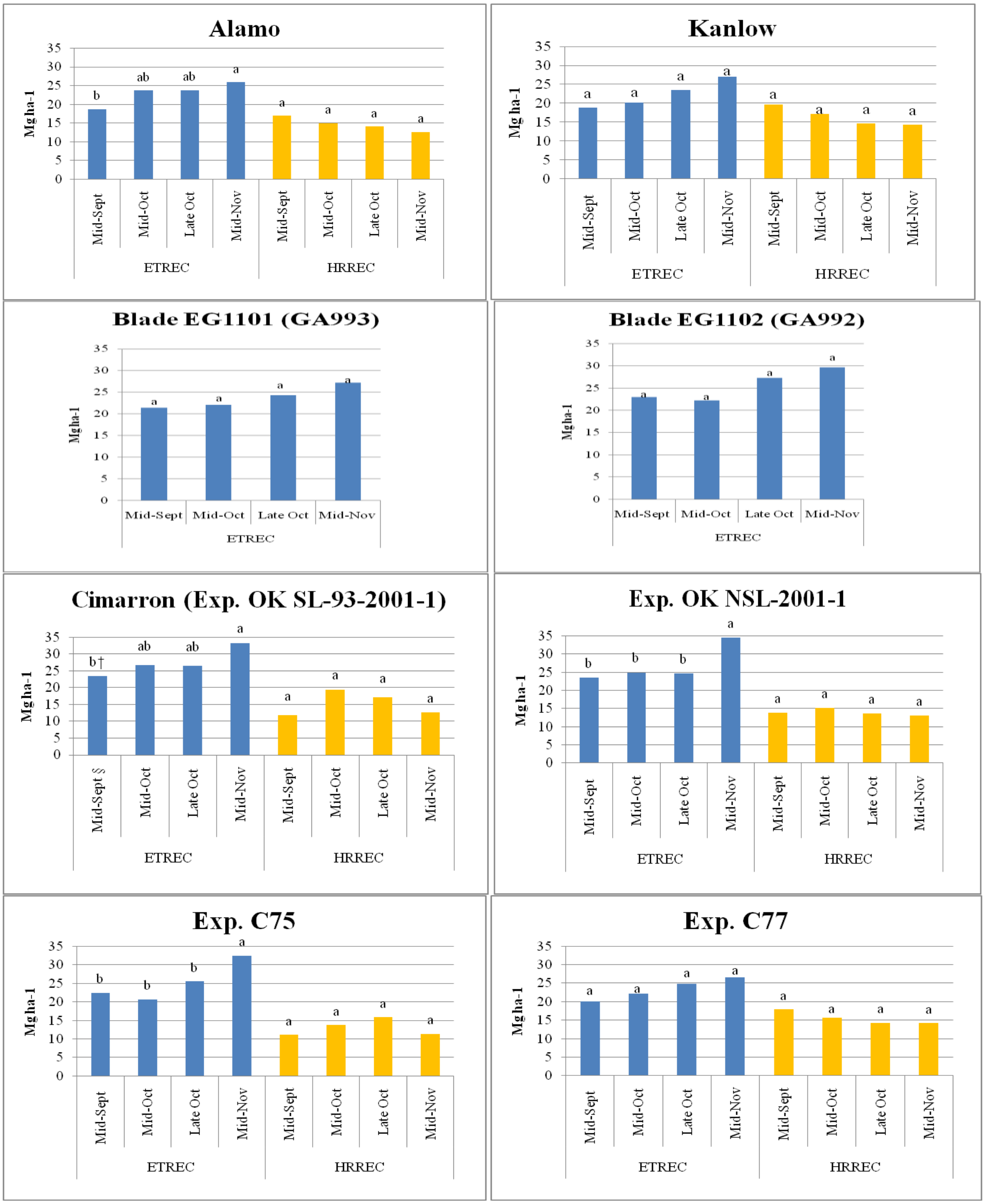

Figure 3.2 Average dry matter yield per lowland variety at four harvest dates at East Tennessee (ETREC) and Highland Rim (HRREC) Research and Education Centers, 2010.
† Means within a location followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P \leq 0.05$)
§ 2010 dates for ETREC: 17 Sept., 15 Oct., 29 Oct., and 11 Nov.
HRREC: 17 Sept., 15 Oct., 1 Nov., and 22 Nov.

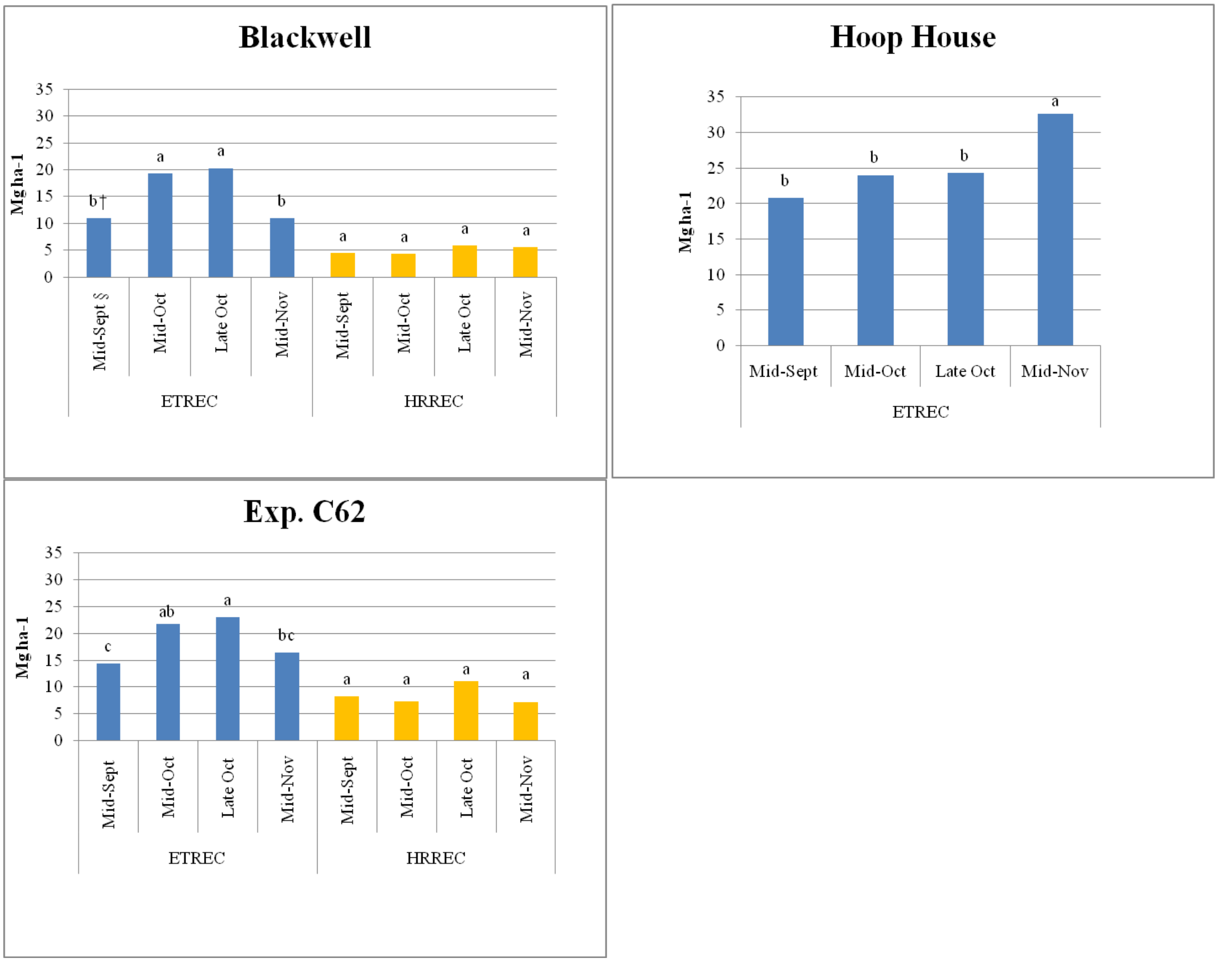

Figure 3.3 Average dry matter yield per upland variety at four harvest dates at East Tennessee (ETREC) and Highland Rim (HRREC) Research and Education Centers, 2010.

† Means within a location followed by a common letter are not significantly different based on Duncan's Multiple Range Test ($P \leq 0.05$)

§ 2010 dates for ETREC: 17 Sept., 15 Oct., 29 Oct., and 11 Nov.
HRREC: 17 Sept., 15 Oct., 1 Nov., and 22 Nov.

Summary

The ultimate objective of this study was to evaluate the current harvest recommendation for switchgrass in a one-cut system because the recommendation is based on the premise that nutrient removal may be reduced when harvest is delayed until nutrients have remobilized from shoots to belowground tissues, such as crowns and roots. The focus of this study was to determine if delaying harvest until November was justified by decreases in P and K as well as yield increases. The concern with later harvest is that weather and field conditions during that time of year can be unpredictable and undesirable for harvesting. Other objectives included evaluating the concentration of P and K in above and belowground tissues, which included stems, leaves, panicles, entire shoots, roots, and crowns, to evaluate increases and decreases over time. Evaluating and comparing the trends of benchmark and new varieties of upland and lowland switchgrass was also an objective. The final objective was to determine if the yields of these varieties would suffer if harvest could be implemented earlier in the fall. Data were collected in mid-September, mid-October, late October, and early November throughout the study.

Part I:

This section of the study dealt with determining P and K levels at four harvest dates in shoots and whole plants of Alamo and Kanlow. Overall, Alamo and Kanlow followed similar trends of change, with no significant differences among harvest dates. Potassium was found to be present in concentrations up to six times higher than P, which was supported by data observed in leaf, stem, and panicle data as well as shoot, crown, and root data. Based on this study, P and K in shoots did not appear to decline from mid-September to mid-November and crowns and roots did not significantly increase during this time. Therefore, fall harvest as early as mid-September is justifiable based on P and K levels in shoots.

Part II:

The purpose of this section was to evaluate differences in several different traditional, newly released, and experimental varieties of upland and lowland types of switchgrass. Data indicated that when averaged across the four harvest dates, no significant changes in P and K concentrations were observed. The benchmark varieties, Alamo and Kanlow, followed consistent trends through the fall. New varieties had P and K concentrations that were similar to Alamo and Kanlow, also with similar trends across harvest dates. The P and K levels in upland and lowland types of switchgrass were present in relatively similar amounts. As observed in the previous section, data support earlier harvest since P and K in shoots of these varieties do not decline from mid-September through early November.

Part III:

The objective in this part was to determine if the yield of different switchgrass varieties would be significantly reduced by harvesting earlier than the current harvest recommendation of early November. Results were based on one year of data. Alamo and Kanlow consistently performed similarly and the average dry matter yield did not change through the fall. Alamo was evaluated in four experiments, in which three out of four experiments confirmed that yield does not suffer when Alamo is harvested earlier. New varieties reflected trends observed in Alamo and Kanlow, with similar trends through the fall. Overall, lowlands were typically higher yielding than uplands varieties. Data suggests that most varieties of switchgrass grown for biomass could be harvested as early as mid-September without reducing yield.

In summary, based on the data collected for this project, switchgrass could be conservatively harvested as early as October without removing significantly more P and K from the land in harvest biomass, in addition, biomass yield will not be significantly reduced by executing harvest before early November.

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Appendix D

Table 4.1 Summary of treatment and plot description for variety tests at East Tennessee (ETREC Plant Sciences, 2008-2010) and Highland Rim (HRREC, 2010) Research and Education Centers.

		ETREC			HRREC		
Variety/ Experimental Line	Source	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
Cimarron	OK St. Univ.	101†	206	312	101	206	303
Blade EG1101	UGA (Bouton)	102	205	301	—	—	—
Kanlow	Feyh Farm Seed (KS)	103	208	308	105	203	307
C77	Noble Found. (Bouton)	104	209	304	108	204	301
C62	Noble Found. (Bouton)	105	202	311	106	207	308
Hoop House	Gum Tree Nursery	106	210	303	—	—	—
Alamo	USDA -- TX	107	211	307	—	—	—
Blackwell	Bammert Seed	108	207	310	104	201	302
OSU-2	OK St. Univ.	109	201	305	102	208	305
Alamo	Bammert Seed	110	203	302	103	205	306
C75	Noble Found. (Bouton)	111	212	306	107	202	304
Blade EG1102	UGA (Bouton)	112	204	309	—	—	—

†Plot number within each location

Table 4.2 Harvest dates for shoots and whole-plants of Alamo and Kanlow varieties of switchgrass at the East Tennessee (2008-2010) and Highland Rim (2010) Research and Education Center.

ETREC Plant Science Unit & Holston Unit (Shoots)			HRREC (Shoots)	Holston Unit (Whole Plants)	
2008	2009	2010	2010	2009	2010
July 21					
Aug. 22					
Sept. 25	Sept. 18	Sept. 15	Sept. 21	Sept. 29	Sept. 25
Oct. 9	Oct. 9	Oct. 12			
Oct. 15			Oct. 15		
Oct. 24	Oct. 28	Oct. 26		Oct. 21	Oct. 29
Oct. 31			Nov. 1		
Nov. 10	Nov. 13	Nov. 11	Nov. 22	Nov. 17	Nov. 8

Table 4.3 Timeline of harvest for dry matter yield, 2010.

Harvest Timing	ETREC Variety Test	HRREC Variety Test	ETREC Holston Unit	ETREC Alamo Only
Mid-September	17 Sept.	17 Sept.	1 Oct.	20 Sept.
Mid-October	15 Oct.	15 Oct.	18 Oct.	15 Oct.
Late October	29 Oct.	1 Nov.	28 Oct.	29 Oct.
Mid-November	11 Nov.	22 Nov.	9 Nov.	11 Nov.

Table 4.4 Soil test results and ratings per harvest date at East Tennessee Research and Education Center Plant Sciences and Holston Units, 2010.

Location	Harvest Date	P		K	Water pH
ETREC: Exp. 1	Mid-Sept	35 (M)	---kg ha^{-1}---	161 (M)	6.84
	Mid-Oct	34 (M)		149 (M)	6.83
	Late Oct	23 (M)		206 (M)	6.73
	Early Nov	29 (M)		166 (M)	6.73
ETREC: Exp. 3	Mid-Sept	37 (H)		143 (M)	5.73
	Mid-Oct	35 (H)		147 (M)	5.76
	Late Oct	27 (M)		138 (M)	5.84
	Early Nov	28 (M)		127 (M)	5.92
ETREC: Exp. 4	Mid-Sept	15 (L)		237 (H)	6.91
	Mid-Oct	15 (L)		222 (H)	7.14
	Mid-Oct	9 (L)		197 (H)	6.45
	Mid-Nov	9 (L)		155 (M)	6.85

Table 4.5 Site description for Tennessee experiment stations, 2008-2010.

			Site Description			
Location	Soil Type	Year	Annual Precip. (cm)	Avg. Annual Temp. (°C)	Fall Freeze (<0°C)	Previous Mgmt.
ETREC	Sequatchie loam (fine-loamy, siliceous, semiactive, thermic Humic Hapludults)	2008	129.4	14.3	October 29	tall fescue (*Festuca arundinacea*) grass
		2009	172.5	14.3	October 19	
		2010	123.6	14.4		
Holston	Huntington silt loam (fine-silty, mixed, active, mesic Fluventic Hapludolls)	2008				orchardgrass (*Dactylis glomerata*) hay
		2009				
		2010				
HRREC	Sango silt loam Dickson silt loam	2008	133.9	13.9	October 29	winter wheat (*Triticum aestivum*)
	(coarse-silty, siliceous, semiactive, thermic Glossic Fragiudults), (fine-silty, siliceous, semiactive, thermic Glossic Fragiudults)	2009	136.5	13.9	October 18	
		2010	107.5	14.4		

VITA

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