Switchgrass Yield on Reclaimed Surface Mines for Bioenergy Production

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The high cost of transportation fuels and the environmental risks associated with acquiring and using nonrenewable energy sources have created a demand for developing renewable bioenergy crops. Switchgrass (*Panicum virgatum* L.), a warm-season perennial grass, is a promising feedstock due to its high biomass production under a wide range of growing conditions and its satisfactory forage quality and chemical composition. West Virginia contains vast expanses of reclaimed surface mine lands that could be used to produce switchgrass as a bioenergy feedstock. This study determined dry matter yields of three switchgrass varieties (Cave-In-Rock, Shawnee, and Carthage) during the second to fourth years of production. Two research sites were established on reclaimed surface mines in southern West Virginia: Hobet and Hampshire. The Hobet site was prepared using crushed, unweathered sandstone as the soil material, and yields were significantly lower at 803 kg ha^{-1} averaged across varieties and years than annual yields at Hampshire. The highest yield at Hobet, with Shawnee in the third year, was 1964 kg ha^{-1}. The Hamphire site, which was reclaimed in the late 1990s using topsoil and treated municipal sludge, averaged 5760 kg ha^{-1} of switchgrass across varieties and years. The highest yield, obtained with Cave-in-Rock during the third year, was 9222 kg ha^{-1}. Switchgrass yields on agricultural lands in this region averaged 12,000 kg ha^{-1}. Although average switchgrass yields at Hampshire were about 50% lower than agricultural lands, they were greater than a target yield of 5000 kg ha^{-1}, a threshold for economically feasible production. Yields during the fourth year from a two-harvest per year system were not significantly different from a single, end-of-year harvest at both sites. Reclaimed lands show promise for growing bioenergy crops such as switchgrass on areas where topsoil materials are replaced and amended like that at the Hampshire site.

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Changes in energy usage from fossil fuels (oil, coal, and gas) to biomass (recent plant-based organic materials) has gained considerable interest with climate change legislative mandates, rising oil prices, and world market uncertainty (Ragauskas et al., 2006; Tilman et al., 2009). This change in the use of petroleum products, which make up 94% of consumed transportation fuel in the United States (U.S. Energy Information Administration, 2011b), and the increased environmental and political concerns associated with fossil fuels have sparked abundant research in the development of bioenergy and the need for reliable feedstocks (McLaughlin et al., 2002).

In 2010, biomass-based fuels provided about 4% of the energy in the United States, with 43% of that being transportation biofuels (U.S. Energy Information Administration, 2011a). The majority of the United States' current biofuel demands for bioenergy are met by conversion of corn grain (*Zea mays* L.) to ethanol, but concerns associated with world food demands, use of quality farm land to produce fuel rather than food, and energy and carbon balance of bioenergy production have led researchers to examine other biofuel feedstock options (Somerville et al., 2010). Many perennial herbaceous plants have been evaluated as sources of cellulose to be converted to biofuel (Lewandowski et al., 2003; Lemus and Parrish, 2009). Perennial herbaceous plants can also be used to produce *biopower*, a term sometimes used to describe heat or electricity produced from burning biomass (Parrish et al., 2008).

Switchgrass (*Panicum virgatum* L.), a tall, warm-season perennial grass native to North America and commonly used as a conservation and forage species, has been investigated extensively as a source of bioenergy feedstock (Parrish and Fike, 2005). An assessment of several herbaceous feedstocks initiated in the 1980s led to selection of switchgrass as a "model" bioenergy feedstock (Lynd et al., 1991; Sanderson et al., 1996; McLaughlin and Walsh, 1998; McLaughlin and Kszoz, 2005; Wright and Turhollow, 2010). It is considered the model feedstock of herbaceous energy crops because of its high productivity, widespread geographic range, ability to grow under a wide variety of soil types and environmental conditions, and low water and nutrient requirements (Wullschleger et al., 2010; Shield et al., 2012).

Switchgrass can grow up to 3 m in height and forms dense sods over time. It is adapted to the tall grass prairie, and native

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Abbreviations: DM, dry matter; EC, electrical conductivity; PLS, pure live seed; SMCRA, Surface Mining Control and Reclamation Act.

stands are most abundant east of 100°W longitude, north to Nova Scotia and Ontario, and south to Mexico (Hitchcock, 1971; Vogel, 2004). Varieties or cultivars of switchgrass fall into two distinct ecotypes: upland and lowland (Casler, 2005). Lowland ecotypes are found on areas prone to flooding, and upland ecotypes typically favor drier soils and more semiarid climates. Lowland ecotypes are typically more fibrous and taller than upland (Vogel, 2004). In general, switchgrass tolerates low fertility, persists in acid to moderately alkaline soils, and is tolerant of drought and heat (Parrish et al., 2008).

Growing hardy perennial herbaceous energy crops such as switchgrass compared with annual energy crops such as corn offers environmental benefits, including (i) reduced erosion and runoff, which reduces loss of nutrients and organic matter from the soil; (ii) increased incorporation of soil carbon with perennial root systems, which improves soil properties; and (iii) reduced use of agricultural chemicals such as herbicides and pesticides (McLaughlin and Walsh, 1998).

Along with providing environmental benefits, switchgrass can produce high yields across a range of growing environments. A 3-yr study conducted by Fike et al. (2006a) showed yields of 14,100 kg dry matter (DM) ha^{-1} averaged across four cultivars from eight sites in five southeastern states. Similarly, yields as high as 14,900 kg DM ha^{-1} were reported from three midwestern states (Vogel and Masters, 1998). Annual switchgrass DM yields of over 22,400 kg ha^{-1} have also been reported west of the Rocky Mountains on irrigated research plots in Washington (Fransen, 2009).

Switchgrass is also capable of producing high yields from stands that have been in place for long time periods. Yields from 6- through 9-yr-old stands in mid-Atlantic states averaged 14,200 kg ha^{-1} (Fike et al., 2006b). In a 10-yr study with field sites in 13 states, average yields of the three best commercial cultivars were 12,000 to 19,000 and 11,600 to 15,500 kg ha^{-1} for Alamo and Kanlow cultivars, respectively, and 13,500 to 18,600 kg ha^{-1} for the cultivar Cave-in-Rock (McLaughlin and Kszoz, 2005). In research plots, switchgrass produced 22,000 to 33,000 kg ha^{-1}, but on a commercial scale 11,000 to 22,000 kg ha^{-1} seems to be a more reasonable expectation (Lemus and Parrish, 2009; Monti et al., 2009).

Switchgrass can be successfully grown as a bioenergy feedstock under normal agronomic conditions (Sanderson et al., 1996; Lemus et al., 2002; McLaughlin and Kszoz, 2005; Fike et al., 2006a, 2006b; Fransen, 2009), but using agricultural cropland for biomass production for biofuel has raised controversy. With a world population now over 7 billion (Population Reference Bureau, 2012) and malnutrition affecting nearly 800 million people (World Health Organization, 2012), growing biofuel crops instead of food on prime agricultural land may constitute a moral issue. As bioenergy production gains popularity through policymakers and as the biofuel industry expands, more agricultural land may be used for bioenergy production, which will then increase demand and costs of food (Chakravorty et al., 2009). A key barrier to the success of energy production from biomass, beside costs and conversion processes, is feedstock availability, which includes competition for arable land with food and fiber production (International Energy Agency, 2007). Producing biomass feedstock on nonprime agricultural land could benefit the bioenergy industry.

One potential solution is the use of marginal land rather than agricultural land for bioenergy crop production. Switchgrass grown on marginal land (Conservation Reserve Program land) in South Dakota yielded about 40% less DM compared with agricultural lands (Mulkey et al., 2006). Schmer et al. (2008) found switchgrass yields of 5200 to 11,100 kg ha^{-1} on 10 farms of marginal cropland in the midwestern United States. Skousen and Venable (2008) established switchgrass along newly constructed highways in West Virginia, where it achieved good cover and soil stabilization after 2 yr. Balasko et al. (1984) grew productive stands for 3 yr in West Virginia with no amendments on what was considered marginal crop land, with average yields ranging from 6600 to 8900 kg ha^{-1}.

Extensive coal mining in West Virginia produces large expanses of reclaimed surface mines. To encourage proper reclamation practices, the Surface Mining Control and Reclamation Act of 1977 (SMCRA) requires mine operators to post sufficient bonds to cover the complete cost of reclamation should a mining operation fail to properly reclaim the land. The SMCRA also requires mine operators to specify how land will be used after reclamation. Bonds are only released to the mine operator when the land is properly reclaimed and used for the specified land use. To meet regulatory reclamation standards, mine operators commonly apply topsoil and soil amendments (fertilizer, lime, and mulch) to grow cool-season grasses and legumes, which establish quickly and aggressively for ground cover and erosion control. However, mine soils in Appalachia are rocky and often infertile, with low levels of nitrogen, phosphorus, and organic matter (Shukla et al., 2004; Skousen et al., 1998), which causes many people to categorize these reclaimed soils as marginal land (Akala and Lal, 2001). These reclaimed pastures are often underused or unused, and forage yield declines over time without management. Using switchgrass for biofuel feedstock production as a postmining land use could be of economic value to West Virginia landowners due to the many acres of marginal reclaimed land available for bioenergy crop production and the proximity of these areas to US energy markets. Large expanses of older reclaimed areas with low-producing, cool-season forages could be converted to switchgrass for enhanced economic opportunities for landowners. Developing an alternative postmining land use such as bioenergy production with switchgrass would meet reclamation standards and provide economic incentives to landowners.

In amended mine soil collected from a surface mine in Pennsylvania, Dere et al. (2011) found switchgrass DM yields of 4000 to 5000 kg ha^{-1} when compost was added. Skousen and Call (1987) found DM yields of 24,000 kg ha^{-1} with Alamo switchgrass after the third year on Texas lignite mine soils. As a postmining land use in West Virginia, target yields of switchgrass on reclaimed surface mined land should reach 5000 kg ha^{-1} to be economically feasible (Ken Ellison, personal communication, WV Department of Environmental Protection, Charleston, WV).

Switchgrass is relatively slow to establish after planting. It typically reaches only 33 to 66% of its production capacity during the first and second years of production (McLaughlin and Kszoz, 2005). Two common problems that contribute to slow switchgrass establishment are seed quality and weed competition (Vogel, 2004; Schmer et al., 2006). Switchgrass seeds are very small compared with seeds of annual grain crops, and therefore switchgrass seeds have little reserves for germination and initial growth. Planting seeds of good quality and with a high percentage of germinable seeds is important when establishing stands. Wolf and Fiske (1995) recommend seeding rates of 8.9 to 11.2 kg pure live seed (PLS) ha^{-1}, whereas Teel and Barnhart (2003) recommend slightly lower rates of 5.6 to 6.7 kg PLS ha^{-1}. Seedbeds should be firm, and seeds should be planted at a depth of 0.6 to 1.2 cm to ensure good soil to seed contact (Wolf and Fiske, 1995; Teel and Barnhart, 2003; Parrish et al., 2008). Germination occurs best when soils are warm (>15°C). Nitrogen applications are not commonly recommended at planting because fertilizer enhances weed competition on agricultural land. Coarse-textured and low-fertility mine soils are typically considered to have poor physical and chemical soil properties for plant growth, and slower establishment and growth may be expected on mine soils (Skousen and Zipper, 2009). To successfully establish switchgrass stands on reclaimed mine soils, using seed with a high germination rate and minimizing weed competition is important.

As a biomass feedstock, maximizing switchgrass yields while maintaining long-term stands with few inputs is desirable. Switchgrass has the potential to be harvested several times during the growing season or can be harvested once at the end of the season. Maximum yields of 10,500 to 12,600 kg ha^{-1} were recorded in the midwestern United States when the variety Cave-in-Rock was harvested once per growing season during anthesis (pollen-shedding) (Vogel, 2004). Conversely, Fike et al. (2006b) found that yields increased with a two-harvest per year management system compared with a single-harvest system when data were averaged across eight switchgrass sites in five midwestern states. They also showed that two upland cultivars used in the study (Cave-in-Rock and Shelter) had a 38% increase in yield when harvested twice per year. Vogel et al. (2002) found that the optimal time to harvest switchgrass for maximum biomass production in the midwestern United States was during the reproductive stage at the R3 to R5 stage of maturity (panicles fully emerged to postanthesis) (Moore et al., 1991), and sufficient regrowth may be obtained for a second harvest after a killing frost.

Once established, switchgrass can have productive stands for up to 10 yr, but multiple harvests per year may decrease stand longevity. Harvesting only once at the end of the growing season preserves carbohydrate reserves used for tiller production the following growing season (Casler and Boe, 2003). Late in the growing season, N is remobilized from the aboveground biomass to the stem bases, crowns, or roots of switchgrass plants harvested after a killing frost (Vogel et al., 2002). Switchgrass establishment and management, as well as long-term production potential, on reclaimed surface mines are important considerations for mine operators interested in biofuel production as a postmining land use.

The objectives of this study were to determine establishment methods with three switchgrass cultivars and harvest management effects on switchgrass yields on reclaimed surface mines in West Virginia. Results of the first 2 yr of research showed that switchgrass was successfully established with hand-broadcast seeding and by hydroseeding techniques (Keene and Skousen, 2010). This paper reports on yields of three switchgrass varieties during the second through fourth years after planting. Study sites were at two surface mines in West Virginia that were reclaimed and managed differently. These two sites represented opposite ends of the reclamation spectrum; one site had topsoil and organic amendments applied, and the other site had no topsoil and no amendments. Yields from one- and two-harvest per year systems were compared during the fourth year. Soil chemical and physical properties on these sites were determined to examine relationships with production on these sites.

Materials and Methods

Site Locations

Switchgrass plantings were established in 2008 at two mine sites in West Virginia (Fig. 1). The Hobet site (38°03′50.29″N, 81°58′12.39″W), located on a large surface mine in Boone County operated by Hobet Mining Company, was reclaimed in 2007 with a 1-m-thick layer of crushed, unweathered rock material overlaying compacted overburden material. The Hampshire site (39°26′07.36″N, 79°03′37.53″W) is located on a small contour mine in Mineral County. Mining ceased in 1998, and the site was reclaimed by overlaying the backfilled area with 30 cm of topsoil. Lime-treated municipal sludge from the Westernport, Maryland municipal wastewater treatment facility was placed over the topsoil at a rate of 225 Mg (dry) ha^{-1} (Keene and Skousen, 2010). Additional treatments of sludge from the wastewater treatment facility were applied at a similar rate in 2003 and again in 2008 before planting.

Experimental Design and Analyses

The experimental design included three cultivars of switchgrass harvested once at the end of the growing season during the second through fourth year after planting. One- and two-harvest systems were implemented after the fourth season only. In 2008, nine 0.4-ha plots were established, and three varieties of switchgrass (Cave-in-Rock, Carthage, and Shawnee) were randomly assigned to plots in three replications at both sites. Plots were seeded with the specified switchgrass variety at a rate of 11.2 kg PLS ha^{-1}. Seeds of each variety were purchased from Ernst Conservation Seeds, and seeding was done using a hand-broadcast seeder (Keene and Skousen, 2010). At the Hampshire site, glyphosate herbicide was

Fig. 1. Location of Hobet and Hampshire research sites in West Virginia.

applied to kill all existing vegetation in April 2008. No vegetation existed at Hobet since the site was newly reclaimed. Seeding was accomplished the first week of June 2008.

Yield (aboveground biomass) was determined by randomly selecting six locations within each plot and clipping all switchgrass in a 0.21-m^2 quadrat at a stubble height of 10 cm during the last week of September. In a review of switchgrass research trials (Parrish and Fike, 2005), clipping heights from 5 to 30 cm were used to determine yield. The review concluded that (i) more biomass was collected when clipped to a lower stubble height, (ii) more regrowth occurred during multiple-harvest systems when earlier clippings were at higher stubble height, and (iii) clipping at a higher stubble height (>10 cm) typically resulted in better stand persistence. For this study, switchgrass within the 0.21-m^2 quadrat was clipped at 10 cm with the goal of collecting the maximum amount of biomass without lessening stand persistence. Clipped samples were oven dried at 60°C to constant weight to determine DM yield.

Yield data from 2009 through 2011 were analyzed using a mixed model, repeated measures factorial ANOVA of SAS (SAS Institute, 2008) with years as repeated measures and main effects of year, variety, site, and interactions. Statistical significance was based on a p value of 0.05. Four possibilities were explored for the covariance structure of the mixed model procedure: compound symmetry, unstructured, autoregressive, and Toeplitz. The unstructured covariance best fit the data and was therefore selected for the model. Yield data analysis used square root–transformed data to meet the assumption of normally distributed data. Data were transformed according to the Box-Cox method (Faraway, 2004). Means and standard deviations were transformed back to yields in kg DM ha^{-1}.

During the fourth year of production (2011), biomass was clipped at two time points to represent single-harvest and two-harvest management systems. Switchgrass was clipped in 0.21-m^2 quadrats from six randomly selected points within each plot on 19 July at Hobet and 20 July at Hampshire. Plants at Hobet had flowers just beginning to emerge (R0 to R1 reproductive stage) (Moore et al., 1991), whereas plants at Hampshire were at stem elongation (E3 to RO). At the end of the growing season (late September, which coincided with previous year's single-harvest clippings), regrowth was clipped from the same points within 0.21-m^2 quadrats. Total yield for the two-harvest system was determined by combining the oven-dried weights of both biomass samples. Single-harvest system samples were collected at the end of the growing season only (postanthesis). Single- and two-harvest system clipping locations were within 3 m of each other.

Yield data for harvest system were analyzed using a mixed model, factorial ANOVA of SAS (SAS Institute, 2008). Independent variables used for this analysis were site, variety, and harvest system. Statistical significance was based on a p value of 0.05. Data were square root–transformed to satisfy the assumption of a normal distribution required for the analysis. Yields were compared among single-harvest, total of two harvests, July only, and regrowth (October) only.

Soil Sampling and Analysis

Soil samples were collected at both sites from six randomly selected points where clippings were taken and analyzed separately for soil chemical and physical properties. Soil samples were collected to a depth of 15 cm. Samples were air dried, weighed, and wet-sieved with a 2-mm sieve. The fine fraction (Fines, <2 mm) was used for chemical analysis. The rock fraction (>2 mm) was collected, dried, and weighed to determine the percentage of rock fragments.

Using the Fines of each sample, pH, electrical conductivity (EC), and available nutrients were determined. For pH, 5 g of soil were combined with 5 mL of distilled deionized water, shaken for 15 min, and equilibrated for 1 h, after which pH was determined (Mettler Toledo SevenEasy pH Meter). Electrical conductivity was determined by combining 5 g of soil with 10 mL distilled deionized water, shaken for 15 min, and equilibrated for 1 h, after which EC was determined (Amber Science Inc. Digital Conductivity Meter).

Mehlich 1 solution, also referred to as Dilute Double Acid solution (0.0025 mol L^{-1} H_2SO_4 + 0.05 mol L^{-1} HCl), was used to extract available elements from the soil (Wolf and Beegle, 1995). For the extraction, 25 mL of Mehlich 1 solution was added to 5 g of soil, shaken for 5 min, and allowed to equilibrate for 1 h. Samples were filtered through Whatman no. 2 filter paper. The filtrates were analyzed for available nutrients (Al, Fe, Mn, Mg, Ca, K, P, Ni, Cu, and Zn) using an optical emission spectrometer (PerkinElmer Optima 2100 DV).

Soil chemical and physical data were analyzed using a mixed-model, repeated measures factorial ANOVA of SAS (SAS Institute, 2008) with years as repeated measures. Because only a few significant differences were found for chemical properties across years within sites, only data from the first and fourth years are reported. However, significant differences were found for many properties between sites.

Results and Discussion

Soil Physical and Chemical Properties

Hampshire had significantly higher (p < 0.05) Fines (76%) than Hobet (55%) (Table 1), which confirms the use of some

Table 1. Values for selected soil physical and chemical characteristics at Hobet and Hampshire sites.

Parameter†	Hobet		Hampshire		Significance between sites
	2008	2011	2008	2011	
Fines, %	55 (8)‡	55 (5)	77 (8)	74 (7)	*
pH, su	7.7	8.0	7.2	7.4	*
EC, μS cm^{-1}	187a§ (118.0)	109b (15.3)	1245a (378.5)	421b (73.2)	*

* Means between sites significant at the 0.05 probability level.

† EC, electrical conductivity; Fines, fine fraction (<2 mm).

‡ Values are averages with SD in parentheses.

§ Means with different letters across years for each parameter within sites are significantly different at p < 0.05. Means with no letters are not significantly different.

Table 2. Values of extractable soil nutrients using Mehlich 1 solution at Hobet and Hampshire.

Parameter	Hobet 2008	Hobet 2011	Hampshire 2008	Hampshire 2011	Significance between sites
	——— cmol charge kg^{-1} soil ———				
Mg	1.4 (0.3)†	1.3 (0.2)	1.7 (0.2)	1.3 (0.1)	NS‡
K	0.1 (0.02)	0.1 (0.60)	0.3 (0.05)	0.2 (0.05)	*
Na	0.05 (0.04)	0.03 (0.01)	0.4 (0.10)	0.03 (0.01)	NS
Ca	3.1 (2.4)	2.0 (1.1)	30.7 (6.3)	22.7 (5.3)	*
	——— mg kg^{-1} soil ———				
Al	59a§ (36.5)	31b (5.5)	104 (83.8)	98 (57.9)	*
Fe	123a (50.0)	52b (14.0)	59a (72.4)	22b (25.1)	*
Mn	46 (14.5)	29 (8.1)	173a (51.3)	49b (11.9)	NS
P	53 (19.4)	50 (13.1)	5 (2.2)	8 (4.5)	*
Ni	1.3 (0.6)	0.9 (0.3)	0.4 (0.4)	0.4 (0.1)	NS
Cu	2.3 (1.0)	1.9 (0.6)	2.7 (2.5)	1.4 (1.3)	NS
Zn	2.7 (0.9)	2.4 (0.5)	8.6 (5.5)	6.7 (2.7)	*

* Means between sites are significantly different at $p < 0.05$.

† Values are averages with SD in parentheses.

‡ Not significant.

§ Means with different letters across years for each parameter within sites are significantly different at $p < 0.05$. Means with no letters are not significantly different.

topsoil placement at Hampshire. The low Fines and high rock fragment contents (material >2 mm in size) at Hobet are typical for mine soils in West Virginia where no topsoil is applied (Skousen et al., 1998; Haering et al., 2004; Emerson et al., 2009). Both sites consistently had a pH slightly above neutral, and Hampshire consistently had a higher EC compared with Hobet, which was due to multiple applications of lime-treated municipal sewage sludge before planting. Electrical conductivity decreased between 2008 and 2011 at both sites due to leaching of salts over time.

Concentrations of available nutrients (Table 2) revealed that Hampshire had significantly higher ($p < 0.05$) K and Ca levels compared with Hobet, which were due to treatments of lime-treated municipal sewage sludge. However, extractable P at Hobet was significantly higher ($p < 0.05$) than Hampshire, which is a common finding on unweathered mine soils like Hobet. Emerson et al. (2009) showed that P was higher in alkaline sandstones than weathered soils using Mehlich 1 extractions, but Skousen and Emerson (2010) found that this extra P was not available to plants. Aluminum, Fe, and Zn were also significantly different ($p < 0.05$) between sites. Between 2008 and 2011, Al and Fe concentrations declined at Hobet, and Fe and Mn decreased at Hampshire. Decreases in these elements could have been due to the high pH of these soils and binding of these elements with carbonates (Havlin et al., 1999).

Switchgrass Yields

Average yields were significantly higher at Hampshire (5760 kg ha^{-1}) than at Hobet (803 kg ha^{-1}) across 3 yr (Table 3). The average yield at Hampshire surpassed the target goal of 5000 kg ha^{-1} established by the WV Department of Environmental Protection in 2010. The application of topsoil and lime-treated sludge as well as the additional years of soil development at Hampshire provided a better soil medium for switchgrass compared with the unweathered and unamended overburden material at Hobet. Yields at Hampshire were likely increased due to greater Fines, a slightly lower pH, and higher levels of K and Ca compared with Hobet.

Site × variety interactions showed that Shawnee produced significantly higher ($p < 0.05$) yields than Cave-in-Rock and Carthage at Hobet, and Cave-in-Rock produced significantly

Table 3. Mean switchgrass yields, standard deviations of the means, and significance of main effects of site, variety, year, and interactions.

Effect	Significance†	Mean yield
		kg ha^{-1}
Site	<0.0001	
Hobet		803b‡ (734)
Hampshire		5760a (2389)
Variety	0.002	
Cave-in-Rock		4298a (3853)
Carthage		2479b (2460)
Shawnee		3069a (2520)
Year	<0.0001	
2009		2359c (2472)
2010		4457a (3511)
2011		3029b (2363)
Site × variety	<0.0001	
Hobet		
Cave-in-Rock		743d (751)
Carthage		581d (419)
Shawnee		1086c (930)
Hampshire		
Cave-in-Rock		7853a (1594)
Carthage		4376b (2141)
Shawnee		5051b (1945)
Variety × year	NS§ (0.56)	
Site × year	NS (0.17)	
Site × variety × year	NS (0.27)	

† Mean contrasts were based on square root–transformed data.

‡ Values are means with SD in parentheses. Different letters for average yield for effects are significant at specified levels.

§ Not significant.

higher ($p < 0.05$) yields than the other varieties at Hampshire (Table 3). Carthage had significantly lower ($p < 0.05$) yields at both sites. The three upland varieties used in this study are common and commercially available, but Cave-in-Rock produced the highest yield at the more fertile Hampshire site. Shawnee, an improved forage variety selected from Cave-in-Rock, outperformed the other varieties at the less fertile and coarser-textured Hobet site. Cave-in-Rock is an Illinois upland ecotype that has been grown widely in the midwestern and northeastern United States with good biomass production (Lemus et al., 2002). Shawnee was selected from Cave-in-Rock and is purported to have better biomass production and forage quality. Carthage is an upland ecotype selected from North Carolina and is known for a more leafy growth habit with high nutrient value (Casler, 2005). Sanderson (2008) found Cave-in-Rock and Shawnee varieties to be superior for hay yields on agricultural lands in the northeastern United States.

Year had a significant effect on yield, with the third year (2010) of production being significantly higher ($p < 0.05$) than the second and fourth years across site and variety (Table 3). We expected the yield to continue to increase with time as switchgrass became better established on the sites, as it did from 2009 to 2010. However, average yield declined between 2010 and 2011, and this decline was due to a decrease in yield with all three varieties at Hampshire (Table 4). Yields at Hobet for Cave-in-Rock and Carthage slightly increased from 2010 to 2011, but they decreased by half for Shawnee. Kering et al. (2011) found no yield decline with switchgrass from the second to third year of production and reported that a decline in yield was not expected unless hindered by a natural phenomenon such as climate.

Precipitation and temperature records were checked for the two sites. No abnormal weather conditions occurred during 2011 that should have hindered growth (Marra, 2012). Precipitation during the years 2009 through 2011 at the Hamlin, West Virginia weather station near Hobet was within 15% of the average 112 cm per year. Similarly, the weather station at Keyser, West Virginia near Hampshire showed precipitation to be within 20% of the 120 cm yr^{-1} average. Temperatures were also near normal at both sites (average annual temperatures: 13°C at Hobert and 12°C at Hampshire).

At Hampshire, one reason for the decline may have been due to cutting the aboveground biomass with a rotary mower in the spring of 2011 and leaving the debris on the surface. The large amount of debris of up to 10 cm thick lying on the surface may have blocked regrowth of switchgrass in 2011. If this material had been removed from the site as in a conventional haying operation, the heavy cover of debris and dead material on the surface would have had a lesser effect on regrowth of switchgrass at Hampshire.

Table 4. Interaction means (site × variety × year) for switchgrass yields.

Year and variety	Site: Hobet	Site: Hampshire	Average
	kg ha^{-1}		
2009			
Cave-in-Rock	72	6478	3275
Carthage	125	3592	1859
Shawnee	452	3436	1944
2010			
Cave-in-Rock	1058	9222	5140
Carthage	720	6560	3640
Shawnee	1964	7221	4592
2011			
Cave-in-Rock	1099	7860	4479
Carthage	897	2978	1938
Shawnee	842	4497	2669

Yields for other interactions (variety × year, site × year, and site × variety × year) were not found to be significant. Although the site × variety × year interaction was not significant (Table 3), the means of this interaction are worth reporting because of the trends they provide for interpretation (Table 4). At Hobet, all varieties increased yield from 2009 to 2010 from 5 to 15 times (Table 4). From 2010 to 2011, Cave-in-Rock and Carthage yields only slightly increased, but Shawnee yield decreased by 57%. After the second growing season (2009) at Hampshire, substantial yields of 3436 to 6478 kg ha^{-1} were achieved. Increases in yield from 2009 to 2010 varied between 1.4 to 2 times with Cave-in-Rock, which produced the highest yield of 9222 kg ha^{-1}. However, from 2010 to 2011, yields decreased by 15% for Cave-in-Rock and 40 to 55% for the other two varieties. Declines in yield at Hampshire were attributed to cutting and leaving the aboveground biomass on the site, but further monitoring of yield in 2012 and thereafter will determine stand longevity and yields on this site.

Yields for one-harvest (yield taken once only at the end of the growing season), two-harvest (total yield combining first and second harvests), and July-only harvest systems were not significantly different (Table 5). The only significant difference was found when comparing the yield obtained from the regrowth in the two-harvest system with the others. The first harvest taken in July produced the majority of the two-harvest system total yield, and the second harvest of the year added less than 20% of the total yield. This finding was consistent at both sites (interaction of site × harvest system). Yields for site and variety were significant main effects (Table 3).

Table 5. Mean switchgrass yields and significance of effects of harvest system and site × harvest system interactions in 2011.

Effect	Significance†	Yield
		kg ha^{-1}
Harvest system	<0.0001	
One-harvest		3029a‡ (2863)
Two-harvest total		2922a (3162)
July-only harvest		2504a (2746)
Regrowth-only harvest		419b (499)
Site × harvest system	0.04	
Hobet		
One-harvest		946b (597)
Two-harvest total		631b (331)
July-only harvest		528b (324)
Regrowth-only harvest		103c (42)
Hampshire		
One-harvest		5112a (2703)
Two-harvest total		5213a (3053)
July-only harvest		4479a (2670)
Regrowth-only harvest		734b (552)

† Mean contrasts were based on square root transformed data.

‡ Values are means with SD in parentheses. Different letters for average yield for effects are significant at specified levels.

Comparing the means of the site × harvest interactions, the two-harvest system at the more fertile Hampshire site resulted in a slightly greater total yield (<5%) than the one-harvest system. Fike et al. (2006b) found a 30% increase in yield with a multiple-harvest system on agricultural lands in midwestern states. At the less fertile and more coarse-textured Hobet mine site, total yields decreased with the two-harvest system.

Interaction means for site × variety × harvest system are reported in Table 6. At Hobet for all three varieties, harvesting only once at the end of the year (one-harvest system) produced the most yield, and yield was reduced by 28 to 38% by harvesting twice (two-harvest system) (Table 6). At Hampshire, yield was increased by about 10% for Cave-in-Rock and Shawnee with the two-harvest system but not for Carthage. Similar to the results found at Hobet, less than 20% of the total yield was collected at the second harvest of the two-harvest system, with about 80% being produced by the first harvest in mid-July.

At the more fertile Hampshire site, the two-harvest system resulted in greater total yields than the one-harvest system. At the less fertile and more coarse-textured Hobet mine site, total yields decreased with the two-harvest system. This finding may suggest that on reclaimed sites with limited soil productivity like Hobet, a multiple-harvest system will not give greater yields for switchgrass. Even on sites where greater yield was achieved by harvesting twice, the increase of yield by only 10 to 20% probably would not justify the additional costs of a second harvest.

Conclusion

Based on findings from this study and previous research, switchgrass is capable of producing economically feasible yields on marginal agricultural land and reclaimed surface mines. The Hamphire site, which was reclaimed with topsoil and municipal sludge, produced 5760 kg DM ha^{-1} averaged across variety and years. During the third year after planting, Cave-in-Rock yielded 9222 kg DM ha^{-1}. The Hobet site, with only unweathered sandstone as the soil material, yielded significantly less at 803 kg DM ha^{-1} averaged across variety and years. The highest yield at Hobet was during the third year after planting, with Shawnee at 1964 kg DM ha^{-1}. Switchgrass yields at Hampshire achieved the target yield of more than 5000 kg ha^{-1}. During the fourth year at both sites, a two-harvest per year system was not significantly different from a single, end-of-year harvest. Cave-in-Rock and Shawnee were the best performers on mine sites in this area. Continued monitoring will determine stand persistence and yield on these surface mines and will reveal whether decreases in yield from 2010 to 2011 will be repeated in 2012 and beyond.

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Table 6. Interaction means for switchgrass yields of one- and two-harvest systems by variety at Hobet and Hampshire in 2011

Site and variety	Harvest system			
	First harvest	Second harvest†	Total two-harvest system	Total one-harvest system
	kg DM ha^{-1}			
Hobet				
Cave-in-Rock	592	85	677	1094
Carthage	494	108	602	893
Shawnee	490	115	605	838
Hampshire				
Cave-in-Rock	7227	1219	8446	7822
Carthage	1869	374	2243	2964
Shawnee	4278	599	4877	4476

† Mean yields for the second harvest were significantly lower than first harvest, total two-harvest, and total one-harvest systems at both sites and with all cultivars.

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