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Switchgrass Biofuel Production on Reclaimed Surface Mines: I. Soil Quality and Dry Matter Yield

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Abstract Growing food crops for biofuel on productive agricultural lands may become less viable as requirements to feed a growing human population increase. This has increased interest in growing cellulosic biofuel feedstocks on marginal lands. Switchgrass (*Panicum virgatum* L.), a warm-season perennial, is a viable bioenergy crop candidate because it produces high yields on marginal lands under low fertility conditions. In other studies, switchgrass dry matter (DM) yields on marginal croplands varied from 5.0 to 10.0 Mg ha^{-1} annually. West Virginia contains immense areas of reclaimed surface mined lands that could support a switchgrass-based biofuel industry, but yield data on these lands are lacking. Field experiments were established in 2008 to determine yields of three switchgrass cultivars on two West Virginia mine sites. One site reclaimed with topsoil and municipal sludge produced biomass yields of 19.0 Mg DM ha^{-1} for Cave-in-Rock switchgrass after the sixth year, almost double the varieties Shawnee and Carthage, at 10.0 and 5.7 Mg ha^{-1}, respectively. Switchgrass yields on another site with no topsoil were 1.0 Mg ha^{-1} after the sixth year, with little variation among cultivars. A second experiment was conducted at two other mine sites with a layer of topsoil over gray overburden. Cave-in-Rock was seeded with fertilizer applications of 0, 34, and 68 kg N-P_2O_5-K_2O ha^{-1}. After the third year, the no fertilizer treatment averaged biomass yields of 0.3 Mg ha^{-1}, while responses to the other two rates averaged 1.1 and 2.0 Mg ha^{-1}, respectively. Fertilization significantly increased yields on reclaimed mine soils. Where mine soil fertility was good, yields were similar to those reported on agricultural soils in the Northeastern USA.

Keywords Biomass · Carthage · Cave-in-Rock · Harvest management · Revegetation · Shawnee · Switchgrass fertilization

Abbreviations

ANOVA	Analysis of variance
DM	Dry matter
EC	Electrical conductivity
WV	West Virginia

Introduction

Switchgrass was chosen as a "model" bioenergy crop because of its ability to grow at commercial scales as a potentially profitable agricultural system [30]. Initially, the main attraction to switchgrass as a bioenergy crop was its ability to grow in many different soil types and climates throughout the USA [15]. As a warm-season (C4) species, it can grow in warmer and drier climates than cool-season species. This grass is known as a bunchgrass, but it has short rhizomes which allows it to form a sod over time [15]. It is a long-shooted species and can grow up to 3 m in height [32]. Cultivars are classified into lowland and upland phenotypic groups, with both groups growing well throughout the switchgrass adaptation zone [33]. Lowland ecotypes tend to be more productive [5, 31], but this advantage decreases with increasing latitude [4]. The ability to grow with low or little fertilizer inputs and less pesticide application provides economic and environmental

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advantages over annual crops that require annual seeding and fertilization [30], and that may provide less winter cover for soil and water conservation. Switchgrass can be harvested using standard agricultural haying equipment so producers can switch readily from traditional haying systems to bioenergy crop production [15].

Research has shown that switchgrass grown in the Midwestern USA can produce high yields when managed as a biofeedstock. Switchgrass grown in Nebraska, North Dakota, and South Dakota had biomass yields ranging from 5.2 to 11.2 Mg ha^{-1} averaged over the third to fifth harvest years [17]. Fike et al. [5] showed yields of 14.2 Mg ha^{-1} for 10-year-old switchgrass stands averaged over treatments and sites within the upper Southeastern USA. Averaged over four cultivars and two management treatments, switchgrass planted in West Virginia yielded approximately 13.8 Mg ha^{-1}, while two sites in Virginia averaged 16.6 Mg ha^{-1} annual production [5]. Three cultivars grown in Pennsylvania and harvested in the fall had an average yield of 7.9 Mg ha^{-1}[1]. In Iowa, 20 switchgrass cultivars yielded an average of 9.0 Mg ha^{-1} over a period of 5 years [10].

Growing switchgrass on reclaimed surface mines in Eastern USA could provide an alternative to growing biofeedstocks on agricultural lands. Surface mining for coal is estimated to affect approximately 4.9 million ha of land across West Virginia, Kentucky, Virginia, and Tennessee [26]. The goals of reclamation for surface-mined lands are to restore the site's pre-disturbance land capability and to develop a profitable and sustainable post-mining land use for owners. A current popular post-mining land use is hay and pasture production from agricultural grasses and legumes, which are relatively inexpensive and reliable to establish and are desired by landowners because they provide income from haying and livestock grazing. This reclamation approach is also desired by coal operators because it provides quick ground cover necessary to meet revegetation regulatory requirements and to obtain release of reclamation surety bonds[22].

Although switchgrass performance has been evaluated on productive USA agricultural land, very little research has been done with switchgrass grown on reclaimed mine areas. Research on switchgrass growth on marginal land may provide evidence of potential switchgrass yields on mined lands. Marginal lands are those with low crop production potential due to inherent soil or climatic limitations or because they are located in areas that are difficult to seed or vulnerable to erosion [6]. Schmer et al. [17] measured annual average biomass yields of 5.2 to 11.1 Mg ha^{-1} of switchgrass when managed as a biomass energy crop on marginal cropland in the northern Great Plains, USA. Even greater yields on marginal lands in Oklahoma were shown by Kering et al. [8], with switchgrass producing 16.0 Mg ha^{-1} during the fifth year of production. Along newly constructed highways in West Virginia with rocky soils, switchgrass achieved good cover and soil stabilization after 2 years, although yields were not measured [21].

Optimizing N application to switchgrass stands has been a focus of research because N is often a limiting nutrient for switchgrass growth [7, 13, 14, 25]. Determining economically optimum N application rates will help switchgrass producers maximize profits with high yields while reducing fertilizer and environmental costs. Unfortunately, there is no consensus on the amount of nutrients, particularly N, to apply to a field for switchgrass growth [8, 16] because the amount varies with soil type and location [7]. The amount of N required by switchgrass is a function of the desired yield, N concentration of the biomass, potential productivity of the site, soil nutrient supply, and management practices [27]. To maintain productive stands under specific harvest systems and soil/site conditions, N additions may be needed at periodic intervals.

Switchgrass is known to use N efficiently because it is a C4 grass and upon senescence at the end of the season and during drought, it transports N from its shoots to roots and rhizomes [16]. Cutting switchgrass too low, which affects carbohydrate storage, and also harvesting two or three times per year will increase the amount of N needed by the plant [16]. Owens et al. [14] showed that switchgrass growth responds better to fertilization when initial soil N is low. Switchgrass N recovery varied between 10 and 30 % [14, 24].

Vogel et al. [27] reported maximum yields of the upland cultivar Cave-in-Rock at 120 kg N ha^{-1} in Nebraska tests, even though higher rates of fertilizer were applied (which included up to 300 kg N ha^{-1} in their trials). Another study in Nebraska with Sunburst, also an upland variety, showed that maximum yields were reached with an N rate of 56 kg ha^{-1} in a test that included 112 kg N ha^{-1} [14]. The critical N rate to reach maximum yield for three different harvests in Illinois ranged from 50 to 165 kg N ha^{-1} [2]. Hong et al. [7] reported a wide yield response to N fertilization across their study from New York to Oklahoma, with location and year having the greatest impacts on yield. All of these reports support the idea that supplemental N requirement is site-specific.

Economically viable switchgrass yields may be achievable with little or no fertilizer input. Without fertilization, one study in Georgia showed 8.6 Mg ha^{-1} of biomass production averaged over the first 4 years of switchgrass growth [9]. Kering et al. [8] showed only an 18 % increase in Alamo production with an N fertilizer rate of 135 kg N ha^{-1} and a potassium (K) rate of 68 kg K_2O ha^{-1} as compared to the no fertilizer control. This indicates that switchgrass grown on marginal lands may benefit from the addition of K along with N. Switchgrass can grow without fertilizer inputs, but it clearly responds positively to fertilizer [12].

Many of these cited studies were conducted in agricultural soils with residual soil N and moderate organic matter levels, and such results might not apply to mine soils which typically have very low residual N amounts and little soil organic matter [3]. Adding fertilizer to mine soils is important because low N concentration in mine soils is most frequently the growth-limiting nutrient for plants [3]. It was shown by Shrestha and Lal [19] that a significant amount of total N is lost during mining activities and in some cases no topsoil is replaced as a growth medium, which contains a large supply of nutrients in organic matter. For soil depths of 0–15 cm, unmined sites had total soil N contents ranging from 1.10 to 2.96 g kg^{-1} while mine soils had total soil N concentrations ranging from 0.54 to 1.10 g kg^{-1}. The latter values are much lower than the total soil N found in unmined areas used for switchgrass growth studies in South Dakota, New York, Oklahoma, and Virginia, which averaged 1.93 g kg^{-1} within the top 15 cm [14]. This study showed that N use efficiency for switchgrass was highest in Virginia soils, which had the lowest total soil N concentrations of 0.84 g kg^{-1}. This further supports that switchgrass will respond well to fertilizer inputs on mine soils or soils with low N content.

Careful fertilizer management will likely reduce the economic investment and prevent pollution of the surrounding environment with nutrients not utilized by switchgrass. Nitrogen that is leached from the soil can cause contamination of groundwater and eutrophication of water systems. To meet the regulatory ground cover standards on surface mines, the best establishment method for switchgrass on mine soils should be determined. Therefore, to reduce economic investment and prevent pollution, evaluating the optimum rate of fertilizer applied to mine soils seeded with switchgrass was one of the aims of this study.

To determine switchgrass growth on reclaimed surface mines, we conducted field-scale experiments and measured biomass yields for switchgrass cultivars in West Virginia. Our objective in experiment 1 was to determine the effect of mine soil quality on the yields of three switchgrass cultivars on two sites. We also determined the effect of N-P-K fertilizer on switchgrass yield on newly reclaimed, coarse-textured mine soils with no topsoil.

The objective of experiment 2 was to determine the best establishment methods and fertilizer rate for switchgrass growth on two reclaimed surface mines in West Virginia that simulated common reclamation practices in the area with topsoiling. Cave-in-Rock was seeded immediately after the sites were backfilled and topsoiled. Three rates of mulch and fertilizer were applied at switchgrass seeding.

Materials and Methods

Site Locations and Management

Experiment 1

This experiment was established in 2008 on two reclaimed surface mine areas in West Virginia. The first site, Hampshire (39.4° N, 79.1° W), is located on a small contour mine in Mineral County, which stopped operations in 1998. The 30-year average annual precipitation at the site is 110 cm, average temperature is 9 °C, and elevation is 680 m. This site utilized smaller mining equipment and trucks, and in 1996 during reclamation, 0.3 m of topsoil was placed over re-graded overburden. In 1998, 2003, and 2008, lime-treated sludge was applied at a rate of 225 dry Mg ha^{-1}. The sludge consisted of municipal sewage waste from the Westernport, MD, municipal wastewater treatment facility and paper mill pulp from the nearby NewPage paper mill. Because of the application of topsoil and sludge, the site had favorable soil properties which greatly enhanced revegetation potential. This site was selected for planting because it represented very favorable reclamation conditions available for establishing switchgrass.

The second site, Hobet (38.1° N, 81.6° W), is located on a large mountaintop surface mine in Boone and Kanawha counties (near Madison, WV) operated by Hobet Mining Company. Average 30-year annual precipitation at this site is 115 cm, average temperature is 13 °C, and elevation is 380 m. This mine utilizes a large dragline for overburden removal in order to reach the coal seam. Overburden was dumped with the dragline bucket and regraded to approximate original contour by large bulldozers after mining. The compacted overburden was covered with 1 m of crushed, unweathered rock material. The heavily compacted overburden material placed as soil was broken up with a large offset disk before planting. This reclamation strategy was selected to simulate unfavorable reclamation conditions where no topsoil was applied and soil fertility was poor.

At each site, nine 0.4-ha plots were laid out in 2008 in a completely randomized design with three replications. Three cultivars of switchgrass (Cave-in-Rock, Carthage, and Shawnee) were randomly assigned to plots and broadcast-seeded at a rate of 11.2 kg pure live seed (PLS) ha^{-1} on 8–10 June 2008 [see 11]. Poor growth at Hobet led to fertilizing subplots within each plot in 2009 and 2013. These subplots were randomly chosen and fertilized with 224 kg ha^{-1} of 19-19-19 (N-P_2O_5-K_2O) to obtain 43 kg ha^{-1} of N, P_2O_5, and K_2O.

Experiment 2

Two newly reclaimed sites in West Virginia were chosen to determine switchgrass establishment with two levels of N-P_2O_5-K_2O fertilization and mulch at planting. The Coal Mac site (37.7° N, 82.0° W) is located on a large mountaintop surface mine in Mingo, Logan, and Boone counties operated by Arch Coal, Inc. The 30-year average annual precipitation at the site is 118 cm, average temperature is 14 °C, and elevation is 550 m. This mining operation utilizes large draglines, shovels, and

Table 1 Selected soil chemical and physical properties at Hampshire and Hobet averaged over 2010–2013, and at Black Castle and Coal Mac averaged over 2011–2013

Property	Hampshire	Hobet	Black Castle	Coal Mac
pH	7.3 a[a]	7.7 b	5.8 x[c]	6.1 x
EC (μS cm^{-1})	648 a	140 b	460 x	96 y
% Fines (%)	78 a	57 b	37 x	42 x
% Sand	42 b	63 a	51 x	60 x
% Silt	47 a	27 b	25 x	28 x
% Clay	11 a	10 a	13 x	12 x

Soil data from Hampshire and Hobet in 2010 and 2011 were previously published in Marra et al. [11]

EC electrical conductivity

[a] Values with different letters for Hampshire and Hobet for each property are different at $p \leq 0.05$

[b] Values with different letters for Black Castle and Coal Mac for each property are different at $p \leq 0.05$

loaders to remove overburden and coal. The experimental area was leveled and reclaimed in 2011 with 0.6 to 0.9 m of topsoil and weathered sandstone mixture that was placed over gray sandstone overburden. The Black Castle site (38.1° N, 81.7° W) is located in Boone County on a large mountaintop surface mine and owned by Alpha Natural Resources. Long-term average annual precipitation at the site is 115 cm, average temperature is 13 °C, and elevation is 540 m. Reclamation was done in 2011 by leveling unweathered overburden and covering it with 0.2 to 0.3 m of topsoil mixed with crushed weathered rock.

Plots at each site were established in a randomized complete block design with five replications. Each block was 0.4 ha and divided into four plots to which four treatments were randomly assigned. Cave-in-Rock was broadcast-seeded at 11.2 kg PLS ha^{-1} on 5 June 2009. Treatments applied at planting were as follows:

1. No fertilizer, light mulch: Control; 1.5 Mg ha^{-1} application of hydromulch (dry wt)
2. Low fertilizer, light mulch: 34 kg N-P_2O_5-K_2O ha^{-1} and 1.5 Mg ha^{-1} application of hydromulch
3. Low fertilizer, heavy mulch: 34 kg N-P_2O_5-K_2O ha^{-1} and 3.0 Mg ha^{-1} application of hydromulch
4. High fertilizer, light mulch: 68 kg N-P_2O_5-K_2O ha^{-1} and 1.5 Mg ha^{-1} application of hydromulch

Surface mining reclamation regulations in West Virginia require a minimum of 68 kg ha^{-1} of N-P_2O_5-K_2O and 1.0 Mg ha^{-1} of mulch be applied during reclamation [28]. Either 340 or 680 kg ha^{-1} of commercial 10-10-10 fertilizer was applied to plots for fertilizer-mulch treatments. Hydromulch was used instead of hay or straw mulch because hydromulch is commonly used with hydroseeding, the preferred method for revegetating surface mines in this region. Hydromulch is a paper-based product that helps to protect the soil and retain soil moisture while seeds are germinating. Our treatment rates were based on the assumptions that switchgrass needed less N fertilizer for establishment than standard cool-season agricultural grasses used for revegetation and that the slow establishment rate of switchgrass would require more mulch to reduce erosion.

Table 2 Values of extractable soil nutrients using Mehlich 1 solution at four sites

Parameter	Hampshire	Hobet	Black Castle	Coal Mac
	cmol charge kg^{-1}			
Mg	0.84 a[a]	0.73 a	0.86 x[b]	0.16 y
K	0.16 a	0.10 a	0.11 x	0.21 x
Na	0.04 a	0.01 a	0.05 x	0.05 x
Ca	7.74 a	1.20 b	1.32 x	0.24 y
	mg kg^{-1}			
Al	67.8 a	22.0 b	29.7 x	11.0 y
Fe	17.4 a	38.8 a	18.6 x	6.2 y
Mn	41.3 a	19.0 a	31.1 x	3.03 y
P	5.2 b	26.4 a	5.7 x	2.1 y
Ni	0.3 a	0.6 a	0.46 x	0.03 y
Cu	1.1 a	1.0 a	0.77 x	0.14 y
Zn	4.4 a	1.4 b	1.1 x	0.13 y

Hampshire and Hobet were averaged over 2010–2013, while Black Castle and Coal Mac were averaged over 2011–2013; soil data from Hampshire and Hobet in 2010 to 2011 were previously published in Marra et al. [11]

[a] Values with different letters for Hampshire and Hobet for each property are different at $p \leq 0.05$

[b] Values with different letters for Black Castle and Coal Mac for each property are different at $p \leq 0.05$

Vegetation Measurement and Analysis

Biomass samples were taken each year during the last week of September at post-anthesis stage. Six sampling points were located in each plot at Hampshire and Hobet, providing 18 subsamples of yield per cultivar-site. At Black Castle and Coal Mac, three sampling points were located in each plot of the five blocks, providing 15 subsamples of yield per treatment at each site. A 0.21-m^2 quadrat was placed on the ground at each randomly selected sampling point, and all switchgrass inside the quadrat was clipped to a 10-cm stubble height. Parrish and Fike [16] suggested in a literature review that a 10-cm stubble height resulted in better stand persistence than clipping at lower heights. Herbage from plants other than switchgrass (such as legumes and weeds) within the quadrat was discarded, which accounted for less than 1 % in most samples. Samples were oven-dried to constant weight at 60 °C to determine dry matter (DM) yield, and average yields were calculated. Biomass was not removed from plots annually other than in random, non-repeating sampling areas. Biomass collected in our plots was composed of current year's growth, with less than 5 % being from previous year's growth. Yield data from 2010 and 2011 (previously published in [11]) were included with 2012 and 2013 yield data to analyze over a 4-year period.

Yields in experiment 1 (Hampshire and Hobet) were analyzed using a mixed-model, repeated-measures analysis of variance (ANOVA) of the Statistical Analysis System [23] with years as repeated measures and effects of site, cultivar, year, and interactions. Sites, cultivars, and years were considered fixed effects, while plot and replication were considered random effects. No data transformations were necessary in experiment 1 because the assumptions of normal distributions for ANOVA were satisfied according to the Shapiro-Wilk normality test [18]. Statistical significance was based on a p value of 0.05. When necessary, Tukey's honestly significant difference (HSD) multiple comparison test was used to separate means among cultivars and years. When comparing yields at Hobet and Hampshire, the fertilized subplots at Hobet were removed from the model because Hampshire had not been subjected to the same treatment. Yields at Hobet were analyzed separately to see if fertilization affected yield under the same significance criterion.

Yields in experiment 2 (Black Castle and Coal Mac) were analyzed using a mixed-model, repeated-measures ANOVA [23] with years as repeated measures and effects of site, treatment, year, and interactions. Sites, treatments, and years were considered fixed effects, while blocks and replications were considered random effects. Data in experiment 2 were log-transformed to satisfy the assumptions of normal distributions for ANOVA according to the Shapiro-Wilk normality test [18]. Untransformed means are shown in the table and figure for this experiment. Statistical significance was based on a p value of 0.05, and Tukey's HSD test was used to separate means among treatments and years.

Table 3 Mean switchgrass yields and significance of main effects of site, cultivar, and year

Effect	Significance	Yield[a]
		Mg ha^{-1}
Site	<0.01	
Hampshire		8.4 a[a]
Hobet		1.0 b
Cultivar	<0.01	
Carthage		2.8 c
Cave-in-Rock		7.0a
Shawnee		4.3b
Year	<0.01	
2010[b]		4.2bc
2011		3.0c
2012		5.0ab
2013		6.5a

Interactions were significant for cultivar × site ($p < 0.01$) and site × year ($p < 0.01$)

[a] Data from Hampshire and Hobet in 2010 to 2011 were previously published in Marra et al. [11]

[b] Different letters for each main effect denote difference at $p \leq 0.05$ according to ANOVA or Tukey's HSD

Soil Sampling and Analysis

Soil samples were collected at each sampling point as shallow shovel slices to approximately 15-cm depth at all sites annually and analyzed for percent fines, pH, electrical conductivity (EC), and available elements specified later. At Hampshire, two samples per plot were obtained: Three subsamples were composited from each pair of three biomass sampling points.

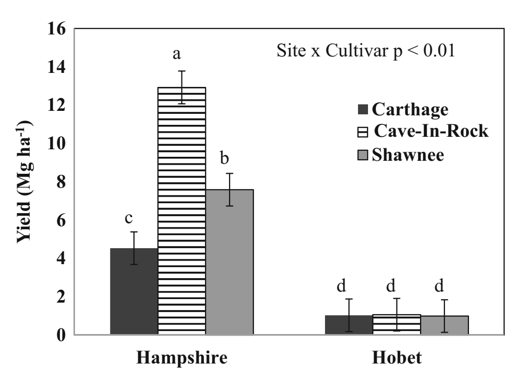


Fig. 1 Yield of switchgrass cultivars at each site averaged over years (2010–2013). *Vertical bars* represent standard errors. *Different letters* on *bars* denote difference at $p \leq 0.05$ according to Tukey's HSD. Yield data in 2010 to 2011 were previously published in Marra et al. (2013)

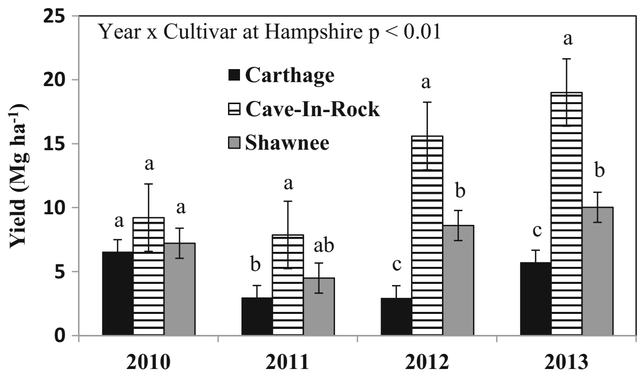


Fig. 2 Yield of switchgrass cultivars for each year at Hampshire only. Combining the data for Hampshire and Hobet showed a nearly identical figure since Hobet yields were essentially the same for all cultivars during all years. Yield data in 2010 and 2011 were previously published in Marra et al. [11]

For Hobet, three samples were composited per fertilizer treatment subplot, giving two soil samples per plot. For Black Castle and Coal Mac, soil samples were collected at biomass sampling points and composited for each treatment providing four soil samples per block, so five samples were obtained for each treatment. Soil samples were air-dried, weighed, and sieved to pass through a 2-mm sieve. Percent fines were determined by subtracting the weight of material passing through the sieve from the whole sample weight. Subsamples of the fine fraction were taken using a riffle splitter and used for soil analysis of pH, EC, and available nutrients.

For pH, 5 g of soil was combined with 5 mL of distilled deionized (DDI) water. The mixture was placed on an orbital shaker table and mixed for 15 min and then allowed to equilibrate for at least 1 h. A pH meter (Seven Easy, Mettler Toledo) was used to measure pH. Electrical conductivity was determined by combining 5 g of soil with 10 mL DDI water. The mixture was placed on an orbital shaker table and mixed for 15 min and then allowed to equilibrate for at least 1 h. A conductivity meter (Seven Compact S230, Mettler Toledo) was used to measure EC.

Available elements were extracted from soils with a Mehlich 1 solution [29]. For extraction, 25 mL of Mehlich 1 solution was added to 5 g of soil, mixed on an orbital shaker for 5 min, and then allowed to equilibrate. Samples were filtered through Whatman No. 2 filter paper, and an inductively coupled plasma emission spectrometer (ICP-ES; Perkin Elmer) was used to analyze the filtrate for available Al, Fe, Mn, Mg, Ca, K, P, Ni, Cu, and Zn. Soil chemical data were analyzed using a mixed-model, repeated measures ANOVA [23] with years as repeated measures. Few differences were found across years within sites, so an average value is reported for each site. However, significant differences were found for many properties between sites. Soils data from 2010 and 2011 (previously reported in [11]) were included with values from 2012 and 2013 to calculate 4-year means.

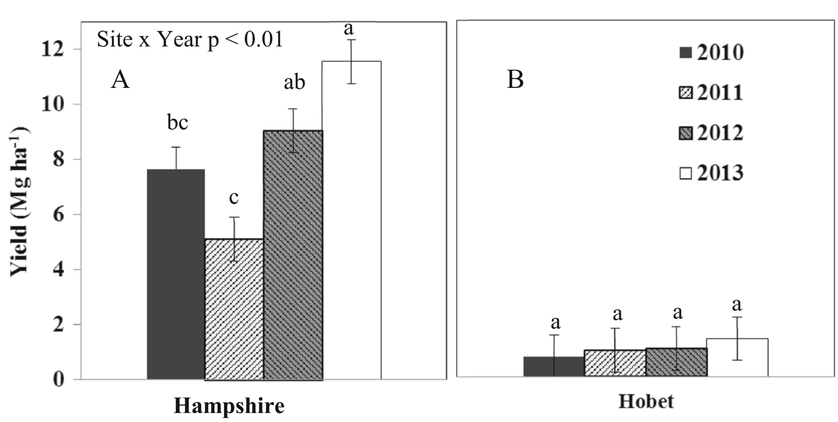
Results and Discussion

Soil Properties

Due to the different reclamation techniques, soil properties between Hampshire and Hobet were very different (Table 1). Hampshire had more fine material and higher EC than Hobet because of topsoiling and amendments (Table 1). The topsoil and lime-treated sewage/paper sludge at Hampshire resulted in a better soil medium for plants than the unweathered overburden material used at Hobet. This material had not been given much time to weather and therefore the larger rock fragments translated into lower percent fines and presumably lower fertility and water holding capacity than Hampshire mine soils.

Only Ca, Al, P, and Zn concentrations differed between mine soils at Hampshire and Hobet (Table 2). Due to the sludge amendments, finer texture, and lower pH, Hampshire mine soils contained higher Ca, Al, and Zn than Hobet. High P at Hobet with no topsoil and coarse texture is commonly found on these types of mine soils. When extracted with

Fig. 3 **a** Yield of switchgrass at Hampshire for each year averaged across cultivar. **b** Yield of switchgrass at Hobet for each year averaged across cultivar. *Vertical bars* represent standard errors. *Different letters* on bars denote significant differences at $p \leq 0.05$ according to Tukey's HSD. Yield data at Hobet in 2010 to 2011 were previously published in Marra et al. [11]



Mehlich 1, these overburden-derived mine soils often contain high levels of P, but Skousen and Emerson [20] found that the P is tightly bound to Ca minerals and unavailable to plants.

Black Castle soils had higher values for Mg and Ca, as well as all the micro-nutrients we measured, than Coal Mac (Table 2). Even though less topsoil was applied at Black Castle and this material had a slightly lower pH, it apparently was of better quality and fertility. The Black Castle EC value was four times higher than that of Coal Mac, which may indicate higher levels of nutrients and ions in solution (Table 1).

Experiment 1—Switchgrass Yields at Hampshire and Hobet

Yields of switchgrass at Hampshire were significantly higher at 8.4 Mg ha^{-1} compared to 1.0 Mg ha^{-1} at Hobet when averaged across cultivars and years (Table 3). Clearly, the more fertile mine soil at Hampshire resulted in exceptionally high yields for all three cultivars. The low yields at Hobet could be attributed to poor soil conditions and soil moisture sensitivity of switchgrass [5] since fines were <60 (Table 1). Hampshire also had a higher EC quantity which relates to more fertile soils (Table 1).

Yield was significantly different among cultivars (Table 3) and site × cultivar and year × cultivar interactions were significant. All cultivars at Hobet had poor yields (1.0 Mg ha^{-1}) and were much lower than cultivar yields at Hampshire (Fig. 1). The highest-performing cultivar at Hampshire was Cave-in-Rock, yielding 12.9 Mg ha^{-1} averaged over years (Fig. 2). Yields of Shawnee (7.6 Mg ha^{-1}) and Carthage (4.5 Mg ha^{-1}) were lower than Cave-in-Rock, and Carthage was lower than Shawnee.

A significant site × year interaction was found (Fig. 3a, b). Hobet had similar yields across cultivars for all years and showed only a slow upward trend with time (Fig. 3b). At Hampshire, yields increased from 7.7 Mg ha^{-1} in 2010 to 11.6 Mg ha^{-1} in 2013. It was expected that switchgrass yields would continue to increase with time, which was seen except for 2011. At Hampshire after 6 years of growth, Cave-in-Rock yielded 19.0 Mg ha^{-1}, while Shawnee was 10.0 Mg ha^{-1}, and Carthage 5.7 Mg ha^{-1} (Fig. 2).

Similar yields for these cultivars have been documented in this region with better soils. For example, Cave-in-Rock grown on agricultural soils in West Virginia and fertilized annually with 50 kg N ha^{-1} had comparable yields of 15 Mg ha^{-1} [5]. Cave-in-Rock yielded 8.6 Mg ha^{-1} and Shawnee yielded 8.5 Mg ha^{-1} on agricultural soils in Pennsylvania [1]. Yields of these cultivars from plots on a research farm in Iowa were Carthage, 9.9; Cave-in-Rock, 9.3; and Shawnee, 8.8 Mg ha^{-1} [10]. These stands in Iowa also received 112 kg N ha^{-1} as ammonium nitrate.

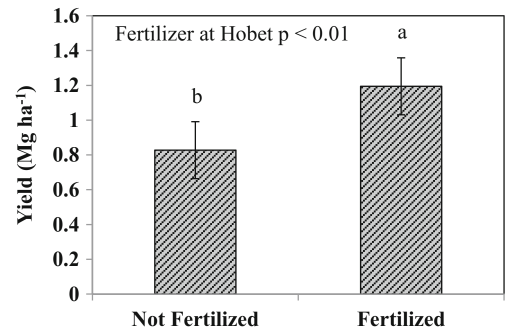


Fig. 4 Yield comparison of fertilizer treatment across cultivars and years to the harsh mine soil conditions at Hobet. *Vertical bars* represent standard errors

Experiment 1—Comparison of Fertilization at Hobet

To see if yields could be increased in the harsh mine soils at Hobet, 43 kg N-P_2O_5-K_2O ha^{-1} was added to subplots in 2009 and 2013. Fertilizing increased switchgrass yields at Hobet (Fig. 4) to 1.2 Mg ha^{-1} compared with 0.85 Mg ha^{-1} for unfertilized plots across years and cultivars. Differences in yield may have been greater if fertilization was done annually rather than in only 2 out of 5 years. We found a year, but no cultivar effect on yields (data not shown), with a small increase in yield with time at Hobet (similar to that seen in Fig. 3b). Even with fertilization, yields were still very low at Hobet with the majority of mean values being <1.5 Mg ha^{-1}. Fertilizing does not appear to compensate for the poor mine soil conditions (coarse texture, low water-holding capacity, low organic matter) at Hobet to produce good yields. Adding topsoil and organic material, such as sewage sludge or paper mill sludge, may accelerate the transformation of soils into a suitable medium for switchgrass growth, as clearly seen at Hampshire.

Table 4 Mean switchgrass yields for main effects of site, treatment, and year at Black Castle and Coal Mac

Effect	Significance	Yield
		Mg ha^{-1}
Site	0.94	
Black Castle		0.98 a[a]
Coal Mac		0.97 a
Treatment	<0.01	
0 fertilizer; light mulch		0.32 c
34 kg fertilizer ha^{-1}; light mulch		1.14 b
34 kg fertilizer ha^{-1}; heavy mulch		1.12 b
68 kg fertilizer ha^{-1}; light mulch		1.95a
Year	<0.01	
2011		0.28c
2012		0.95b
2013		2.70a

[a] Different letters for main effect yields denote difference at $p \leq 0.05$

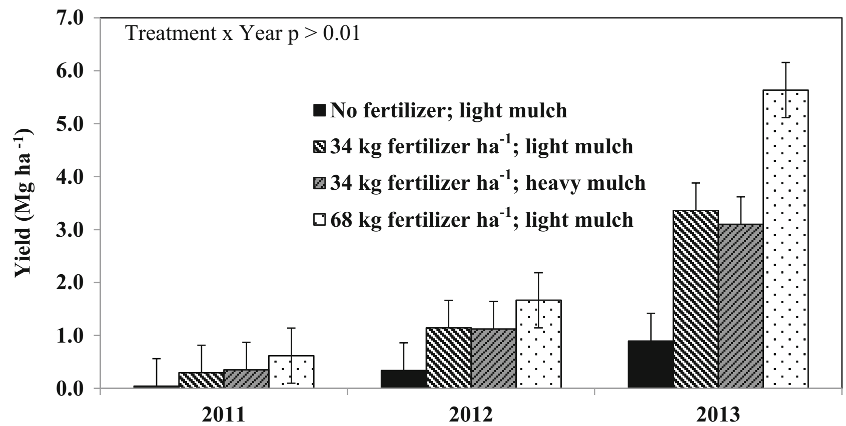


Fig. 5 Yield of switchgrass for four treatments for each year averaged over the two sites. *Vertical bars* represent standard errors

Experiment 2—Comparison of Fertilizer Treatments at Black Castle and Coal Mac

Higher soil micro- and macro-nutrient concentrations at Black Castle than at Coal Mac (Tables 1 and 2) could have supported higher switchgrass yields at Black Castle. Site yields, however, were nearly identical over 3 years (Table 4) with Black Castle and Coal Mac producing 0.98 and 0.97 Mg ha^{-1}, respectively, averaged over years and treatments. Even with the differences in nutrient values, the sites were reclaimed in a similar manner with a mixture of topsoil and brown weathered sandstone, which resulted in very similar switchgrass yields (Table 4).

A significant treatment effect was found in this experiment. The treatment with no fertilizer and light mulch had the lowest yields at 0.32 Mg ha^{-1} averaged over years and sites. Plots fertilized with 34 kg N-P_2O_5-K_2O ha^{-1} averaged 1.13 Mg ha^{-1}, while those fertilized with 68 kg ha^{-1} yielded 1.95 Mg ha^{-1}. No effect on yield was found for light versus heavy hydromulch rates at 34 kg N-P_2O_5-K_2O ha^{-1}.

Results showed a significant treatment × year interaction (Fig. 5). Yields in 2011 were only 0.04 Mg ha^{-1} with no fertilizer and 0.62 Mg ha^{-1} with 68 kg N-P_2O_5-K_2O ha^{-1}. After the third growing season in 2013, yields were 0.90 Mg ha^{-1} with no fertilizer and 5.64 Mg ha^{-1} with 68 kg ha^{-1} fertilizer. This result is consistent with reports of slow switchgrass establishment and low amounts of biomass during the first few years after planting [5, 11, 16, 27]. Higher yields were apparent by 2013, after the third growing season, and should continue to increase based on the yields at Hampshire after 6 years. On surface mine soils, fertilization was found to be essential to increase yields.

Conclusions

With the placement of a proper soil medium during reclamation and the addition of amendments, reclaimed surface mine soils produced comparable yields of switchgrass to those produced on regional agricultural soils. As shown at Hampshire, reclaiming with topsoil and organic amendments created good soil conditions for switchgrass growth, while the unweathered overburden at Hobet produced poor growing conditions and low switchgrass yields. It is clear that switchgrass would benefit from at least some topsoil or weathered overburden to provide a more suitable soil for a thicker and higher-yielding switchgrass stand. Cave-in-Rock was the highest performing cultivar at Hampshire, which indicates that it would be a better cultivar to grow in West Virginia compared to Carthage and Shawnee. Fertilization with 43 kg ha^{-1} of N-P_2O_5-K_2O was unable to compensate for the poor mine soil conditions at Hobet, although yields were increased slightly with fertilization.

On newly reclaimed sites, fertilization was shown to significantly increase switchgrass yields during the first 3 years after seeding. The control with no fertilizer and light mulch treatment yielded much lower biomass than the other treatments. Fertilizing at 34 kg N-P_2O_5-K_2O ha^{-1} increased yields by threefold, while fertilizing at 68 kg N-P_2O_5-K_2O ha^{-1} increased yields more than sixfold. The heavier mulch treatment in this study had little effect on yield. These experiments were conducted without annual biomass removal, and future research must address nutrient removal and fertilizer inputs required for switchgrass grown in mine soils under annual harvesting.

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