Hardwood Tree Growth after Eight Years on Brown and Gray Mine Soils in West Virginia

L. Wilson-Kokes, P. Emerson, C. DeLong, C. Thomas, and J. Skousen*

Surface coal mining in Appalachia disturbs hundreds of hectares of land every year with the removal of valuable and ecologically diverse eastern deciduous forests. After the passage of the Surface Mining Control and Reclamation Act in 1977, coal mine operators began planting a variety of grasses and legumes as a fast and economical way to reestablish a permanent vegetative cover to meet erosion and site stabilization requirements. However, soil compaction and competitive forage species have arrested the recolonization of native hardwood tree species on these reclaimed sites. Three 2.8-ha demonstration plots were established at Catenary Coal's Samples Mine in Kanawha County, West Virginia, of weathered brown sandstone and unweathered gray sandstone. Half of each plot was compacted. Each plot was hydroseeded with a low-competition herbaceous cover and planted with 11 hardwood tree species. After eight growing seasons, average tree volume index was nearly 10 times greater for trees grown in the brown sandstone treatments, 3853 cm^3, compared with 407 cm^3 in gray sandstone. Trees growing on compacted treatments had a lower mean volume index, 2281 cm^3, than trees growing on uncompacted treatments, 3899 cm^3. Average pH of brown sandstone was 5.2 to 5.7, while gray sandstone was 7.9. The gray sandstone had much lower fine soil fraction (<2-mm) content (40%) than brown sandstone (70%), which influenced nutrient- and water-holding capacity. Brown sandstone showed significantly greater tree growth and survival and at this stage is a more suitable topsoil substitute than gray sandstone on this site.

Surface coal mining in Appalachia drastically disturbs hundreds of hectares of land every year, which removes valuable and ecologically diverse eastern deciduous forests (Emerson et al., 2009; Zipper et al., 2011). More than 600,000 ha of land have been disturbed in the eastern United States since the enactment of the Surface Mining Control and Reclamation Act in 1977 (U.S. Office of Surface Mining Reclamation and Enforcement, 2008). After the passage of state and federal laws beginning in the 1940s, coal mine operators began reclaiming these disturbed lands by backfilling mined-out areas and regrading the overburden material to approximate the original contour (Bowling, 1978; Zipper, 2000). Operators then planted a variety of grasses and legumes as a fast and economical way to reestablish a permanent vegetative cover to meet erosion and site stabilization requirements (Bennett et al., 1978; Vogel and Berg, 1968). Early reclamation research focused on determining the quality of overburdens as plant growth media (Berg and Vogel, 1973; Kohnke, 1950; Smith and Sobek, 1978; Sobek et al., 2000). Many studies showed that low pH and nutrient deficiencies could be corrected by applying lime and fertilizer according to standard agricultural testing procedures to ameliorate these conditions (Barnhisel, 1975; Mays and Bengtson, 1978; Mays et al., 2000). Once the acidity of the soil was neutralized by amendments, no toxicities of heavy metals or other contaminants were found in the soils (Bussler et al., 1984; Roberts et al., 1988), and plants became established and grew rapidly (Ditsch and Collins, 2000; Vogel, 1981; Vogel and Berg, 1968). While these practices of grading, amending, and planting are accepted reclamation performance standards on surface mines, excessive soil compaction and competitive herbaceous cover have hindered the recolonization of native hardwood tree species on these reclaimed sites (Franklin et al., 2012).

Recently, reclamation scientists have encouraged the reestablishment of hardwood forests on surface-mined land through careful selection and placement of rooting media and the proper selection and planting of herbaceous and tree species (Burger et al., 2007). The practice of planting hardwood trees to restore a forest enhances wildlife habitat, promotes soil and water conservation, improves timber value, and provides an economically valuable post-mining land use for the landowner

J. Environ. Qual. 42:1353–1362 (2013)
doi:10.2134/jeq2013.04.0113
Freely available online through the author-supported open-access option.
Received 2 Apr. 2013.
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Abbreviations: FRA, Forestry Reclamation Approach.

(Burger, 2009; Larkin et al., 2008). The Appalachian Regional Reforestation Initiative (2012) recommends using current Forestry Reclamation Approach (FRA) technology. The five FRA steps are (Burger et al., 2005): (i) create a suitable rooting medium for tree growth; (ii) loosely grade the topsoil or topsoil substitute; (iii) seed a tree-compatible ground cover; (iv) plant early successional tree species and commercially valuable crop trees; and (v) use proper tree planting techniques. These techniques will increase the survival and growth rates of trees, increase overall productivity, and promote natural colonization and succession of plant and wildlife communities (Appalachian Regional Reforestation Initiative, 2012; Zipper et al., 2011).

Studies have shown that selecting the appropriate material from the overburden to create mine soils is important when forestry is designated as the post-mining land use. Fine-textured soils that develop from siltstone and shale contain elevated levels of soluble salts, which can negatively impact the growth and survival of tree seedlings (Torbert et al., 1988; McFee et al., 1981). Torbert et al. (1990) reported that sandstone-derived mine soils produced five times more stem volume than siltstone-derived mine soils due to lower soluble salts. Showalter et al. (2010) reported that weathered sandstone was more conducive to native hardwood tree growth than unweathered sandstone or unweathered shale. The lower pH and higher water retention of the weathered sandstone were the major contributors to better growth. Emerson et al. (2009) found that tree growth and volume were significantly greater on brown sandstone than gray sandstone.

The FRA recommends using weathered brown sandstone mixed with pre-mining forest soil during reclamation to achieve a depth of at least 1.2 m (4 ft). In the event of inadequate quantities of weathered brown sandstone and forest soil, researchers recommend mixing unweathered gray sandstone with the available weathered brown sandstone and forest soil (Skousen et al., 2011).

In forestry reclamation post-mining land uses, highly compacted mine soils hinder tree establishment and growth (Burger, 1999). In early reforestation research, Tyner et al. (1948) reported that compacted surface layers down to 45 cm created survival problems for tree seedlings and some grasses during dry periods. Conlin (1996) found that root development and growth in both Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] and lodgepole pine (*Pinus contorta* Douglas ex Loudon) decreased in response to increasing levels of compaction. Another study found that seedling growth of red oak (*Quercus rubra* L.) and scarlet oak (*Quercus coccinea* Muench.) was severely hindered by soil compaction (Jordan et al., 2003). In particular, they reported a decrease in seedling height and total dry matter (roots, stems, and leaves). Due to the detrimental effects of soil compaction, the FRA recommends lightly grading the soil surface when forestry is the assigned post-mining land use.

The objective of this study was to determine tree growth and survival on weathered brown sandstone and unweathered gray sandstone with and without compaction. Herbaceous ground cover and soil chemical properties were also monitored on all treatments.

Materials and Methods

Experimental Design

In January 2005, Catenary Coal Company constructed three 2.8-ha demonstration plots at the Samples Mine in Kanawha County, West Virginia (38°5′28″ N, 81°26′37″ W), to evaluate the survival and growth of commercially valuable hardwood trees on weathered brown and unweathered gray sandstones. The area was reclaimed by placing overburden from adjacent pits into mined-out areas and grading the material to the approximate original contour with bulldozers. The first plot was composed of 1.5 m of weathered brown sandstone placed on the regraded surface, the second plot was composed of 1.2 m of weathered brown sandstone placed on the surface, and the third plot was composed of 1.5 m of unweathered gray sandstone placed on the surface.

One-half of each plot was compacted with several passes of a bulldozer and the other half received only one or two passes of a bulldozer and was considered to be uncompacted (Fig. 1–3). Overall, six treatments were created. At plot establishment, it was observed that bulldozer tracks covered the compacted plots, while bulldozer tracks were 3 m apart on the uncompacted sites. Bulk density measurements were not made at plot establishment, but 5 yr after plot establishment a bulk density study was performed on these plots (DeLong et al., 2012). We found no difference in bulk density among the plots using four different measurement techniques, with average bulk density values varying from 1.7 to 1.8 Mg m^{-3}. We speculated that while it appeared evident that compaction differences existed early after plot establishment, time and weathering caused consolidation and settling of the uncompacted plots, causing them to be very similar to the compacted plots. It is also possible that freeze–

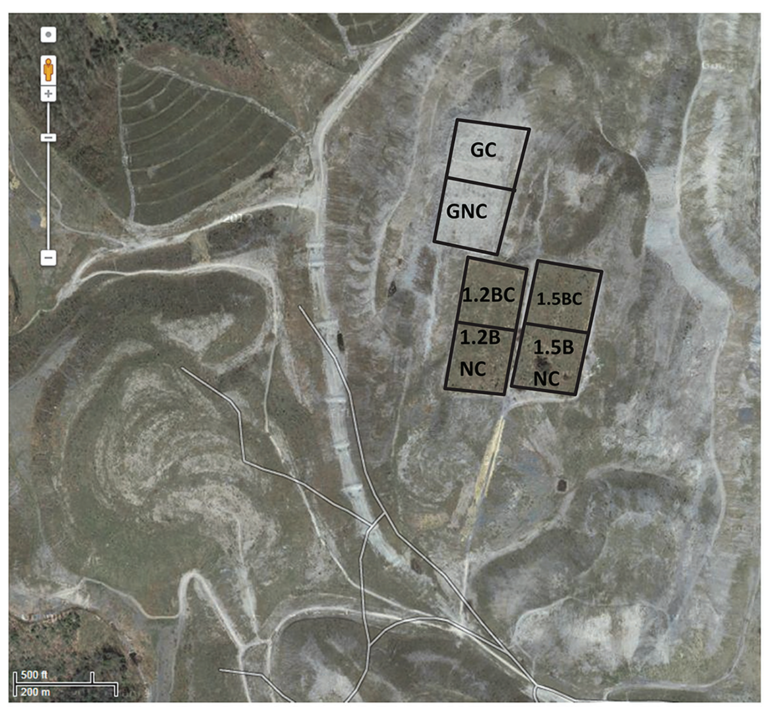

Fig. 1. Location of the three demonstration plots at Catenary Coal's Samples mine in Kanawha County, WV (B, brown sandstone; G, gray sandstone; C, compacted; NC, not compacted). (Map data: Google, Commonwealth of Virginia, DigitalGlobe, USDA Farm Service Agency, TerraMetrics, 2013.)

Fig. 2. Brown sandstone compacted plots before planting with trees.

Fig. 3. Brown sandstone uncompacted plots before planting with trees.

thaw cycles and the rooting of plants could have loosened the compacted soils, resulting in lower bulk density values.

In March 2005, 11 species of 2-yr-old tree seedlings were planted by a commercial crew on 2.4- by 2.4-m centers (Table 1). In the fall of 2007, the plots were hydroseeded with a mixture of tree-compatible vegetation (Table 2) at a rate of 15.4 kg ha^{-1}. At the time of seeding, a rate of 440 kg ha^{-1} of 10–10–10 (N–P_2O_5–K_2O) fertilizer was applied according to FRA recommendations.

Tree Sampling

Two, 2.7-m-wide by 195-m-long transects were established in an “X” pattern across each of the 2.8-ha plots. Any tree within the 2.7-m-wide transect was identified by species and measured for height and diameter. Tree height was measured to the highest live growth, and tree stem diameter was measured approximately 2.5 cm above the soil surface. Tree growth was assessed using the formula (Emerson et al., 2009)

$$\text{Tree volume index}\left(\text{cm}^3\right) = \text{height}\left(\text{cm}\right) \times \text{stem diameter}\left(\text{cm}^2\right)$$

Tree survival for the demonstration plots was calculated by comparing the number of trees measured in 2005 with the number of trees measured in 2012. Tree sampling was conducted during late July to early August every year.

Ground Cover

The ground cover was evaluated within a 1-m^2 quadrat. The quadrat was placed at 20 random locations within each treatment. Live herbaceous cover, litter cover, live tree cover, standing water, bare soil, and rocks were estimated to the nearest 5%. Ground cover was evaluated every year during late July to early August.

Soil Sampling

Soil samples were collected to a depth of 15 cm from five randomly selected points along each transect within each treatment. Soil samples were air dried and sieved to pass through a 2-mm screen, which was defined as the fine soil fraction based on weight. The fine soil fraction was used to determine the pH, extractable nutrients, and electrical conductivity. Soil pH was determined with a 1:1 mixture in distilled, deionized water using a Fisher Scientific Accumet Model 915 pH meter. Electrical conductivity was determined using a 1:2 mixture comprised of 5 g of soil and 10 mL of distilled, deionized water using a Mettler Toledo S230 electrical conductivity meter. Nutrient availability was determined using the Mehlich 1 extracting solution (0.0125 mol L^{-1} H_2SO_4 + 0.05 mol L^{-1} HCl). The extracted solution was analyzed for available K, Ca, Mg, P, Fe, and Al using a PerkinElmer Optima DV 2100 emission spectrophotometer.

Statistics

Tree data were analyzed using one-way ANOVA by sandstone type, compaction, depth, interactions, and species

Table 1. Species and number of trees planted in 2005 at Catenary Coal’s Samples Mine in Kanawha County, WV.

Species	Trees planted	
	no.	% of total
Red oak (*Quercus rubra* L.)	3,400	22
White oak (*Quercus alba* L.)	2,500	16
White ash (*Fraxinus americana* L.)	2,500	16
Sugar maple (*Acer saccharum* Marsh.)	1,500	10
Chestnut oak (*Quercus prinus* L.)	1,250	8
Tulip-poplar (*Liriodendron tulipifera* L.)	1,250	8
White pine (*Pinus strobus* L.)	1,250	8
Black cherry (*Prunus serotina* Ehrh.)	465	3
Dogwood (*Cornus alternifolia* L.)	465	3
Eastern redbud (*Cercis canadensis* L.)	465	3
Black locust (*Robinia pseudoacacia* L.)	465	3
Total	15,510	100

Table 2. Species and rates of groundcover hydroseeded in 2007 at Catenary Coal’s Samples Mine in Kanawha County, WV.

Species	Rate
	kg ha^{-1}
Redtop (*Agrostis gigantea* Roth)	2.2
Perennial ryegrass (*Lolium perenne* L.)	2.2
Birdsfoot trefoil (*Lotus corniculatus* L.)	11.0
Total	15.4

(R language). Tukey's Honest Significant Difference test was used to separate means at the $P \leq 0.05$ level. The tree volume index data contained unequal variances so the volume data were logarithmically transformed to equalize the variances. Soil data were analyzed using one-way ANOVA by treatment combinations within year for pH, electrical conductivity, extractable nutrients, and fine soil fraction (R language). Tukey's test was used to separate means at the $P \leq 0.05$ level. The ground cover data were analyzed using a one-way ANOVA to compare cover types (herbaceous, tree, bare soil or rock, water, and total cover) by soil treatment combinations for 2012. Tukey's test was used to separate means at $P \leq 0.05$. All statistical analyses were performed using the statistical program R (R Development Core Team, 2012).

Results and Discussion

Soils

The average pH for unweathered gray sandstone (7.9) was significantly higher than the pH of the weathered brown sandstone (5.2–5.7) (Table 3). There were no statistically significant differences in pH between compaction treatments, nor were there differences in average pH when comparing pH values from 2005 to 2012 within each treatment (Table 3). The mean pH ranges for both sandstone types in this study fell within the typical range for weathered and unweathered sandstones in the Appalachian coal region. Weathered brown sandstones typically range in pH from 4.5 to 5.5. while unweathered gray sandstones fall between 7.5 to 8.0 (Angel et al., 2008; Haering et al., 2004; Thomas and Skousen, 2011).

The fine soil fraction was significantly greater in the brown sandstone than the gray sandstone. The average fine soil fraction for the brown sandstone plots ranged from 68 to 76%, while the gray sandstone ranged from 36 to 41% (Table 3). For compaction, the only significant difference in the fine soil fraction between 2005 and 2012 was for the 1.2-m, compacted brown sandstone treatment, which had 47% fine soil fraction in 2005 and 76% in 2012 (Table 3).

Electrical conductivity values in 2012 were all very low, ranging from 0.03 to 0.06 dS m^{-1} across all treatments (Table 3). No significant differences in electrical conductivity were found for sandstone type, compaction, or treatment interactions; however, the average electrical conductivity values in 2005 for the brown sandstone treatments were significantly higher than in 2012 (Table 3).

For extractable elements, Al, P, and K concentrations were significantly different between the brown and gray sandstones (Table 4). As expected, compaction was not a significant factor in extractable element concentrations within treatments in 2012. The significantly higher levels of Al in the brown sandstone treatments may be due to the highly weathered nature of the brown sandstone compared with the gray sandstone, which had little weathering. Gray sandstone treatments had significantly lower levels of K than brown sandstone treatments (Table 4). While unweathered sandstones are generally thought to provide a long-term source of K, this study found that the gray sandstone had significantly lower levels of K than the brown sandstone treatments (Skousen et al., 2011). Low levels of K in the gray sandstone may be due to leaching (Bradshaw, 1997). Extractable P was significantly greater in the gray sandstone than the brown sandstone, but elevated levels of Fe in the gray sandstone could result in Fe–P complexes, which could limit the future availability of P to plants (Haering et al., 2004; Fitter and Bradshaw, 1974). Some treatments showed differences in extractable elements between 2005 and 2012. Magnesium, K, Al, and Fe declined in almost all treatments from 2005 to 2012, while Ca and P increased in most treatments between 2005 and 2012.

Ground Cover

After eight growing seasons, the vegetative ground cover in 2012 was significantly higher on the brown sandstone (70%) than the gray sandstone (10%) (Table 5). Inversely, bare soil and rock cover was significantly greater in the unweathered gray sandstone treatments (90%) than the brown sandstone treatments (22–40%) (Table 5). After 8 yr, the vegetation was primarily the seeded species on the brown sandstone, but other unseeded herbaceous and weed species had invaded and colonized the site. The small amounts of herbaceous vegetation on the gray sandstone were primarily weedy species that had colonized the site from nearby areas.

Trees

The average tree survival was higher on the brown sandstone treatments (76%) than the gray sandstone treatments (55%)

Table 3. Soil properties of samples from six soil treatments at Catenary Coal's Samples mine in Kanawha County, WV. The 2005 soil data are from Emerson et al. (2009).

Property	Brown sandstone				Gray sandstone	
	1.2-m depth		1.5-m depth			
	Compacted	Uncompacted	Compacted	Uncompacted	Compacted	Uncompacted
pH						
2005	4.77 c†	5.15 bc	5.88 b	4.64 c	7.39 a	8.23 a
2012	5.23 b	5.36 b	5.62 b	5.71 b	7.93 a	7.99 a
EC	——— dS m^{-1} ———					
2005	0.65 a*	0.29 ab*	0.46 ab*	0.48 ab*	0.18 b	0.23 b
2012	0.04	0.04	0.05	0.03	0.04	0.06
Fine soil fraction	——— % ———					
2005	47 abc*	49 abc	53 ab	57 a	40 bc	38 c
2012	76 a	69 a	69 a	68 a	41 b	36 b

* Significantly different between 2005 and 2012.

† Means for each treatment combination within a row with the same letter are not significantly different at $P \leq 0.05$.

(Table 6). The average tree survival on the compacted treatments was 79% compared with 62% on the uncompacted treatments. Black locust (*Robinia psuedoacacia* L.) had the highest survival at 100%, followed by white ash (*Fraxinus americana* L.) with a survival rate of 66%. Black cherry (*Prunus serotina* Ehrh.) and sugar maple (*Acer saccharum* Marsh.) had the lowest survival rates at 11 and 27%, respectively.

Previous measurements on this site (Emerson et al., 2009; DeLong, 2010; Thomas, 2012) showed no difference in tree survival between brown sandstone and gray sandstone treatments (Fig. 4–7). Tree measurements in 2012 revealed for the first time that sandstone type influenced survival. Clearly the uncompacted gray sandstone treatment was the reason for the difference, with only 31% survival, while the compacted gray sandstone treatment had 83% survival, similar to the brown sandstone treatments. One explanation for this result was that the greater fine soil fraction in the brown sandstone allowed the soil to hold more plant-available water and nutrients than the smaller fine soil fraction in the gray sandstone (Miller et al., 2012). In addition, compaction of the gray sandstone treatment may have broken up the rocks more than in the uncompacted gray sandstone treatment, thereby providing a greater fine soil fraction.

Brown sandstone treatments had significantly higher mean tree volume indices (3853 cm^3) than gray sandstone treatments (407 cm^3) (Table 6). Uncompacted treatments had significantly higher tree volume indices, with an average tree volume index of 3899 cm^3 compared with 2281 cm^3 for the compacted treatments. The depth of the brown sandstone treatment did not result in statistically significant differences at $P \le 0.05$ (Table 6).

Overall, trees growing on brown sandstone displayed superior performance to those on gray sandstone (Fig. 8–11). The average tree volume index across all species on the brown sandstone was nearly 10 times greater than the average tree volume index on the gray sandstone. These results were consistent with similar studies

Table 4. Soil properties of samples from six treatments at Catenary Coal's Samples mine in Kanawha County, WV. The 2005 soil data are from Emerson et al. (2009).

Element	Brown sandstone				Gray sandstone	
	1.2-m depth		1.5-m depth			
	Compacted	Uncompacted	Compacted	Uncompacted	Compacted	Uncompacted
	cmol$_c$ kg^{-1}					
Mg						
2005	9.6*	7.7	10.3*	6.8	7.8	7.6
2012	4.0	4.6	4.9	5.3	6.7	6.1
K						
2005	0.20	0.19	0.17	0.18	0.17*	0.16*
2012	0.37 a†	0.51 a	0.50 a	0.42 a	0.07 b	0.03 b
Ca						
2005	2.3	2.3	2.8	1.8*	3.2	2.8*
2012	4.7	4.9	7.1	6.8	8.4	8.9
	mg kg^{-1}					
Al						
2005	708 a	626 ab	452 ab	593 ab*	302 ab*	202 b*
2012	356 a	289 a	256 a	229 a	76 b	81 b
Fe						
2005	430	873*	322	357	617	1054*
2012	149	134	137	149	203	243
P						
2005	22 c	23 c	36 b	20 c*	59 a*	63 a*
2012	44 b	39 b	71 b	56 b	176 a	191 a

* Significantly different between 2005 and 2012.

† Means for each treatment combination within rows with the same letter are not significantly different at $P \le 0.05$.

Table 5. Mean groundcover on six soil treatments in 2012 at Catenary Coal's Samples mine in Kanawha County, WV.

Cover	Brown sandstone				Gray sandstone	
	1.2-m depth		1.5-m depth			
	Compacted	Uncompacted	Compacted	Uncompacted	Compacted	Uncompacted
	%					
Herbaceous	58 a†	52 a	72 a	58 a	5 b	9 b
Litter	1 b	6 ab	1 b	10 a	0 b	0 b
Tree	6	2	5	6	6	1
Total Cover	65 a	60 a	78 a	74 a	11 b	10 b
Bare/Rock	35 b	40 b	22 b	26 b	89 a	90 a

† Means for each plot within a row followed by the same letter are not significantly different at $P \le 0.05$.

Table 6. Treatment effects for survival and volume index after eight growing seasons in six soil treatments at Catenary Coal's Samples mine in Kanawha County, WV.

	Survival	Volume Index
Substrate	%	cm^3
Brown sandstone	76	3853 a†
Gray sandstone	55	407 b
Compaction		
Compacted	79	2281 a
Uncompacted	62	3899 b
Depth, m		
1.2	73	3314
1.5	80	4354
Interaction		
1.2-m, compacted brown	69	2550 a
1.2-m, uncompacted brown	77	3913 a
1.5-m, compacted brown	84	3556 a
1.5-m uncompacted brown	75	5182 a
Compacted gray	83	449 b
Uncompacted gray	31	309 b
Species		
Black cherry	11	1456 ab
Black locust	100	5443 b
Dogwood	44	2517 ab
Redbud	33	1390 a
Red oak	60	1923 ab
Sugar maple	27	314 b
Tulip-poplar	52	1238 ab
White ash	66	1166 ab
White oak	65	3147 ab
White pine	51	2942 ab

† Means for each treatment within a column group followed by the same letter are not significantly different at $P \leq 0.05$.

(Angel et al., 2008; Thomas and Skousen, 2011; Torbert et al., 1990). In a study by Showalter et al. (2010), white ash (*Fraxinus americana* L.) and northern red oak (*Quercus rubra* L.) displayed greater stem and root biomass on weathered sandstone than on unweathered sandstone or unweathered shale. Tree performance was attributed to the lower pH and larger fine soil fraction. Showalter et al. (2010) concluded that weathered sandstone was the best topsoil substitute and more closely mimicked the native forest soil of the Appalachian region.

This was the first year since this study began in 2005 when tree volume indices were significantly lower in compacted vs. uncompacted treatments. Soil compaction limits water infiltration, increases resistance to root penetration, and constricts root growth resulting in a shallow root space. Burger and Fannon (2009) reported that trees growing on mined soils using traditional grading and compaction reclamation practices were less productive than tree stands growing on uncompacted soils. On a surface mine site in eastern Kentucky, Burger and Evans (2010) found that sweetgum (*Liquidambar styraciflua* L.), tulip-poplar (*Liriodendron tulipifera* L.), loblolly pine (*Pinus taeda* L.), and white pine (*Pinus strobus* L.) planted on compacted mine soils grew poorly.

Average tree height was also significantly higher on the brown sandstone than the gray sandstone treatments in 2012. The brown sandstone treatments had an average height for all species of 131 to 166 cm compared with a range of 66 to 72 cm for all species for the gray sandstone treatments (Table 7). The average tree height has continued to be significantly greater on the brown sandstone treatments than the gray sandstone treatments since 2009 (Table 7).

Black locust had the highest average tree volume index at 5443 cm^3, and white oak (*Quercus alba* L.) was second with 3147 cm^3 (Table 6). Sugar maple had the worst growth, with an average volume index of 314 cm^3.

Black locust is an early-successional tree that has repeatedly performed well on mined lands (Emerson et al., 2009; Miller et al., 2012). Its excellent performance in mine soils is probably due to its ability to grow on a variety of soil types and its tolerance of a pH range from 4.6 to 8.2 (Huntley, 1990). Black locust is ecologically important to forest ecosystems because it provides shelter for many animals as well as food for mammals and birds (Larkin et al., 2008). Black locust also serves as an N_2 fixer, which can be beneficial to drastically disturbed lands with marginally available nutrients.

White oak grows well on a variety of soils from many different parent materials, and it is tolerant of slightly acidic soils (Natural Resources Conservation Service, 2012). It does not grow well on extremely dry, shallow soils (Minckler, 1965), however, so the brown sandstone with its greater fine soil fraction provided more water- and nutrient-holding capacity. Miller et al. (2012) found that brown sandstone treatments with fewer coarse rock fragments had more plant-available water than gray sandstone treatments. Soils with more available water have a positive influence on tree productivity, which may explain why white oak performed well on the brown sandstone (Table 8) (Rodrigue and Burger, 2004).

Initially, white pine trees in this study displayed the lowest survival and the lowest volume across all treatments (Emerson et al., 2009). With time, however, they improved in growth and persistence. White pine has been extensively planted on reclaimed mine sites because of its tolerance to acidic soil pH; however, it is intolerant of high levels of soluble salts and shallow soils (Torbert et al., 1988).

White ash had the second highest survival of all species in this study. Similar studies also found that white ash exhibited high survival rates on a variety of mined soils in Kentucky and West Virginia (Miller et al., 2012; Emerson et al., 2009; Zeleznik and Skousen, 1996). Miller et al. (2012) reported that white ash displayed the greatest tree height in brown sandstone treatments vs. gray sandstone, mixed brown–gray sandstone, and shale treatments. In this study, we found white ash had higher tree volume on brown sandstone compared with gray sandstone (Table 8).

Sugar maple performed the most poorly of all species, with the lowest tree volume index and a very low survival rate. Sugar maple has consistently exhibited poor growth across all treatment combinations in this study. While sugar maple trees can tolerate a pH range of 3.7 to 7.3, they grow best on soils with pH 5.5 to 7.3. Sugar maple also prefers deep, moist, and well-drained, fine-textured soils (Emerson et al., 2009). Miller et al. (2012) reported that sugar maple grew poorly on both brown sandstone and gray sandstone mine spoils, which was consistent with our findings.

Fig. 4. Brown sandstone compacted plots after the second growing season.

Fig. 5. Brown sandstone uncompacted plots after the second growing season.

Fig. 6. Gray sandstone compacted plots after the second growing season.

Fig. 7. Gray sandstone uncompacted plots after the second growing season.

All tree species showed a wide range of volume indices within each treatment type. Black locust displayed a wide range of volume indices from 328 to 7407 cm^3, while sugar maple had the smallest variation in average tree volume indices, ranging from 6 to 596 cm^3 (Table 8).

Due to the planting strategy of the commercial tree planting crew, the tree species were unevenly distributed among treatments. This uneven distribution of trees among treatments could have misrepresented tree growth in specific treatments because some trees grew larger than others (Table 9). If large-growing tree species were planted more and overrepresented in a particular treatment, the average volume index for that particular treatment may have been significantly higher than another simply because it had more large-growing tree species planted within its boundaries. For example, black locust, one of the largest growing trees, was planted in greater numbers in the brown sandstone treatment (n = 21–40) compared with seven or fewer in the gray sandstone treatments (Table 9). This would result in a conclusion that the brown sandstone substrate had a higher volume index, not because of better growth conditions but simply due to more numerous large black locust trees being present in the plot. A better comparison across treatments to show tree growth effects may be to evaluate species with similar numbers across treatments, such as red oak and white ash. With red oak (n = 8–19, Table 9), clearly all treatments on the brown sandstone showed a 10-fold greater tree volume index than gray sandstone treatments (Table 8). For white ash (n = 8–15), the volume index trend was not nearly as strong, with only one of the brown sandstone treatments (1.2-m depth, uncompacted brown sandstone) showing a much greater volume index (3500 cm^3) and uncompacted gray sandstone showing a substantially lower index (218 cm^3). Volume indices for white oak and white pine both showed the same trend as red oak: brown sandstone much greater than gray sandstone.

Trees grown on weathered brown sandstone exhibited a higher level of performance than trees grown on unweathered gray sandstone during an 8-yr period. Results during the previous 7 yr of this study found no differences in survival between brown and gray sandstone plots, but data from 2012 confirmed that tree survival was higher on brown than gray sandstone plots. Weathered brown sandstone was more conducive to the growth and survival of hardwood tree species

Fig. 8. Brown sandstone compacted plots after the eighth growing season.

Fig. 9. Brown sandstone uncompacted plots after the eighth growing season.

Fig. 10. Gray sandstone compacted plots after the eighth growing season.

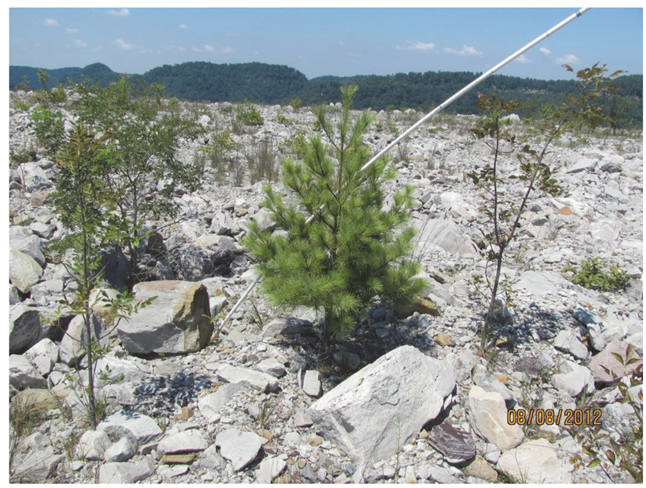

Fig. 11. Gray sandstone uncompacted plots after the eighth growing season.

Table 7. Mean tree height for 2005, 2009, and 2012 growing seasons in six soil treatments at Catenary Coal's Samples min in Kanawha County, WV. The 2005 and 2009 data are from Emerson et al. (2009) and DeLong (2010).

Year	Brown sandstone				Gray sandstone	
	1.2-m depth		1.5-m depth			
	Compacted	Uncompacted	Compacted	Uncompacted	Compacted	Uncompacted
	cm					
2005	37 a†	40 a	37 a	40 a	38 a	40 a
2009	99 ab	131 a	108 ab	86 b	56 c	43 c
2012	131 a	157 a	142 a	166 a	72 b	66 b

† Means for each volume within a row followed by the same letter are not significantly different at $P \leq 0.05$.

than unweathered gray sandstone and was a more suitable topsoil substitute than gray sandstone when reforestation is the post-mining land use. Although previous reports on this study found that compaction did not significantly impact the tree volume index, the data collected in 2012 suggested that compaction has begun to limit tree growth. The chemical properties of the brown sandstone are more sufficient for supporting a variety of tree species than the chemical properties associated with gray sandstone.

Acknowledgments

We thank Paul Ziemkiewicz of West Virginia University for assistance in funding forestry research at WVU. We also thank Scott Eggerud of the U.S. Office of Surface Mining as well as John McHale, Mitch Kalos, Jonathan Sanchez, and Jeff Andrews of Magnum Coal (now Patriot Coal, Inc.) for financial and construction support during this study. We also greatly appreciate the help of Ellie Bell, Lindsey Bishop, Carol Brown, Travis Keene, Nathanael Kokes, and Jessica Odenheimer in field data collection. This article is scientific contribution no. 3176 from the West Virginia Agric. Exp. Stn., Morgantown.

Table 8. Mean tree volume index of tree species in 2012 after eight growing seasons in six soil treatments at Catenary Coal's Samples mine in Kanawha County, WV.

Species	Brown sandstone				Gray sandstone		Avg.
	1.2-m depth		1.5-m depth				
	Compacted	Uncompacted	Compacted	Uncompacted	Compacted	Uncompacted	
	cm^3						
Black cherry	–	–	–	930	1981	–	1456
Black locust	4943	5324	4618	7407	328	413	5443
Dogwood	812	2534	1027	8491	1064	–	2517
Redbud	–	2058	1400	358	1762	376	1390
Red oak	2999	3609	1838	3181	397	301	1923
Sugar maple	–	354	596	154	108	6	314
Tulip-poplar	687	3910	154	1682	284	908	1238
White ash	1009	3500	1487	880	711	218	1166
White oak	1167	3027	6427	5392	74	285	3147
White pine	2121	762	6820	4646	154	114	2942
Avg.	2550	3913	3556	5182	449	309	

Table 9. Distribution of tree species in 2012 after eight growing seasons in six soil treatments at Catenary Coal's Samples mine in Kanawha County, WV.

Species	Brown sandstone				Gray sandstone		Total
	1.2-m depth		1.5-m depth				
	Compacted	Uncompacted	Compacted	Uncompacted	Compacted	Uncompacted	
	no.						
Black cherry	–	–	–	1	1	–	2
Black locust	21	35	29	40	7	1	133
Dogwood	1	2	3	2	4	–	12
Redbud	–	4	2	1	1	2	10
Red oak	8	14	14	10	19	9	74
Sugar maple	–	4	5	4	3	1	17
Tulip-poplar	5	5	2	4	10	2	28
White ash	15	6	13	8	13	8	63
White oak	13	17	13	12	8	6	69
White pine	6	1	5	1	4	1	18
Total	69	88	86	83	70	30	426

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