YOUNG FOREST COMPOSITION AND GROWTH ON A RECLAIMED APPALACHIAN COAL SURFACE MINE AFTER NINE YEARS[1]

C.E. Zipper[2], J.A. Burger, D.M. Evans, P. Donovan

Abstract: A 29-ha mine site in Buchanan County, Virginia, was reclaimed using methods intended to produce favorable conditions for reforestation and planted with forest trees in early 2002. After soil grading, the site was mapped for forest site quality considering rock type, aspect, and soil compaction. Trees of eleven species and one shrub species were prescribed for planting as four species mixes, each targeted for conditions on different locations within the mine site. In 2010, 68 measurement plots, each 0.01 ha in size, were established on a gridded pattern. Within each, soils were characterized and living trees and shrubs were measured for breast-height diameter and height. Data were analyzed to assess density and volume, overall and by species, and to evaluate how these metrics responded to soil and site conditions. After nine growing seasons, 24 tree and three shrub species were recorded as growing on the site; most living trees were non-planted native species. Prominent volunteers were black locust (*Robinia pseudoacacia*), sourwood (*Oxydendrum arboreum)*, and sweet birch (*Betula lenta*); prominent planted species were ash (*Fraxinus* spp.), white oak (*Quercus alba*), and American sycamore (*Platanus occidentalis*). Volunteers established and grew best on more acidic soils, on sloped areas where soils were not compacted, and on areas rated as having higher forest site quality. Community composition and volume also varied with these site features. Planted trees' species composition varied with planting mix and site conditions. On non-compacted soil areas, planted trees' overall density and volume metrics exhibited few differences that were directly related to site conditions, in part because species selected for and planted preferentially on areas with soil properties poorly suited for most native trees were able to establish and grow.

Additional Key Words: Afforestation, Reforestation, Ecosystem Restoration

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[2] C.E. Zipper is corresponding author and Associate Professor, D.M. Evans is Research Associate, and Patricia Donovan is GIS Lab Manager, Department of Crop and Soil Environmental Sciences; J.A. Burger is Professor Emeritus, Forest Resources and Environmental Conservation. Virginia Tech, Blacksburg, Virginia 24061

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Introduction

The eastern USA's Appalachian region supports the world's most extensive temperate deciduous forests (Riitters et al. 2000). However, the region also contains abundant coal reserves that have been mined for more than a century. Surface mining of Appalachia's coals has transformed forests to other land-cover types (Sayler 2008; Drummond and Loveland 2010). Since 1980, more than 6,000 km^2 have been mined for coal in Appalachia (Zipper et al. 2011b).

Appalachia's forests provide ecosystem services, including carbon storage, watershed and water quality protection, and habitat for diverse flora and fauna; and they supply high-quality hardwood timber to the world economy. The progressive conversion of forest to other land-cover types by mining causes ecosystem service loss and diminishes the region's capacity to produce renewable resources. However, since 2006, some mining firms have been using a reclamation method known as the Forestry Reclamation Approach (FRA) for the purpose of restoring native hardwood forests and their products and services on reclaimed coal mines (Burger et al. 2005). Although many controlled studies support the FRA's potential to restore productive and diverse forest vegetation after mining (Torbert and Burger 2000; Zipper et al. 2011b), operational FRA applications by industry have not been assessed and documented in published literature. The operational success of the FRA must ultimately be judged by the composition and rate of growth of a new forest and the likelihood that it will provide similar values as the pre-mining forest when mature.

In 2001-2002, a prototype version of the FRA was applied by a mining firm in Buchanan County, Virginia. Company personnel worked with the authors to apply reclamation methods intended to restore forested vegetation (Burger and Zipper 2002) while re-mining and reclaiming an older mine site. Weathered mine spoils with properties favorable for tree growth were applied over much of the site; reclamation grading operations were conducted with the intent of avoiding surface compaction; a tree-compatible herbaceous seeding mix was applied, and trees of species native to eastern USA were planted. Here, we report results of a site assessment conducted in 2010 after nine growing seasons. Specific goals are to measure species composition and growth at this stage of canopy closure, evaluate how community composition and tree growth responded to soil and site conditions, and assess the outcome of prescribed, planted species mixes and their likely contribution to a valuable forest at rotation age.

Methods

Site Description

Most of the reclaimed site is comprised of steep slopes that drain into a gently sloping area that runs from north to south through the mining disturbance (Fig. 1). The site's southeastern area is a ridgeline that also includes some relatively flat areas created by reclamation grading. The site's far eastern edge drains from that ridgeline to the east.

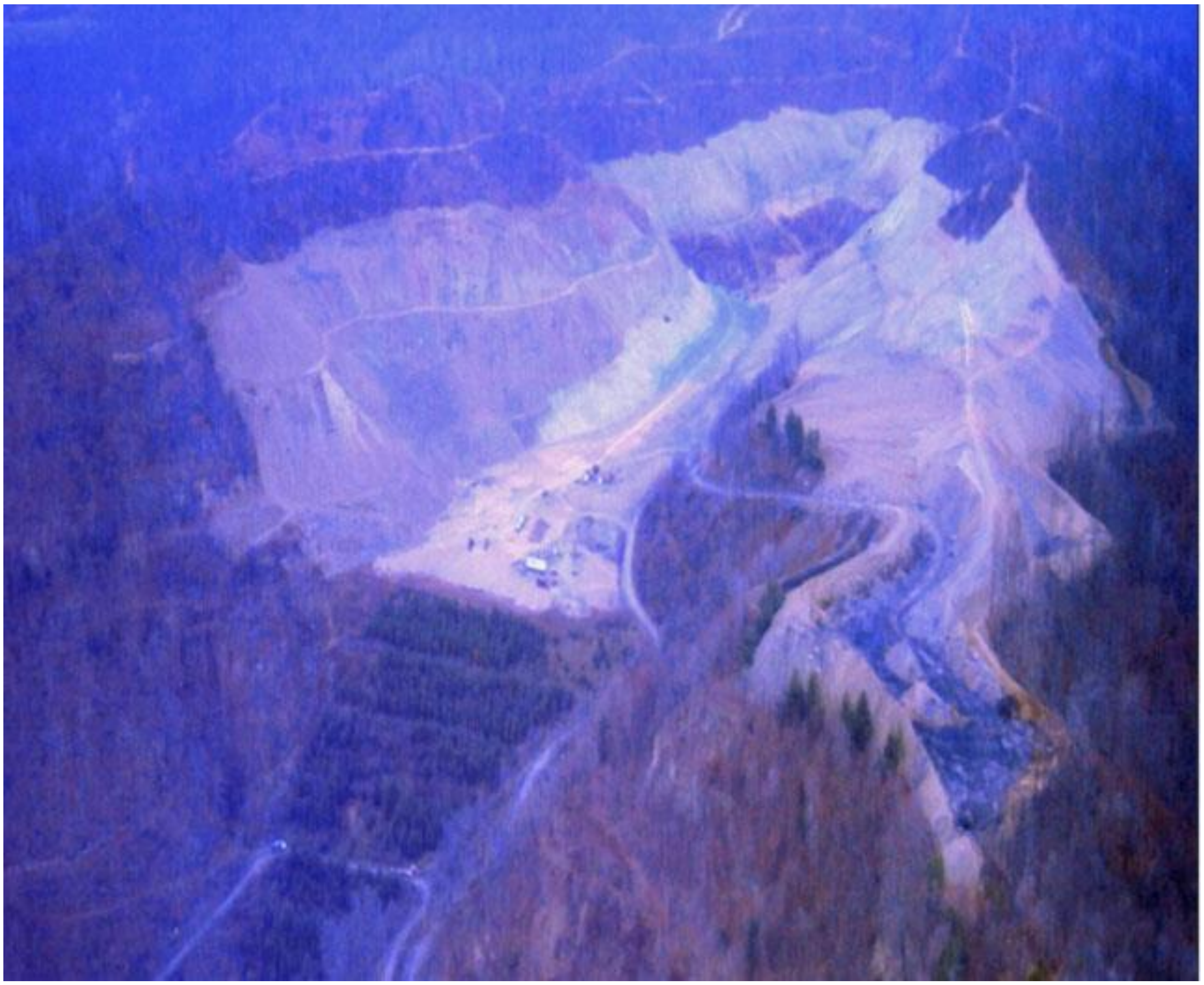

Figure 1. The mine site viewed from southeast with north in the upper right corner, 7 December 2001 while equipment was still present, prior to surface spoil placement in the southeastern-most area.

Spoil types used to construct mine soils varied over the site. Most areas were reclaimed with weathered sandstones, often mixed with unweathered sandstones, siltstones, and shales; in some areas, unweathered siltstones and shales were used on the surface. Reclamation grading of slopes was minimized but some flatter areas were compacted by equipment. A seed mix comprised of annual ryegrass (*Lolium multiflorum*, 27 kg ha^{-1}), redtop (*Agrostis gigantean*, 2 kg ha^{-1}), weeping lovegrass (*Eragrostis curvula*, 2 kg ha^{-1}), perennial ryegrass (*Lolium perenne*, 4 kg ha^{-1}), orchard grass (*Dactylis glomerata*, 13 kg ha^{-1}), and birdsfoot trefoil (*Lotus corniculatus*, 4 kg ha^{-1}) was applied with fertilizer (34 kg N, 29 kg P, and 56 kg K ha^{-1}) over the site by a hydroseeding contractor in early spring, 2002.

Soil Mapping and Site Assessment

After reclamation grading but prior to revegetation, the site was assessed for reforestation potential. Using field observations, the site was divided into soil mapping units judged to have similar characteristics for reforestation (Fig. 2, left). Mapping unit locations and boundaries were marked and recorded with a GPS unit. Soils were characterized for density at multiple locations within each mapping unit using a hand-held spade to determine depth of penetration by the spade tip when forced downward through application of moderate foot pressure; and an average density class was recorded for each mapping unit. Aspect at the center of each mapping unit was recorded using a hand-held compass. A composite sample was taken from each mapping unit and characterized for rock-type composition.

A forest site quality (FSQ) classification model (Burger et al. 2002, Showalter 2005) was applied to characterize the reforestation potential for each mapping unit. That model included three site factors: compaction, rock type, and aspect. Within each mapping unit, each site factor was evaluated and scored on a scale of 1 (best) to 5 (worst) using quantitative criteria (Table 1). A weighting factor (WF) was assigned to each site factor to reflect relative importance as derived by Burger et al. (2002). For each mapping unit, each of the three site factor scores was multiplied by its respective WF, and those values summed to obtain an FSQ rating. FSQ ratings were rounded to integers and used to classify each mapping unit as an FSQ class, with possible values ranging from I (most favorable) to V (least favorable).

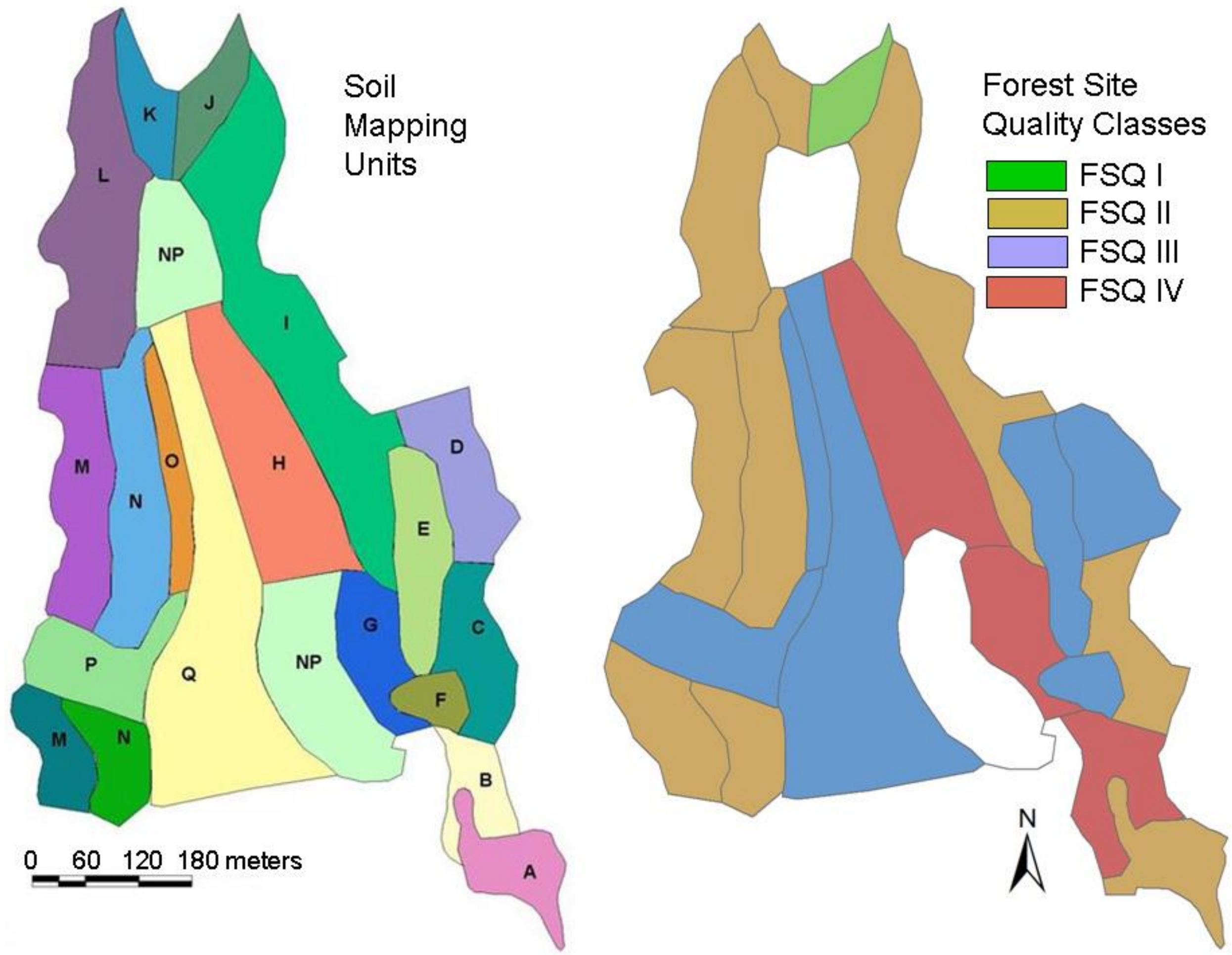

Figure 2. Soil mapping units (left) and forest site quality (FSQ) (right), as determined by applying the site quality classifications to soil mapping units (NP = not planted; other letters are mapping unit designators). FSQ classes are scaled from I (most favorable) through V (least favorable), but no soil mapping units were found to be FSQ V.

Table 1. Site factor gradients and weighting factors (WF) used to determine forest site quality classifications for soil mapping units.

Site Factor	Criterion	- - - - - - Site Factor Rating and Scales - - - - - - 1	2	3	4	5	WF
Rock Type	Weathered Sandstone : Unweathered Siltstone ratio	90:10	70:30	50:50	30:70	10:90	0.52
Compaction	Depth of Spade Penetration with Moderate Foot Pressure (cm)	50	40	30	20	10	0.28
Aspect	Degrees from North	0 – 90 (NE)	90 - 135 315 -360	Flat	135 - 180 270 - 315	180 - 270 (SW)	0.20

Tree Species Prescriptions and Planting

The area was segmented into different site types for prescribing trees for planting (Table 2, Fig. 3). Areas with mine spoils comprised predominantly of un-compacted sandstones were classified as either dry (south- and west-facing aspects) or moist (east- and north-facing aspects) based on landscape position. Areas with mine spoils comprised predominantly of un-compacted siltstones and shales, and areas with compacted spoils, comprised the other two site types. Tree planting mixes were prescribed for each site type by specifying species considered suitable for each area. For the un-compacted sandstone site types, planting prescriptions emphasized commercially valued native hardwoods suited for dry and moist growing conditions, respectively; while species known for ability to survive and grow in less favorable spoil conditions were prescribed for the siltstone/shale site type. Four species (white oak, *Quercus alba*; white ash, *Fraxinus americana*; eastern white pine, *Pinus strobus*; and the N-fixing shrub bristly locust, *Robinia hispida*) were prescribed for all site types. The site was planted in spring, 2002, by a commercial contractor..

Table 2. Tree-planting mixes prescribed for different site types† (stems per ha)

Species	Role	SS Moist, 1	SS Dry, 2	SiS Loose, 3	Compact, 4	Site Average
TREES						
white ash	Crop	371	494	297	‡	395
white oak	Crop	371	494	297	‡	395
sycamore	Crop	-	-	297	‡	65
burr oak	Crop	-	-	297	‡	65
northern red oak	Crop	371	-	-	‡	168
white pine	Nurse	124	124	124	‡	124
chestnut oak	Crop	-	494	-	‡	162
dogwood	Nurse	62	62	62	‡	62
red maple	Crop	-	-	297	‡	65
sugar maple	Crop	371	-	-	‡	168
SHRUBS						
bristly locust	Nurse	124	124	124	‡	124
Total TREES and SHRUBS §		1792	1792	1792	1792	1792

† SS = predominantly sandstone; SiS = predominantly siltstone and shale.

‡ Mix number 4 prescribed as "Plant mixture of all remaining trees and shrubs."

§ Some totals do not add correctly due to independent rounding.

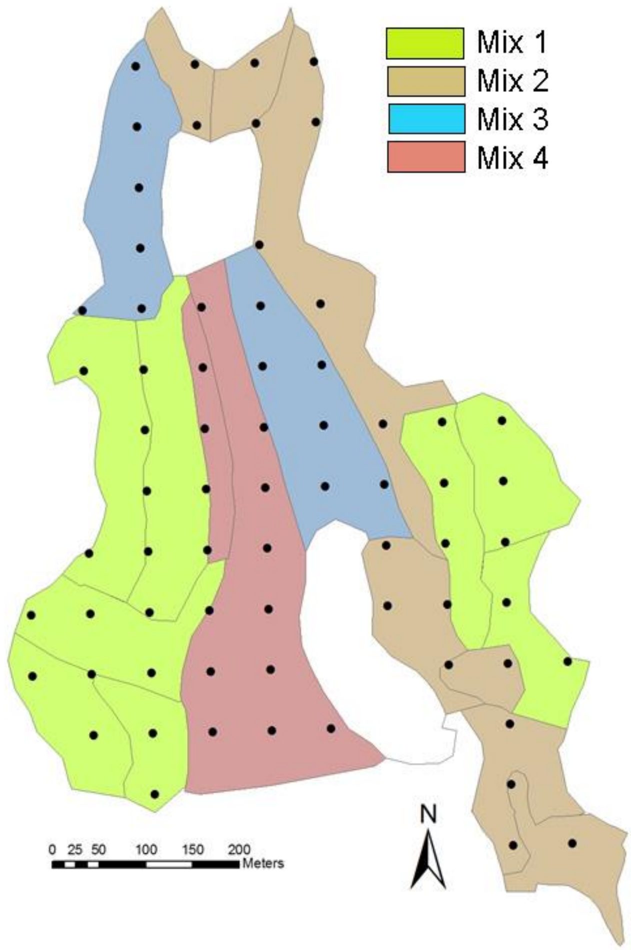

Figure 3. Tree planting mixes applied to various areas of the site (mix 1, with northern red oak and sugar maple; mix 2, with chestnut oak; mix 3, with American sycamore, burr oak, and red maple; and mix 4, comprised of all species remaining after planting other areas. Additional species were included in all species mixes, as per Table 3). The black dots on a gridded pattern are the center points for the 68 measurement plots.

Measurement Methods in 2010

Measurement plot centers were laid out on a 0.4 ha (1-acre) gridded pattern (Fig. 3). The distance of each measurement plot center from the nearest un-mined forest tree line was determined using aerial photos and geographic information system software.

Soils were sampled from each measurement plot in June, 2010. Samples were taken from the top 15 cm at four locations, each about 3 m and in a cardinal direction from the plot center, and composited. In the laboratory, soil samples were air dried and weighed, and coarse fragments (CF) were separated from fines using a 2 mm sieve. The fraction of the original sample comprised of CF particles (>2 mm) by mass was recorded. The CF were compared visually to samples of five rock types (siltstone, weathered sandstone, unweathered sandstone, black shale, and coal or coal-like). Using a combination of physical separation and visual estimation, approximate fractional composition for each fragment type was recorded. A subsample of the fines were characterized by Virginia Tech Soil Testing Laboratory for extractable nutrients, soluble salts (electrical conductivity in a 2:1 water:soil mixture), pH, and estimated organic matter as loss on ignition (LOI) using methods described by Maguire and Heckendorn (2009).

Trees and shrubs were measured in fall of 2010. On each measurement plot, all trees within a 0.01 ha (5.64 m radius) area and taller than breast height (approx. 1.5 m) were measured for height (h) using an extendable height-pole and for diameter at breast height (dbh); the species was recorded for each. All shrubs within a 0.005-ha radius taller than breast height were measured for height and for dbh, and species were recorded. Where shrubs of a single species occurred in dense clumps, an individual considered to be representative of that clump was measured for height and dbh, and stems within the clump were counted.

Data Analysis:

All trees were classified as either "planted" or "volunteer" based on the planting prescriptions: if a living tree was found in an area where it had been prescribed, it was tallied as planted; otherwise living trees of species known to be growing in the local area were tallied as volunteers. All burr oaks (*Quercus macrocarpa*) were tallied as planted since that species is not known to be growing in the local area. White ash was planted at all sites, but green ash (*Fraxinus pennsylvanica*) and white ash could not be discriminated during site survey; therefore, all *Fraxinus* species were tallied as planted and are listed here as ash.

A volume index was calculated for each living tree as $h*dbh^2$. Living shrubs and trees were summed to estimate species density, and per-shrub/tree volume indices within measurement plots were both averaged and summed to calculate measurement plot totals.

Site and soil mapping unit survival and stocking metrics were estimated from measurement plot totals. Potential influences by measurement plot soil and topographic characteristics on tree density and volume metrics were evaluated using two methods. For continuous and independent soil and site variables, correlation analyses were performed. Because density and volume metrics are non-normally distributed, the Spearman correlation procedure was used. We also evaluated associations between FSQ class, tree planting mix, and soil pH with forest establishment, composition, and growth metrics by defining measurement plot groupings with similar characteristics, calculating mean density and growth metrics for each from measurement plot data, and evaluating those groupings for significant differences using Wilcoxon signed-rank procedures. All statistical analyses were conducted using JMP 9.0 software (SAS Institute, Cary NC) and interpreted at the $\alpha = 0.05$ level of significance unless otherwise noted.

Importance values for all recorded tree and shrub species were calculated (Curtis and McIntosh 1951; Kuers 2010). An importance value is a measure of the relative dominance of species in a forest community. Importance values rank species within a site based upon three criteria: the frequency at which the species is recorded within measurement units; the total number of individuals recorded; and the total amount of forest area occupied as basal area. Importance values were calculated for the site as a whole and for soil quality classes, site types targeted by tree planting mixes, and soil pH classes. Because importance values areas are calculated using multiple measurement points, importance value comparisons are nominal.

Results

Soil and Site Properties

Mine soils were high in CF with a mean value of 57% (Table 3), as is common on Appalachian coal surface mines (Zipper et al. 2011a). Siltstone (mostly unweathered), weathered sandstone, and unweathered sandstone were the most common rock types recorded as CF. Mine soils were predominantly acidic, with a pH mean of 5.0. Soil pH was negatively correlated with siltstone and shale (% of CF) and positively correlated with unweathered sandstone, indicating that that siltstones and shales may contain acid-forming pyritic minerals. Soluble salts were positively correlated with CF siltstone and shale contents and were negatively correlated with weathered sandstones, as commonly occurs on Appalachian mine soils.

Loss-on-ignition values were positively correlated with the recorded presence of coal fragments, indicating that LOI values are influenced by the geologic materials' C contents and therefore cannot be considered as indicators of pedogenic organic matter content. Slope was negatively correlated with the recorded presence of coal and with LOI, indicating that high-C geologic materials occur preferentially on the site's flatter areas. Slope was positively correlated with CF, indicating that steeply sloped areas were constructed using rocky spoils.

Table 3. Mean values of soil and site properties, including rock type composition; and correlation of soil rock-type composition with soil and site properties at 68 sampling points

	Mean ± Std Deviation	CF	pH	Soluble salts	LOI	Slope	Tree line distance
		- - - - - - - - Spearman Correlation Coefficients - - - - - - - -					
Siltstone (% of CF)	38 ± 25	0.06	-0.32***	0.34***	- 0.14	0.01	- 0.20
Weathered sandstone (% of CF)	34 ± 22	- 0.12	0.19	- 0.55***	- 0.14	0.17	0.16
Unweathered sand-stone (% of CF)	24 ± 22	0.16	0.24**	- 0.02	0.16	- 0.12	0.09
Black shale (% of CF)	3 ± 9	- 0.01	- 0.22*	0.26**	0.02	- 0.04	- 0.08
Coal (% of CF)	2 ± 7	- 0.36***	0.01	0.10	0.51***	- 0.31**	- 0.03
Coarse fragments (CF) (% of soil mass)	57 ± 12		0.28**	0.08	- 0.08	0.33***	- 0.18
pH	5.0 ± 1.1			- 0.22*	0.41***	0.02	- 0.10
Soluble salts (ppm)	169 ± 187				0.29**	- 0.16	- 0.16
Loss on ignition (LOI) (%)	2.8 ± 1.1					- 0.28**	- 0.22
Slope (%)	37 ± 26						- 0.09
Tree line distance (m)	48 ± 34						

* = 0.05<p<0.10; ** = 0.01<p<0.05; *** = p<0.01

Reforestation Success Indicators: Tree Establishment, Density, and Volume Production

Twenty-four tree and three shrub species were recorded (Table 4). Trees tallied as volunteers were more numerous than those tallied as planted. Three non-native invasives (autumn olive, *Elaeagnus umbellata*; ailanthus, *Ailanthus altissima*; and paulownia, *Paulownia tomentosa*) were observed, all in small numbers. Two species that are native to the eastern US but do not occur commonly as natives of the local area were observed: burr oak, which was planted, and eastern cottonwood (*Populus deltoides*), tallied as a volunteer. All other species recorded occur as natives in the local area.

Table 4. Mean tree and woody plant density and growth at the Rapoca reforestation site. Tree and shrub species are listed in order of importance value (See Fig. 4).

	Frequency	Density - Planted	Density Volunteer	Height	DBH †	Basal Area	Avg VI ‡	Total VI ‡
	(plots)	(stems ha^{-1})	(stems ha^{-1})	(cm)	(cm)	(m^2 ha^{-1})	(cm^3)	(m^3 ha^{-1})
Shrubs§								
bristly locust	33	2,815	-	256	2.1	1.09	1,318	3.71
autumn olive	5	-	62	401	5.7	0.18	15,287	0.94
sumac	7	-	112	260	2.7	0.07	2,432	0.27
Total		2,815	174	259	2.2	1.35	1,649	4.93
Trees§								
black locust	41	-	326	432	4.1	0.64	16,274	5.31
ash	53	222	-	349	3.0	0.22	5,903	1.31
sourwood	15	-	231	273	1.9	0.1	1,444	0.33
white oak	38	104	-	343	3.4	0.13	6,186	0.65
sycamore	19	25	21	604	6.4	0.19	41,248	1.88
burr oak	17	44	-	428	5.9	0.14	19,115	0.84
n. red oak	22	38	32	345	3.2	0.07	5,226	0.37
sweet birch	18	-	51	333	2.5	0.04	3,952	0.20
white pine	12	22	-	372	4.9	0.05	13,610	0.30
chestnut oak	13	16	10	433	3.9	0.04	8,688	0.23
tulip poplar	13	-	25	343	2.5	0.02	7,067	0.18
dogwood	9	53	-	217	0.9	0	190	0.01
red maple	12	15	10	368	2.4	0.01	3,516	0.09
sugar maple	11	12	9	300	1.7	0.01	1,153	0.02
ailanthus	2	-	3	553	14.8	0.05	150,134	0.44
pitch pine	4	-	15	192	1.6	<0.01	641	0.01
black cherry	3	-	15	291	1.9	0.01	2,333	0.03
paulownia	1	-	1	329	12.7	0.02	53,094	0.08
eastern redbud	2	-	4	219	1.6	<0.01	599	<0.01
cottonwood	1	-	1	732	7.0	0.01	35,844	0.05
scarlet oak	1	-	1	418	4.8	<0.01	9,621	0.01
Virginia pine	1	-	1	204	1.3	<0.01	345	<0.01
sassafras	1	-	1	213	0.9	<0.01	173	<0.01
serviceberry	1	-	1	198	0.4	<0.01	32	<0.01
Planted Trees		551		357	3.3	0.71	8,093	4.47
Volunteer Trees			762	363	3.2	1.03	10,368	7.89
All Trees	310	1313		360	3.2	1.74	9,413	12.36
Trees + Shrubs		3,366	936	306	2.7	3.09	4,019	17.29

† Diameter at breast height ‡ Volume index

§ Sumac, *Rhus* sp.; black cherry, *Prunus serotina*; eastern redbud, *Cercis canadensis*; scarlet oak, *Quercus coccinea*; sassafras, *Sassafras albidum*; serviceberry, *Amelanchier* sp.; with other scientific names as stated in text.

Of all tree species observed, the volunteer black locust (*Robinia pseudoacacia*) occurred at the highest density and with the highest importance value (Fig. 4). Black locust was responsible for ~30% of total woody volume. Like the most commonly observed shrub, the planted bristly locust, black locust is an N-fixing legume. Black locust often proliferates on coal surface mines (Zipper et al. 2011a). Unlike bristly locust, black locust has the potential to grow tall and become part of the tree canopy. At high density it can compete for space and other resources to the detriment of planted oaks and other species. However, black locust can become infested with the locust borer (*Megacyllene robiniae*) which limits its competitiveness. Sourwood (*Oxydendrum arboreum*), also a volunteer, had the second-highest average density although it occurred within only 15 measurement plots. Sourwood, an appropriate site occupant at this successional stage, is a slow-growing, small tree that does not occur as a dominant component of mature forest canopies.

Overall survival of planted species is calculated at 33% (Table 5), likely an overestimate as some species that were planted may also have volunteered. Two planted species, ash and white oak, were among the four species with highest importance values. However, both species were observed within some measurement plots at higher densities than would have been expected based on average planting rates. Dogwood (*Cornus sp.*), a planted species throughout the site, also occurred at some measurement plots at greater than average planting densities, indicating it may also have established as a volunteer.

The highest survival rates were calculated for dogwood and ash. American sycamore (*Platanus occidentalis*) and burr oak, planted in only mixes 3 and 4, also survived at high rates relative to other species. Red maple (*Acer rubrum*) and dogwood were also observed in significant numbers within the areas designated for planting mixes 3 and 4. Of the planted species, sugar maple (*Acer saccharum*) and chestnut oak (*Quercus prinus*) had the lowest survival rates.

The volunteer black locust was responsible for ~30% of all woody volume recorded the largest fraction by any single species. Three planted species -- American sycamore, ash, and burr oak – and the planted shrub bristly locust also had high volume. Of those species occurring on >10% of measurement plots, American sycamore, black locust, and burr oak had the greatest volume per tree.

All measurement plots had at least one tree. Combined density by planted and volunteer trees ranged from 100 to 5800 trees per ha (Fig. 5). Planted and volunteer tree densities were positively correlated (Spearman's rho = 0.19) but that correlation was weak ($0.05 < p < 0.10$).

Table 5. Survival of planted trees, by site type[†] / planting mix and overall.

	Living Trees (n/ha)					Survival Rates				
Site type / planting mix	SS moist, 1	SS dry, 2	SiS loose, 3	Compact, 4	Avg	SS moist, 1	SS dry, 2	SiS loose, 3	Compact, 4[‡]	Avg
ash	208	217	242	238	222	56%	44%	82%		56%
white oak	120	156	67	38	104	32%	31%	22%		26%
sycamore			108	31	25	-	-	37%		39%
burr oak	16	28	158	15	44	-	-	53%		68%
n. red oak	100			8	38	27%	-	-		23%
white pine	36	28		8	22	29%	22%	0%		18%
chestnut oak		50		15	16	-	10%	-		10%
dog wood	24	128	58		53	39%	207%	94%		86%
red maple			58	23	15	-	-	20%		23%
sugar maple	32				12	9%	-	-		7%
Total	536	606	692	377	551	32%	36%	41%	23%	33%

[†] SS = predominantly sandstone; SiS = predominantly siltstone and shale.

[‡] Species survival rates are not calculated for compacted sites planted with mix 4, but Mix 4 surviving trees are considered in calculating site averages.

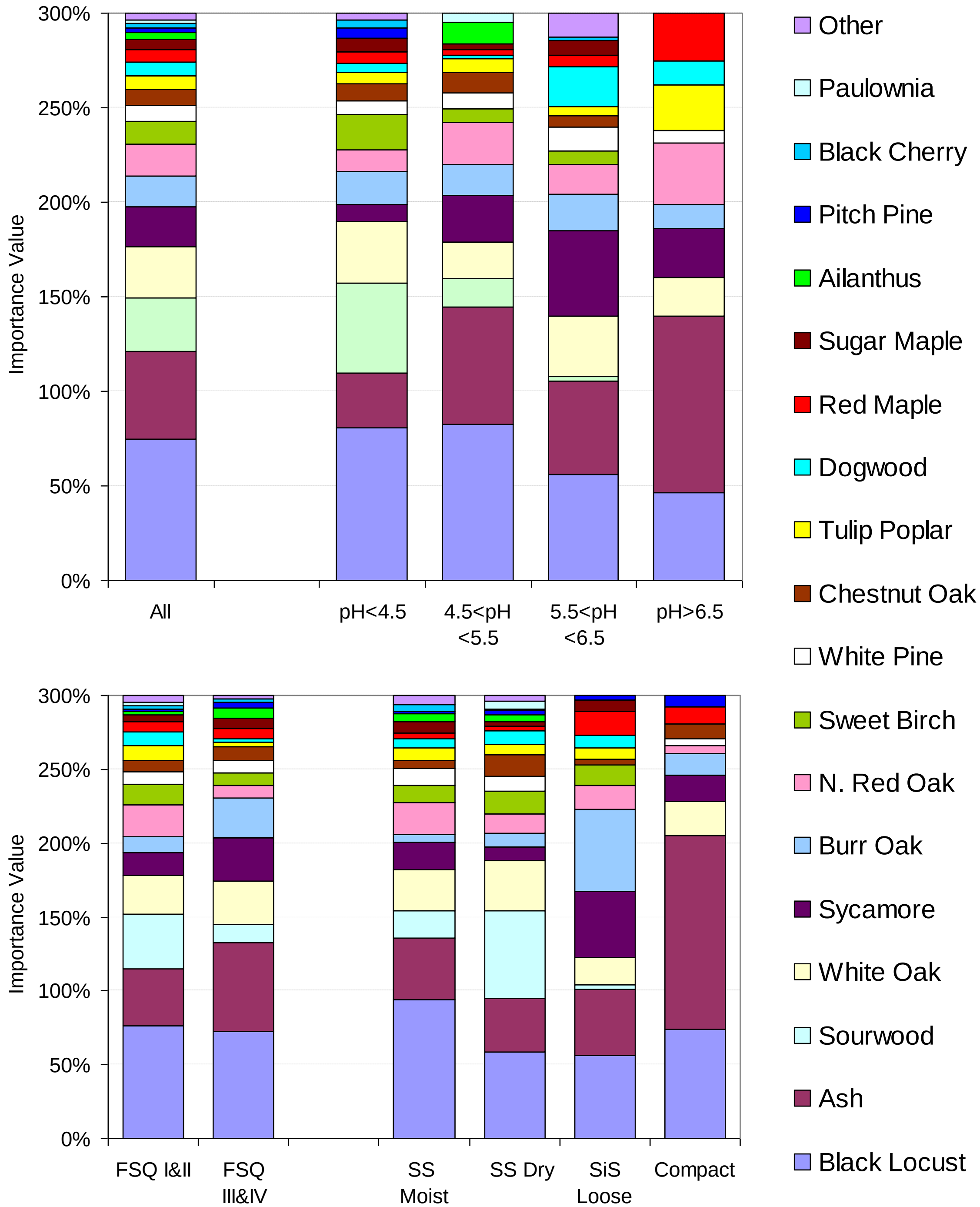

Figure 4. Importance value metrics for all measurement plots; and for soil pH classes, forest site quality (FSQ) classes, and site types (SS = sandstone, SiS = siltstone). "Other" are species that did not achieve importance values > 5% overall or within any soil pH class, FSQ class, or site types (eastern redbud, cottonwood, scarlet oak, Virginia pine, sassafras, and serviceberry).

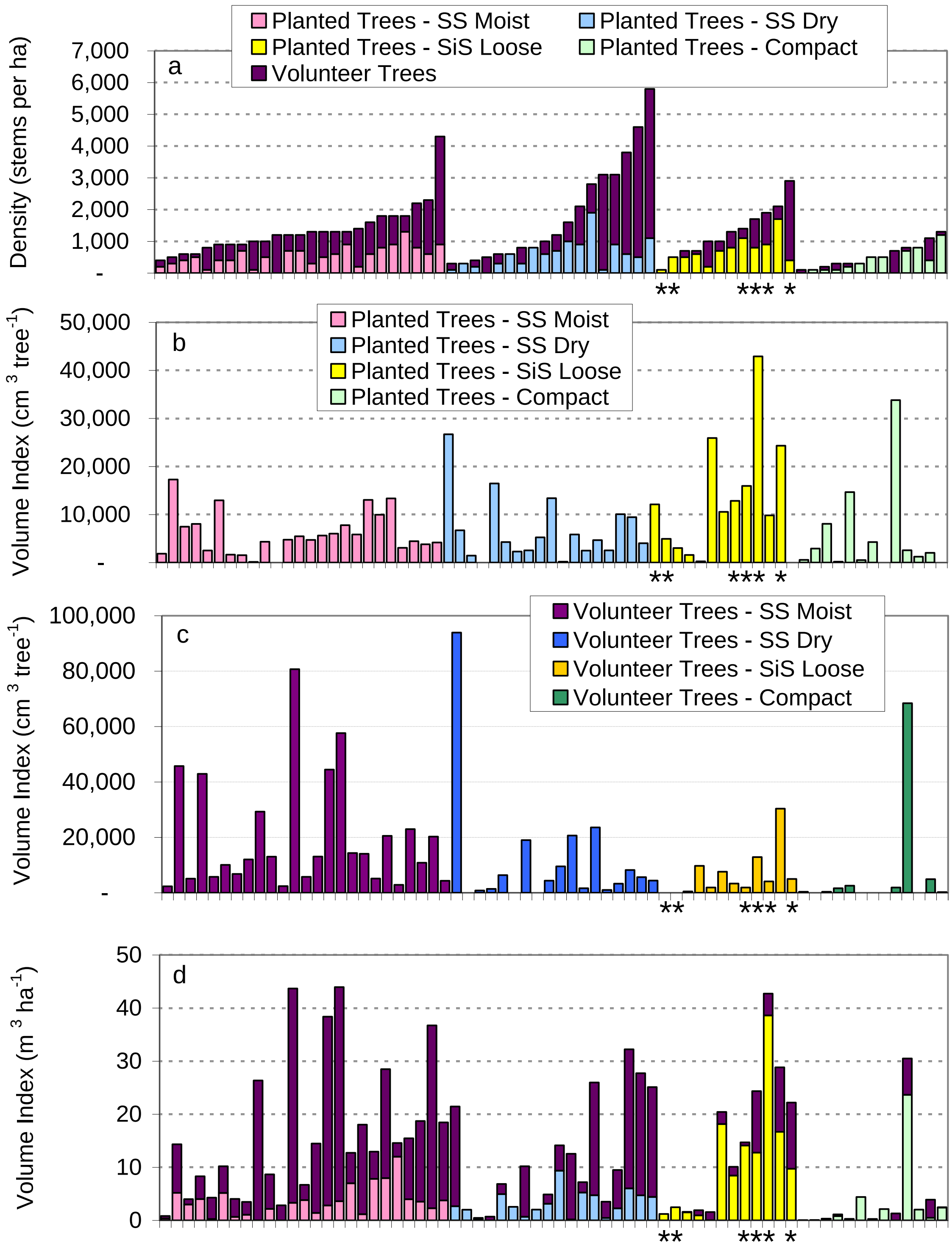

Figure 5. Density by planted and volunteer trees (a); planted and volunteer trees' average volume (b and c); and total volume by planted and volunteer trees (d). X-axes for all charts are identical: the measurement plots ordered, from left to right by site type and by total density within each site type. Chart (a) legend also applies to chart (d). *s designate the acidic soil mapping unit H, as discussed in the text.

Soil and Site Properties' Relationships with Reforestation Indicators

Few significant correlations between reforestation indicators (density, average per-tree volume, and total volume, for planted trees and volunteers) and CF rock-type compositions (data not shown) were found, and most of those that did occur were weakly significant ($0.05 < p < 0.10$). Exceptions included the CF content of coal and coal-like materials which was negatively correlated with several growth metrics. Given the significant correlations of soil CF and those fragments' coal content with slope (Table 3), these correlations may reflect the observed association of lower soil densities with steeper slopes. Slope is positively correlated with several density and growth metrics (Table 6), a likely consequence of compaction effects since some near-level soils were compacted by mining equipment (Fig. 1). Soil CF contents were positively correlated with average per-tree volume index, a possible result of the higher CF contents of soils on steeper slopes.

Table 6. Correlations of soil and site properties to planted (P) and volunteer (V) tree establishment and growth metrics.

Variable	Coarse Fragments (%)	Slope (%)	pH	SS (ppm)	Distance (m) to Tree Line
	- - - - - - - - Correlation Coefficients - - - - - - - -				
P Density (stems ha^{-1})	0.06	0.43***	- 0.04	- 0.13	- 0.18
V Density (stems per ha)	- 0.08	0.36***	- 0.44***	- 0.06	- 0.19
P + V Density (stems per ha)	- 0.07	0.44***	- 0.36***	- 0.11	- 0.25**
P Volume Index (cm^3 $tree^{-1}$)	0.13	0.07	- 0.14	- 0.11	0.13
V Volume Index (cm^3 $tree^{-1}$)	0.22 *	0.32**	0.11	- 0.21	0.03
P + V Volume tree (cm^3 $tree^{-1}$)	0.25 **	0.36 ***	- 0.06	- 0.14	0.07
P Volume Index (m^3 ha^{-1})	0.23 *	0.36***	0.07	- 0.19	0.01
V Volume Index (m^3 ha^{-1})	0.06	0.46***	- 0.21*	- 0.09	- 0.17
P + V Volume Index (m^3 ha^{-1})	0.11	0.47***	- 0.21*	- 0.16	- 0.12

Soil pH was negatively correlated with volunteer density and, by extension, with combined density by planted and volunteer trees, and was weakly correlated with volunteer and total (per-ha) volume index.

Distance to tree line was negatively correlated with total density. The top four per-plot densities for both planted and volunteer trees, respectively, were within 30 m of the un-mined forest areas bounded by the tree line. The three highest-stocked plots for sourwood, white oak, dogwood, and tulip poplar (*Liriodendron tulipifera*) were all within 30 m of the tree line.

<u>Soil pH</u>

Soil pH was not significantly correlated with slope or tree line distance (Table 3). Soils with pH<4.5 had higher soluble salt contents than 4.5<pH<5.5 soils (Table 7), indicating potential contributions by pyritic materials to pH<4.5 values. The lowest soil pH recorded was 3.2; all other soil pHs were >3.5.

Soil pH exhibited significant but negative relationships with both volunteer and total density (Table 6), indicating that volunteers established preferentially on lower pH sites. A comparable result occurred when analysis was performed by grouping sites by pH class (Table 7), as both volunteer and total density were greatest on pH<4.5 soils, but no planted tree density differences were noted. Total volunteer volume at pH<4.5 was also greater, on average, than at pH>6.5.

Densities for the most common volunteer species (black locust, sourwood, and sweet birch, *Betula lenta*) all showed statistically significant and negative associations with soil pH; white oak and ash both showed weakly significant associations with soil pH, negative for white oak and positive for ash (data not shown). Average volume per tree, however, showed no significant association with soil pH for any of the widely planted or prominent volunteer species.

Black locust had the highest importance values where pH<6.5, but ash species had a higher importance value at pH>6.5 (Fig. 4). Importance values for red maple, tulip poplar, and northern red oak (*Quercus rubrum*) were also greater when pH>6.5 than at lower soil pH levels, but these species' density and growth metrics did not show a statistically significant response to soil pH (data not shown); their increased importance at higher pH's occurred because some other species responded negatively to increasing pH, leaving these species as more dominant stand components. For example, black locust's density was strongly and negatively correlated with pH (p<0.01; data not shown). No chestnut oak or sugar maple were recorded at pH>5.9, and two volunteer pine species (pitch pine, *Pínus rígida*; and Virginia pine, *Pinus virginiana*) occurred only where pH<4.5. White and northern red oak established and grew across a range of soil pH values. White oak's density was negatively correlated with pH, but that correlation was weak (0.05<p<0.10).

Table 7. Variation of selected soil properties and of planted (P) and volunteer (V) tree establishment and growth metrics among soil pH groups.

	Soil pH group			
	pH<4.5	4.5<pH<5.5	5.5<pH<6.5	pH>6.5
Number of Measurement Plots	25	22	13	8
Soil coarse fragments (%)	55^{b}	53^{b}	65^{a}	60^{ab}
Soil soluble salts (ppm)	234^{a}	119^{b}	146^{ab}	141^{ab}
Slope (%)	37	33	39	48
Distance to tree line (m)	155	176	152	111
P Density (stems per ha)	548	486	646	588
V Density (stems per ha)	$1,324^{a}$	559^{b}	354^{b}	225^{b}
P + V Density (stems per ha)	$1,872^{a}$	$1,045^{b}$	$1,000^{b}$	813^{b}
P Volume Index (cm^3 $tree^{-1}$)	7,824	8,168	8,671	5,535
V Volume Index (cm^3 $tree^{-1}$)	7,726	21,819	16,829	14,747
P + V Volume Index (cm^3 $tree^{-1}$)	7,643	12,551	12,766	7,015
P Volume Index (m^3 ha^{-1})	4.3	5.2	3.9	3.6
V Volume Index (m^3 ha^{-1})	8.9^{a}	9.8^{ab}	5.7^{ab}	3.0^{b}
P + V Volume Index (m^3 ha^{-1})	13.3	15.0	9.7	6.6

pH Group means followed by different letters are significantly different (p<0.05).

Forest Site Quality Class

For this analysis, FSQ classes I and II were combined and compared to combined classes III and IV, creating two groupings with similar plot numbers. FSQ classes I&II occurred on steeper slopes, with lower soluble salts, and closer to the tree line, on average, than FSQ classes III&IV

(Table 8). Both planted and volunteer tree density varied with FSQ class, with FSQ I&II having greater density as expected.

Per-tree and total volume did not differ statistically among FSQ class groupings for planted trees (Table 9), in part because tree species used only in tree planting mixes 3 and 4 – American sycamore, burr oak, and red maple – survived well on FSQ III&IV sites. Both volunteer and total volume ha^{-1} for FSQ I&II exceeded FSQ III&IV. Average volunteer per-tree volume did not differ statistically by FSQ class, in part because small-statured volunteer species (including sourwood) were prolific on FSQ I&II areas.

Average per-tree volume was nominally greater on FSQ I&II than on FSQ III&IV sites for species including chestnut oak, northern red oak, sweet birch, sugar maple, sourwood, sycamore, tulip poplar, and eastern white pine (data not shown), but that difference was statistically significant only for black locust. In contrast, pitch pine and burr oak had greater nominal growth on Class III & IV sites.

Species' Importance Values also varied by FSQ class. Black locust did well on all FSQ classes, while ash, sycamore, white oak, and burr oak were more important as stand components on FSQ III&IV sites. In contrast, sourwood, northern red oak, sweet birch, and tulip poplar were had higher importance values on FSQ I&II sites.

Site Type Differences

Site-type effects on stand establishment represent both site characteristics and the different tree-planting prescriptions. Planting mixes 1 and 2 were applied to what were expected to be more productive sites (loose graded, with a significant component of sandstone spoil materials). The loose siltstone/shale-dominated sites, planting mix 3, were located on two soil units with contrasting properties: Unit H, apparently containing pyritic materials and acidic (mean pH = 3.9); and unit L, with a relatively high pH (mean = 6.6); mapping unit L was closer to the tree line than unit H. Mix 2 sites (dry) were closer to tree lines than mix 1 (moist) and mix 4 sites (compact).

Table 8. Variation of selected soil properties, of planted (P) and volunteer (V) tree density and volume metrics with forest site quality class.

	- - Forest Site Quality Class[†] - -				- Combined Classes[‡] -	
	I	II	III	IV	I & II	III & IV
Number of Mapping Units	1	7	6	3	8	9
Number of Measurement Plots	2	31	24	11	33	35
Soil Coarse Fragments (%)	64	59	55	53	59	54
Soil pH	4.8	5.2	4.9	4.8	5.2	4.9
Soil soluble salts (ppm)	115	109	207	267	109 [b]	226 [a]
Slope (%)	64	54	20	23	54 [a]	21 [b]
Distance to tree line (m)	33	121	205	168	116 [b]	194 [a]
P Density (stems per ha)	1,400	613	417	518	661 [a]	449 [b]
V Density (stems per ha)	1,050	1,068	467	491	1,067 [a]	474 [b]
P + V Density (stems per ha)	2,450	1,681	883	1,009	1,727 [a]	923 [b]
P Volume Index (cm^3 $tree^{-1}$)	4,167	7,480	6,464	12,804	7,273	8,445
V Volume Index (cm^3 $tree^{-1}$)	2,601	15,107	7,556	4,342	14,955	14,385
P + V Volume Index (cm^3 $tree^{-1}$)	6,351	10,738	0,653	8,003	10,472	9,820
P Volume Index (m^3 ha^{-1})	5.0	4.6	2.7	7.8	4.6	4.3
V Volume Index (m^3 ha^{-1})	11.6	11.1	5.8	2.7	11.1 [a]	4.8 [b]
P + V Volume Index (m^3 ha^{-1})	16.6	15.7	8.5	10.5	15.8 [a]	9.1 [b]

[†] Site quality class means are calculated from measurement plots; statistical comparisons not performed.

[‡] Combined class means are calculated from measurement plots. Means followed by different letters are significantly different ($p<0.05$).

Table 9. Effects of tree-planting mix-specific species† on planted trees' density, by forest site quality class grouping.

Mix	Mix-specific species†	Mix fraction (trees only)	Fraction of planted trees, where planted, by Forest Site Quality Class I&II	III&IV	All
1	Northern red oak, sugar maple	44%	29%	16%	21%
2	Chestnut oak	30%	10%	4%	7%
3	American sycamore, burr oak, red maple	53%	38%	58%	51%
4	All above	n/a	n/a	24%	24%

† Tree species that were included in only one of the three primary tree planting mixes.

Density and volume metrics on compacted areas (mix 4) demonstrated consistent differences with other areas (Table 10), as both planted and volunteer trees performed poorly. The only metric not showing this effect was planted trees' average volume, as ash constituted >50% of surviving planted trees and grew well.

Volunteers' volume metrics were greater for areas planted with mix 1, moist sites with predominantly sandstone spoils, than for mix 3 and mix 4 areas (Table 10).

Variation of importance values for tree species among site types was evident. Black locust had high importance values on all site types, especially on those planted with mixes 1 and 4. Black locust gained its prominence on sandstone-dominated moist (mix 1) areas primarily through rapid growth and was responsible for 46% of these areas' total volume. It was also a major contributor on the compacted (mix 4) areas with 31% of total volume. Sourwood was also prominent on the sandstone-dominated un-compacted areas (mixes 1 and 2). Burr oak and sycamore were prominent on siltstone/shale dominated sites where they comprised 36% of trees planted and 46% of total volume index. These species did well on both mapping units L and H, with average per-tree volumes exceeding all other species; but they were more prominent on the alkaline mapping unit H (mean density = 333 trees ha^{-1}, constituting 62% of planted trees and 38% of all living trees) than on the acidic unit L (200 trees ha^{-1}; 19% of planted trees and 13% of all trees).

Table 10. Variation of selected soil properties, of tree density and volume metrics with site type and associated tree planting mix.

	- - Site Type / Tree Planting Mix† - -				SiS Loose / Mix 3 Soil Units‡	
	SS Moist, 1	SS Dry, 2	SiS Loose, 3	Compact, 4	H	L
No. Measurement Plots	25	18	12	13	6	6
No. of Plots: FSQ I&II	16	11	6	0	0	6
No. of Plots: FSQ III&IV	9	7	6	13	6	0
Soil Coarse Fragments (%)	58 ^{a}	56 ^{ab}	63 ^{a}	49 ^{b}	55	70
Soil pH	4.9	5.0	5.3	5.1	3.9 ^{x}	6.6 ^{y}
Soil soluble salts (ppm)	191	170	169	126	246 ^{x}	92 ^{y}
Slope (%)	46 ^{ab}	34 ^{b}	54 ^{a}	9 ^{c}	34 ^{x}	74 ^{y}
Distance to tree line (m)	170 ^{a}	86 ^{b}	151 ^{ab}	231 ^{a}	66 ^{x}	26 ^{y}
P Density (stems per ha)	536 ^{ab}	606 ^{ab}	692 ^{a}	377 ^{b}	633	750
V Density (stems per ha)	808 ^{a}	1,250 ^{a}	583 ^{a}	162 ^{b}	783	383
P + V Density (stems per ha)	1,344 ^{a}	1,856 ^{a}	1,275 ^{a}	538 ^{b}	1,417	1,133
P Volume Index (cm^3 tree $^{-1}$)	6,239	6,956	13,685	6,431	18,846	8,524
V Volume Index (cm^3 tree $^{-1}$)	19,685 ^{a}	13,578 ^{ab}	7,714 ^{b}	10,023 ^{b}	5,959	8,884
P+V Volume Index (cm^3 tree $^{-1}$)	12,887 ^{ab}	9,551 ^{c}	10,042 ^{bc}	5,743 ^{d}	11,998	8,086
P Volume Index (m^3 ha $^{-1}$)	3.5 ^{b}	3.1 ^{ab}	10.4 ^{a}	2.8 ^{b}	13.2	7.6
V Volume Index (m^3 ha $^{-1}$)	13.0 ^{a}	8.5 ^{ab}	3.9 ^{b}	0.9 ^{c}	4.8	3.1
P + V Volume Index (m^3 ha $^{-1}$)	16.4 ^{a}	11.6 ^{a}	14.3 ^{a}	3.8 ^{b}	17.9	10.7

† Planting mix means followed by different letters are significantly different from one another ($p<0.05$).
‡ Mapping unit means followed by different letters are significantly different from one another ($p<0.05$)

Discussion

Reclamation procedures were intended to encourage establishment of planted and volunteer forest trees and a forest with similar composition and productivity of the pre-mining forest. These data indicate those efforts were effective over much of the site. Studies of older mine sites reclaimed using conventional methods are often dominated by non-native herbaceous species, and invasive or early-successional woody species (Simmons et al. 2008; Zipper et al. 2011a). Over most of this site, native woody species with potential to form mature forest were dominant vegetative components. Black locust, the most common species, is an early successional invader but has potential to grow into the mature forest canopy. Most of the other high-frequency woody species are also present in the region's mature forest. Density was ≥ 1000 trees ha^{-1} over > 50% of the site's area.

Both volunteer and planted species were major contributors to reforestation success on the strongly and moderately acidic soils that were established intentionally over most of this mine site, but more than half of total density (59%) was comprised of volunteers. Other studies have found prolific volunteering of native trees on older Appalachian mine sites with soils similar to those of native forests (Brenner et al. 1984; Holl and Cairns 1994; Skousen et al. 1994, 2006).

The most common native volunteer (black locust), planted shrub (bristly locust), and non-native invasive woody species (autumn olive) are capable of fixing atmospheric N. Mine soils constructed from rock materials in the Appalachians are often lacking in plant available N (Li and Daniels 1994). Other studies have noted the tendency for N fixing plant species to proliferate on Appalachian mine sites (Zipper et al. 2011a).

On this reclaimed mine, survival by planted trees (~33%) was lower than has been documented in other studies of Appalachian mines reclaimed using methods intended to stimulate forest re-establishment, although those studies have taken place on controlled experimental areas and over shorter time frames. Working in West Virginia, Emerson et al. (2009) reported survival rates ranging from 59% and 88%; while Angel et al. (2008) found survival exceeding 80% on un-compacted weathered and unweathered sandstones after two years in eastern Kentucky. Those sites were more favorable in some respects to planted trees' establishment than this site. First, those study sites were not seeded with herbaceous vegetation, which can inhibit planted trees' establishment (Davidson et al. 1984; Chaney et al. 1995; Burger et al. 2008). Also, planted trees on those sites were not subjected to the vigorous competition from volunteers as occurred here. Our site was older and directly adjacent to and often downslope from forested areas, allowing gravity and wind to carry live seeds into the reclamation area. This combination of close proximate factors is generally not present on Appalachian mines, which are often larger and with reclamation areas upslope from the nearest forest seed sources. Studies have shown, however, that the soil conditions associated with high rates of volunteer establishment on this site (e.g. un-compacted and moderately acidic) are also conducive to survival by planted native trees (e.g. Angel et al. 2008; Emerson et al. 2009).

Another factor that may have depressed survival was variable site conditions. Most areas with low slope had been compacted by mining equipment and had few living trees. Prior studies have shown that high soil densities inhibit planted trees' survival and growth (Torbert et al. 1988; Andrews et al. 1998; Skousen et al. 2009). Dense soils create unfavorable conditions for trees (Pritchett and Fisher 1987; Gale et al. 1991).

Soil chemical properties on some areas appear to have limited both survival of planted tree species native to Appalachian upland forest and recruitment of volunteers. Volunteer density was negatively correlated with soil pH (Table 6), indicating less recruitment on high pH soils; the most recruitment occurred on the most acidic soil areas (pH<4.5); and volunteers grew more slowly on pH>6.5 soils than on other site areas. These findings are consistent with prior studies that found acidic mine spoils to be favorable and alkaline spoils to be unfavorable for growth of planted trees and for recruitment of unplanted species (Angel et al. 2008; Emerson et al. 2009). In southern West Virginia, Skousen et al. (1994) found high densities of volunteered native trees on older mine sites with acidic soils (pH<5.0). Also in West Virginia, Skousen et al. (2006) found fewer volunteer species and lower densities on bench areas, with higher pH's and denser soils, than on out-slope areas with looser and more acidic soils. Unweathered spoils constitute the bulk of mine spoils on large Appalachian surface mines and are commonly alkaline when non-pyritic (Haering et al. 2004). Thus, purposeful placement of weathered and acidic spoils as a plant-growth medium, as occurred over much of this site, will generally be favorable to reforestation (Skousen et al. 2011).

Unlike the volunteers in our study, planted trees' density was not associated with soil pH. One factor contributing to that finding was that two tree species not occurring commonly as components of upland forests in Appalachian coalfields, burr oak and American sycamore, were planted preferentially and survived well on some higher-pH spoil areas. Ash, likely a combination of planted white ash with volunteered green ash, was also prominent as a stand component on site areas with soil pH>6.5. These species have an affinity for soils with a neutral pH and can tolerate alkaline soils.

Given the stocking, composition, and productivity of this new, young forest, we expect it to develop into an Appalachian hardwood forest similar to the surrounding forest. Few studies, however, have assessed whether a combination of planted trees and invading volunteers are able to fully restore forest tree communities to reclaimed Appalachian mine sites over the long term (e.g. Holl 2002).

A key strategy of the FRA is to plant site-specific, silviculturally-compatible species mixes, composed of mid- to late-successional species that will accelerate stand development and have a composition of native trees similar to the surrounding un-mined forest. This requires planting the slower-growing, heavy-seeded species that are important components of the native forest, allowing them to compete at an early stage of stand development. Ecologically, this is a short-term initial floristics successional strategy whereby the species composition expected in the maturing forest is largely a result of the combination of planted and volunteer species managed at time of establishment (Egler 1954). Without site management and site-specific species selection, a long-term (200+ years) relay-floristics strategy would be expected, whereby early-successional and some invasive species persist for long periods while finally yielding to late successional species common to surrounding native forest.

Conclusions

A mine site in Buchanan County, Virginia, was reclaimed using methods intended to establish forest trees in early 2002. These reclamation methods included low-compaction grading and application of weathered spoil materials for mine soil construction over most areas. Because soil conditions varied, different tree planting mixes were prescribed in an effort to ensure successful reforestation. After nine years, the majority of living trees are non-planted and of native species. Volunteer tree density and total volume varied in response to soil and site conditions. Both volunteer and planted trees were suppressed on compacted and alkaline soil areas. On non-compacted areas, overall density and growth by planted trees exhibited few differences that could be directly related to site conditions, in part because tree species selected for planting on conditions poorly suited for most native forest species were able to establish and grow. Volunteers established and grew best on more acidic soils, where soils were not compacted, and on areas rated as having higher forest site qualities. More time is needed to validate the success of this FRA-reclaimed mine site. Given the stocking, growth and compositional trajectories observed and measured since stand establishment, we predict that this new forest will be similar to and provide ecosystem services similar to those provided by the forest prior to mining.

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