Rebuilding Soils on Mined Land for Native Forests in Appalachia

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The eastern U.S. Appalachian region supports the world's most extensive temperate forests, but surface mining for coal has caused forest loss. New reclamation methods are being employed with the intent of restoring native forest on Appalachian mined lands. Mine soil construction is essential to the reforestation process. Here, we review scientific literature concerning selection of mining materials for mine soil construction where forest ecosystem restoration is the reclamation goal. Successful establishment and productive growth of native Appalachian trees has been documented on mine soils with coarse fragment contents as great as 60% but with low soluble salt levels and slightly to moderately acidic pHs, properties characteristic of the region's native soils. Native tree productivity on some Appalachian mined lands where weathered rock spoils were used to reconstruct soils was found comparable to productivity on native forest sites. Weathered rock spoils, however, are lower in bioavailable N and P than native Appalachian soils and they lack live seed banks which native soils contain. The body of scientific research suggests use of salvaged native soils for mine soil construction when forest ecosystem restoration is the reclamation goal, and that weathered rock spoils are generally superior to unweathered rock spoils when constructing mine soils for this purpose.

Abbreviations: CF, coarse fragments (>2 mm); EC, electrical conductivity; SI, site index; SMCRA: Surface Mining Control and Reclamation Act.

Eastern U.S. Appalachian region supports the world's most extensive temperate deciduous forests (Riitters et al., 2000), but those forests are being lost due to expanding surface coal mining. Appalachian forests are significant ecological and commercial resources, with nearly 40 commercially important trees and associated plant species forming what are among the world's most diverse non-tropical ecosystems (Ricketts et al., 1999). Appalachian forests also store large quantities of C in soil and biomass, and they provide ecosystem services, including watershed and water quality protection, and plant and faunal habitat. The region's forests provide commercial timber, support a forest industry that is a major regional employer, and supply forest products for economic uses worldwide. Coal surface mining is also an important industry and employer within the region.

More than 600,000 ha of land have been mined for coal in Appalachia since the late 1970s (Zipper et al., 2011b). Over that time, the Appalachian region has experienced significant forest loss and fragmentation (Wickham et al., 2007; Sayler, 2008; Townsend et al., 2009; Drummond and Loveland, 2010). Zipper et al. (2011a) assessed 25 mine sites randomly selected from mining agency databases in four states, mined and reclaimed under the Surface Mining Control and Reclamation Act (SMCRA), and found these lands not in active

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use or management. Dominant vegetation on more than half of surveyed areas was non-native, including tall fescue (*Festuca arundinacea* Schreb.), sericea lespedeza [*Lespedeza cuneata* (Dum. Cours.) G. Don], and autumn olive (*Elaeagnus umbellata* Thunb.). Given the Appalachian forests' ecologic and economic value, these findings give rise to concerns of progressive forest loss due to expanding coal surface mining.

Coal mine reclamation in the United States is governed by the SMCRA, a federal law established in the late 1970s that requires mining firms to restore post-mining land to "a condition capable of supporting the uses which it was capable of supporting before any mining, or higher or better uses for which there is reasonable likelihood …" (515 b 2). The SMCRA contains the general performance standard (515 b 5): "…remove the topsoil from the land in a separate layer, replace it on the backfill area, …except if topsoil is of insufficient quantity or of poor quality for sustaining vegetation, or if other strata can be shown to be more suitable for vegetation requirements, then the operator shall remove, segregate, and preserve in a like manner such other strata which is best able to support vegetation."

In response to Appalachian forest loss, new reclamation practices have been developed. Some mining firms are implementing a "forestry reclamation approach" in an effort to restore native forests on reclaimed areas (Burger et al., 2005; Zipper et al., 2011b). This method calls for mining firms to "Create a suitable rooting medium for good tree growth that is no less than 1.2 m deep and comprised of topsoil, weathered sandstone and/or the best available material" (Burger et al., 2005). It is well known that soil compaction and restricted rooting depth will inhibit or prevent forest re-establishment on mine sites (Davidson et al., 1984; Torbert et al., 1988; Andrews et al., 1998; Jones et al., 2005; and other studies). This manuscript focuses on material selection for mine soil construction, recognizing that low bulk densities and adequate rooting depths are essential for optimum tree growth.

Here we review scientific literature concerning selection of disturbed materials for surface placement as mine soils when attempting to restore native forest ecosystems on Appalachian coal mines. As background, we describe mine soil construction practices as they generally occur in Appalachia. Then we describe studies that have identified mine soil material characteristics that are favorable to Appalachian forest vegetation reestablishment and growth, studies conducted as direct mine soil material comparisons, and studies which assess mine soil properties that influence forest productivity. We conclude by synthesizing the above information to describe material selection practices for soil construction when attempting to restore native forest on Appalachian coal surface mines.

Throughout, we use the term "mine spoil" to mean all non-coal materials disturbed by the mining operation, including rocks, rock fragments, soil and other natural materials; and the term "mine soil" to describe mine spoil materials placed on the surface as a plant growth medium, both initially and as it develops soil-like properties. We use the term "native soil" to describe the soil present before mining, including the O, A, E, B, and C soil horizons; and the term "rock spoils" to describe all mining-disturbed materials located beneath the native soil.

Mine Soil Construction

Coal surface mining removes vegetation, native soil, and rock spoils overlying coal as a means of extracting coal for economic use. The mine spoils are then redistributed to construct the postmining landscapes. The materials placed on the surface become mine soils. After placement and grading, surface materials are revegetated by hydroseeding with grasses, legumes, and fertilizer nutrients. If shrubs or trees are prescribed for reclamation, these are generally hand planted as bare-root seedlings. The nature of materials used for mine soil construction influences soil properties immediately following mining and reclamation (Roberts et al., 1988a; Torbert et al., 1990; Miller et al., 2012) and for as long as 28 yr later (Nash, 2012).

The Appalachian mountains are predominantly forested landscapes with soils that generally exhibit low cation exchange capacity, low organic matter content below the A horizon, and low natural fertility by agricultural standards (Buol et al., 1973; Rodrigue and Burger, 2004). Soils on side slopes are generally Inceptisols, relatively young soils with few diagnostic features that are often <1 m to rock. Soils forming on ridge tops and in coves are mostly Alfisols and Ultisols, which are older and deeper and have well-defined horizons. The sedimentary rocks immediately beneath the native soil are weathered, meaning that they have been affected by earth-surface environmental processes such as oxidation and leaching (Fig. 1). Typically, weathered rocks are brownish in color due to oxidation of Fe-bearing minerals. Beneath the weathered rocks are unweathered rocks, often grayish in color and of varying mineral composition. Most rocks associated with Appalachian coals are clastics: sedimentary sandstones, siltstones, shales, and mudstones.

Reduced-sulfur minerals, pyrites and sulfides, occur within certain geologic strata in the Appalachian mining regions. These minerals oxidize and acidify when exposed to water and oxygen (Singer and Stumm, 1970), often causing damage to water resources (Herlihy et al., 1990). Under SMCRA, rock spoils with high acid-forming potential must be managed to prevent such exposure. Other sedimentary rocks often contain carbonates within the minerals that bind their clastic components.

Rebuilding soil on mined land is essential to restoring land capability as required under SMCRA. For many years, mining firms used rock spoils for producing mine soils as an alternative to soil salvage and replacement. Rock spoils can vary widely in their physical and chemical constituency and suitability for various plant species. Because the unweathered non-pyritic rock spoils often maintain near-neutral to slightly alkaline soil pHs that are favorable to reclamation grasses (Roberts et al., 1988b; Haering et al., 2004) and are often less costly to access for mine soil construction, such materials have been and are often used as topsoil substitutes under SMCRA. Rapid establishment of agricultural grasses and legumes has been common reclamation

Fig. 1. Example of a stratigraphic profile of geologic materials disturbed by an Appalachian surface mine operating in previously unmined terrain. The uppermost materials are soils and vary in thickness between 0.3 and 1 m. The rock materials immediately below the soils to a depth of approximately 10 m are brownish in color because they have been affected by surface environmental processes, and are said to be "weathered." Below the weathered rocks are lighter-colored rock materials, often said to be "unweathered."

practice, encouraged by mine-regulating agencies as a means of preventing mining-related environmental problems (Angel et al., 2005). Hence, mining firms often conducted reclamation under SMCRA to establish post-mining land uses that were compatible with dense grasses and legumes. These include "pastureland" (Ditsch and Collins, 2000) and other uses that could be established through planting of woody species able to tolerate alkaline soil conditions and herbaceous competition such as "wildlife habitat" and "unmanaged forests" comprised of such plant species.

Mine soils constructed of rock spoils, when revegetated, often form soil-like properties over time including incipient soil horizons (Roberts et al., 1988a; Sencindiver and Ammons, 2000; Haering et al., 2004). However, such mine soils differ from native soils in several ways, especially when formed from unweathered rock spoils (Daniels and Amos, 1985). Although base cations (Ca, Mg, K) and S are often adequate for plant nutrition, these materials contain no pedogenic organic matter on initial placement and thus little to no plant available N and P unless fertilized. They have different hydrologic properties, as they have yet to undergo processes essential to soil development including aggregation and structure formation (Skousen et al., 1998). Aggregation and structure formation is a very slow process in mine soils that involves the downward migration of clays, Fe and Al oxides, and organic matter which accumulate in lower soil layers via precipitation and various bonding mechanisms (Sencindiver and Ammons, 2000). The lack of significant structural development for decades limits water infiltration, percolation and internal soil drainage, which in turn limits gas exchange and soil aeration, processes that are essential to deep-rooted plant species such as Appalachian forest trees. On the other hand, some properties of new mine soils constructed from unweathered materials can change rapidly as they undergo weathering. For example, some spoils undergo rapid physical disintegration following initial placement, transforming coarse fragments to soil fines and changing the particle-size distribution of the fine earth fraction (Roberts et al., 1988a), and they undergo physical settling and consolidation (Miller et al., 2012). Essential soil properties, including pH and soluble salt contents, can also change rapidly in mine soils constructed from unweathered spoils (Roberts et al., 1988a; Sencindiver and Ammons, 2000). Historically, soil compaction by mining equipment has often influenced mine soil development, but current practices often aim to avoid soil compaction when reforestation is the reclamation goal.

Mine Soil Properties Influencing Reforestation Potentials

Mine spoil properties and their treatment influence mine soil development, and these mine soils control reforestation potentials. A series of field studies has been conducted to determine mine soil properties which are most influential to tree growth (Table 1). Each study defined a reforestation success metric that is comparable across sites, and then evaluated a suite of soil physical and chemical factors and the reforestation success metric across a number of field sites. The scientists conducted various statistical analyses to determine relationships of the reforestation success metric with measured soil properties. Eastern white pines (*Pinus strobus* L.) were sometimes used in these studies because they were widely planted on mines in the 1980s and 1990s; and they occur naturally in mixed hardwood forest stands in the central Appalachians, indicating preference for similar soil properties as many native hardwoods (Braun, 1964; Smith, 1994).

Physical properties controlled by spoil selection include particle sizes. The mass-fraction comprised of soil fines (<2 mm-sized particles), inversely expressed as coarse-fragment (CF) content, affects the soil's ability to provide plants with water and nutrients. Mine soils often have high CF contents relative to what is typical in natural soils. Although Andrews et al. (1998) found mine soil CF content did not exert a primary influence on white pine productivity, Torbert et al. (1988) found soil fines to be a positive influence on white pine growth when expressed as a component of rooting volume index in mine soils with CF contents ranging up to 90% (Table 1). Zipper et al. (2011a) reported nominally higher CF contents on pre-SMCRA mine sites with poor productivity (mean = 66%) than on sites with restored productivity (mean = 50%). We interpret these data to indicate that CF contents of <~60% are generally adequate for forest tree re-establishment when other soil properties are favorable.

The particle-size distribution of soil fines is another influential soil property. Silts and clays are essential to a soil's capability to provide adequate nutrition and water to growing plants, and low levels of sands in the soil matrix are generally favorable to water and nutrient retention. In mine soils, however, high silt+clay fractions (the fraction of soil fines comprised of silts and clays) can limit tree productivity (Jones et al., 2005; Showalter et al., 2007), likely by restricting soil aeration and drainage. Sandy loam and sandy clay loam textures in mine soils are generally considered favorable for trees (Burger et al., 2005). However, soil fine contents may be less influential where soil drainage is aided by landscape features, as slope has been found to have a positive association with planted trees' growth (Andrews et al., 1998).

Soil chemical properties are also influenced by material selection. The soil measure known as soluble salts, commonly quantified by measuring electrical conductivity (EC) in a soil/water solution (Rhoades, 1996), has been found to be negatively associated with reforestation success metrics (Torbert et al., 1988; Andrews et al., 1998; Rodrigue and Burger, 2004). We interpret these findings to indicate that native Appalachian trees are adapted to growing in soils with dilute soil solutions, such as those that occur within the region's native soils. Unweathered rock spoils subjected to leaching by dilute waters commonly produce higher levels of soluble salts than do weathered spoils (Orndorff et al., 2010). In situ weathering can lower mine soils' EC over time (Burger et al., 2007; Nash, 2012). Because relevant studies have been conducted using different soil/water ratios when measuring EC and because EC changes over time due to weathering, we are unable to interpret current studies to suggest an EC threshold for use in mine soil selection for reforestation.

Table 1. Summary of field studies of soil properties influencing reforestation

Study	Reforestation success metric	Soil properties influencing reforestation success metric	
		Positive	Negative
Torbert et al. (1988)	Height of 34 10-yr-old eastern white pines in Virginia	Rooting volume index (rooting depth × percent soil fines)	Electrical conductivity
Andrews et al. (1998)	Two-year terminal height growth at ages 4 to 5 of 5- to 9-yr-old eastern white pines at 78 sampling locations in southern West Virginia and Virginia	Rooting depth, slope, bicarbonate-extractable P	Electrical conductivity, exchangeable Mn
Rodrigue and Burger (2004)	White-oak-equivalent site index for 14 pre-SMCRA mine sites in seven eastern and midwestern states	Percent soil fines, available water, C horizon porosity, base saturation	Electrical conductivity
Jones et al. (2005)	Growth of 10- to 18-yr-old eastern white pines at 52 sampling locations in Virginia and southern West Virginia, expressed as 50-yr site index equivalent	Rooting depth Influence by nonlinear functions of silt+clay fraction of soil fines (with ~30–40% as most favorable) and soil pH (with ~4.5–5.8 as most favorable)	Soil density
Showalter et al. (2007)	Height of 72 3-yr-old white oaks on a mine site with variable soil properties in Virginia	Mehlich-extractable K, mineralizable N, bicarbonate-extractable P, microbial biomass	Silt+clay fraction of soil fines, soil pH
Zipper et al. (2012)	Volunteer tree stems at 68 measurement points on a mine site with variable soil properties in Virginia	Slope	Soil pH

Soil pH varies widely among mine soils and is influenced by material selection. Fresh, unweathered non-pyritic sandstones, siltstones, and shales often give rise to soil materials with pHs ranging from 7.0 to 8.5 when used for soil construction (Roberts et al., 1988a; Angel et al., 2008; Emerson et al., 2009; Miller et al., 2012) in contrast to the moderately acidic pH range (~4.5–~6.5) that is common in Appalachia's native soils (Cotton, 2006; Simmons et al., 2008). Roberts et al. (1988a) found mine soils constructed from unweathered siltstones declined from pH 7.1 to 6.4 over 2 yr, but other mine spoils were found more resistant to pH decline over similar periods (Angel et al., 2008; Emerson et al., 2009). Response by Appalachian forest trees to soil pH is well established (Bennet et al., 1978), and the range 5.0 to 6.5 is often cited as being generally favorable although pH preferences vary by species (Burns and Honkala, 1990; Zipper et al., 2012). Native Appalachian trees are often able to survive when growing in alkaline mine spoils, but growth rates are often suppressed (Showalter et al., 2007; Angel et al., 2008; Emerson et al., 2009; Miller et al., 2012). Volunteer tree establishment is also favored by more acidic soil pHs within the range of ~4.5 to 6.5 (Skousen et al., 1994; Zipper et al., 2012). When rock spoils have aged sufficiently to leach soluble salts and stabilize in pH (i.e., ~10–20 yr), soils with pHs in the slightly acid to circumneutral range can in some cases be more productive for native hardwoods than more acidic soils (Rodrigue and Burger, 2004; Burger et al., 2007; Burger and Fannon, 2009), perhaps due to greater P and base cation availability. These reports show that reforestation potentials on Appalachian coal surface mines will be aided by mine soils that are slightly to moderately acidic, non-pyritic, and with high base cation levels.

Rock spoils are initially devoid of pedogenic organic C and low in plant-available soil N and P (Daniels and Amos, 1985). Although total C measured by combustion (Nelson and Sommers, 1996) may indicate a measureable C content for rock spoils (Zipper et al., 2011a; Miller et al., 2012), such methods also measure geogenic (fossilized) organic C forms (Maharaj et al., 2007) which, when derived from bituminous coals and spoils, are not known to contribute to soil quality (Fox and Campbell, 2010). Pedogenic organic C does accumulate in vegetated mine soils constructed from rock spoils (Roberts et al., 1988a) but typically remains below levels present in native soils (Acton et al., 2011), even after periods as long as 50 yr (Amichev et al., 2008). Pedogenic organic C is critical to the development of humus, a slowly-degrading organic pool, which is essential for nutrient cycling and soil microbial communities, soil-based ecosystem functions (Carter and Stewart, 1996; Robinson et al., 2009) and for maintaining porosity in fine-textured soils (Carter, 2002).

Bioavailable soil P is often measured in Appalachian mine soils via bicarbonate extraction (Kuo, 1996) because more acidic soil extractants cause mineral dissolution (Daniels and Amos, 1985). Howard et al. (1988) found that bicarbonate-extractable P in Virginia rock spoils (≤14 mg kg^{-1}) was only a small fraction of the total P released by a sequential fractionation which included a strong acid (>225–530 mg kg^{-1}). These authors concluded that most mine spoil P is mineral bound and not bioavailable in the short term. Howard et al. (1988) also found that some soil P released to the soil solution via mineral weathering becomes non-bioavailable due to fixation by Fe oxides. Simmons and Currie (2005) also found bicarbonate-extractable P levels in the upper 10 cm on a Maryland mine site (13 mg kg^{-1}) to be below total P (371 mg kg^{-1}) and lower than in nearby non-mined forest soils (79 mg kg^{-1}). Andrews et al. (1998) found bicarbonate-extractable soil P to be positively associated with eastern white pine growth in a study of 78 post-SMCRA Appalachian mine sites, while Showalter et al. (2007) found bicarbonate-extractable P to be positively associated with growth of white oak (*Quercus alba* L.) seedlings on a Virginia mine site. Collectively, these studies suggest that bioavailable P in mine soils constructed from rock spoils is often low.

The development of soil organic N pools and cycles has been noted as an essential ecosystem recovery process on mine sites within the Appalachians (Li and Daniels, 1994) and generally (Bradshaw, 1983, 1997). Nitrogen-fixing plant species often become established as prominent components of the plant communities on mine sites, perhaps in response to soil N deficiencies (Zipper et al., 2011a, 2012; Evans et al., 2013). Appalachian mine soils constructed from rock spoils can contain N in various forms, including ammonium forms within clay mineral interlayers, fossilized organic forms contained in coal and coal-like fragments, and residues from ammonium nitrate explosives. Chabbi et al. (2008) found that mineral N released by weathering of lignite spoils became bioavailable, aiding plant nutrition. More recently, Morford et al. (2011) found that forests associated with N-rich parent material contained more C in aboveground tree biomass and the upper 30 cm of the soil than similar sites underlain by N-poor rocks, raising the possibility that bedrock N input may be an important component of ecosystem N and C cycling. Li and Daniels (1994), however, found no evidence for plant nutrition contributions by geogenic N in Appalachian bituminous rock spoils. Mine soils are usually fertilized with N during revegetation, but inorganic fertilizer N is subject to loss from soil pools if not taken up by plants. In summary, the scientific literature reveals no basis for selecting Appalachian rock spoils that have greater or lesser capacity to supply growing trees with soil N other than their capability to support development of plant communities that will develop organic C and N pools. Thus, use of native soils with organic N, C, and P pools developed by pre-mining ecosystem processes for mine soil construction may be a best practice when restoring forested ecosystems on Appalachian mines.

The adequacy of bioavailable K, Ca, and Mg (base cations) will also influence tree nutrition on Appalachian mine sites. Showalter et al. (2007) found positive correlations of extractable K with growth of 3-yr-old white oaks on a Virginia mine, while Rodrigue and Burger (2004) found base saturation to be a positive influence on tree productivity for pre-SMCRA mines. Bioavailability of base cations in mine soils has not been well studied, perhaps because of the common assumption that K, Ca, and Mg release from spoil weathering will be adequate for tree growth. Leachates and runoff from Appalachian mine sites are often high in Ca and Mg, providing evidence of their release via spoil weathering (Pond et al., 2008; Orndorff et al., 2010; Agouridis et al., 2012). Howard et al. (1988) found K availability unlikely to be a problem in fresh mine soils of the Wise formation in southwestern Virginia, due to a "great reservoir" of K in the parent rocks and lack of ready fixation capacity. In summary, potential availability of base cations, as revealed by base saturation and similar soil measures, may be considered a positive attribute when selecting materials for forest establishment. However, given the tendency of alkaline spoils to produce high base saturations using traditional soil tests and considering the abundance of base cations in most rock spoils, base saturation should be considered as secondary in importance to more essential chemical properties (pH, EC, pedogenic C, bioavailable N and P) when selecting materials for forest soil construction.

Mine Soil Comparisons

Several direct comparisons of mine-soil type effects on forest tree establishment and growth have been performed (Table 2). Torbert et al. (1990) reported on a 5-yr comparison of hybrid pitch × loblolly (*Pinus rigida* Mill. X *Pinus taeda* L.) pines on partially weathered sandstone, unweathered siltstone, and three mixtures of those two materials in Virginia. Roberts et al. (1988a) reported on soil development for those same mine soil materials planted with tall fescue on adjacent experimental plots constructed contemporaneously. Burger et al. (2007) reported northern red oak (*Quercus rubra* L.) growth over 5 yr on those same experimental plots after pine removal.

Angel et al. (2008) reported on a comparison of three rock spoils (a weathered sandstone, an unweathered sandstone, and a mixture of both with shale) planted with four Appalachian hardwoods in Pike County, Kentucky. Emerson et al. (2009) reported a comparison of weathered and unweathered sandstone planted with 11 tree species in Kanawha County, West Virginia; here, we discuss only results of these authors' non-compacted treatments. Miller et al. (2012) reported a comparison of unfertilized mine soils in Pike County, Kentucky, constructed from four rock spoil types planted with nine Appalachian hardwood tree species and monitored over two growing seasons.

Showalter et al. (2010) reported on results of a greenhouse experiment using materials obtained from a different Kanawha County, West Virginia mine. Three tree species–white ash (*Fraxinus americana* L.), yellow-poplar (*Liriodendron tulipifera* L.), and northern red oak–were grown in 7.6-L pots over a growing season. Their growth was compared on four mine soil materials: native forest topsoil, weathered sandstone, unweathered sandstone, and unweathered shale. Tree growth was assessed in each material unamended (Table 2) and amended via a surface application of 2.5-cm fresh forest topsoil. Fertilizer nutrients were not added.

All studies compared weathered or partially weathered sandstone spoils to unweathered rock spoils. The spoils evaluated by Showalter et al. (2010) had been retrieved within months after being excavated on the mine. All other mine soil materials were evaluated during or at the completion of the experimental period and had been subjected to weathering in the field.

The weathered rock spoils for all but one study were reported with soil pHs within the range generally considered favorable for Appalachian forest trees (~4.5–6.5), while Miller et al. (2012) reported weathered rock spoils with pH of 7.0. In contrast, all unweathered rock spoils, excepting those evaluated by Burger et al. (2007) in Virginia 25 yr after placement, had pH values above 6.5 and several had pHs >8.0. The Virginia results (Roberts et al., 1988a; Burger et al., 2007) demonstrate that in situ spoil weathering can cause pH change, while the unweathered sandstones evaluated by Angel et al. (2008) and Emerson et al. (2009) exhibited pH >7.5 after three growing seasons. Unweathered sandstones sampled by Showalter et al. (2010) and Miller et al. (2012) were reported with pHs of 8.9 and 8.8, respectively, although Showalter's was sampled as freshly fractured rock spoil after minimal, if any, ambient weathering. The unweathered shale sampled by Miller et al. (2012) had a slightly acidic pH (6.8), but with an EC that was high relative to other materials suggesting the presence of trace pyrites and possible acidification due to pyrite oxidation. Collectively, these studies demonstrate that weathered rock spoils generally have the moderately to slightly acidic pH levels that are more favorable to Appalachian forest trees than the alkaline pH's that occur commonly in unweathered and non-pyritic rock spoils.

Low EC, commonly found in weathered spoils, is also favorable to forest tree growth on Appalachian mine soils. Roberts et al. (1988a) and Showalter et al. (2010) found weathered spoils had lower ECs than unweathered spoils, while Miller et al. (2012) found weathered sandstones to be lower in EC than unweathered shales but not unweathered sandstones. Angel et al. (2008) did not find this pattern, likely because one of the replicate weathered plots contained pyritic materials (Agouridis et al., 2012). The unweathered sandstones studied by Emerson et al. (2009) also had EC levels that did not differ significantly from those of the weathered materials used in these experiments, a result that may have occurred because these materials were highly siliceous sandstones. As demonstrated by their high coarse fragment content (66% after 3 yr), the unweathered rock materials studied by Emerson et al. (2009) were resistant to weathering. For all spoil comparisons, pH, EC, or both were higher for the unweathered rock spoils than for the weathered rock spoils.

Comparisons of spoil P levels, both within and among the comparison studies (Table 2), must be evaluated considering the variety of testing methods used. Showalter et al. (2010) found bicarbonate-extractable soil P levels to be higher in the topsoil and weathered sandstone than in the unweathered rock spoils; while Burger et al. (2007) and Angel et al. (2008) found extractable soil P concentrations in weathered rock spoils to be nominally greater than in unweathered rock spoils. In contrast, Emerson et al. (2009) found soil P to be greater in unweathered than in weathered rock spoils, but these researchers used a highly

Table 2. Summary of mine spoil comparisons for reforestation; soil properties are as reported at terminal point except for Torbert et al. (1990) after 3 yr, and Showalter et al. (2010) and Miller et al. (2012) at initiation of experiment.

Study/Material	Coarse fragments	Silt+ Clay	pH	EC†	Soil P‡	Tree survival	Tree growth §	Comments
	%	% of fines		ds m^{-1}	mg kg^{-1}			
FIELD STUDIES								
Torbert et al. (1990)¶				(1:5)	(NH$_4$ Ac)			Upper 20 cm soil sampled after Year 3; pitch × loblolly pines over five growing seasons
Sandstone (partially weathered)	54%	27%	5.7	0.4	47	91%	1858 cm^3	
Siltstone	72%	42%	7.1	1.3	42	91%	382 cm^3	
Burger et al. (2007)#				(1:2)	(bicarbonate)			Two 1-kg soil samples per plot, composited; northern red oak, age 5, growing on 25-yr-old mine soils (following Torbert et al., 1990)
Sandstone	47%		4.7	0.10	14	25%	1822 cm^3	
1:2 Sandstone/Siltstone	62%		5.9	0.10	6	72%	3026 cm^3	
Siltstone	72%		6.4	0.13	7	69%	1696 cm^3	
Angel et al. (2008), Angel (2008)				(1:3)	(Mehlich 3)			Coarse fragments from bulk sample in Year 0; other soil properties from multiple subsamples of upper 3 cm, composited in Year 3. Four hardwood species over 3 yr.
Weathered sandstone	78%	35%	6.5	0.17	7.5	~83%	~240 cm^3	
Mixed	74%	32%	8.4	0.16	1.6	~81%	~80 cm^3	
Unweathered sandstone	77%	26%	8.5	0.14	2.5	~87%	~40 cm^3	
Emerson et al. (2009)				(2:1)	(Mehlich 1)			Soil data from upper 20 cm, 3-yr averages; 11 species of native trees, over 3 yr
Weathered sandstone	50%	SL‡‡	4.9	0.33	7	88%	308 cm^3	
Unweathered sandstone	66%	SL‡‡	8.1	0.24	24	86%	34 cm^3	
Miller et al. (2012)				(1:5)	(Mehlich 3)			
Weathered sandstone	55%	21%	7.0	0.09	10.1	94%	94 cm	Mine soil data from 0- to 10-cm and 40- to 50-cm depths averaged over 2 yr. Survival are averages for nine species; growth is second year height averaged for nine species.
Unweathered sandstone	56%	21%	8.8	0.08	1.8	88%	47 cm	
Mixed sandstone/shale	68%	29%	8.3	0.19	2.2	91%	52 cm	
Unweathered shale	81%	53%	6.8	0.38	3.0	75%	60 cm	
GREENHOUSE STUDY								
Showalter (2005), Showalter et al. (2010)				(1:5)	(bicarbonate)			Spoils collected shortly after placement in the field, analyzed as bulk samples before pot placement; three tree species in greenhouse pots for one growing season (unamended treatments only)
Forest topsoil	59%	48%	5.2	0.23	2.8		~180 cm	
Weathered sandstone	43%	33%	5.5	0.12	2.0		~150 cm	
Unweathered sandstone	62%	21%	8.9	0.30	0.6		~140 cm	
Unweathered shale	68%	45%	8.4	0.62	0.6		~100 cm	

† Soil/water ratios used for electrical conductivity (EC) measurement are listed parenthetically for each study, where reported.

‡ Soil P extractant is listed parenthetically for each study.

§ Expressed as height growth for Showalter, and as volume index (height × diameter2) for other studies.

¶ 2:1, 1:1, and 1:2 sandstone/siltstone ratios were also tested (data not shown).

2:1 and 1:1 sandstone/siltstone ratios were also tested (data not shown).

†† Non-compacted treatments only.

‡‡ SL = sandy loam (textural fractions are not reported).

acidic Mehlich 1 extractant (Kuo, 1996). However, leaching these materials with Morgan's extract (a weak, moderately acidic extractant; Morgan, 1941) produced a significantly higher release of P from mine soils constructed of weathered rock spoils compared to those constructed of unweathered materials (Skousen and Emerson, 2010). The Showalter et al. (2010) greenhouse study found mineralizable N, as well as total N, to be greater in the topsoil than any of the rock spoils. Collectively, these studies indicate that mine soils constructed of weathered rock spoils release more P to weakly acidic extractants ($NaHCO_3$, Morgan's extract) than do mine soils constructed of unweathered spoils, suggesting a greater capability to provide growing trees with bioavailable soil P; and that salvaged soil has greater capability to provide bioavailable N than rock spoils.

For the comparison studies conducted in natural environments, survival of planted trees did not often differ significantly between weathered and non-weathered materials. Tree growth, however, was often significantly greater on the weathered materials (Torbert et al., 1990; Angel et al., 2008; Emerson et al., 2009; Miller et al., 2012 for six of the nine species). The mean volume indices of trees growing on weathered rock spoils exceeded unweathered spoil means by four times (Torbert et al., 1990; Emerson et al., 2009), and six times (Angel et al., 2008), respectively. Combined data for the three species compared by Showalter et al. (2007) (reported in Showalter, 2005) showed that average height growth on the topsoil and weathered sandstone were nominally greater than growth on the unweathered sandstone, but those three treatments did not differ significantly. All three of those treatments, however, produced greater growth than the unweathered shale. The addition of topsoil improved tree growth on the unweathered shale so that it did not differ significantly from growth on the topsoil and weathered sandstone mine soil treatments. Collectively, these studies demonstrate that weathered rock spoils are generally superior to unweathered rock spoils as tree-growth media during the first few years (up to 5 yr, in the reviewed studies) of tree establishment.

The Burger et al. (2007) study produced a different result on mine soils that had weathered for 20 yr before northern red oak seedling establishment. Mean height growth on the 1:2 sandstone/siltstone mix (174 cm) exceeded mean height growth on the sandstone (116 cm) and siltstone (122 cm) spoils; the volume index metrics reported in Table 2 were not compared statistically by the authors. The 25 yr of weathering experienced by these plots caused both EC and pH for the unweathered spoils to decline to levels more favorable to native trees, while the partially weathered sandstone spoils' pH also declined to <5. The authors attributed productivity differences among these spoil mixes to several factors. Northern red oak, they reasoned, is a nutrient-demanding species, and it is possible that the siltstone-dominated materials were superior in providing essential nutrients of geologic origin, including base cations and soil P, compared to lower-fertility sandstone-dominated rock spoils which had been weathered before mine soil placement. They also noted the possibility that 100% siltstone spoils, although potentially capable of supplying even higher soil nutrient levels, also gave rise to soils with fine textures that may have inhibited subsurface soil water and air movement on this nearly flat-lying experimental area. This result demonstrates that the suitability for trees of mine soils constructed from rock spoils changes with time and weathering, and the need for additional study to increase scientific understanding of these changes.

These studies also revealed that topsoil and weathered sandstone were more favorable than the unweathered rock spoils to non-planted vegetation. Angel et al. (2008) found 61 unplanted species growing in their weathered sandstone plots, but only 12 unplanted species in their unweathered sandstone plots after 3 yr. These researchers attributed the greater tendency for non-planted species to invade the weathered rock spoils to their greater similarity to native Appalachian forest soils (i.e., slightly to moderately acidic pH, higher fine-earth fraction), compared to the unweathered spoils, which allowed seed entering the site via wind and wildlife greater opportunity to establish successfully. Emerson et al. (2009) did not tally non-planted species but they observed apparent greater cover and richness by non-planted species on the weathered spoils (Skousen et al., 2011a). Showalter et al. (2007) found an average of four species per pot emerging from the forest soil treatment, two to three species per pot emerging from the rock spoil treatments amended with topsoil, and less than one species per pot for the unamended rock spoils. They attributed this difference to the effects of viable seeds, living roots, and other propagules that were present in the forest soil. Other studies have also found that use of fresh topsoil in reclamation aids establishment of unplanted native species on Appalachian mine sites (Farmer et al., 1982; Wade, 1989; Wade and Thompson, 1993; Hall et al., 2010).

Productivity Assessments

A test of mined land capability for forests is forest productivity over the long term. Trees are long-lived and over decades their roots exploit soil for nutrients, water, and oxygen to depths exceeding 3 m provided the soil is of good quality (Fisher and Binkley, 2000). In the U.S. eastern hardwood region, forest productivity is commonly measured using a site index (SI), the height of the codominant trees in the forest canopy at age 50 yr. An estimate of SI can be made at an earlier age by determining the height growth trajectory of a forest or tree stand and comparing that trajectory to standardized growth curves (Avery and Burkhart, 2002). Several studies have assessed the productivity of forest trees on mined landscapes and compared that productivity to pre-mining or comparable unmined forests (Table 3).

Rodrigue and Burger (2004) assessed mine soil productivity on non-compacted pre-SMCRA mine sites in six states by measuring forest SI, and they assessed productivity in unmined forested areas adjacent to each site as a means of estimating the influence of mining on productivity. They found that productivity on 12 of the 14 sites assessed did not differ significantly from pre-mining productivity while two sites failed to achieve pre-mining productivity levels. Soil data from this study were re-analyzed by Zipper et al. (2011a), who found that silt+clay fractions of soil fines were significantly lower on the poor-productivity sites; and that CF were nominally higher, and soil pH, base saturation, and soil P were nominally lower on the poor-productivity sites. When viewed collectively, these soil property differences suggest that the poor-productivity sites may have been unable to provide growing trees with water and nutrients in amounts adequate to support productive growth. Because pre-SMCRA mines often excavated to less depth than post-SMCRA mines, the authors speculated that the forest growth media on the pre-SMCRA mine sites studied were comprised of native soil, weathered spoils, or were mixtures of soil and weathered and unweathered spoils.

Casselman et al. (2007) measured the productivity of eastern white pine growing on a Virginia mine site reclaimed in 1979 with mine soils constructed from weathered sandstones. At age 26, the projected 50-yr SI exceeded the average SI for natural soils in the southern Appalachians. Data from Rodrigue (2001) showed these soil materials to be acidic (with most pHs in the 4.0–5.0 range) and low in EC (<0.1 ds m^{-1}). Soil textures were recorded in the field as sandy loams and sandy clay loams. This was a shallow contour mine with the mine soils comprised of weathered sandstone, possibly mixed with native soil.

Cotton (2006) measured height and diameter growth of white oak and yellow-poplar growing on a mixture of weathered and unweathered spoils in eastern Kentucky experimental plantings. In spoils treated with 114 Mg ha^{-1} organic mulch but not compacted or graded, growth approached that measured on unmined reference sites of same age, but all other treatments (including no mulch on loose-graded plots) failed to achieve reference productivity.

Franklin and Frouz (2007, as documented by Franklin in Zipper et al., 2011b) reported that the 50-yr SI of 40-to-50 yr-old yellow-poplars growing on uncompacted pre-SMCRA mine sites in Tennessee averaged 32.3 m, greater than the 26.5-m regional average. Soil data for these sites were not reported. However, given the shallow contour mining cuts that produced these mine soils, they appear to have been constructed using weathered rock spoils, possibly mixed with native soils.

In all of the above studies, restoration of pre-mining tree productivity occurred on mine sites reclaimed using uncompacted mine spoils comprised weathered rock spoils, in some cases possibly mixed with native soil and/or unweathered rock spoil. With an emphasis on smoothly graded surfaces, topsoil substitutes, and agricultural grasses and legumes, common post-SMCRA reclamation methods were not conducive for restoring native forest ecosystems. In all cases where forest productivity was studied on such sites, growing trees failed to achieve productivities comparable to unmined reference levels.

Burger and Fannon (2009) measured forest SI on a Virginia mine site reclaimed in 1990 with grasses and legumes, and planted in 1992 with three replications of seven native tree species. The mine soils were a mix of unweathered siltstone and sandstone moderately compacted on 35 to 50% slopes. Yellow-poplar and northern red oak were used for pre-mining productivity comparisons because their productivities were reported in the county USDA Soil Survey. The average weighted (by extent of all soil

Table 3. Studies that have compared post-mining forest productivity on mine soils to unmined forest references, with soil properties as measured at time of productivity assessments.

Study	Trees	Mine soil type	Coarse fragments	Silt+Clay	Soil pH	Electrical conductivity	Soil P	Notes
			% of soil fines					
Comparable to or exceeded unmined productivity								
Rodrigue and Burger (2004)	Various; converted to 50-yr white oak site indices	Pre-SMCRA† (most presumed to include unweathered spoils)	50%	38%	5.7	0.05 dS m^{-1}	7.2 mg kg^{-1} (bicarbonate)	Soil data are reference-site averages, from Zipper et al. (2011a)
Casselman et al. (2007)	Eastern white pine on a SMCRA interim bench, Wise County, Virginia	Weathered sandstone, shallow contour mine		Predominantly sandy loam, sandy clay loam	3.6–5.0	0.03–0.09 dS m^{-1}		Soil data from Rodrigue (2001)
Cotton (2006)	White oak and yellow-poplar, 9-yr old	Run of mine spoils, mix of weathered and unweathered, loose dumped with mulch amendment			5.0–6.0	Most <0.1 ds m^{-1}	~1–4 mg kg^{-1} (Mehlich 3)	Mine site was nominally less productive, on average, but within 1 standard deviation of reference sites
Franklin and Frouz (2007)	Yellow-poplar, 40- to 50-yr old	Loose dumped weathered mine soils						As cited by Zipper et al. (2011b)
Failed to exceed unmined productivity								
Rodrigue and Burger (2004); poor productivity sites		Pre-SMCRA	66%	13%	4.8	0.09 dS m^{-1}	6.6 mg kg^{-1} (bicarbonate)	Soil data are averages, from Zipper et al. (2011a)
Cotton (2006)	White oak and yellow-poplar, 9-yr old	Run of mine spoils, predominantly unweathered, loose dumped without mulch and conventionally graded			5.0–6.0	Most <0.1 ds m^{-1}	~1–4 mg kg^{-1} (Mehlich 3)	
Burger and Fannon (2009)	Northern red oak, yellow-poplar	Unweathered spoils, conventional SMCRA reclamation			5.1–7.2	0.04– 0.10 dS m^{-1}	3–33 mg kg^{-1} (Mehlich 1)	
Burger and Evans (2010)	Five tree species in Martin County, Kentucky, after 19 yr	Derived from unweathered siltstone spoils			>7			In mine soils that were ripped (to alleviate compaction) and in unripped mine soils

† SMCRA, Surface Mining Control and Reclamation Act.

series) SI of 4000 ha in the mined sites' vicinity for yellow-poplar and northern red oak were 25 and 22 m, respectively, compared to 17 m measured for both species on the mined sites.

Burger and Evans (2010) reported productivity for five tree species, including yellow-poplar and three other native Appalachian species, growing on an eastern Kentucky mine site constructed of unweathered siltstone spoils for 18 yr. These mine soils had been compacted initially as per standard post-SMCRA reclamation practice. A portion of the site had been ripped to a 1-m depth before tree planting for the purpose of alleviating soil compaction. Yellow-poplar SI on the ripped sites ranged from 17 to 23 m compared to 29 m for surrounding undisturbed soils. Although the subsoil ripping increased growth rates, tree growth potential and projected value on these ripped treatment plots was less than half that of pre-mining capability based on average productivity values listed in the county soil survey.

When viewed collectively, these reports show that long-term forest productivity can be maintained and even increased after mining if a mixture of native soils and weathered, underlying bedrock materials are placed on the mine surface as an uncompacted mine soil. Alternatively, mine soils constructed of unweathered rock spoils do not have physical, chemical, or biological properties conducive to native forest growth and productivity, at least in the years immediately following construction. High pH and salinity, low bioavailable N and P levels, slow internal soil drainage, and no native soil fauna and flora collectively limit tree growth and productivity, even when such materials are left uncompacted.

As demonstrated above, the materials used to construct Appalachian mine soils will influence their potential to support productive forest trees. Avoidance of soil compaction and assurance of adequate rooting depth are also essential practices when constructing mine soils for reforestation.

Summary and Synthesis

Selection of material for use in soil construction is an important consideration when reforesting Appalachian mine sites. When favorable materials are placed on the surface as mine soils without compaction, pre-mining forest productivities can be restored. Properties of materials selected for soil construction also influence plant community development as both salvaged soils and weathered rock spoils are more favorable for plant recruitment than are unweathered rock spoils; while fresh salvaged soils also aid plant community development by carrying live seed banks and other propagules.

Two mine-soil chemical properties essential to successful reforestation are pH and EC. Appalachian forest trees grow well on native soils with slightly to moderately acidic pHs and low levels of EC. Weathered rock spoils are generally low in EC and moderately acidic, in contrast to unweathered non-pyritic spoils which are commonly more saline and/or alkaline, often with pH >7.5 on initial placement.

Mine soils must also provide growing trees with adequate soil nutrients. Base cations are often adequate in rock spoils, but neither weathered nor unweathered rock spoils contain bioavailable N or P in significant quantities. Native soils, when excavated during mining and replaced on reclamation areas, contain N and P in organic forms that can become plant available; and they contain pedogenic organic C that is essential to soil microorganisms and nutrient cycling and enhances ecosystem processes and quality.

Some physical properties of spoils selected for surface placement appear less vital as selection criteria than chemical and biological properties. When soil pH, EC, and other soil chemical properties are adequate, growing trees can tolerate a wide range of coarse fragment contents. When soil drainage is also adequate (as on most slopes), forest trees are tolerant of a wide range of silt+clay contents. However, soil drainage that provides adequate soil aeration can be a major factor limiting forest productivity on mine soils constructed from rock spoils, especially on sites with little surface relief.

Our review of these studies, and our collective experience, lead us to conclude that the native soils, including those excavated from areas that were supporting forest vegetation before mining, will be the most favorable material available on most mine sites for use in constructing mine soils for reforestation. These materials often contain soil fines, soil N and P in bioavailable forms, soil flora and fauna, and plant propagules that will aid establishment of non-planted forest species. Mixing soil materials, including stumps and woody debris, with rock spoils will enhance those spoils' chemical, biological, and physical properties (Skousen et al., 2011b).

We, therefore, recommend that native soils be salvaged and used together with underlying weathered rock strata to achieve sufficient mine soil depth and quality when re-establishing native forest. This recommendation is based on native soils' demonstrated capacity to support forest vegetation in their pre-mining condition and on basic soil and forest science principles, including the importance of soil pedogenic C, N, and P to ecosystem functions and development. Replacing salvaged soils on disturbed sites, although not often studied in Appalachia, has been demonstrated in other regions as a viable practice (Tacey and Glossup, 1980; Ferraz, 1993; Ghose, 2001) and, in some cases, as an essential practice when forest ecosystem restoration is an explicit mine reclamation goal (Parrotta and Knowles, 1999; Parrotta, 2001; Grant et al., 2007; Koch 2007).

Weathered spoils are also favorable to reforestation, and are generally the most favorable materials if native soils are unavailable for salvage. Weathered spoils have chemical properties that are favorable (moderately acidic pH, low EC) to tree growth, and they often break down easily to form soil-sized particles. Planted forest trees have been shown to grow more rapidly, and unplanted species to invade more easily, on slightly acid weathered spoil materials than on unweathered spoils with alkaline pHs and less favorable physical properties. Given that weathered spoils are not known to contain native bioavailable N or P in significant quantities; and that adequate N and P are essential to the emerging forest's growth and development over the long term, native soils should be considered superior to weathered spoils when available.

When salvaged soils and weathered spoils are not available in adequate quantities for replacement of soil cover over the entire mine site (such as on re-mined sites or previous disturbances), mixing weathered with unweathered spoils can be a viable strategy. As shown by Burger et al. (2007), mixtures of weathered and unweathered spoils can be productive. However when viewed collectively, these studies also make it clear that unweathered spoils can vary dramatically in their physical and chemical properties. If native soils and unweathered materials are not available in sufficient quantities for soil construction, unweathered materials with favorable properties (i.e., non-pyritic, relatively low EC and pH, and lacking excessively high coarse fragments) can be used to supplement the weathered spoil and soil materials.

Removing and replacing native soils and underlying materials can be done operationally on most forested sites. In preparing a forested site for mining, operators typically have the merchantable timber removed, and then excavate the tree stumps and roots for disposal. This process causes the seed pool, forest litter layer, and much of the surface mineral soil to be lost. We recommend that all surface organic debris (including stumps, stems, roots, and litter), all soil layers, and the soft saprolite and weathered rock materials under the soil be removed, mixed in the process of excavating, hauling and dumping, and placed on the surface of reclaimed mined sites to a depth of 1 to 2 m as a process of "direct haulback" or contemporaneous reclamation. To avoid compaction, reduce erosion, and increase water infiltration, this mix of materials could be end dumped in piles and roughly leveled with an excavator without tracking on the surface of the new mine soil materials. On slopes that cannot be traversed by trucks, the salvaged materials can be dumped at the top and pushed down slope with a dozer while minimizing compaction.

The above statements are based on our assessment of available scientific literature and decades of research and experience in the Appalachian coalfields. We offer our observations while recognizing that scientific knowledge on this topic is far from complete and that research needs remain. Primary among these are issues concerning long-term N and P nutrition of trees growing on mine soils derived from rock spoils, rates of soil structure formation to enhance aeration and porosity in such materials, and interpretation of EC measures in rock spoils. Other research questions concern the role of coarse woody debris on mine soil drainage, vegetative propagation, and animal habitat; and the nutritional adequacy of highly weathered rock spoils for forest trees over the long term.

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