Forest Reclamation of Coal Mined Sites in the Appalachian Region

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Abstract

Efforts to restore forested plant communities on coal-mined sites in the eastern USA have increased over the years. Up until the late 1970s, Appalachian coal mining operations frequently transformed forested lands into grasslands. The Surface Mining Control and Reclamation Act of 1977 (SMCRA) legislated specific requirements for reclaiming lands mined for coal. Early post-SMCRA reclamation strategies focused on the establishment and maintenance of herbaceous plant species and used other techniques that were largely not suitable for forest growth. Major limitations included appropriate soil pH, soil compaction, and use of species that competed with tree seedlings. Strategies for successful forest establishment and growth were developed through experimentation with revegetation practices on mined sites and observations of existing productive forest stands on non-mined sites. Building on this research, the Appalachian Regional Reforestation Initiative (ARRI) was established in 2005 to focus on re-forestation efforts in the eastern US. A collaborative approach to improving forest vegetation (Forestry Reclamation Approach; FRA) was developed by scientists and adopted by the mining industry and its regulators. The FRA prescribed five steps that were deemed most critical to successful forest establishment. These steps include: (1) create a suitable rooting medium for good tree growth that is no less than 1.2 m (4 feet) deep and comprised of topsoil, weathered sandstone and/or the best available material, (2) loosely grade the topsoil or topsoil substitutes, (3) use ground covers that are compatible with growing trees, (4) plant the right mix of tree species, and (5) use proper planting techniques. The FRA has been used successfully and widely throughout the Appalachians to reclaim surface coal mined sites and establish native tree species. Use of the FRA can improve other forest services such as timber production, carbon sequestration, and wildlife habitat.

Introduction

The Appalachian region contains some of the world's largest deciduous forests that also overlie valuable coal reserves. A recent study of mined areas in Central Appalachia found that since the 1970s, a cumulative footprint of 5900 km^2 has been mined (Pericak et al. 2018). The Appalachian region continues to be a significant source of coal, supplying close to 25% of the U.S. coal needs (EIA 2018). Prior to the 1970s, reclamation strategies did not always take into account post-mining land uses. For example, some contour mining methods would dump mining spoils over existing hillsides, forming steep outslopes and exposed highwalls (Daniels and Amos 1985). The federal Surface Mining Control and Reclamation Act (SMCRA) was enacted in 1977 to provide performance standards that mining operators had to follow to improve environmental conditions on coal mining sites. Two such provisions required (a) return of the disturbed area to the original approximate contour and (b) establishment of a land cover to support the post-mining land use. One example of a general standard stipulated by SMCRA [Sec. 515.b.2]:

> "restore the land affected to a condition capable of supporting the uses which it was capable of supporting prior to any mining, or higher or better uses of which there is reasonable likelihood, so long as such use or uses do not present any actual or probable hazard to public health or safety or pose any actual or probable threat of water diminution or pollution, and the permit applicants' declared proposed land use following reclamation is not deemed to be impractical or unreasonable, inconsistent with applicable land use policies and plans, involves unreasonable delay in implementation, or is violative of Federal, State, or local law."

Early post-SMCRA reclamation efforts were concerned with erosion control, eliminating steep slopes, and establishment of herbaceous covers (Chaney et al. 1995; Torbert and Burger 2000). Since SMCRA did not specify what types of ground cover was necessary, many mining operators in the Appalachian region used grass species that quickly established a ground cover to achieve bond release in a timely manner. The reclamation strategies used by the mining operators were not focused on establishing native species or tree cover. Thus, the goals for mining operators and post-mine landowners who desired forest restoration were not always aligned (Torbert and Burger 2000), and most mining operators had little incentive to take the extra effort to establish hardwood species. However, many landowners did have long-term interests in post-mining land use potentials. Post-SMCRA reclamation approaches focused on resolving issues such as sedimentation and erosion, but they also created other problems like compaction and competitive ground cover species that hindered tree growth (Angel et al. 2005). Faced with these challenges, re-forestation efforts were not a focal point in post-mining reclamation strategies.

Prior to SMCRA, some states enacted their own legislation to help control mining operation's detrimental effects on mined lands (Davidson et al. 1984). Pre-SMCRA reclamation strategies were different than post-SMCRA, and did provide for suitable tree growth conditions on some sites for several different reasons (Rodrigue et al. 2002). First, the depth of mining in pre-SMCRA mines was less than post-SMCRA mines, so the material that was excavated was more geochemically weathered and lower in pH than the material commonly obtained in post-SMCRA mines. Second, even though compaction was a problem pre-SMCRA (Daniels and Amos 1985), post-SMCRA grading requirements increased overall compaction on many mining sites. Third, many of the grasses planted post-SMCRA were chosen for their high growth rate to achieve bond release, which increased competition between grasses and trees on the post-SMCRA sites.

As discussed above, post-SMCRA reclamation efforts were concerned primarily with erosion control, and many adopted revegetation strategies led to mining sites being smoothly graded, thus allowing for highly compacted soils which were not suitable for tree growth. Establishment of non-native herbaceous covers also led to heavy competition and inhibited tree growth. This was coupled with compaction and limited re-forestation efforts for many years (Angel et al. 2005; Zipper et al. 2011). SMCRA stipulated a period that the designated post-mining vegetative cover had to be established and maintained for at least five years after application of supplemental seed or fertilizer. Controlling water quality and erosion were higher priority problems in the initial post-SMCRA years (e.g. 1980s), and practices developed to address these problems negatively impacted site productivity, reforestation, C-sequestration, and development of other productive land uses (Boyce 1999).

The focus on establishment of herbaceous covers post-SMCRA also had the unintended consequence of limiting re-population of native plant species and limiting tree growth. The establishment of thick herbaceous covers also meant that competition for nutrients and sunlight increased, limiting seedling survival rate. Physical properties of mine soils that were better tolerated by herbaceous plants vs. forest species included higher bulk density, lower porosity, lower permeability, higher coarse fragment and clay content, and lower water-holding capacity (Bussler et al. 1984). Mine soil chemical properties that are more favorable to herbaceous species than tree species include higher pH, increased soluble salts, and nutrient content (Burger et al. 2009; Skousen et al. 2011). Soil pH greater than 7.5 and electrical conductivities greater than 1000 µS/cm are generally unsuitable for reforestation with native trees (Skousen et al. 2011). Higher nitrogen levels favor growth of early-season grasses that decrease seedling survival rates while higher phosphorous levels will be more beneficial to tree growth (Burger et al. 2009). One study (Torbert et al. 2000) highlighted the mine site productivity difficulties in re-forestation on pre-SMCRA vs. post-SMCRA sites. In this study, three species of pines (*Pinus taeda*, *Pinus virginiana*, and *Pinus strobus*) were planted on areas where both pre-SMCRA and post-SMCRA conditions were present. The study tracked growth for 11 years and found that tree growth was greater on the pre-SMCRA sites with loblolly pines (*Pinus taeda*) growing faster than the other pine species. Similarly, Rodrigue et al. (2002) studied forest growth on pre-SMCRA mined lands and found that 12 out of the 14 sites examined had forest productivities similar to nearby non-mined lands. It is important to note that the sites selected by Rodrigue et al. (2002) were not selected at random but chosen because the researchers had observed excellent tree growth on the pre-SMCRA sites. Studying a pre-SMCRA site in West Virginia, Gorman et al. (2001) found that reclaimed sites planted with white pines (*Pinus strobus*) had greater forest productivity than mining area left to natural regeneration. The area of the site that was not planted did not receive any treatments and the only tree species were volunteer species. Forest productivity was evaluated by basal area, average diameter, and average height of canopy trees.

The following sections of this report will review and discuss scientific literature used in developing more effective reforestation practices for the Appalachian region. The Forestry Reclamation Approach (FRA) is a specific reclamation approach developed to aid reforestation efforts of mined lands and will be discussed in detail here. Relevant scientific research providing the rationale for implementation of the FRA will be reviewed along with examples where the FRA has been successfully implemented, concluding with several areas the FRA could impact in the future.

Chemical and Physical Properties of Mine Soils

Mining activities dramatically alter the chemical and physical properties of soils and associated post-mine landscapes. Understanding the properties of the overburden, soil and rock is very important to planning reclamation efforts and the handling of potentially toxic strata. Sufficient topsoil is not always available in the Appalachian region to be used in post-mining reclamation. In many cases, the use of topsoil substitutes is desirable to rebuild productive soil. Selecting mine spoils with suitable physical and chemical properties for use in soil construction can lead to mine soils that resemble native Appalachian topsoil (A + E horizons) (Daniels and Amos 1985).

Surface mining operations access geologic strata that have not been exposed to weathering conditions. The composition and properties of these materials, such as sulfur content, can dramatically alter the reclamation strategy. Standard practices to predict mine-spoil weathering include acid-base accounting where samples are taken from the pre-mine strata, and their chemical composition is determined. The properties of the rocks in the overburden will determine how they weather and what elements will be introduced, such as S. From this analysis, the amounts of acid-generating materials and acid-neutralizing materials are determined. Early work in acid-base accounting culminated in research that outlined field and laboratory procedures for acid-base accounting (Sobek et al. 1978). Acid-base accounting is a critical step to preventing potential reclamation errors and providing a chemical rationale for surface placement of specific overburden layers, and for determining which layers can be used to neutralize acid-forming materials. Acid-base accounting is an important tool but can be misleading if the results are not interpreted correctly. For example, if the pyritic S content of the overburden is not accurately determined, then the amount of neutralizing material needed may be undercalculated and pyrite oxidation can produce acidic conditions (Sobek et al. 2000).

Soil salinity is another important chemical property that occurs in arid and semiarid mining regions and can also be limiting in certain Appalachian mines. Overburden containing newly exposed materials will weather rapidly to produce soluble salts. One example is siltstone that can contain pyritic materials along with carbonates that will oxidize and be quickly neutralized to produce sulfate salts. Since the Appalachian region receives enough rainfall to move sodium and other salts through the soil, the buildup of salts is generally not a problem in native soils. However, using unweathered strata in Appalachian mining operations to produce mine soils can lead to high salinity and produce unfavorable conditions for tree growth such as inhibiting water and carbon dioxide uptake and inactivating necessary enzymes (Rodrigue and Burger 2004). Increased soluble salts can be especially problematic from shales and siltstones weathering into finely textured soils (Torbert et al. 1988). This study found that soluble salt content was a critical mine soil property for supporting forest growth. Andrews et al. (1998) also found that levels of soluble salts were inversely proportional to tree height.

Another important chemical property of mine spoils is toxic metals contents. Mine soils containing reduced sulfides and metals can produce acidic conditions capable of mobilizing certain metals such as Fe and Mn. Some common acid-soluble metallic elements to be released in acid-mine drainage are Al, Cu, Fe, Mn, and Zn. Higher levels of Mn have been reported to hinder tree growth, but are not as limiting as other chemical or physical properties (Andrews et al. 1998). Other elements that are mobilized at lower levels include B, Mo, and Se which can be problematic for soil and water quality at elevated concentrations in certain mine spoils.

Physical properties of mine spoils can be just as important, if not more so, than chemical properties as influences in plant growth. Chemical properties of a new mine soil will initially be responsible for the mine soil's productivity. As the materials weather and pedogenic processes occur, the physical properties exert a greater influence on productivity.   Several important physical properties include: bulk density, particle size and distribution, and rooting depth. Bulk density is a critical property because high densities limit overall plant and tree growth. Compaction can cause high soil densities and reduce the following properties: aeration porosity, water holding capacity, and infiltration rates (Torbert and Burger 2000). Coarser particle size and high rock fragment content can limit water and nutrient availability to plants. A higher proportion of fine particles will allow more water and nutrients to be available to rooting systems. Silts and clays are necessary to supply plants with water and nutrients. However, preferred soil textures for forest growth are sandy loam and sandy clay loam (Burger et al. 2005). Rockier soils will have less water holding capacity since water will easily flow down through the soil and into the lower soil depths and potentially away from the rooting zone. However, plants are often capable of penetrating deeper into more rocky soils, assuming they are not compacted, potentially offsetting their reduction in water-holding. Thus, analysis of mine spoil and resultant mine soil physical properties is another important piece of the pre-mining plan needed for successful reclamation.

When choosing what material to use for rebuilding the soil there are several factors to consider. Native topsoil is the usually the preferred material when available. Native soils provide organic matter that supply nutrients, including N and P, and have superior water retention as compared to rockier mine spoils. However, topsoil in the Appalachian region can be thin and difficult to separate from other strata making sequestration impractical. A more common and cost-effective method is to use a topsoil substitute in place of native soil. Unweathered non-pyritic spoil material has been widely used to establish grasses and legumes since these spoils are close to neutral or slightly alkaline pH. Careful selection of the spoil material is important for topsoil substitution. Specific factors that determine a suitable topsoil substitute include acid-base accounting, pH, soluble salts and nutrient holding capacity (Daniels and Amos 1985). It is important to note that spoil pH alone can be an inaccurate measure for selection of optimal strata. Pyrite oxidation and leaching of salts can lower the pH over time, necessitating the need for accurate measure of acid-forming materials and need for isolation of toxic strata. High iron content in spoils is another limiting factor in the Appalachian region that needs to be avoided when selecting a topsoil substitute. The iron content in a mine spoil will fix phosphorus limiting the plant-available phosphorus. As a result, mine soils high in iron content need heavier phosphorus fertilization. Unweathered spoil material usually provides the base cations (Ca, Mg, K) and S necessary for plant growth. Additional amendments and fertilization are needed to supply organic matter, N and P.

With respect to pedogenesis, mine soil horizons can develop rather quickly and are typically A-C or A-AC-C (Sencindiver and Ammons, 2000) in sequence. Weak A horizons can be developed in about one year and in subsequent years form weak granular structures (Roberts et al. 1988) while Bw cambic horizons can form in decades (Haering et al. 2004). Structural development of mine soils comparable to native soils is a long process but selection of overburden strata, coupled with the proper amendments and avoidance of soil compaction can create suitable topsoil substitutes capable of equaling native soil productivity.

Appalachian Reforestation Research

Removal of forests from Appalachian mining sites has numerous negative consequences that are not just limited to water-quality and erosion issues. Mountaintop mining has many impacts on the environment with the following specific to forest removal: habitat and stand fragmentation, reduction of suitable conditions for long-term forest succession, and lack of carbon sequestration (Wickham et al. 2013). Forest fragmentation is the reduction of forest into smaller patches resulting in negative qualities such as increased mortality and increased proliferation of nonnative species. Forest fragmentation reduces understory species that replenish forest soil nutrients and provide wildlife habitats. Thus, forest succession has been hindered due to mining practices on many sites. Reclamation practices pre-SMCRA removed native soils and frequently created unstable landforms. Post-SMCRA reclamation efforts attempted to alleviate these issues but created soil conditions that were often unfavorable to forest growth. As a result, many of the trees used were early successional that could thrive under the reclamation site conditions (Zipper et al. 2011). These woody species impeded the invasion of native hardwoods common in the Appalachians, especially in mine sites with soils unfavorable to forest-tree re-establishment. Removal of forests removed a natural carbon sink and converted the mined area into a short-term carbon source without reforestation efforts (Fox and Campbell 2010). The removal of forest before mining can occur through harvest or burning, reducing non-soil carbon sequestration. As vegetation and seedlings are established, the reclaimed area will once again become a carbon sink. Amichev et al. (2008) evaluated the total carbon accumulation of 20 to 55-year-old reclaimed forest sites and reference forest sites and found that reclaimed forest sites had less total ecosystem carbon than reference forest sites. They attributed this finding to lower soil carbon pool in the reclaimed forest sites. The lower soil carbon pool in the reclaimed sites means that the reclaimed sites may potentially have the capability to sequester more carbon than reference sites. However, as the soil carbon pool in the reclaimed sites increases over time, the reclaimed forests might not continue to be superior to reference sites for carbon sequestration.

In the 1980s, tree planting on coal mined sites became more common and regulators began to recognize reforestation as an important post-mining land use (Davidson et al. 1984). Multiple studies in the 1980s tracked the limitations in reforestation efforts (Bussler et al. 1984; Davidson et al. 1984; Josiah 1986). Compaction and dense herbaceous cover were the two most prominent factors limiting tree growth. Controlling erosion and re-establishing stable landforms were the primary focus driving reclamation strategies, and as a result reforestation efforts suffered. Continuing through the 1990s compaction was a leading problem for reforestation while other alternative revegetation practices that improved water quality and established ground cover were preferred (Ashby 1990; Boyce 1999).

Research in West Virginia (Gorman and Skousen 2003) focused on hardwood growth and survival in five tree species [red oak (*Quercus rubra*, black cherry (*Prunus serotine*), black walnut (*Juglans nigra*), white ash (*Fraxinus americana*), and yellow-poplar (*Liriodendron tulipifera*)] under various conditions. Among the conditions tested, the ripped vs. unripped mine soils, and mowed vs. unmowed groundcover had the greatest effect on tree survival. The procedures for mowing consisted of using a rotary mower to cut the grass to 5 cm every month for the first year. Ripping of the soil went to a depth of one meter. Mortality rates varied between species and conditions, but the most favorable conditions for tree survival were in ripped and unmowed plots. The ripped plots provided better rooting conditions for seedling survival and the unmowed plots had less ground cover competition as mowing practices led to denser grass/legume growth. Another related study examined the types of spoil used for afforestation and restoring native vegetation on a Kentucky surface coal mine (Sena et al. 2014). Three spoil types were used: unweathered gray sandstone, weathered brown sandstone, and mixed sandstone/shale. Four tree species [green ash (*Fraxinus pennsylvanica*), red oak, white oak (*Quercus alba*), and yellow-poplar) were planted as seedlings. Significantly increased tree growth and volume were evident in the brown weathered sandstone over the other two spoils. Additionally, natural colonization and native ground cover species richness was much more favorable in the brown weathered sandstone versus the unweathered spoil. A similar study in West Virginia comparing brown weathered sandstone to unweathered gray sandstone was done to examine several soil parameters for favorable hardwood tree growth (Wilson-Kokes et al. 2013). Weathered brown sandstone produced more favorable conditions for tree growth with the average tree volume index up to 10 times higher than the unweathered gray sandstone. The gray unweathered sandstone had a lower soil-sized fraction that reduced its ability to hold water and nutrients while the brown sandstone's lower pH was more suited for hardwood growth.

Holl (2002) also conducted research that focused on long-term vegetation and forest species restoration on mined sites, and found that different recovery strategies vary in success depending on whether shorter or longer recovery timelines are prioritized. Composition of herbaceous and woody species in reclaimed and reference hardwood forest sites was measured to compare if species richness was different between the sites. The sites were divided into quadrats and the percentages of total and individual species cover was determined. Herbaceous species composition was similar across the reclaimed and reference sites, but hardwood species were more prevalent in the reference sites. Despite similar overall forest species composition when reclaimed sites were compared to reference sites, the reference sites contained several fewer common species than the reclaimed sites. Favoring non-native herbaceous species has short-term benefits like limiting erosion but hinders long-term forest development. This study emphasized using herbaceous species and strategies that allow for long-term forest succession as part of the reclamation plan.

In a very different study conducted in southwestern Virginia, Jones et al. (2005) developed a classification model intended to determine the most important mine soil properties needed for white pine growth on mined lands. The study selected multiple properties and combined them into a classification model. The most important soil factors that affected white pine growth were bulk density, rooting depth, soil texture, and soil pH. This study also used conventional site index (tree height at age 50) as part of its model. The site index measurement projects the growth of dominant trees after 50 years and is commonly used for estimating forest productivity (Torbert et al. 1988; Rodrigue and Burger 2004). This study concluded that among the factors studied, bulk density was the most influential factor contributing to successful tree growth. Applying a productivity model to mining sites can be another tool for reforestation practices.

The Forestry Reclamation Approach

Reforestation researchers were acutely aware of the issues associated with establishing trees on surface coal mines through the 1990s, namely compaction and competitive ground covers. A new focus on establishing hardwood forests culminated in a detailed approach, the Forestry Reclamation Approach (FRA). The FRA is an advanced reclamation strategy aimed at reestablishing native forests on mine sites in the eastern USA (Burger et al. 2005; Zipper et al. 2011). The FRA aims to restore native hardwood forests in a much quicker timeline than natural succession. Following these reclamation strategies can provide the opportunity to convert disturbed lands into productive ecological systems with native species of ecological and economic value (Zipper et al. 2011). Improving re-forestation efforts improves short term environmental health of coal mined lands, but also long-term resistance to potential ecological threats such as climate instability and anthropogenic activities. These guidelines focused on several fundamental principles. One, reclamation planners need to be very particular in the composition of mine soil composition, depth, and compaction to create the ideal rooting medium and surface to encourage tree growth. Two, the FRA emphasizes using groundcover species that will not compete with native tree species coupled with appropriate tree planting practices to ensure seedling survival. The FRA meets SMCRA's guidelines for establishing vegetation consistent with certain post-mining land uses and is approved for use by regional state and federal mining agencies.

Forestry Reclamation Approach Step 1

The first step in FRA is to "create a suitable rooting medium for good tree growth that is no less than 1.2 m (4 feet) deep and comprised of topsoil, weathered sandstone and/or the best available material" (Burger et al. 2005). The best available materials will depend on the local conditions within the mining site but should also have similar properties to the native soil (Zipper et al. 2013). The ideal growth media for tree growth will have low soluble salts, a pH range of 5.0-7.0, low pyritic S content, and textures allowing for water infiltration (Burger et al. 2005). Controlling the pH is an important part of creating a suitable medium for tree growth. Hardwood species favor a slightly acidic pH, but having a pH that is too low or is alkaline will hinder growth.

Appalachian natural soils are typically acidic, have lower levels of soluble salts, and allow for proper drainage. Pre-mining testing will determine what the optimal materials on-site are. Highly acidic or alkaline soils will restrict tree growth. If there are highly alkaline or acidic material produced during mining, then those materials need to be sequestered or covered with a material capable of allowing tree growth. Natural soils within the Appalachian region are often thin and rocky, meaning it is very difficult to salvage and retain the topsoil during mining operations. Even though the availability of native topsoil is often limited, native soils and underlying weathered rock spoils are preferable to use in soil construction when possible. Native soils contain three important properties that favor their use: native soils contain seed banks, they have organic matter rich in nitrogen and phosphorous, and native soils contain animals and microorganisms that cycle nutrients (Skousen et al. 2011). Hall et al. (2010) studied the benefits of salvaging and reutilizing topsoil for its seed bank and found that topsoil application leads to an increase in native species diversity and reestablishment. However, it is important to point out that topsoil substitutes are allowed under SMCRA if the substitute material properties have capability to support the post-mining land use in a manner that is comparable to natural soils.

Understanding the properties of the topsoil substitute is vital for developing reclamation strategies for native hardwood forest establishment and growth. A higher proportion of soil fines within a topsoil substitute will allow for higher water retention and nutrient holding. A lower proportion of coarse fragments will also increase the rooting volume and water holding. Selection of spoil type to account for coarse fragment content is important since mine soils often have higher coarse fragment content than natural soils (Zipper et al. 2013). Soil pH and soluble salt content are two significant chemical properties affecting the quality of a topsoil substitute. Highly acidic pH can have negative effects such as making some metals soluble, thus allowing uptake of these acid-soluble metals by root systems and potential toxicity. Aluminum is one such acid-soluble metal; root and microbial toxicity due to soluble aluminum in the soil will hinder growth (Schaedle et al. 1989). Soils constructed with unweathered and non-pyritic spoils will have a higher surface pH than natural soils or soils constructed with weathered spoils (Zipper et al. 2013). Soils with a high pH negatively affect tree survival and growth. Alkaline spoils are also more favorable to competing ground cover species (Skousen et al. 1994) and can limit seedling survival for native acid-soil adapted species. Alkaline conditions have been shown to negatively correlate with tree growth and is a significant limiting factor (Showalter et al. 2007; Torbert et al. 1990). High soluble salt content can negatively affect trees growing in topsoil substitutes, so spoils with higher saturated conductivities should be avoided (Daniels and Amos 1985). Soluble salt content has also been shown to be negatively correlated with growth of white ash (*Fraxinus americana*) and red oak (*Quercus rubra*) (Showalter et al. 2010).

Using weathered materials for soil reconstruction may produce soil characteristics similar to natural soil systems and will lead to soil horizons beginning to develop in as little as six months (Haering et al. 2004). Weathered materials will enhance conditions for optimal tree growth, as shown in several studies (Angel et al. 2008; Emerson et al. 2009; Torbert et al. 1990). Unweathered materials have different chemical and physical properties than weathered materials including higher coarse fragment composition, soluble salts and pH. However, use of these unweathered materials in mixed spoils will be able to supply certain cations (Ca, Mg and K) over time as the rock's component minerals weather. Supplying these cations is important because Ca, Mg, and K are macronutrients required in relatively large quantities for productive tree growth. Since native Appalachian forest plant communities prefer mildly acidic soils, using weathered materials that lowers pH favors forest growth. Some coarse fragments in unweathered spoils will break down to some extent over time to more fine materials increasing water and nutrient holding capacity (Emerson et al. 2009). However, coarse texture combined with a high percentage of rock content may limit the amount of plant available water (Bramble and Ashley 1955). Organic matter content is also an important component of natural soils that must be developed over time in mine soils. Organic matter provides essential nutrients to the forest ecosystem, and as the constructed mine spoils develop and accumulate organic matter these essential nutrients will become increasingly available (Zipper et al. 2013).

Forestry Reclamation Approach Step 2

The second step in the FRA is to "loosely grade the topsoil or topsoil substitutes" (Sweigard et al. 2007). Soil compaction negatively impacts tree survival and growth (Bussler et al. 1984; Torbert et al. 1988). SMCRA practices, both early and current, encourage grading of post-mined lands with heavy equipment and have likely contributed to increased bulk density on mine sites (Angel et al. 2005). This can lead to compacted soils, limiting rooting potential and water-holding capacity. Limiting compaction, a process that leaves the surface loosely graded, is beneficial for many reasons. Soil surfaces that are loosely graded will allow rainwater to infiltrate the soil making more water available to the planted trees. Compaction compresses the soil particles, meaning the space between soil particles is reduced limiting the water holding capacity of the soil. Loosely compacted soils will allow for greater air exchange, retain more water for tree roots and other organisms, and allow for roots to penetrate the soil and grow more freely.

Even if the chemical composition of the soil is ideal, the result of soil compaction will be a soil poorly suited for tree growth. Soil bulk density has been negatively correlated with tree growth and in several studies has been shown to be the most limiting factor (Torbert et al. 1988; Ashby 1990; Conrad et al. 2002). One alternative approach is to use normal methods to compact the backfill but keep the final surface at least 1.2 m deep and graded loosely such that compaction is minimal. One example for how to minimize compaction is the practice of "end-dumping" where the trucks will empty material in tightly-spaced piles that are close to each other within the designated area, and then lighter equipment will grade the spoil piles to the necessary four feet (Sweigard et al. 2007).

Higher bulk densities of mine soils have been shown to restrict water movement and plant rooting (Haering et al. 2004). Trees containing a larger root system will be able to access a higher amount of water and nutrients, enabling increased survival. Planters can get trees planted correctly without damaging the roots if the soil is loose enough to allow normal planting practices (Sweigard et al. 2007). Ripping is a practice that can help alleviate compaction. A common strategy for ripping is to attach a single or multiple shank ripper implement onto a piece of heavy equipment, e.g. bulldozer, and apply the treatment to a certain depth. In one study, tree growth on a compacted soil was improved through ripping treatment to a depth of 1 m before planting (Skousen et al. 2009).

Forestry Reclamation Approach Step 3

The third step in the FRA is to "use ground covers that are compatible with growing trees" (Burger et al. 2009). Tree-compatible ground covers are not established via the same techniques as the "grassland reclamation approach" (Burger et al. 2009). Planting regular hayland/pasture herbaceous covers [e.g. Kentucky-31 tall fescue (*Festuca arundinacea*), and sericea lespedeza (*Lespedeza cuneata*)] that grow rapidly enhance competition with seedlings and should be limited. The following guidelines should be followed for tree-compatible ground cover: (a) use species that limit competition (Table 1); (b) reduce seeding rates; (c) reduce nitrogen application; and (d) work with regulators to agree upon reduced ground cover in the immediate years following seeding (Burger et al. 2009). Following these steps will result in a vigorous but less dense and lower growing ground cover that does not out-compete the tree species.

An important early study by Burger et al. (2008) demonstrated that reducing competition between grasses and trees will result in improvement in growth and survival of tree species. Fertilizers applications low in overall nitrogen rate should be used to reduce the herbaceous species growth but sufficient phosphorous for tree growth must be applied initially. When picking the types of herbaceous cover to use, a mixture of relatively non-competitive perennial and annual grasses are chosen so that there will be some immediate ground cover to reduce erosion and to supply organic matter (Burger et al. 2009). Perennial, slow-growing grasses (Table 1) are also chosen so that there will be long-term organic matter supply and to aid erosion control. Legumes fix nitrogen and are essential to provide long-term nitrogen to trees and associated grasses. Lastly, this approach to seeding practices also provides for long-term succession of the plant community (Burger et al. 2009). The typical strategy for planting trees and tree-compatible ground covers is to plant seedlings in late winter and to apply seed for ground cover in the following spring or fall. This ensures that the seedlings are given time to establish and less competition between the ground cover and seedlings. Franklin et al. (2012) outlined a similar strategy to improve forest restoration by developing seeding mixes to control erosion, facilitate tree survival, and allow invasion and establishment of unplanted native species.

Forestry Reclamation Approach Step 4

The fourth step in the FRA is to "plant the right mix of tree species" (Davis et al. 2012). If the long-term goal for forest development is crop trees then hardwood species such as white oak, black cherry (*Prunus serotina*), and yellow poplar should be planted in large numbers, relative to early-successional trees like flowering dogwood (*Cornus florida*) and eastern redbud (*Cercis canadensis*) (Davis et al. 2012). Crop trees are species that have economic value to the landowner, e.g. timber industry. Early successional species, also referred to as nurse trees, are faster growing species that supply nutrients to crop trees and can provide a habitat for wildlife which will then allow for other native tree species to be introduced by the wildlife carrying seeds in from other areas. Mature forests are a vital habitat for many wildlife species. Establishing conditions that favor development of mature forests will ensure that wildlife species have the opportunity for long-term viability (Wood et al. 2013). Thus, a mix of nurse and crop trees should be planted to establish forest growth and provide the right conditions for long-term forest development.

Forestry Reclamation Approach Step 5

The fifth step in the FRA is to "use proper planting techniques" (Davis et al. 2010). Incorrect storage conditions, handling and planting methods are limiting factors to tree survival (Vogel 1981). Seedlings are typically obtained from nurseries as bare-root stock. Seedlings from nurseries are generally not costly and should have a vigorous root system (Davis et al. 2010). Ideally, seedlings should be from the same region as the reclamation site to improve long-term success. The handling and storage of seedlings are critical to their survival. Since seedlings are living organisms, practices should limit the amount of stress during storage and planting to increase survival rates. If possible, the seedlings should be shipped immediately prior to planting so that the seedlings are not being stored more than a day or two before planting. The seedlings should be transported and stored in cool conditions, never frozen, and kept away from direct sunlight until the seedlings are ready for planting. Planting seedlings as soon as possible greatly increases their chances of survival. Spacing the seedlings appropriately is important for tree survival and performance over time and the guidelines for tree spacing will depend on state mining agency requirements. While planting seedlings might seem like an easy step in the FRA, following the other earlier steps to prepare the reclamation site will be useless if the seedlings are improperly planted and not given a chance to grow.

Application of FRA

The FRA has been used successively to restore native hardwood forests, confirming the efficacy of the approach. Researchers at the University of Kentucky tested reclamation strategies that focused on limiting compaction and bulk density (Conrad et al. 2002). This study was performed on the Starfire Mine in Eastern Kentucky. This site had been extensively mined since the 1980s in a mostly forested region. The researchers found that compacted areas had lower tree-survival rates than areas where loose-dumping techniques were used, thereby testing the efficacy of step 2 of the FRA. The Powell River Project has shown that reclaimed mined sites, if appropriate soil preparation and seeding techniques are used, can have equally or more productive hardwood forests than the native un-mined forests (Burger and Zipper 2018). In a different mining site in Virginia, the local mining firm applied FRA principles while re-mining and reclaiming older mined lands (Zipper et al. 2012). Results indicated that the FRA based reclamation procedures were effective over much of the site and provided a prevalence of native woody species capable of producing mature forests. In a different study, a research team tested the FRA on a steep-slope contour mine (Kumar and Sweigard 2011) and found that approximately 70% of the trees survived with no significant slope stability issues.

In a specific application, the FRA is being implemented to restore the American Chestnut (*Castanea dentata*) tree on mining sites. The American Chestnut was once a dominant hardwood species found in Appalachia and other forested areas of the Eastern US. This species was desirable for the timber industry for its high quality and resistance to rot. The chestnut's population was nearly eliminated due to a fungus blight. Efforts to restore the chestnut went largely unsuccessful until a breeding program crossed the American chestnut with a Chinese chestnut (*Castanea mollissima*) resistant to the blight. The ARRI began work on establishing backcross and pure chestnut species on mine sites reclaimed with the FRA (French et al. 2017). Preliminary work with backcross chestnuts demonstrated similar survival rates of the chestnut to other hardwood species (Skousen et al. 2013). Use of the FRA to re-populate forested areas of the Appalachian region with the chestnut is a unique opportunity to test the FRA, but to also propagate a once-dominant native hardwood species.

Future FRA Impacts

More widespread use of the FRA could provide a range of environmental and economic benefits. Restoring native forests returns ecosystem processes and services to Appalachian coal-mined landscapes. Producing high-value timber in commercial forests enhances the long-term security of the timber industry which is a major employer in Appalachia. Alternative energy sources have garnered increased interest in recent years, including woody biomass. New technologies may soon allow woody biomass to be used as a conversion source for liquid fuels (Williams et al. 2009). Increasing tree establishment on mined sites is one way to partially offset carbon emissions and may provide significant C-sequestration potential (Amichev et al. 2008). Reforestation on mined sites has been shown to sequester significantly more total-C (soil + biomass) carbon than reclaimed grasslands (Burger and Zipper 2018).

Conclusions

Post-SMCRA reclamation practices in the central Appalachian region have focused on improving water quality, creating stable landforms, and limiting erosion. These practices often used non-native herbaceous grasses to establish ground cover quickly. The heavy equipment used to create stable landforms compacted the surface and increased the soil's bulk density. Compaction and competitive ground covers were two factors that inhibited tree growth on reclaimed mining sites. Using unweathered strata as a substitute for topsoil was a common practice and less costly than salvaging native topsoil. Several physical and chemical properties of topsoil substitutes frequently made them inferior to native topsoil for reforestation purposes including higher pH, higher soluble salts, and higher proportion of coarse fragments. Non-native plant species were able to tolerate and thrive in some of these conditions, but native hardwood tree species had difficulty growing. Realizing this, researchers experimented with different conditions to establish a standard set of parameters that would allow for hardwood species to survive and grow. The FRA was the result of observation and experimentation and outlined as five steps that, when followed properly, would provide conditions on mined lands suitable for reforestation. This report has detailed the scientific rationale for the specific soil properties and reclamation practices developed by the FRA for reforestation. Following the steps in the FRA has been successful in establishing forests on coal mined lands. In addition, this report has listed specific examples of case studies using the FRA, and examples of how the FRA could be of use to alleviate future environmental problems.

Table 1: Species of Ground Cover Compatible with FRA[1]

Species of Ground Cover		
Perennial Grasses	Annual Grasses	Legumes
perennial ryegrass (*Lolium perenne*)	foxtail millet (*Setaria italica*)	birdsfoot trefoil (*Lotus corniculatus*)
orchardgrass (*Dactylis glomerata*)	rye (*Secale cereale*)	ladino clover (*Trifolium repens*)
timothy (*Phleum pratense*)		

[1]Burger et al. (2009) provided most of the species used in the above table.

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