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Restoring Forests and Associated Ecosystem Services on Appalachian Coal Surface Mines

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Abstract Surface coal mining in Appalachia has caused extensive replacement of forest with non-forested land cover, much of which is unmanaged and unproductive. Although forested ecosystems are valued by society for both marketable products and ecosystem services, forests have not been restored on most Appalachian mined lands because traditional reclamation practices, encouraged by regulatory policies, created conditions poorly suited for reforestation. Reclamation scientists have studied productive forests growing on older mine sites, established forest vegetation experimentally on recent mines, and identified mine reclamation practices that encourage forest vegetation re-establishment. Based on these findings, they developed a Forestry Reclamation Approach (FRA) that can be employed by coal mining firms to restore forest vegetation. Scientists and mine regulators, working collaboratively, have communicated the FRA to the coal industry and to regulatory enforcement personnel. Today, the FRA is used routinely by many coal mining firms, and thousands of mined hectares have been reclaimed to restore productive mine soils and planted with native forest trees. Reclamation of coal mines using the FRA is expected to restore these lands' capabilities to provide forest-based ecosystem services, such as wood production, atmospheric carbon sequestration, wildlife habitat, watershed protection, and water quality protection to a greater extent than conventional reclamation practices.

Keywords Afforestation · Appalachia · Coal mines · Forest restoration · Land reclamation

Introduction

The Appalachian region of the eastern USA is more than 80% forested, but large forest areas have been lost due to numerous impacts including coal surface mining. In Appalachia, more than 600,000 ha have been mined for coal under the USA's national coal mine reclamation law, the Surface Mining Control and Reclamation Act (SMCRA), and >10,000 additional ha are being mined each year (Figs. 1, 2). Reclamation of most mined lands has been accomplished as required by law, but the pre-mining forests have been largely replaced by plant

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communities dominated by persistent herbaceous species, including grasses sown during reclamation, and early successional woody species (Chaney and others 1995).

Appalachian forests are a globally significant ecological resource (Riitters and others 2000). These forests host an assemblage of nearly 40 commercially important tree species and a rich understory of grasses and herbs that vary across this mountainous landscape forming what is among the most diverse non-tropical ecosystems in the world (Ricketts and others 1999). These forests provide ecosystem services including carbon storage, watershed and water quality protection, and habitat for plants and fauna. Appalachian forests supply timber to local users as well as the world economy, and the forest industry is a major employer. Coal surface mining, however, has caused forest fragmentation and a net loss of productive forestland (Wickham and others 2007; Sayler 2008; Townsend and others 2009; Drummond and Loveland 2010).

The ongoing loss of Appalachian forest has occurred under the regulatory structure established by SMCRA. With the advent of SMCRA in the late 1970s, regulatory practices emphasized avoidance of pre-SMCRA mining problems, especially land instability, sedimentation, and surface water contamination caused by uncontrolled placement of excavated rock materials (mine spoils) in Appalachia's steep terrain. Hence, agencies implementing SMCRA emphasized reclamation practices intended to stabilize land surfaces, including surface compaction by mining equipment and rapid establishment of dense herbaceous vegetation (Angel and others 2005). As an unintended consequence, the resulting land surfaces often hindered re-colonization by native plants from adjacent lands and caused planted trees to perform poorly (Simmons and others 2008). Where trees were planted, the vigorous ground covers, fertilized to stimulate rapid growth, competed for water, nutrients, and sunlight with planted seedlings and harbored herbivorous animals that damage seedlings (Skousen and others 2006; Burger and others 2008); while compacted soil surfaces limited planted trees' root growth and access to soil air, water, and nutrients (Bussler and others 1984; Burger and Evans 2010). Soil chemical properties, although usually well-suited for herbaceous plant species encouraged by regulatory policies, were often not favorable to planted trees. Hence, trees were not commonly planted on SMCRA mine sites because mine operators understood that they often did not survive. When trees were planted, mine operators often favored early successional and non-native species able to withstand site conditions created by the reclamation. Certain commonly planted woody species, including the native black locust (*Robinia pseudoacacia*) and the non-native and invasive autumn olive (*Elaeagnus umbellata*), were able to proliferate on SMCRA-reclaimed landscapes (Zipper and others 2007). Once established, these fast-growing woody species also hinder movement of the native woody species that are dominant in Appalachian forests onto the mine sites.

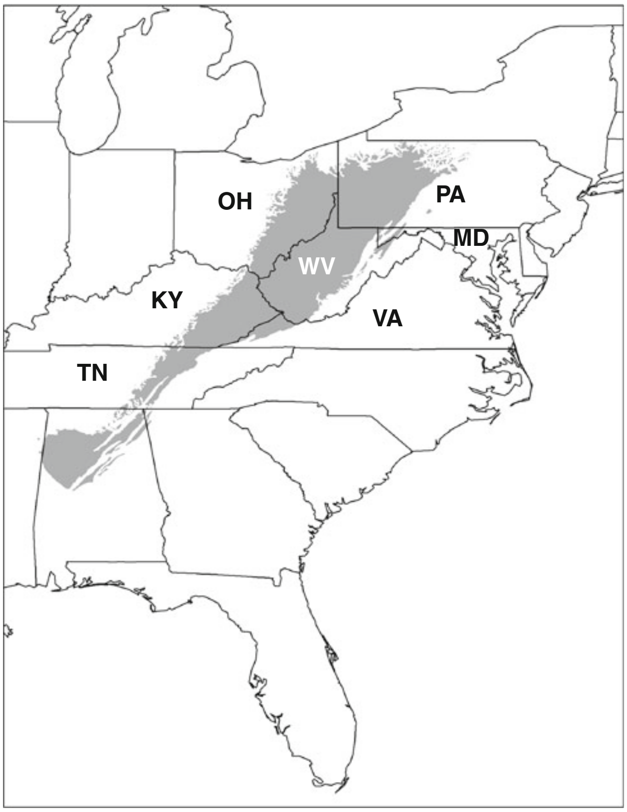

Fig. 1 The Appalachian coalfield of eastern USA, as it occurs in seven states that harbor Appalachian hardwood forest ecosystems

Despite these common post-SMCRA results, reclamation scientists observed that forest vegetation can be diverse and productive when Appalachian coal mines are appropriately reclaimed (Gorman and others 2001; Rodrigue and others 2002), and have developed reclamation methods that can restore forest vegetation. Here, we describe a prescription for effective coal-mine reforestation called the Forestry Reclamation Approach (FRA) and its application under SMCRA; and we address the FRA's potential to restore ecosystem services that are characteristic of unmined forests.

The Forestry Reclamation Approach

The Forestry Reclamation Approach (FRA) was developed as a set of practices for reclaiming mined land to support forest vegetation (Burger and others 2005; see also Burger and Zipper 2002); it is based on decades of research. The FRA can be applied by coal mine operators while reclaiming as mandated by SMCRA. The FRA is

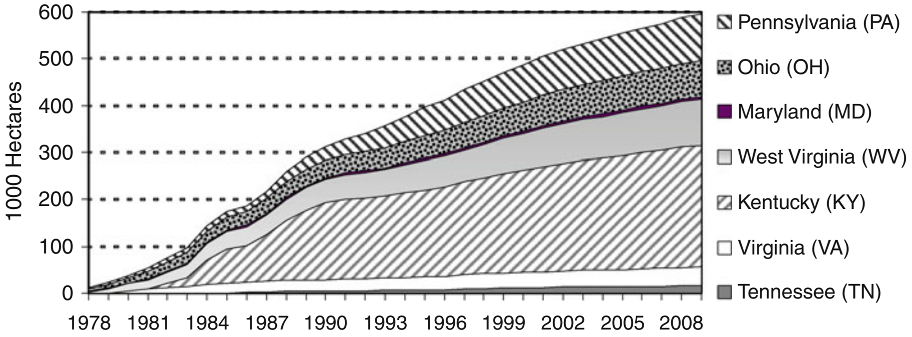

Fig. 2 Cumulative Appalachian areas reclaimed and released from SMCRA regulation in seven states, 1978–2009. Eastern Kentucky areas are estimated from Kentucky totals in proportion to annual coal production. At the end of 2009 for the seven states, an additional 50,000 ha is reported as partially reclaimed but not released from SMCRA regulation. Data from US Office of Surface Mining

composed of “five steps,” each of which is essential to successful application.

Native Appalachian forests host numerous plant species, and it is not feasible under current economic conditions to re-establish the full forest community by seeding and planting. Reestablishment of essential soil properties and processes is necessary for forest restoration (Walker 2005), and planted trees can act as catalysts in natural succession (Parrotta and others 1998). The FRA is intended to establish site conditions suitable for survival and growth of planted trees while also enabling colonization by native vegetation whose seeds are carried by fauna and wind.

FRA Step 1: Create a suitable rooting medium for good tree growth that is no less than four feet deep and comprised of topsoil, weathered sandstone, and/or the best available material.

The properties of materials used to create a surface growth medium will influence survival and growth of planted trees and colonization by native vegetation. Thus, the FRA’s first step is to select and place suitable plant-growth materials on the surface. The “best available” growth medium will depend on local conditions. While topsoil can be a valuable resource for reclamation, its availability in quantities adequate for soil construction on modern mines is often limited by factors that include physical depth, miner safety when soils occur as thin layers on steep mountains slopes, and mine operators’ economic concerns. Thus, alternate growth media are often used.

Native forest soils in the Appalachians are generally moderately acidic, low in soluble salts, and well drained. Alternate soils with similar properties can often be constructed on coal surface mines by using weathered rock materials, those which occur close enough (usually within 10 m) to the surface to have been affected by environmental processes. When soils are constructed with weathered rocks that are non-pyritic, they often become more favorable to tree growth (Burger and others 2007) and develop chemical properties similar to those of native soil materials over time (Showalter and others 2010).

Several studies have found that weathered rock materials are generally superior to unweathered rocks of deeper origin as growth media for Appalachian hardwoods. Working on experimental plots in southwestern Virginia, Torbert and others (1990a) found weathered sandstone to support greater growth of pitch x loblolly hybrid pine (*Pinus rigida x P. taeda*) than unweathered siltstone spoil materials. Working with a mix of nine native hardwoods and one pine on an active mine site in southern West Virginia, Emerson and others (2009) recorded more rapid growth on weathered than on unweathered sandstone materials (Fig. 3). Working with four native hardwoods in eastern Kentucky, Angel and others (2008) found that weathered sandstone spoils supported faster growth than either unweathered sandstones or a mixture of the two spoil materials.

Fig. 3 Forest vegetation growing on a weathered sandstone mine soil in West Virginia, in the sixth year after trees were planted (Emerson and others 2009)

Unweathered spoils are available on modern mines in far larger quantities than either weathered spoils or native soils (Haering and others 2004), but tend to be higher in coarse fragments, soluble salts, and pH (Haering and others 1993; Burger and others 2007; Emerson and others 2009). Unweathered spoils commonly supply high levels of the base cations Ca^{++}, Mg^{++}, and K^{+} (Howard and others 1988; Roberts and others 1988), essential nutrients that can be deficient or depleted in native forest soils, especially soils that have experienced acidic deposition in the Appalachians (Adams 1999). Weathering processes remove soluble minerals, including carbonates, from alkaline mine spoils (Orndorff and others 2010), causing reductions of both electrical conductivity and pH (Burger and others 2007; Skousen and others 2009), often to ranges comparable to native forest soils. Coarse fragments also tend to break down as mine soils weather, increasing soil fines and thus improving soil nutrient and water holding capacities (Emerson and others 2009; Taylor and others 2009b)

Use of native soil materials, either alone or mixed with rock spoils, for surface construction can provide benefits that are not provided by rock spoils. Unlike spoils, native forest soils have organic matter pools which can supply essential nutrients, including N and P, and also increase soil water holding and cation exchange capacities. When rock spoils are used to construct productive soils, organic matter pools develop over time (Roberts and others 1988; Haering and others 1993; Bendfeldt and others 2001).

Use of weathered spoils and/or salvaged soils for surface medium construction also accelerates development of forest plant communities and ecosystem succession. Weathered spoils with properties similar to the region's natural soil provide more favorable media for plant recruitment than unweathered spoils (Angel and others 2008), while use of fresh topsoils as plant growth medium can further aid plant diversity by giving rise to living plants from seeds and propagules (Wade 1989; Wade and Thompson 1993; Skousen and others 2006; Hall and others 2009). Further, topsoil contains the propagules of mycorrhizal fungi, important to plant growth and minesoil development (Miller and Jastrow 1992), along with organic nutrients and soil biota for nutrient cycling.

While weathered spoils and salvaged soils are often favorable for reforestation, this may not always be the case. Spoils weathered from acidic rock strata, for example, can be poorly suited for reforestation and may cause degradation of water quality (Isabell 2001). Trees planted in fresh, unweathered non-acidic spoils typically survive at rates comparable to plantings in weathered materials, although early growth is commonly suppressed (Torbert and others 1990a; Angel and others 2008; Emerson and others 2009).

FRA Step 2: Loosely grade the topsoil or topsoil substitutes established in step one to create a non-compacted soil growth medium.

High soil density caused by mining equipment traffic often impairs plant productivity on Appalachian mine soils (e.g., Davidson and others 1984; Daniels and Amos 1985; Haering and others 2004). Mine reforestation studies consistently have revealed negative relationships between soil density and tree survival (Torbert and Burger 1990; Conrad and others 2002; Burger and Evans 2010) and between soil density and tree growth (Torbert and others 1988; Torbert and Burger 1990, 1994; Ashby 1990, 1997; Andrews and others 1998; Jones and others 2005; Skousen and others 2009; Burger and Evans 2010). Dense soils impede root growth and water infiltration, and limit soil water holding capacity. The lack of air spaces within dense soils limits oxygen availability, further inhibiting the growth and function of roots and soil microbes, leading to poor water and nutrient uptake.

Because of these effects, minimizing soil compaction is essential for effective reforestation. Mine operators preparing lands for reforestation are advised to limit grading by large bulldozers; to use small equipment for surface grading; to avoid grading operations when soils are wet; and to exclude subsequent mining equipment traffic (Sweigard and others 2007b). When mine soils do become compacted, mine operators are advised to loosen them using deep-tillage equipment prior to planting trees (Sweigard and others 2007a; Skousen and others 2009).

If land stability requires compaction, subsurface spoils can be compacted prior to covering the site with ≥1.2 m of additional media that remain uncompacted. Soils with loose, rough, uneven surfaces can produce lower soil losses than smooth soils on many mine sites (Torbert and Burger 1994; Fields-Johnson and others 2010), likely because rough, loose surfaces allow more water infiltration and impede water flows during storm events. Increased water infiltration aids tree growth, and rough soil surfaces enhance plant recruitment by providing features to hold seeds carried by wind and wildlife to the mine site (Groninger and others 2007)

FRA Step 3: Use less competitive ground covers that are compatible with growing trees.

Mine operators commonly apply herbaceous vegetation seed during reclamation. For reforestation, herbaceous vegetation should supply plant cover sufficient for soil surface protection and erosion control, but also should be low in stature and in water and nutrient demands to limit competition with both planted trees and potential plant colonizers. Excessive herbaceous competition on mine sites will impair survival and growth of planted trees, as occurs on natural soils (Davidson and others 1984). Several studies have found that herbaceous vegetation control aids establishment of planted trees on coal mine sites (Chaney and others 1995; Ashby 1997; Torbert and others 2000). On a Virginia mine planted with native hardwoods, Burger and others (2008) demonstrated that reducing herbaceous competition accelerates both survival and growth of late-successional trees, such as the oaks. Skousen and others (2006) found that native Appalachian hardwood trees were able to establish on older mine sites that were not seeded with herbaceous vegetation, while seeded areas supported only sparse tree cover several decades after reclamation. Some herbaceous vegetation, however, is often required to control erosion, especially on steep slopes (Jeldes and others 2010), and the SMCRA is explicit in requiring erosion control. Hence, the FRA's third step emphasizes establishment of tree-compatible herbaceous vegetation as an important complement to planted trees.

Fast growing grasses and legumes that have been used traditionally in coal mine reclamation, such as tall fescue (*Festuca arundinacea*) and certain clovers (*Trifolium* sp.), are competitive with trees. Alternatively short-statured, bunch-forming grasses such as redtop (*Agrostis gigantean*) and timothy (*Phleum pretense*) are less competitive and can be established on mine sites easily (Burger and others 2009, 2010). Native warm season grasses such as little bluestem (*Schizachyrum scoparium*) and indiangrass (*Sorghastrum nutans*) can be used successfully (Rizza and others 2007; Franklin and Buckley 2009). To further discourage heavy ground cover growth, applied fertilizers should be low in N but with sufficient P to support tree growth (Burger and others 2009, 2010). N-fixing legumes such as birdsfoot trefoil (*Lotus corniculatus*) and white clover (*Trifolium repens*), less competitive than traditional reclamation legumes, are also recommended for seeding as a means of supplying additional N.

The tree-compatible ground cover is typically sparse in its first growing season, which minimizes competition with seedlings and allows recruitment of non-seeded plants. If mine soils have been prepared using FRA steps 1 and 2, seeded and volunteer vegetation will develop to approach full cover over 2 to 3 growing seasons (Angel and others 2008; Fields-Johnson and others 2010).

The FRA approach to reclamation seeding is also intended to accelerate ecosystem succession by recruiting native plant species to the mine site (Fig. 4). Prior studies have shown that reclamation seeding effects on the developing plant community to be persistent. Skousen and others (2006) found that revegetation practices strongly influenced community composition on reclaimed surface mines 20 years after reclamation as more species were present on areas that had not received conventional ground cover seeding; while Holl (2002) found the influence of reclamation practices on plant community structure remained evident 15–30 years later.

FRA Step 4: Plant two types of trees—early successional species for wildlife and soil stability, and commercially valuable crop trees.

Crop trees are long-lived species that are characteristic of the region's mature forests and produce saleable forest products. Yellow poplar (*Liriodendron tulipifera*), oaks (*Quercus* sp.), ash (*Fraxinus* sp.), maple (*Acer* sp.), and other native deciduous species are commonly planted as crop trees on mines reclaimed using the FRA.

Early successional trees are also planted to add organic matter and nitrogen to the soil, promote the formation of valuable timber in crop trees, and attract seed-carrying wildlife. Common and effective nurse trees include eastern redbud (*Cercis canadensis*), hawthorne (*Crataegus* sp.), and dogwood (*Cornus* sp.). Nitrogen fixing nurse species such as bristly locust (*Robinia hispida*) bring additional N into the emerging forest system. Species that produce edible fruits and seeds at a relatively young age, such as dogwood, are often selected to attract wildlife that bring seeds to the mined site.

When mine soils are prepared with favorable properties, a wide variety of tree species can be established by planting. Vogel (1981), based on his extensive experience with pre-SMCRA coal mine plantings, recommends 60 tree species for planting on coal mines in eastern United States, including >30 that are native in Appalachian forests. Emerson and others (2009) found survival rates for nine hardwood and one pine species established on a West Virginia mine site averaged nearly 80%. Fields-Johnson and others (2010) documented lower average first-year survival rates (39%) over an unusually hot, dry summer for 12 native hardwood and one pine species planted on Virginia mine sites; but stocking densities were increased to adequate levels by re-planting during the following winter and a summer with more typical weather and better survival.

FRA Step 5: Use proper tree planting techniques.

It is essential that tree seedlings be stored and planted properly (Davis and others 2010). Mine sites are commonly planted by commercial contractors who maintain large crews and equipment; who can properly care for seedlings while planting; and who can plant large mine sites quickly. Proper tree planting requires a planting hole that is deep enough to accommodate the seedling's root system. If FRA steps 1 and 2 have been used, the soil material will be loose, making it easier for tree planters to open a hole sufficient to plant trees properly.

FRA Implementation

Reclamation scientists and agency collaborators recognized that the FRA's development, although a significant step towards successful forest reestablishment on coal mines, was not in itself sufficient to achieve this goal. In order to have impact, the FRA required communication to the mining industry and change was required in some aspects of the regulatory culture. As a result, the Appalachian Reforestation Initiative (ARRI) was established in 2004. ARRI's goals are to communicate and encourage mine reclamation methods that plant more high-value hardwood trees, increase planted trees' survival and growth, and develop forest habitat through natural succession (ARRI 2010).

The SMCRA requires that active coal mines "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 …" Since most lands mined for coal in Appalachia are forested prior to mining and are not placed in other managed uses after mining, restoration of forested ecosystems of comparable species and productivity satisfies this SMCRA requirement.

Under U.S. Office of Surface Mining (OSM) leadership, ARRI formed a Science Team comprised of scientists who have expertise in mined land reclamation and reforestation; and a Core Team comprised of officials from OSM and state agencies that enforce SMCRA. ARRI describes its activities as identifying and removing "barriers" to effective reforestation under SMCRA (ARRI 2010).

"Cultural barriers" are perceptions within industry and agencies that hinder forest vegetation reestablishment, including beliefs that mine reforestation is difficult, expensive, or impossible; and/or that reforestation practices are not compatible with SMCRA. Cultural barriers developed over time as SMCRA enforcement evolved into encouraging excessive soil grading and aggressive herbaceous vegetation. Actions to combat cultural barriers included direct communications from agencies to the mining industry and to mine inspectors, an annual Mined Land Reforestation Conference that attracts industry and agency personnel, and public events involving industry and agency personnel that call attention to the merits of reforestation and FRA reclamation practices.

OSM and state agencies determined that FRA reclamation is consistent with SMCRA, and few obstacles to effective reforestation had been codified as SMCRA regulations. Those few obstacles were identified as "Regulatory Barriers" and are being addressed with regulatory revisions. For example, agencies in Tennessee and Virginia changed regulations to allow less herbaceous ground cover on mine sites being reclaimed with the FRA (Burger and others 2009).

"Technical Barriers" are lack of technical knowledge by reclamation personnel regarding how to re-establish forest vegetation successfully on mine sites. ARRI's actions included preparing a series of Forest Reclamation Advisories, publications describing FRA practices (Burger and others 2005, 2009; Davis and others 2010; Groninger and others 2007; Sweigard and others 2007a, b) which are distributed to agencies and industry. Incomplete scientific knowledge concerning mine reforestation practices and outcomes remains as a technical barrier. Therefore, ARRI Science Team members continue conducting research to address relevant questions, while communication between Science and Core teams helps to direct research and to ensure that policy and technical training are based on scientific findings.

FRA Impacts

The FRA is being used by the coal industry in Appalachia (Table 1). Most mines in Virginia and Tennessee have been reclaimed using the FRA since 2006 and 2007, respectively. The state of West Virginia, with far more surface mining area, has more recently begun publishing FRA data, and those data indicate that FRA usage is expanding (OSM 2010). The FRA is being used in Kentucky, although statistics comparable to those of Table 1 are not available for that state. At least one Ohio firm is using the FRA. In total (including KY and OH), more than 4,000 ha have been reclaimed using the FRA, and areas exceeding 12,000 ha have been permitted for FRA reclamation.

FRA usage varies by state for several reasons. Reclamation areas in some states far exceed levels in other states. In some states, most reclaimed lands are forested prior to mining, while in other states land uses such as hay production and grazing are more common in mining areas

Table 1 Documented applications of the forestry reclamation approach in the Appalachian coalfields[a]

	2009	2008	2007	2006
FRA lands: area reclaimed (ha)				
Ohio	47	20	0	0
Tennessee	190	224	24	0
Virginia	623	741	300	698
West Virginia	567	567		
New FRA permitted areas (ha)				
Tennessee	313	530	630	
Virginia	515	1,108	1,120	
West Virginia	3,635	4,414		

[a] *Data sources*: Virginia Department of Mines, Minerals and Energy (unpublished data, Jon Lawson); US OSM Knoxville Field Office (unpublished data, Victor Davis); and OSM (2010)

and hence as post-mining land uses. SMCRA implementation and regulatory policies also differ by state.

While the oldest FRA-reclaimed sites are ~5 years old, development of a forest ecosystem requires decades and restoration of associated ecosystem services may require even longer. Thus, the extent to which these practices are or are not successfully restoring forested ecosystems and services is not yet known. It is clear, however, that native hardwoods are being planted on far more mine sites today than prior to the introduction of the FRA (Angel and others 2009). Our observations indicate that while site conditions produced by routine FRA applications are not always optimal, they are generally more favorable for forest trees than those created by pre-FRA reclamation, and the planted trees are surviving and growing well on many FRA sites. Our observations indicate that coal companies using the FRA are generally successful at creating sites where survival and productive early growth of planted seedlings are evident. However, it is not clear from our observations that all FRA steps are always implemented optimally. For example, determination of what constitutes a suitable soil material varies widely; and excessive, competitive ground covers are sometimes applied.

Under SMCRA, minimum stocking levels of living trees are required on forest land. Survival is typically evaluated 5 years after planting, and replanting is required on sites failing to achieve those minimum levels. Thus, we expect that changing reclamation practices are significantly improving prospects for successful restoration of forest trees on mined lands, compared to common pre-FRA practices.

Role of the FRA in Restoring Ecosystem Services

Even as FRA use expands in Appalachia, the coal industry finds itself facing increased societal demands for environmental protection. Changing federal policies establish expectations beyond SMCRA that seek to minimize mining effects on ecosystems. For example, the US Environmental Protection Agency defines its role in implementing the Clean Water Act's section 404, which governs placement of fill material in streams, as "preserving the long-term integrity of Appalachian watersheds, which is important in protecting their ecological condition and maintaining safe, clean, and abundant water for local communities" (US EPA 2010). Although the FRA's increasing use can be seen as a step toward meeting this goal, successful establishment of native forest trees is only one of many outcomes that are necessary to assure that forest ecosystem services are even partially restored.

Because intact forests provide a broad suite of ecosystem services, it is sometimes assumed that successful restoration of forest vegetation on mine sites will also restore ecosystem services. The FRA's 5 steps are intended to work together as a means of achieving that outcome (Table 2). Following is a review of scientific evidence concerning the FRA's potential to restore ecosystem services.

Forest Productivity

Soil characteristics influence post-mining forest productivity. Several studies have identified the mine soil properties favorable to productive tree growth (Torbert and others 1988, 1990a; Andrews and others 1998; Rodrigue and Burger 2004; Showalter and others 2007; and other studies), including moderately acidic pH (~5.0–6.5), low electrical conductivity, and adequate rooting volumes. The FRA emphasizes construction of mine soils with properties that can support tree growth: deep, uncompacted, and with chemical properties similar to those of native forest soils.

Research demonstrates that forested vegetation on surface coal mines can be productive. When properly reclaimed for reforestation, mine soils provide deeper rooting zones and are richer in the geologically derived nutrients Ca, Mg, and K than many native soils in steep mountain landscapes. Tree productivity on certain pre-SMCRA mine sites has been documented as equivalent to, or better, than that of adjacent unmined forests. In an early study, Ashby and others (1980) found high growth rates for many hardwood species planted on reclaimed coal mines in southern Illinois. More broadly, Rodrigue and others (2002) reported forest growth on 12 of 14 selected older coal mine sites in the eastern and midwestern US achieved productivities similar to local unmined forests. Casselman and others (2007) measured a 50-year site index (expected average height of dominant and co-dominant trees after 50 years) of 32 m for a 26-year-old white pine stand growing on an uncompacted Virginia mine site, greater than the average for natural soils in the southern Appalachians (Fig. 5). The 50-year site index of yellow poplar growing on 40-to-50 year-old Tennessee mine sites with uncompacted soils averaged 32.3 m, greater than the 26.5-m regional average (Franklin and Frouz 2007) (Fig. 6). Cotton (2006) showed that 10-year old yellow-poplar and white oak growing on loose dumped Kentucky spoils exhibited growth similar to that of regenerating non-mined stands of the same age. However, studies of tree growth on mine soils prepared using non-FRA techniques, including traditional grading practices, demonstrate productivities less than pre-mining reference levels (Burger and Fannon 2009), even when soil compaction was mitigated with subsoil ripping (Burger and Evans 2010).

An essential question is if and/or how mine soils constructed from rock spoils can provide adequate N and P to

Table 2 Intended relationship of the FRA's five steps to ecosystem service restoration

FRA steps	Ecosystem service restoration goals					
	Restore Forest productivity	Sequester C	Restore plant communities	Restore faunal habitat	Restore hydrology	Protect water quality
1. Select best-available materials	Generates soil media with physical and chemical properties that are favorable to tree survival and growth		Favorable soils aid native plant recruitment	Use of soil with organic debris aids restoration of soil habitat structure	Use of soil with organic debris can aid infiltration	"Best available" materials are often low TDS
2. Place loose and uncompacted			Aids recruitment	Loose soils aid restoration of soil habitat structure	Loose soils aid water infiltration	
3. Use tree-compatible ground cover	Enables survival of planted trees		Aids recruitment of native plants		Deep rooted by invading natives aids infiltration	Protect against excessive erosion
4. Select native crop and nurse trees	Establishes crop trees that are productive in favorable soils. Restores native trees		Establishes native trees, including nurse trees to attract wildlife and aid native plant recruitment		Deep rooting by native trees aids water infiltration	
5. Plant trees properly	Aids planted trees' survival					

Fig. 4 Planted native hardwoods and volunteer herbaceous growth in a 2008 photo of a Virginia mine site reclaimed in 2002 using conventional seeding, but with herbaceous vegetation controlled for the first 3 years with herbicides (Burger and others 2008)

Fig. 5 A Virginia mine site reclaimed with eastern white pine in 1979, in a 2008 photo (Casselman and others 2007)

support forest productivity over the long term. Rock spoils usually contain little N and P in plant available forms. Thus, N and P are commonly applied as fertilizer at reclamation, but these additions do not approach native forest soil nutrient pool quantities; if larger quantities were applied, the mine soils would be unlikely to retain most as plant available forms. Appalachian rock overburdens often contain both N and P as mineral (geogenic) forms (Howard and others 1988; Li and Daniels 1994; Simmons and Currie 2005; Simmons and others 2008), and some fraction of geogenic N can become plant available in some mine spoils (Reeder and Berg 1977; Chabbi and others 2008). Factors influencing geogenic N release are not well understood, but likely include mineral form as well as soil microbial activity (Showalter and others 2010). Potentials for geogenic N and P release to plant available forms in Appalachian mine spoils have not been studied. Li and Daniels (1994) documented development of plant-available N pools with time in Appalachian mine soils, but at slow rates relative to emerging forest needs and without apparent geogenic contributions. Howard and others (1988) documented P fixation as non-plant-available mineral forms in soils constructed from unweathered Appalachian rock spoils.

Despite lack of known mechanisms capable of supplying plant-available N and P in quantities adequate to support the long-term tree growth, productive and mature

Fig. 6 Native hardwood regeneration on a Tennessee mine site reclaimed in 1958 by planting early successional tree species on loose spoils, without the smooth grading and aggressive groundcovers that have been used commonly under SMCRA (Franklin and Frouz 2007)

forest vegetation has been observed growing in mine spoils (Skousen and others 1994; Zeleznik and Skousen 1996; Rodrigue and others 2002; Casselman and others 2007). The existence of such forest stands indicates that soil-development processes are able to supply adequate N and P, at least on some sites, but the characteristics of mine sites where this result can be expected is not clear. It is clear that native soils salvaged from mining areas contain significant N and P in plant available forms, and that soil salvage and reclamation application can provide growing plants with N and P at higher levels then raw mine spoils (Showalter and others 2010). Nitrogen-fixing plants such as black locust, autumn olive, and non-native invasive forb sericea lespedeza (*Lespedeza cuneata*), are often prominent components of plant communities on older mine sites reclaimed with rock spoils (Zipper and others 2007), suggesting that plant-available N limitations are a common plant-community influence.

Carbon Sequestration

Forests established on mined lands sequester atmospheric C in soil, as plant litter, and as biomass, with above-ground C-sequestration rates occurring as a direct function of site productivity. Amichev and others (2008) found that pre-SMCRA forested mine sites sequestered C at rates comparable to low-productivity unmined forests in nearby areas, but at rates less than the more productive unmined forests. Although biomass C on the more productive older sites was found to approach that of unmined reference forests, the 50+ years of forest growth observed on these mine sites did not enable soil C to approach unmined reference levels.

Habitat for Native Plant Communities

Vegetation recruitment on mine sites is influenced by the nature of surface soil materials and reclamation seeding. FRA reclamation can enable faster return of native plants than conventional post-SMCRA reclamation (Fields-Johnson and others 2010). Fresh topsoil and/or weathered spoils, when used for surface construction allow more recruitment of unplanted species than unweathered spoil materials (Angel and others 2008; Hall and others 2010).

Many forest species are able to colonize mine sites if soil conditions are favorable. Working on pre-SMCRA mines, Skousen and others (1994) found more diverse plant communities developed on favorable soils than on rocky and acidic soils; Thompson and others (1984) and Schuster and Hutnick (1987) also recorded many of adjacent forests' flora as present on older mine sites. Holl (2002) found that 60 species not seeded or planted, 68% of the plant species recorded in adjacent forests, moved onto Virginia mine sites over several decades, but 27 other forest species were not observed on the mines. Brenner and others (1984) found that recruitment and natural succession processes were important influences on plant community structure for 81 Pennsylvania mine sites. While many native species can move onto favorably reclaimed mine sites easily, it is also clear that some native forest species have poor dispersal abilities (Holl and Cairns 1994). The mechanisms and time required for such species to migrate onto reclaimed mines, even those with favorable site conditions, remain as open questions.

As a legacy of past reclamation practices, non-native invasive species often occur on older coal mines and, as a result, often become established on more recently reclaimed coal mines, even though rarely planted today. Open questions concern the effect of FRA reclamation on invasive species' capability to proliferate, and strategies to minimize invasives' establishment.

Faunal Habitat

Because FRA reclamation is a recent practice, use of FRA-reclaimed mine sites by wild fauna has not been studied. However, it is reasonable to expect that wildlife will use mined-land habitats as they would similar habitats on non-mined sites, and thus that successful re-establishment of native plant communities and construction of similar soils would allow mine sites to support comparable faunal communities. Studies of wildlife usage of reclaimed mines generally find habitat composition and structure exert influence as would be expected from studies on non-mined land areas (e.g., Sly 1976; Carrozzino 2009). Brenner and others (1984) found the replacement of reclamation-established plant communities with more diverse communities, which included woody species, through natural succession had a positive effect on site usages by wildlife. Chamblin and others (2004) found that development of woody vegetation with stems >15 cm in diameter along rock-lined drainage channels on coal surface mines increase site usage by Allegheny Woodrat (*Neotoma magister*), an at-risk species that commonly inhabits natural rock outcrops in unmined Appalachian landscapes, but cautioned that finding should not suggest surface mining as beneficial for this species since it causes loss of native habitat features.

Larkin and others (2008) found that loose grading techniques, as recommended for FRA reclamation, increased mined site usage by small mammals compared to conventional smooth-grading. Use of soil materials containing woody debris such as old stumps and branches for surface construction can enhance habitat by providing cover for small mammals, reptiles, and amphibians; and, as embedded woody materials decompose, by providing channels to the subsurface that can be used by borrowing animals (Carrozzino and others 2010).

Watershed Protection and Hydrology

Forest removal often causes hydrologic effects, including increased downstream water yields and flooding peaks (Hornbeck and others 1970; DeFries and Eshleman 2004). Although watersheds containing mined land reclaimed using conventional practices exhibit infiltration and runoff characteristics similar to unmined watersheds under light rainfall conditions, they commonly experience elevated runoff during heavy rains (Bonta and others 1997; Messinger 2003; Negley and Eshlemen 2006; McCormick and others 2009). This result likely occurs due to the soil compaction of traditional reclamation (e.g., Chong and Cowsert 1997; Simmons and others 2008) and the consequent reduction of near-surface macropore development (Guebert and Gardner 2001). Compacted mine spoils also have shallow rooting of reclamation grass and legume species combined with the massive structures below the A horizon (Haering and others 2004, 2005), conditions that limit water infiltration.

Because the FRA emphasizes replacement of loose soil materials, FRA reclamation practices have the potential to aid hydrologic restoration. An early study in Pennsylvania demonstrated that mine sites "evolve" hydrologically, developing infiltration/runoff patterns more like unmined landscapes with time (Ritter and Gardner 1993), and that the rate of hydrologic change is affected by vegetation and soil types. Thus, it is reasonable to expect that effective restoration of uncompacted, deep soils and forests on reclaimed mines will also have more favorable effects on landscape hydrology than conventional reclamation. Recent studies indicate favorable hydrologic effects by FRA reclamation over the short term. Spoil materials prepared for reclamation on experimental plots as per FRA step 2 have infiltration characteristics similar to unmined forest lands (Taylor and others 2009a). Whether or not this effect will persist as gravity causes the loosely placed materials to consolidate; whether deep rooting by planted trees and other native plants will counteract such tendencies and maintain the loose-dumped spoils' favorable hydrologic properties; and, ultimately, whether FRA reclamation is capable of fully restoring pre-mining hydrologic processes over longer terms are unanswered questions.

Water Quality

While acid drainage was coal mine operators' major water quality challenge in past years, total dissolved solids (TDS) and its proxy, electrical conductivity, are concerns today. Waters discharged by mine sites, especially those with valley fills, are commonly elevated in conductivity relative to pre-mining backgrounds (Merricks and others 2007; Fritz and others 2010), and those waters' biological communities are often impaired (Pond and others 2008). Thus, emerging regulatory policies are requiring Appalachian coal mines to limit conductivity in water discharges (US EPA 2010).

Because spoil types differ in TDS generation potentials (Angel and others 2008; Orndorff and others 2010), TDS concerns are causing mine operators to alter spoil handling and mined landform construction practices; FRA reclamation appears as compatible with and complementary to such changes. It is the leaching of soluble salts from spoils that causes conductivities of mine drainage waters to become elevated, as mineral salt dissolution and removal is an essential weathering process; hence, weathered spoils typically generate lower TDS than unweathered spoils (Orndorff and others 2010) unless reactive minerals are present (Angel and others 2008). Non-reactive weathered spoils and salvaged soils are favorable reforestation media for reasons that include low electrical conductivity (soluble salts) in the rooting zone (Torbert and others 1988; Andrews and others 1998). Placement of lower-TDS materials on the surface, in association with practices intended to limit water movement into and through higher-TDS spoils below, can be expected to reduce mine-water discharge conductivities below the discharges from loose-dumped fills that are commonly constructed when mining in non-acidic strata today. Techniques that have been used successfully to isolate acidic spoil materials (Skousen and others 1987), including compaction of the acidic/non-acidic spoil interface, can be adapted to isolate high TDS materials from subsurface water flow paths; such practices can be used while placing the weathered materials that are favorable to reforestation and generate fewer TDS on the surface as preferential hydrologic media.

Although the potential for TDS-source-control practices which incorporate the FRA to improve mine-water discharge quality is apparent, that result has not been demonstrated. In fact, some firms have concluded that the FRA's loose soils may increase TDS in mine effluents by encouraging water movement into and through the spoils that lie beneath the reclaimed mine surface. Should such expectations cause reclamation that employs surface compaction to limit water infiltration, despite SMCRA's extensive legacy of mines with smooth-graded compacted surfaces that discharge high-TDS waters, that result would hinder FRA implementation and reforestation of Appalachian mined landscapes. If TDS source control and FRA reclamation can be employed together to produce a landform that encourages surface-water infiltration and allows near-surface soil waters to emerge into purposefully-constructed stream channels, results would include restoration of several essential ecosystem services. Reclamation practices to achieve such results, although appearing as feasible based on known soil, water, and vegetation management concepts, have not been demonstrated.

International Context: The FRA and SMCRA's Legacy

Like the USA, nations throughout the world face the challenge of balancing mineral extraction benefits with sustainable land-use concerns. Globally, mineral extraction is expanding in response to economic forces that include rapid industrialization of formerly underdeveloped regions. In many nations with expanding mineral extraction sectors, mined land restoration policies are also in a state of development (Weber-Fahr and others 2002; Cao 2007).

The USA's coal mine reclamation law, SMCRA, is widely recognized internationally and is sometimes cited as a model for emerging mining regulatory structures in other nations (Cao 2007; Dutta and others 2005). However, parties seeing SMCRA as a model should be aware that its legacy is not one of complete success. SMCRA has largely succeeded in eliminating the environmental abuses that often occur when mining is unregulated, as occurred in USA in times long past. Mining problems such as acid mine drainage, land instability, excessive erosion, and barren land surfaces rarely, if ever, occur in association with current US coal surface mining, thanks in large part to SMCRA's regulation and industry's compliance. SMCRA, however, has not been as successful in stimulating restoration of mined lands' use potentials. Of the >600,000 ha affected by coal mining in Appalachian US since the advent of SMCRA (Fig. 2), >400,000 ha are in steeply-sloping regions of Virginia, West Virginia, Tennessee, and Kentucky, where the rich and diverse Appalachian forests predominate. On most of these lands, neither productive forest nor other managed and economically viable land uses have been restored.

Although not capable of achieving full forest community restoration, at least in the short term, the FRA nonetheless constitutes a significant advance of mine reclamation practices. The FRA was developed through scientific research; it was formulated by applying basic principles of soil science, forestry, ecology, and agronomy, which are universal and applicable to multiple ecosystems, to lands produced by eastern USA mining disturbances. Climate, geology, soils, and societal needs will ultimately dictate which reclamation goals are best suited for a particular mining region, but the application of scientific research can aid development of the reclamation practices that can achieve those goals, while cooperative engagement by scientists, industry, and regulators can help to ensure those practices are applied to generate as mining outcomes lands with capacity to produce renewable resources sustainably.

A lesson of SMCRA, however, is that regional reclamation goals, and associated practices to achieve those goals, are best developed, established, and implemented early in a mining sector's development. Although the basic principles of the FRA have been known since the early 1990s (Burger and Torbert 1992; Torbert and others 1990b, 1995), ARRI was not founded until 2004, and systemic FRA implementation did not begin until 2006. Although a few pioneering firms implemented FRA-like reclamation practices prior to ARRI, active engagement by ARRI was required to stimulate more widespread applications. The loss of land productive capacity that occurred under SMCRA prior to that development is a tragic legacy that cannot be remedied without significant expense.

This delay in FRA application occurred despite the fact that additional cost of reclaiming with the FRA is either non-existent or modest, relative to conventional SMCRA reclamation (Burger and Zipper 2002). More significant to industry is the cost of changing mining systems that have developed over several decades of SMCRA compliance. For large firms, these systems involve hundreds, if not thousands of people, many of whom must be retrained if a firm's mining system is to change. Relationships with regulators, leases and contracts that are in place with land and mineral owners, and other necessary business factors can all require change for a firm's established mining practices to be altered. In order for industry's reclamation practices to change, mining regulatory procedures also must change. As can be seen from the history of mined land reforestation practices in the eastern US, such changes do not happen easily or quickly. In the eastern USA, that result and legacy remain as an extensive mined-land resource base that lacks the productive capacity that would have been possible had a different reclamation regime been employed.

The FRA and its Future Prospects

Surface coal mining has caused significant forest loss in the Appalachian region of the USA, but a new reclamation method, the FRA, is being used by some coal mining operations. Research indicates that FRA reclamation is capable of re-establishing native hardwood trees, allows invasion by native plant species, and is superior to conventional reclamation practices as a means of restoring mined land capability for forest-based ecosystem services when properly employed.

What does the future hold for mine reforestation in Appalachia? Today, it is clear that regulatory concerns with mining effects on water resources are driving the evolution of mining and reclamation practices. We see this reality as emblematic of broader societal concerns with mining, and of societal demands for further advances in effective restoration. Thus, it is clear the FRA, as currently constituted, should be viewed not as a finished and final reclamation method but as a step along the way. In order to meet societal demands, reclamation scientists are being called upon to increase our knowledge of restoration processes for ecosystem services as well as for forest trees, while the mining industry and agencies are being asked to improve reclamation practices and ensure that those practices achieve their intended outcomes. Mine reforestation research needs include integration of FRA practices with water quality protection, hydrologic restoration, more complete plant community restoration, soil nutrient availability adequate to support long-term productivity, and with practices intended to achieve other environmental restoration goals.

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