MINE SOIL MORPHOLOGY AND PROPERTIES IN PRE- AND POST-SMCRA COAL MINED LANDSCAPES IN SOUTHWEST VIRGINIA[1]

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Abstract. Surface coal mining and reclamation methods in the Appalachians have changed dramatically since the passage of the Surface Mining Control and Reclamation Act (SMCRA) of 1977 and subsequent improvements in mining and reclamation technology. In this study, 30 pre-SMCRA mine soil profiles (4-20 yr old) were examined and sampled in 1980 and compared to 20 mine soil profiles (8-13 yr old) described in the same area in 2002 after it had been completely re-mined by modern deep cut methods. Mine soils in both sampling years had high rock fragment content (42 to 81%), relatively well-developed A horizons, and generally exhibited A-C, or A-AC-C horizonation. Although six Bw horizons were described in 1980, only two met all requirements for cambic horizons. The 1980 mine soils developed in overburden dominated by oxidized, pre-weathered material due to relatively shallow mining cuts. The 1980 mine soils had lower rock fragment content, finer textures, lower pH, and tended to be more heterogeneous in horizonation, morphology, and texture than soils observed in 2002, which had formed primarily in unweathered overburden from deeper cuts. Half the pedons sampled in both years had densic materials within 70 cm of the surface. Four poorly to very poorly drained soil profiles were described in each sampling year containing distinct hydric soil indicators in surface horizons. While older pre-SMCRA mine soils do have many properties in common with newer mine soils, their properties are highly influenced by the fact that they generally have formed in more weathered overburden from higher in the geologic column. Overall, Appalachian mine soils are much more complex in subsoil morphology than commonly assumed, and differential compaction greatly complicates their internal drainage and limits their overall productivity potential.

Additional Key Words: Pedogenesis, overburden, weathering, cambic horizon, densic layers.

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Introduction

The passage of the federal Surface Mining Control and Reclamation Act of 1977 (SMCRA) resulted in major changes in mining and reclamation methods used in Appalachian coal surface mining. Before the mid-1970's, the "shoot and shove" method was often used in contour mining. This resulted in an exposed highwall directly above a level to gently rolling bench covered with varying depths of blasted/bulldozed rocky spoils, and a steep outslope composed of spoils that had been bulldozed over the edge of the bench (Fig. 1a) over the pre-existing slope. No effort was made to control spoil composition, and the final surface on these areas consisted of a roughly graded, heterogeneous, mixture of all overburden strata (Daniels and Zipper, 1988). Native soil materials were seldom salvaged, and generally were either pushed over the outslope or randomly mixed with blasted rock spoils. Reclamation before 1977 was generally limited to liming and fertilization of the bench and outslope areas followed by planting erosion control forages and tree seedlings such as tall fescue (*Festuca arundinacea shreb*.) and white pine (*Pinus Strobus* L.) Tens of thousands of ha of pre-SMCRA mined lands still exist in the Appalachian coalfields, and are generally designated as abandoned mined land (Johnson and Skousen, 1995).

After passage of SMCRA and resultant state permanent regulatory programs, coal mined lands were mandated to be returned as close as possible to approximate original contour, including backfilling highwalls (Figure 1b). Since successful revegetation was rigorously required, either stockpiled natural topsoil, or a topsoil substitute, was placed at the final reclamation surface. Because the natural soils of the area are often thin, rocky, and infertile, and may have been removed in first-cut pre-1970's mining, suitable overburden materials are usually employed as a topsoil substitute (Daniels and Zipper, 1988). Modern mining regulations also require isolation of acid-producing pyritic (FeS_2) materials below the final surface (Skousen et al., 2000).

Many first-cut contour mines, particularly those excavated before the 1980's, were relatively shallow (< 20 m) and the spoil produced contained a high percentage of oxidized pre-weathered materials. Overburden materials that were formerly located near the surface of the geologic column were partially weathered in place, and thus were usually more oxidized, leached, and acidic due to stripping of carbonates and Fe-oxidation when compared with deeper strata. These pre-oxidized zones were recognized by Grube et al. (1982) who presented data indicating that

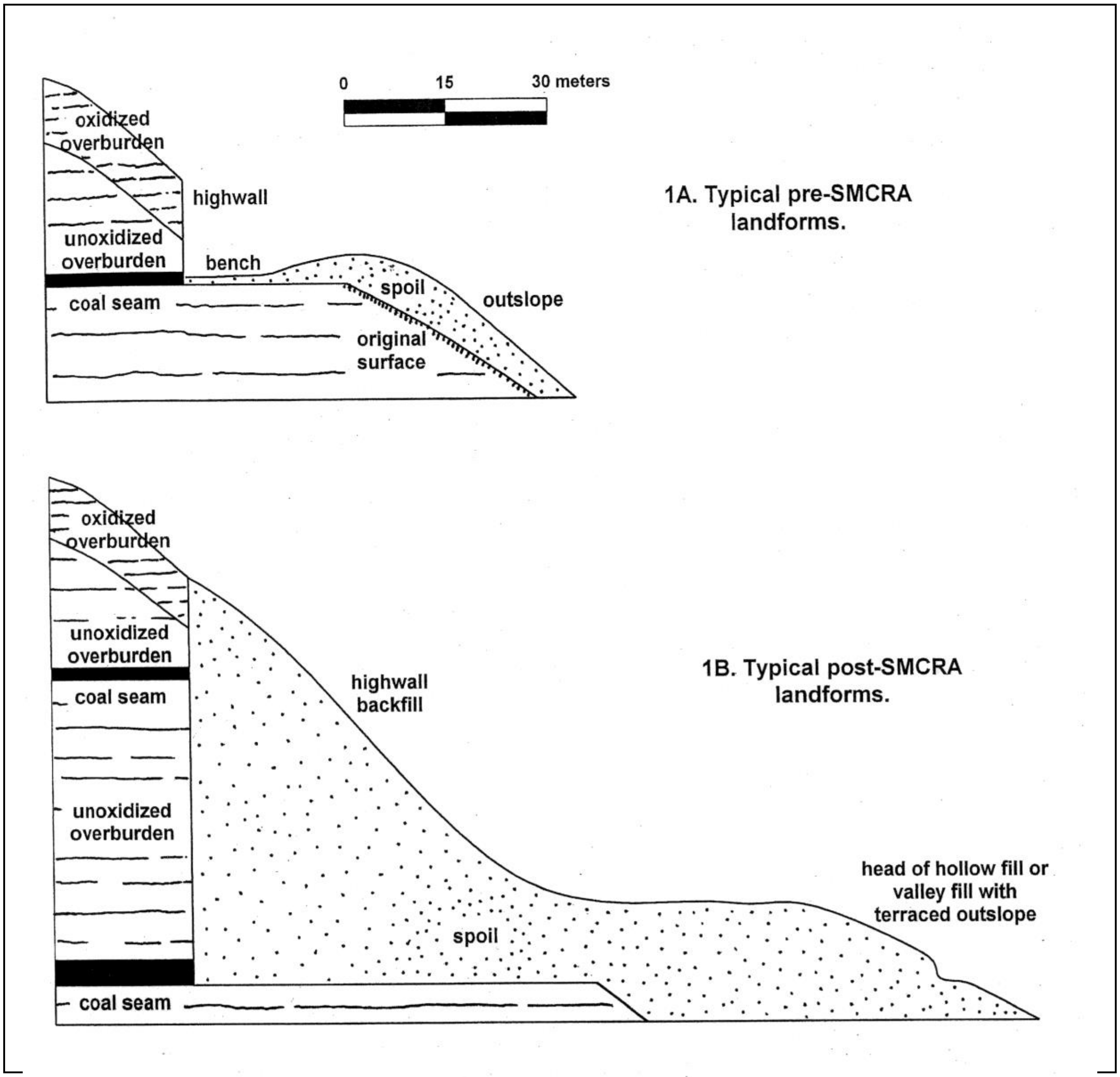

Figure 1. Typical landforms created in the Appalachian coal region by surface coal mining activities before (1A) and after (1B) passage and implementation of the Surface Mining Control and Reclamation Act of 1977. Mining before SMCRA was generally smaller in scale and mining cuts excavated a higher proportion of pre-weathered, leached and oxidized strata. Post-SMCRA mines are generally much larger in extent and take deeper cuts into more reduced geologic strata.

this weathered zone extended from 6-12 m below the soil surface in northern West Virginia and Southern Pennsylvania. The existence of this oxidized zone has also been well- documented by researchers studying acid-base accounting, which is the most commonly utilized method for determining the acid and alkaline-producing potential of overburden prior to disturbance (Sobek et al., 2000). Weathered, oxidized overburden can generally be identified by soil color chromas ≥ 3 due to secondary Fe-oxides and usually contain little reactive pyrite.

The overall post-mining landforms generated by pre-SMCRA mining in the Appalachians were dominated by long sinuous and relatively narrow flat benches and associated highwalls (Fig. 1a) which commonly continued on contour for many km. Multiple mining benches were common on many ridges, and it was not unusual to have two benches so close to one another that the outslope spoils from one bench continued down onto an immediately adjacent bench below, leaving isolated islands of natural soil and undisturbed vegetation between. As mining technology improved through the 1980's, new areas on steeper slopes were mined for the first time, and many older mined areas have been extensively remined. Current Appalachian surface mine operators take wider and deeper cuts into unweathered overburden over much larger areas than were commonly mined before the 1980's. The overall post-mining landscape contains significant areas of steeply sloping highwall backfills and hollow fills, but may also contain large expanses of relatively flat or gently rolling areas where spoils are returned over the older benches associated with previously mined areas (Fig. 2). Since a greater percentage of the overburden in modern mining comes from deeper in the geologic column (Fig. 1B), the resulting spoil materials frequently consist primarily of unweathered and unoxidized materials. These overburden strata and resultant spoils usually have an initial chroma of ≤ 2.5 due to their reduced nature. In southwestern Virginia, these unweathered strata commonly contain significant amounts of carbonate cementing agents (Howard, 1979), but may also contain some reactive pyrite (Sobek et al., 2000). In southwestern Virginia, the pH of unoxidized overburden materials commonly falls between pH 6.5 and 8.0 (Roberts et al., 1988), while that of pre-oxidized and leached materials is between 4.5 and 6.0. Pyritic overburden materials, where present, commonly generate post placement soil pH values of < 4.0 (Daniels and Amos, 1981).

Several researchers have documented the properties of mine soils after surface coal mining in the Appalachian region. Appalachian mine soils typically have a high (35 to $\geq$ 70%) rock fragment content (Pedersen et al., 1980; Ciolkosz et al, 1985; Thurman and Sencindiver, 1986,

Figure 2. Appalachian coal mined landscapes of varying ages and mining methods in Wise County, Virginia. The active mine in the center of the photo is a conventional contour haul-back operation where the highwalls are backfilled to approximate original contour (AOC) with excess spoil disposed of in valley fills. The older pre-SMCRA mines in the immediate foreground and the background date to the 1960's and early 1970's and are clearly recognizable due to many linear km of exposed highwalls. Photo by Carl Zipper.

Roberts et al., 1988), low clay contents, and often have highly variable chemical properties (Roberts et al. 1988). In a different mining environment, researchers working on prime farmland soils in the Midwest have noted that mine soil properties such as texture, color, and subsurface pH are generally inherited from overburden type, while attributes such as bulk density and drainage class result from the reclamation method used (Indorante et al., 1992). Sencindiver and Ammons (2000) report similar overall relationships between overburden type and Appalachian mine soil properties.

Mine soils commonly have A-C, or A-AC-C horizonation (Sencindiver and Ammons, 2000), and A horizons have been observed to form rapidly in mine soils. Roberts et al. (1988) found that weak A horizons characterized by spoil loosening and aggregation formed in southwestern Virginia mine soils after approximately 1 year. After 3 years, 5-6 cm deep A horizons characterized by weak granular or subangular blocky structure and darkening as a result of mixing of organic matter had formed. In the same mine soils after 8 years, A horizons were 5-11 cm thick (Haering et al., 1993). Ciolkosz et al. (1985), in a study of non-topsoiled Pennsylvania mine soils of various ages, estimated that it took approximately 3-13 years to form A horizons. However, they described at least one A horizon in a 1-yr-old mine soil. Thomas et al. (2000) found that A horizons had formed in 2 years in reclaimed West Virginia mine soils. In an unpublished study in Pennsylvania (reported in Sencindiver and Ammons, 2000), A horizon depth in a mine soil chronosequence in similar overburden materials appeared to be controlled by mining and reclamation methods rather than mine soil age. In southwest Virginia mine soils, AC horizons formed within 8 years, and typically exhibited weak structural development, increased rooting relative to the C horizons, and were slightly darkened due to organic matter translocation and/or rhizodeposition (Haering et al., 1993). Ciolkosz et al. (1985) estimated that distinct AC horizons usually formed in 6-20 yrs in Pennsylvania.

Cambic (Bw) horizons also have been described in Appalachian mine soils (Ciolkosz et al., 1985; Haering et al. 1993; Thomas et al., 2000), and some have met the requirements for cambic horizons. The cambic requirements that pertain to mine soils are (1) a depth $\geq$ 15 cm in thickness; (2) soil structure or the absence of rock structure present in more than half the volume, and (3) higher chroma, higher value, redder hue, or higher clay content that the underlying horizon or an overlying horizon (Soil Survey Staff, 1999). Ciolkosz et al. (1985) described Bw horizons in 10 out of 24 pedons of Pennsylvania mine soils with ages ranging from 3-yr-old to 29-yr-old. Although all 10 of these Bw horizons met the structure and thickness requirement for cambic horizons (15 cm), only 5 of these Bw horizons also met the cambic color requirement. Despite these published observations of Inceptisols occurring in mine soil landscapes, all established soil series for Appalachian mine soils are classified as Entisols.

In this study, we compared mine soils described and sampled in 1980 that resulted from pre-SMCRA mining techniques to much newer mine soils forming in the same area after it had been re-mined. The objectives of this study were (1) to compare and contrast mine soil horizonation, morphology, physical properties, and pH in both ages of mine soils and (2) to determine the effect of overburden type, overburden weathering, and reclamation method on these mine soil properties.

Materials and Methods

The study area was located on the Powell River Project Education Center, about 11 km northwest of Norton, in Wise County, VA. The headwaters of the Powell River bisect the original (1980) study area (Fig. 3) and elevations of the benches studied range from 785 to 880 m. Local relief is > 200 m, average slopes are generally > 35%, and most natural soils are well to excessively drained. Dominant native soil series include Jefferson (Fine-loamy, siliceous, semi-active, mesic Typic Halpludults) and Dekalb (Loamy-skeletal, siliceous, active, mesic Typic Dystrudepts) soils. The climate is humid temperate with an average precipitation of approximately 125 cm which is evenly distributed seasonally. The native vegetation in unmined areas is mixed native hardwoods. Reclaimed surface mined benches and backfills are dominated by tall fescue, sericea lespedeza (*Lespedeza cuneata L.*), and other herbaceous revegetation species along with common woody species such as white pine, black locust (*Robinia pseudoacacia L.*) and red maple (*Acer rubrum L.*). The bedrock underlying the area is of Pennsylvanian age, and is composed of horizontally bedded sandstone, siltstone, shale and coal beds of the Wise formation (Nolde et al. 1986). The majority of strata are cemented by a complex of carbonate, Fe, and silica intergranular cements, and are generally low in pyritic-S, although acid-forming materials are present in some strata below and between coal seams.

Mine soils of the area were described and sampled in both 1980 and 2002. The study area was extensively mined between the late 1950's and 1977, and the 30 soil pits examined in 1980 were distributed across four mining bench levels (Fig. 3). These benches were associated with the Upper Standiford (or Wilson), and Lower Standiford, Taggart and Taggart Marker, Low Splint, and Phillips coal seams (Brown, 1952). These areas had been contour mined before the passage of SMCRA, and the contour cuts resulted in a highwall-bench-outslope landform as depicted in Fig. 1A. Prior to description and sampling in 1980, the mine soils on these four benches were sampled at 245 randomly distributed points (Daniels and Amos, 1981). Thirty backhoe pits were then excavated in 1980 in typifying locations determined from the random sampling data and other field observations. Mine soils were described using existing Soil Survey

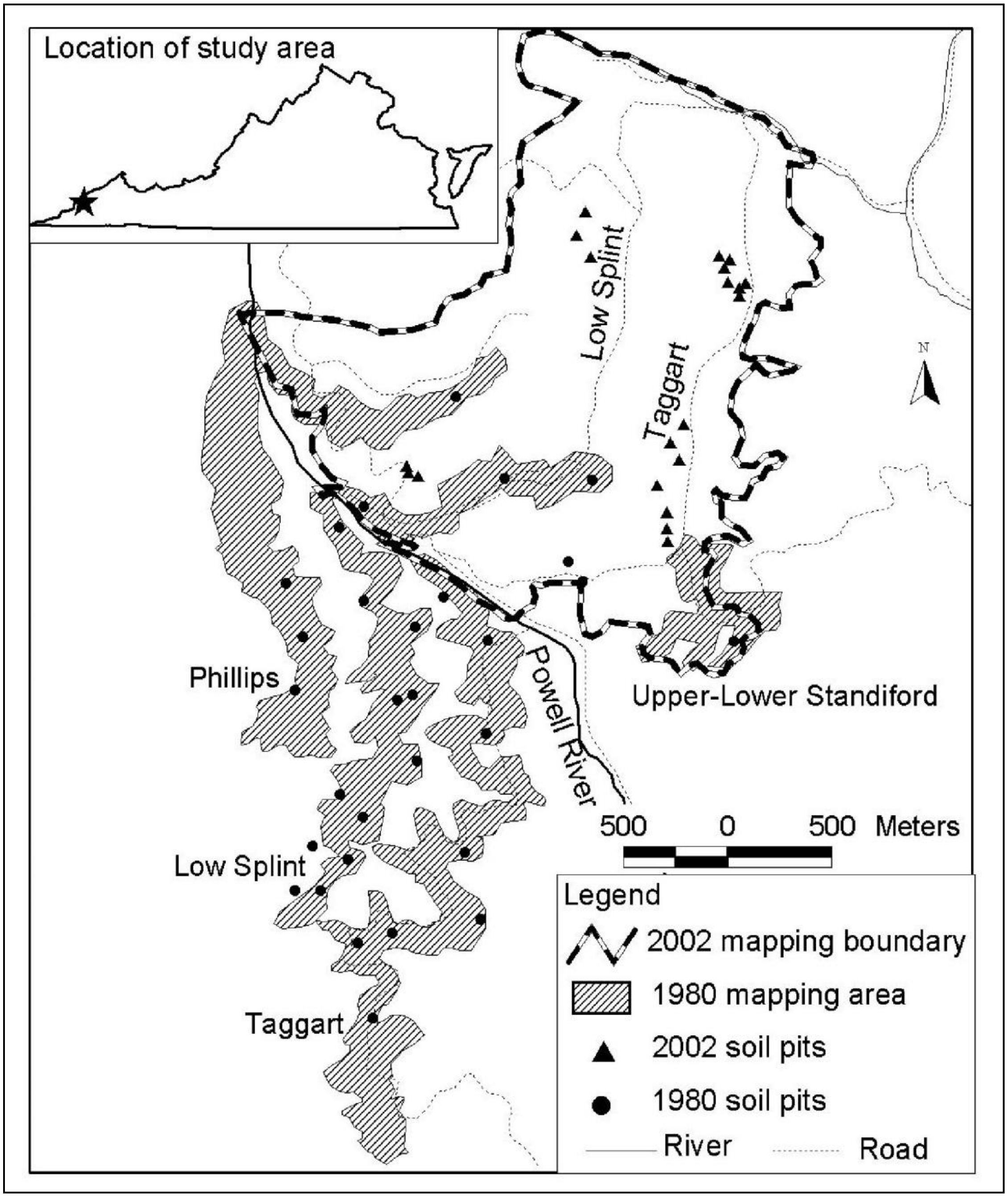

Figure 3. Location of the Powell River Project study area in Wise County, Virginia. Boundaries of detailed mine soil mapping areas are designated along with mine soil study pit locations for 1980 and 2002 studies and sampling.

Manual (Soil Survey Staff, 1962) procedures, but have been updated with current horizon designations (Soil Survey Division Staff, 1993). Of the 30 mine soil profiles, 20 were 4-yr-old, 4 were 8-yr-old, 4 were 12-yr-old, and 2 were 20-yr-old. All mine soils were sampled on relatively flat to strongly rolling benches with overall slopes < 20%.

Between 1980 and 2001, large sections of the research area were remined using second-cut contour mining methods and were then reclaimed in accordance with SMCRA. Return to approximate original contour was accomplished by highwall backfilling and valley fill construction (Figs. 1 and 2). Due to extensive re-mining in the area, none of the 1980 landscapes existed intact at the time of the 2002 soil investigations. However, approximately one-third of the mine soil landscape described in 2002 overlapped with the 1980 study area, but the original 1980 benches had been completely removed. Typifying pedon locations of the mine soils examined in 2002 were determined by USDA-NRCS personnel, who had mapped the area at a working scale of 1:6000 during the fall of 2001 (Haering et al., 2003). Twenty pits were dug by backhoe and described using Soil Survey Manual methods (Soil Survey Division Staff, 1993) on rolling portions of the landscape with slopes < 20%. Fourteen of the 20 pits examined in 2002 were located on reclaimed areas where the Taggart and Taggart Marker coal seams had been remined, and six were located on remined areas of the Low Splint Bench (Fig. 3). These areas had been mined in the late 1980's and early 1990's and were reclaimed in 1989/90 (Taggart), and 1993-1994 (Low Splint); thus mine soils described in 2002 study were 8 to 13-yr-old. Eight of the 2002 profiles had been treated with a composted-wood chip/biosolids mixture as a surface amendment in 1980/81 (Daniels and Haering, 1994), which was incorporated to approximately 15 cm.

Large samples (2 to 5 kg) of each horizon were taken for analysis. The soil was air-dried, gently crushed when necessary, and sieved through a 2mm (10 mesh) sieve. In 1980, large samples (3 to 5 kg) of each horizon were sieved in the field to determine the approximate weight percentage of rock fragments ≥ 75 mm. Content of fragments <75 mm was determined in the lab. In 2002, total rock fragment content and relative percentages of gravels, cobbles, stones and boulders were visually estimated in the field (Soil Survey Staff, 1993). Field rock fragment volume estimates were converted to weight estimates (method 3B1, USDA-NRCS, 1996). Percent of small gravel (≤ 20 mm) content was also quantified in the laboratory by sieving and weighing the 2 to 5 kg samples. However, very large (approximately 60 kg) samples are required to accurately measure the percentage of rock fragments between 25 and 75 mm, and visual estimates are recommended for determining percentage of rock fragments > 75 mm (Soil Survey Staff, 1993; USDA-NRCS, 1996). Therefore, we did not attempt to statistically compare the values for 1980 vs. 2002 whole soil rock fragment contents due to differences in their determination, and due to the uncertainties in accurate estimation. They are reported and discussed qualitatively, however.

Particle size analysis was performed on all samples by the pipette method using oven-dry samples (Method 3A1: UDSA-NRCS, 1996). Prior to particle size analysis, organic material was removed from A horizons by pretreatment with H_20_2. Soil pH was determined in a 1:1 water slurry (Thomas, 1996). Bulk density on selected horizons from the 1980 sampling was determined by the saran clod method (Method 4A1: USDA-NRCS, 1996).

The mine soil profiles were divided into two sections for statistical comparison: the 0-25 cm surface layer and the particle size control section (25-100 cm., or 25 cm to rock contact if shallower than 100 cm). For the purposes of this study, densic materials were included in the analyses of the 25 to 100 cm section. The particle size control section for Entisols/Inceptisols was chosen because all these mine soils would be mapped as Udorthents according to the established mine soil series currently being used in southwest Virginia. Four shallow (depth to rock ≤ 50 cm) mine soils described in 1980 were excluded from statistical comparisons.

Weighted averages for selected soil properties were calculated by multiplying the value for each parameter, by horizon, by thickness (cm). These values were then summed and divided by the total depth sampled in each profile. Mean weighted averages were then determined by summing weighted averages for each profile examined by year (n=30 for 1980 and n=20 for 2002). The mean weighted averages of various parameters were compared using both a Mann-Whitney test and an approximate 2-sample t-test (Minitab, 2000) for different sampling years, and a paired t-test (Minitab, 2000) for depth contrasts within the same year. The Mann-Whitney non-parametric contrast compares median values of test parameters, and was used initially for comparing data from sampling years due to small sample sizes (*n*=20 to 26). The approximate 2-sample t-test was also used to compare parameter means, and we found the results were identical to the results of the non-parametric test at $p \leq 0.05$. Mean contrasts for various soil parameters between sampling years reported in the text therefore reflect results of both the Mann-Whitney test and the approximate 2-sample t-test, while mean depth contrasts within years are the results of the paired t-test.

Results and Discussion

Overall Mine Soil Properties

Sencindiver (1977) and other West Virginia University researchers (Sencindiver and Ammons, 2000) have defined a set of mine soil properties that can be used for the establishment of diagnostic criteria for their classification. Some of these properties are disordered rock fragments, color variegations not associated with horizon formation or redoximorphic processes (often described as lithochromic mottling), splintered or sharp edges on rock fragments, bridging voids, and carbolithic rock fragments. All of the profiles we examined in both 1980 and 2002 had at least three of the above properties. Horizontal layering of differing spoil types was common and was observed in 8 out of 30 of the 1980 profiles (see Profile 1980-1 in Table 1 for example) and in 9 out of 20 of the 2002 profiles. Twenty-one of the 1980 profiles, and all but one of the 2002 pedons had common lithochromic mottling in at least one horizon (see profiles 1980-2 and 2002-1). Differences in color in horizons below the A or AC horizons were likely a result of this spoil layering rather than pedogenic processes.

Since the area studied in 1980 was mined before the advent of current reclamation standards, careful overburden handling and placement strategies were not employed. The strata removed during mining were transported laterally as well as downward, resulting in very heterogeneous mine soils of widely varying depth. As examples of the variation in gross mine soil properties found on the pre-SMCA landscape, three of the 1980 pedons had surface horizons formed in pure siltstone overburden materials that formed a hard vesicular crust (for example, profile 1980-1 in Table 1), while two shallow soils contained intact low-grade coal seams within 30 cm of the surface, and siltstone bedrock was encountered at 37 cm in another soil. Profile 1980-2 (Table 1) was the deepest of the shallow (< 50 cm) soils described in 1980. However, the vast majority of soil profiles described in 1980 were deeper than 1 m to intact bedrock.

Due to the relatively shallow depth of earlier mining operations, the mine soils examined in 1980 contained a high percentage of oxidized overburden, as was evident from relatively high chroma (≥ 3) colors in the majority of the soils. Brown oxidized sandstone was the predominant

Table 1. Profile descriptions of four mine soils sampled in 1980 and 2002.

Horizon	Depth	Description
	-cm-	
		Profile 1980-1
A	0-11	Dark grayish brown (10YR 4/2) gravelly loam; weak fine subangular blocky structure; friable; common fine roots; 20% rock fragments (sandstone and siltstone); 5% carboliths; strongly acid (pH 5.5); clear smooth boundary.
2Cd	11-46	Dark gray (10YR 4/1) gravelly silt loam; massive; very firm; few fine roots along coarse fragment faces; 12% rock fragments (sandstone and siltstone); 6% carboliths; extremely acid (pH 4.4); clear wavy boundary.
3C	46-100+	Dark gray and yellowish brown (10 YR 4/1 and 10YR 5/6) very cobbly sandy loam; structureless; firm; no roots; 34% rock fragments (sandstone); 1% carboliths; very strongly acid (pH 4.7).
		Notes: This mine soil on the Low Splint bench was described in fall 1980. Slope was 3% and vegetation was a sparse stand of sericea lespedeza [*Lespedeza cuneata* (Dum. Cours.) G. Don]. The A horizon in this soil was essentially a thick vesicular crust, while the 2Cd horizon severely limited effective rooting depth.
		Profile 1980-2
A	0-6	Dark grayish brown (10 YR 4/2) very cobbly silt loam; weak very fine to fine subangular blocky structure; very friable; few coarse and common fine roots; 57% rock fragments (siltstone and shale); <1% carboliths; medium acid (pH 5.75); abrupt smooth boundary.
Bw	6-19	Yellowish brown (10YR 5/4) very cobbly loam; weak to moderate medium and fine subangular blocky structure; areas of both firm and friable consistence; common fine roots; 43% rock fragments (siltstone); <1% carboliths; very strongly acid (pH 5.0); clear smooth boundary.
C	19-47	Yellowish brown (10YR 5/6) to brownish yellow (10YR 6/6) cobbly loam, with common coarse gray (10YR 5/1) lithochromic color variegations; massive; firm; few fine roots; 48% rock fragments (sandstone and siltstone); <1% carboliths; strongly acid (pH 5.3); abrupt smooth boundary.
2R	47-70+	Gray (10YR 5/1) sandstone bedrock
		Notes: This shallow soil on the Low Splint bench was described in fall 1980. Slope was 2-3%, with a moderately thick stand of red clover (*Trifolium pratense* L.) and tall fescue (*Festuca arundinacea* Schreb.) A Bw horizon was described because structural development in the B horizon was much stronger than that in the A or C horizons, but this horizon does not meet the thickness requirement for a cambic horizon. The C horizon described here contains a pocket of sandier material, one of many which occurred along the pit wall.

Table 1. (continued) Profile descriptions of four mine soils sampled in 1980 and 2002.

Horizon	Depth	Description
	-cm-	
		<u>Profile 2002-1</u>
Ag	0-14	Dark gray (10YR 4/1) very gravelly sandy loam, with 10% strong brown (7.5 YR 5/8) Fe masses and 2% dark yellowish brown (10YR 4/6) Fe concentrations as pore linings, and common yellowish brown (10YR 5/8) and olive yellow (2.5 Y 6/6) lithochromic color variegations; weak medium subangular blocky structure; friable; 44% rock fragments (65% gray sandstone, 20% brown sandstone, 10% gray siltstone, 5% carboliths); many medium, fine, and very fine roots; slightly acid (pH 6.5); clear wavy boundary.
Cg	14-44	Gray (10YR 5/1) and dark grayish brown (10YR 5/2) extremely gravelly sandy loam, with 15% yellowish brown (10YR 5/6 and 5/8) Fe concentrations and 5% gray (10YR 6/1) Fe depletions as masses and pore linings, and few brownish yellow (10YR 6/8) lithochromic color variegations; mainly massive with pockets of weak medium subangular blocky structure; firm; 77% rock fragments (65% gray sandstone, 20% brown sandstone, 10% gray siltstone, 5% carboliths); common fine and very fine roots; slightly alkaline (pH 6.5); gradual wavy boundary.
Cdg	44-120+	Dark grayish brown (10YR 4/2) extremely gravelly loam, with 5% strong brown (7.5 YR 4/6) and 2% weak red (2.5YR 4/2) Fe concentrations as masses and pore linings; massive; very firm; 81% rock fragments (65% gray sandstone, 20% brown sandstone, 10% gray siltstone, 5% carboliths); few very fine roots along rock faces in upper part of horizon; slightly acid (pH 6.5.)
		Notes: This mine soil was described in spring 2002 on a nearly level (3% slope) portion of a reclaimed pasture area on the Taggart Bench. Vegetation included rushes (*Juncus* sp.) and sedges (*Carex* sp.) The pit area was ponded, and the pit required pumping so that it could be described. The soil was judged to be very poorly drained.

Figure 4. Wet mine soil in 1980. Subsoil was highly compacted and perching this saturated zone above approximately 20 m of unconsolidated spoil fill.

Table 1. (continued) Profile descriptions of four mine soils sampled in 1980 and 2002.

Horizon	Depth	Description
	-cm-	
		Profile 2002-2
Ap	0-7	Very dark brown (10YR 2/2) very gravelly loamy sand; weak fine granular structure; very friable; 55% rock fragments (70% gray sandstone; 10% brown sandstone, and 20% river gravels and other non-native rocks added with biosolids); many fine and very fine roots; moderately acid (pH 6.0); clear wavy boundary. Marks from chisel plowing in 1989 are clearly visible, and the depth of this horizon varies from 2 to 15 cm below the surface.
AC	7-19	Dark grayish brown (10YR 4/2) extremely gravelly loam; mainly weak fine subangular blocky structure with structureless massive in in parts; firm; 77% rock fragments (65% gray sandstone, 30% brown sandstone; 5% carboliths), common to few fine and very fine roots; neutral (pH 7.3); clear smooth boundary.
Cd	19-35	Dark gray (10YR 4/1) extremely stony sandy loam; structureless massive; very firm; 85% rock fragments (75% gray sandstone, 15% brown sandstone; 10% carboliths); few fine and very fine roots along rock surfaces; moderately alkaline (pH 8.3); clear smooth boundary.
C	35-130+	Very dark gray (2.5Y 3/1) extremely bouldery sandy loam; structureless massive; very friable; 91% rock fragments (85% gray sandstone, 10% brown sandstone, 5% carboliths); few fine and very fine roots along rock surfaces in upper part of horizon; strongly alkaline (pH 8.5); common large (20-30 cm) bridging voids.
		Notes: This pedon was described in spring 2002, and was located in a nearly level (approximately 2% slope) portion of a reclaimed pasture area on the Taggart Bench on which a composted wood-chip/biosolids mixture had been applied in 1989 and incorporated by chisel plowing. Vegetation consisted of a closed stand of mixed forage species.

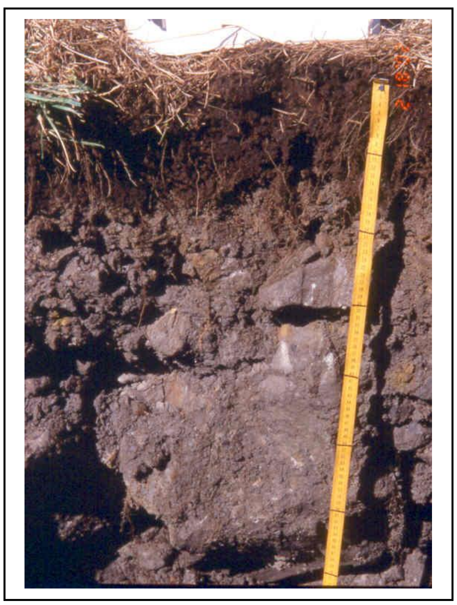

Figure 5. Photo of pedon 2002-2

(>65%) rock fragment type in seven of the 1980 mine soils, and at least 35% oxidized brown sandstone was found in 14 more profiles. Only 4 out of the 30 profiles described in 1980 were dominated by gray unoxidized (chroma ≤ 2.5) sandstone and/or siltstones. In contrast, the predominant rock fragment type in half of the 20 mine soils we described in 2002 was gray unoxidized sandstone (e.g. profiles 2002-1 and 2002-2 in Table 1) and at least 35% gray sandstone was found in six of the remaining profiles, while brown oxidized sandstone was the predominant rock fragment type in only four of the 2002 profiles.

The area studied in 2002 was reclaimed with rock spoil materials that had been designated as a suitable blasted overburden derived topsoil substitute, resulting in good vegetative cover throughout. Almost all of the overburden produced in this mining operation was suitable for use as a topsoil substitute. Thus, there was no effort made to segregate and spread designated strata at the final reclamation surface, although attempts were made to bury the limited (< 5%) amounts of acid-forming materials encountered. Overall, the mine soils we described in 2002 had much more uniform horizonation, particle size, and morphology than those we examined in 1980, although some of the individual profiles we examined contained obvious mixing and layering of unoxidized and oxidized spoil types. All the soils described in 2002 were ≥100 cm in depth.

<u>Rock Fragment Content and Soil Texture</u>

Mean weighted volumetric rock fragment content for both the 1980 (42%) and 2002 (81%) pedons fell within the 35 to ≤70 % range reported previous studies on Appalachian mine soils (Pedersen et al., 1980; Ciolkosz et al, 1985; Thurman and Sencindiver, 1986, Roberts et al, 1988). Rock fragment content in both the upper 25 cm and the particle size control section of the 1980 pedons appeared to be lower than that of the corresponding depths in the 2002 pedons (Table 2). However, the 1980 rock fragment estimates were based primarily on lab sieving, and do not accurately reflect the occurrence of larger cobbles, stones, and boulders in the actual field pedons. Other researchers (Ciolkosz et al. 1985) have reported that surface horizon rock fragment contents are lower in minimally reclaimed mine soils such as the 1980 soils in this study, and have attributed this to physical weathering, but we could not confirm this. However, physical decomposition and slaking of surface rock fragments, particularly in brown, pre-weathered sandstones, and in fissile siltstones and shales, was readily observable in both 1980

Table 2. Soil pH, particle size analysis, and rock fragment content in the upper 25 cm of the 1980 and 2002 mine soil pedons, and in the particle size control section (25-100 cm, or 25cm to bedrock, if less than 100 cm deep) of the 1980 and 2002 mine soil pedons. Shallow and very shallow (<50 cm) soils were excluded.

		Rock Fragments		Sand		Silt		Clay		pH	
Year	Pedons	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
		------------------------------%------------------------------									
		0-25 cm section									
1980	26	42	14.0	47a*†	16.7	37a†	12.2	15a†	5.0	5.56a	0.76
2002	20	68†	7.7	62b	9.7	30b	7.0	8b†	3.3	6.61b	0.96
		Particle size control section									
1980	26	45	16.8	53a	14.6	33a	14.6	14a	4.0	5.59a	0.91
2002	20	85	6.0	59a	8.5	31a	8.5	10b	2.8	6.81b	1.56

*means followed by the same letter in columns within depth sections are not significantly different (α = 0.05)

† means for the 0-25 cm. section followed by this symbol are significantly different (α = 0.05) from particle size control section means for the same sampling year.

and 2002. In previous studies within the same research area (Roberts et al., 1988; Haering et al., 1993), we have observed a reduction in rock fragment content with time in the 0-5 cm layer of mine soils forming in the same overburden, but this reduction was confined to the near-surface (0 to 15 cm) horizons. In the 2002 pedons, however, the rock fragment content of the surface horizons (0 to 25 cm) was significantly lower than the rock fragment content in the 25 to 100 cm zone (Table 2). While some of this may be due to surface weathering, it may also be the result of mechanical grinding of surface spoils by dozers and graders when constructing the final surface.

Twenty-two of the pedons examined in 1980, and all of the soils examined in 2002 fell into the loamy-skeletal particle size family (Table 2), even though actual volumetric rock fragment content was likely underestimated in the 1980 pedons as discussed earlier. The 1980 pedons contained significantly more clay in the particle size control section than the 2002 pedons, and the upper 25 cm of the 1980 pedons contained significantly less sand and more clay and silt than the 2002 pedons (Table 2). Since the parent material overburden of the 1980 soils contained a high percentage of pre-weathered sandstones and siltstones, the initial rock fragment and particle size distribution of mine soils forming in that overburden would be expected to be finer, and these materials would also be more prone to rapid pedogenic weathering of the coarser fractions into finer textures. Dominant textures in both sampling years were sandy loam/loam, although four mine soils with silt loam textures throughout the profile were described in 1980 in pure siltstone/shale overburden materials.

Comparison of the upper and lower profile sections within years indicates that the upper 25 cm of the 1980 soils had significantly less sand, and more silt+clay than the deeper particle size control section (Table 2). In contrast, the upper 25 cm of the 2002 soils did not differ in sand from the underlying particle size control section, so we are unable to draw any firm conclusions about preferential weathering or translocation of <2mm particles in the surface horizons of these mine soils. It is likely, however, that <2mm particles in the surface horizons of mine soils formed in oxidized, pre-weathered, material, would be more subject to pedogenic weathering over time than those of mine soils formed in unoxidized material from lower in the geologic column due to their lower degree of intergranular cementation from long-term carbonate dissolution and Fe-oxide formation (Daniels and Amos, 1981).

Overall, the 1980 pedons contained fewer rock fragments and finer textures than the pedons sampled in 2002. The higher percentage of rock fragments and coarser textures in the 2002 pedons reflect the fact that improvement in mining methods and efficiency over the years allowed mining companies to remove coal from deeper cuts into unoxidized and physically harder portions of the geologic column.

Mine Soil Acidity

Mine soil pH (reaction) is a property inherited directly from overburden parent materials, and can vary widely depending on the amount of acid-producing or acid-neutralizing material present in the parent material overburden. Oxidized, pre-weathered, overburden strata generally contain very little oxidizable pyrite, but may also be leached of carbonates (Sobek et al., 2000). In prior studies within the same watershed, Roberts et al. (1988) and Haering et al. (1993) found that mine soils forming in partially oxidized sandstone overburden had an initial surface pH of 5.5, whereas mine soils forming in unoxidized sandstone and siltstone overburden had an initial pH of 7.5. Mean soil pH of both depth sections of the 1980 pedons was significantly lower than the corresponding soil depths in 2002 (Table 2). We attribute this to the higher proportion of pre-oxidized and weathered parent materials of the 1980 pedons. However, soil pH did not vary with depth in either 1980 or 2002. Average surface and subsurface pH varied widely in both years. It was not unusual to find extremely acid (pH 3.5-4.4) soils within several meters of moderately alkaline (pH 7.9-8.4) soils. Although the overburden of the area was not typically acid producing, there was some acid-forming material associated with the Standiford interburden and underclay below the Low Splint coal. Relatively small amounts of this acid-forming material within a profile could lower the pH dramatically. For example, 2002 soil horizons formed primarily in unoxidized gray sandstone exhibited pH values ranging from 4.8 to 8.4.

Carbolithic materials (coal fragments and high carbon black shales) were detected in at least one horizon in 29 out of 30 of the 1980 pedons, and in all the 2002 pedons. These materials were readily identifiable in the field because they had a color value and chroma of ≤ 3 (Sobek et al, 2000). The average content of carbolithic material in the profile averaged 1-2% in the 1980 pedons, and 5% in the 2002 pedons. Although some carbolithic materials can have high total-S levels, they are not always acid-producing, particularly if they are dominantly high-rank bituminous coal fragments. Black fissile shales and mudrocks are generally more problematic with respect to pH effects in this region (Daniels and Amos, 1981). The percentage of carbolithic materials in a particular horizon of the soils we sampled exhibited no direct relationship to soil pH. Thus, pH measurements coupled with potential acidity estimators (Sobek et al., 2000) are the only reliable way to determine whether a soil formed in unoxidized gray sandstone would have an acid or alkaline reaction, although most gray sandstone spoils can be expected to have a pH > 6.0.

Overall, the soil pH range observed in both 1980 and 2002 was generally well within that suitable for plant growth, particularly for the grasses, legumes, and woody species commonly employed for reclamation in this region. In these mine soils, low water holding capacity due to high rock fragment contents coupled with the compacted zones discussed later are much more likely to be directly controlling of plant growth and long term productivity potentials than is soil reaction.

Mine Soil Horizonation and Morphology

A Horizon Formation. Well-developed A horizons were found in all the pedons examined in our study including the 4-yr-old mine soils described in 1980 (Figs. 5, 6 and 7). These A horizons averaged 13 cm in thickness, and contained weak to moderate granular and/or subangular blocky

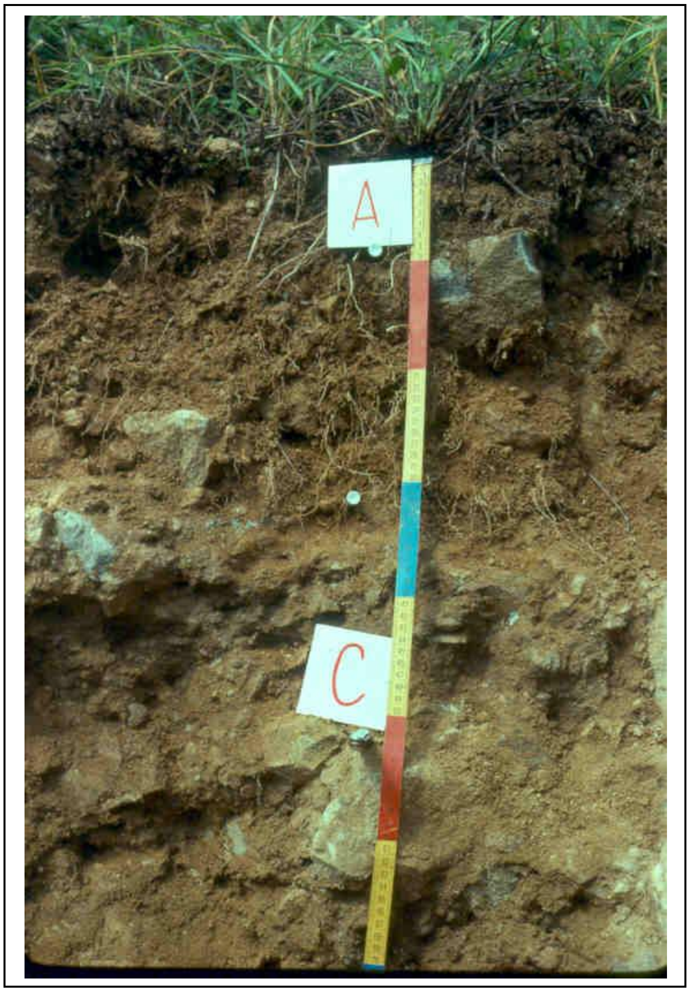

Figure 6. Four-year old mine soil profile sampled on Taggart Bench level in 1980. This soil possessed a well-developed A horizon associated with plant rooting and organic matter accumulation and a heavily compacted (densic) Cd layer at 37 cm which totally limited root and water penetration. These densic layers are formed by repeated traffic during mining and final grading. The intervening AC horizon is not labeled, and the colored scale on the tape is in 10 cm increments.

peds. Several A horizons >20 cm thick were described in 4-yr-old mine soils formed in relatively loose materials. Mean A horizon depth in all 30 1980 pedons was 15 cm, but varied from 5 to 52 cm. Root density in the A horizon varied considerably because the extent of vegetative cover in these minimally reclaimed mine soils ranged between <10% to 100%, with 10 pedons having sparse (< 25%) vegetative cover.

Mean A horizon thickness in the 20 pedons described in 2002 was 11 cm, and was not significantly different ($p \leq 0.05$) from A horizon thickness in the 1980 pedons. Overall A horizon thickness ranged from 5-20 cm. All mine soils described in 2002 had thick (>75%) vegetative cover as a result of improved reclamation practices and contained many very fine to fine roots, and weak to moderate granular structure in their A horizons. We described Ap horizons in the 8 soils that obviously had biosolids chisel-plowed and disked into the surface. Biosolids application resulted in darker (10YR 2/2 to 3/3) A horizons with wavy boundaries caused by chisel plowing (Fig. 7). Mine soils described in 2002 that had not received biosolids had a dark (10YR 2/2-3/3) 3-5 cm A1 horizon underlain by an A2, which was less dark (value ≥4), but was identifiable by granular structure and common to many roots. While the overall thickness of A horizons observed in 2002 did not appear to have been influenced by biosolids application, overall color was darker and root density was higher in A horizons that had received biosolids.

In an earlier study on an adjacent experimental plot area, Haering et al. (1993) found that A horizons in mine soils became thicker and darker over time. This finding, however, was from a controlled experiment done on mine soils that had been carefully constructed with selected overburden materials and vegetation. A horizon depth did not consistently correlate with age in either the 1980 or 2002 pedons in this study, since we examined mine soils formed in a variety of materials, including some with organic surface amendments. Although soils formed in the same overburden materials may develop deeper A horizons over time, depth of A horizons also appears to depend on overburden type, local landscape position, success of revegetation, drainage, and perhaps other factors.

Subsurface Horizons. Over half of the 30 pedons sampled in 1980 exhibited A-C horizonation, and seven had A-AC-C horizonation (Figs. 6 and 7). The mine soils with AC horizons ranged from 4-yr-old to 12-yr-old, so there appeared to be little consistent relationship between mine soil age and presence of an AC horizon. However, 17 of the 20 pedons described in 2002 possessed AC horizons, characterized by weak subangular blocky structure and common roots. It is likely that more AC horizons were present in the 2002 pedons because of increased abundance and depth of plant rooting as a result of better spoil placement and reclamation procedures.

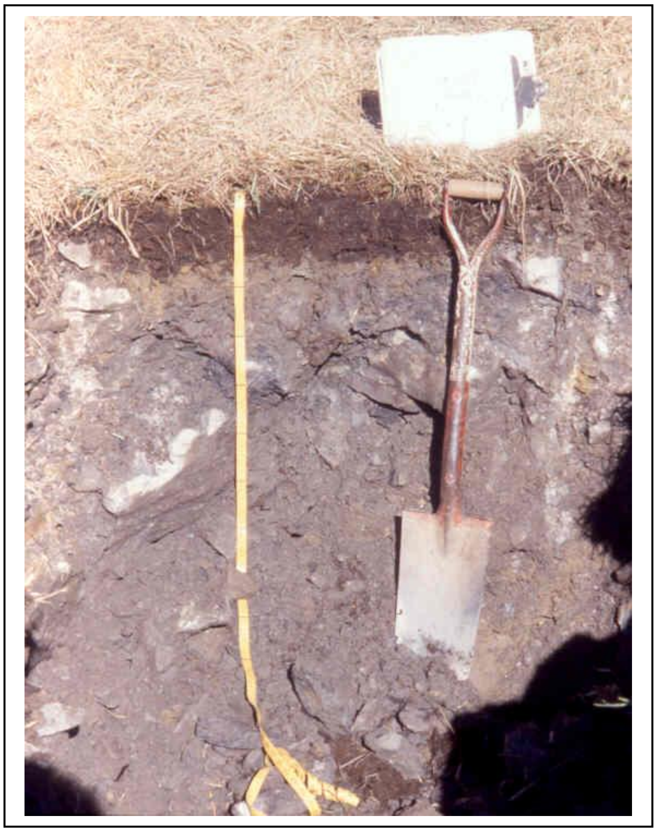

Figure 7. Mine soil sampled in 2002 exhibiting prominently darkened Ap horizon from biosolids application in 1990, twelve years earlier. Overall horizon sequence is Ap-AC-C.

In the 1980 pedons, distinct Bw horizons with moderate subangular blocky structure were present in two 20-yr-old soils (Fig. 8). Bw horizons were also described in three 12-yr-old and one 4-yr-old pedon (Profile 1980-2 in Table 1). These Bw horizons contained stronger structure grades than associated A and C horizons, and were only found in relatively fine-textured (loam to silt loam) mine soils, apparently because finer-textured materials have greater shrink-swell and aggregation potential than coarser textured materials. Of the six Bw horizons described in

1980, only four met the 15 cm thickness requirement. In these four mine soils, none of the Bw horizons met the clay accumulation requirement, and only two met the color requirement for cambic horizons. Since layering of different spoil types is common in these mine soils, it is difficult to determine if the apparent redder hue and/or stronger chroma in these Bw horizons was a result of Fe translocation within the profile. No cambic horizons were described in the 2002 pedons, which were generally coarser in texture, although areas of moderate subangular blocky structure were observed in the AC horizon of one profile. As stated earlier, cambic, or cambic-like horizons have also been reported in other studies of Appalachian mine soils (Ciolkosz et al., 1985, Haering et al. 1993, Thomas et al., 2000).

Figure 8. Moderate medium and coarse subangular and angular blocky aggregates broken out of the Bw horizon of a 12 year-old mine soil formed from a predominantly siltstone spoil.

The C horizons in all pedons described in 1980 and 2002 were structureless and massive. Densic materials (Soil Survey Staff, 1999) were found within 70 cm of the surface in the C horizons of 15 out of the 30 pedons described in 1980 (see profile 1980-1 in Table 1 for example). These heavily compacted zones (Fig. 6) were identified by being very firm in place, and by restricted rooting. The rock corrected bulk density of selected representative 1980 densic layers ranged from 1.75 to 1.92 Mg m^{-3}. In 10 of the 1980 pedons, densic materials were located within 30 cm of the surface. Within the highwall/bench/outslope landform studied in 1980 (Figs. 1 and 2), compacted areas were generally more common in the middle of benches, where traffic was concentrated, but were observed to occur almost anywhere across the bench area. Plant roots were completely limited by most of these compacted layers due to the lack of structural planes of weakness; in others, plant rooting was concentrated along rock fragment faces. These zones apparently resulted from traffic by large rubber-tired loaders and haulers, and were more likely to be found in mine soils that formed after 1970, when usage of this equipment became more common. Research on mine soils reclaimed for farmland in Illinois has shown that compaction resulting from equipment used in soil construction is the major factor limiting row crop production (Dunker et al, 1992).

Over half (11) of the 20 pedons described in 2002 contained a densic contact or layer between 20 to 60 cm below the surface. Eight of these pedons, including profiles 2002-1 and 2002-2 (Table 1) were described as having Cd horizons. Densic layers were described when the horizon was of very firm consistence and obviously compacted and massive in all visible faces of the pit. Compacted horizons in the 2002 pedons were often underlain by friable to very friable material. Rooting in all the pedons in which densic materials were described was confined to rock fragment faces. In some of the 2002 soils, mats of fine to very fine roots had formed along rock fragment faces, and extended to below the densic zone, but were very widely spaced.

In a few soils, deeper C horizon soil material was so loose in place that it fell out of the profile into the pit. Bridging voids (Sencindiver, 1977) were also common in the lower C horizons of many pedons described in both 1980 and 2002. In the 1980 soils, these voids seldom exceeded 15 cm in diameter, apparently because mechanical reworking and mine soil settling appeared to have filled any large voids that might have been present in the fresh soil. In the 2002 soils, however, we observed profiles with large (up to 35 cm diam.) bridging voids between boulders at depths of 1 m or more.

Contrasting spoil types were commonly encountered with depth in both the 1980 and 2002 soils. If an abrupt change in spoil color, texture, or rock content (or frequently all three) was observed, discontinuities (2C or 3C horizons) were described (see Fig. 9). This spoil layering did not appear to have any consistent relationship with landscape position or age; in fact, pedons with different spoil types could often be found within 50-100 m of each other.

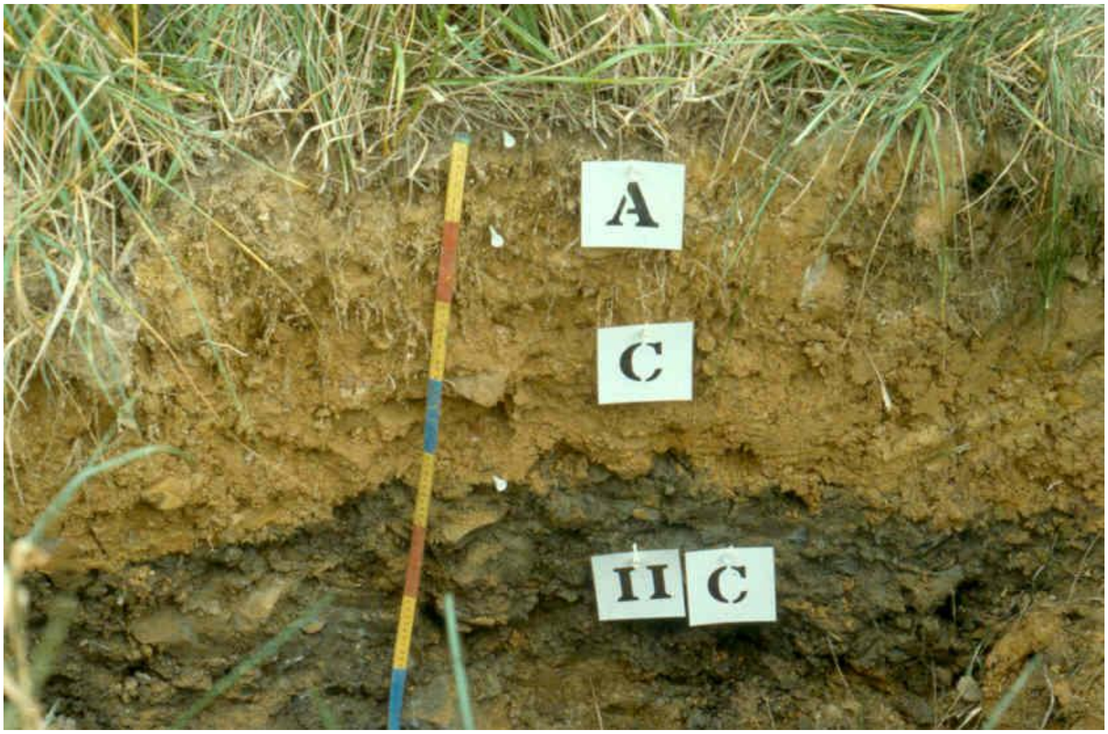

Figure 9. Bisequel mine soil described in 1980. Highly weathered and oxidized sandstone spoil mixed with weathered soil horizon material had been graded over highly compacted gray siltstone derived spoils. Color bands on tape are 10 cm.

Redoximorphic Features. Although mine soils are often assumed to be excessively to well drained because of their high rock fragment content and elevation above local water tables, compacted layers can cause epiaquic conditions in locations that might ordinarily be assumed to be well drained. We have observed that wet mine soils often develop in flat areas that were highly compacted during mining and reclamation (see Fig. 4). These poorly drained areas tend to be concentrated at the bench/highwall contact and over shallow bedrock in pre-SMCRA mine soils, and in local depressions underlain by a compacted layers (Atkinson et al., 1998.) in more recent mined landscapes. In the 1980 study, four of the study pits filled with water within minutes to hours after excavation, and the saturated zones were clearly observed to occur above densic layers, with water flowing down over the pit walls from above. Strongly contrasting (relative to surrounding matrix) low chroma colors were described in three of the 1980 profiles.

Low chroma colors are commonly used as indicators of saturation and anaerobic conditions. However, their interpretation is complicated since mine soils often contain lithochromic colors with chroma ≤ 2, or when formed in gray unoxidized materials, resultant horizons commonly have a matrix with chroma ≤ 2.

In 2002, we deliberately located several soil pits in large (0.1 to 0.3 ha) areas in the middle of reclaimed benches that were dominated by obligate wetland vegetation. Redoximorphic features such as Fe-concentrations along root zones, or Fe-depletions in the center of peds were carefully noted. Two poorly drained and two very poorly drained mine soil profiles were described. These soils contained common distinct redoximorphic features at or near the surface as a result of water table perching. Redoximorphic features such as Fe-concentrations along root zones and Fe depletions in the center of peds were clearly expressed, and were sufficient to meet hydric soil indicator status (USDA-NRCS, 1998) in surface horizons (see Profile 2002-1 in Table 1). Obviously, the results reported here have direct bearing on the classification and mapping of these soils, and those topics will be covered in future articles. Greater detail on the effects of various mined landforms and the presence of cambic horizons, densic layers, and hydric soil indicators on the classification, mapping, and interpretation of these mines soils can be found in Haering et al. (2003) and in our companion paper in this proceedings volume.

Summary and Conclusions

The pre-SMCRA mine soils examined in 1980 were formed in overburden that contained a high percentage of oxidized, pre-weathered material from high in the geologic column. Subsequent improvements in mining technology allowed deeper cuts, and thus the mine soils described in the same area in 2002 were formed primarily in spoils derived from gray, unoxidized overburden material. Although the parent material was quite heterogeneous, the 1980 mine soils were generally finer-textured, and had a lower pH than the post-SMCRA mine soils we examined in 2002. A significant number of the 1980 mine soils were shallow (≤ 50 cm) to rock or coal, while all the 2002 soils were deep (<1m).

Soil pH varied widely in both the 1980 and 2002 pedons. Although mine soils formed in oxidized material tended to be more acidic, the presence of small amounts of acid-forming material resulted in low soil pH in some soils formed in gray unoxidized material. Neither overburden color nor percentage of carboliths was a good predictor of mine soil pH. Regardless, acidity per se did not appear to be a dominant growth limiting factor in these mine soils.

Relatively well-developed A horizons were found in all the soils we examined. Development of subsurface horizons such as AC and Bw horizons appeared to be related more to rooting density and depth and fine silt+clay content than to mine soil age. Densic contacts and layers were found within 70 cm of the surface (often higher) in half the pedons we described. These densic zones were caused by mechanical compaction during mining and post-mining equipment operations, and appear to be permanent features, at least in the 4 to 20-yr pedogenic time frame we studied. Rooting in these densic layers was confined to mats along rock fragment faces or was entirely limited. Densic layers were often underlain by looser material with common bridging voids. Soil compaction during mining and reclamation also appeared to cause water table perching, resulting in poorly and very poorly drained mine soils in depressional landscapes that collect surface runoff. Improvement in mining and reclamation technology between the pre-SMCRA mine soils described in 1980 and the post-SMCRA mine soils described in 2002 led to deeper more uniform soil materials, but did not significantly reduce the occurrence of heavily compacted zones.

The overall mine soil landscape in the central and southern Appalachians contains a mosaic of older more complex mine soils along sinuous highwall/bench/outslope landforms that abruptly interface with much broader expanses of modern post-SMCRA mine soils forming on a mixture of highwall backfills, thick spoil fills over older benches and intervening hollow fills. Pedogenesis occurs rapidly in these parent materials; distinct A and AC horizons form in several years and Bw horizons form in 10 to 20 years in finer textured spoils. While it is commonly assumed that these landscapes contain a thick mantle of well- and excessively drained coarse textured spoils, their internal drainage patterns are actually quite complex, as evidenced by the common occurrence of hydric soils and locally impeded internal drainage due to heavily compacted densic materials. Quite frequently, these heavily compacted zones occur near or at the soil surface, and appear to be the dominant plant growth limiting mine soil property in this region.

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