2017/2018 Research Report

Long-Term Effects of Rock Type, Amendments and Weathering on Mine Soil Properties and TDS Potentials

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Executive Summary

In the early 1980s, the USDI Office of Surface Mining (OSM) and the Powell River Project (PRP) cooperatively funded the construction and establishment of the Controlled Overburden Placement (COP) experiment. This research project is the longest running of its kind in the world and has generated over 50 journal and proceedings articles to date. Results from these plots have largely underpinned regional protocols for topsoil substitute selection since the mid-1980s. Our current research program is completing determination of long-term (30+ years) effects of overburden rock type and surface treatments on important mine soil morphological, physical, and chemical properties. In parallel, over the past project year we measured the net TDS elution potential (in lab columns) from fresh spoil samples taken in 1982 vs. weathered rock fragments from the surface of the current (2016) plots. As a related study component, we continued our long-term monitoring of mine spoil leaching mesocosms at the Virginia Tech Turfgrass Research Center and those findings are also integrated into this annual report.

During the 2017-2018 project year, we completed most chemical and physical analyses on the COP soil pits that were sampled in the fall of 2016. Initial details on the morphology of these profiles were provided in last year's annual report and are expanded upon here along with insights into changes in physical and chemical properties over time. The morphology of these 30+ year-old mine soils is striking. Profound physical x chemical weathering of the rock spoils was noted, particularly in the higher siltstone spoils. Well aggregated ^A horizons have formed to depths > 10 cm and most subsoils contained moderately well-developed cambic ^Bw horizons. Surface horizons in general have declined in pH, exchangeable bases, and acid-extractable cations over time (30 years). However, the surface soils do show evidence of bioaccumulation of cations and associated higher levels of electrical conductance vs. subsoil horizons. The long-term influence of sawdust and biosolids additions in the surface treatment experiment is still apparent in darker colors, stronger aggregation and higher C than the untreated control plots. Perhaps most surprising is the apparent development of compacted subsoil layers in the lower B and C horizons. Since all vehicle traffic has been excluded, we can only hypothesize that these layers are being formed by a combination of (a) net physical illuviation of finer textured soil sized materials downward, and/or (b) physical weathering/slaking of larger weatherable rock fragments leading to collapse of bridging voids and long-term settling and compaction.

The combined results from the COP column leaching studies coupled with the long-term (6-year) Harlan spoil leaching field mesocosms reconfirm that while our lab column protocol is a relatively accurate predictor of peak vs. long-term leachate specific conductance (SC; a proxy for TDS), it probably under-predicts peak winter seasonal ion release in younger reactive materials.

The dramatic differences in SC production between the 1982 and 2016 spoil samples (from the COP experiment) also clearly demonstrate that we can expect a significant drop in TDS risk for a given "leaching increment" of a spoil over a decadal timeframe. These results generally support our earlier predictions (e.g. Evans et. al, 2014) of the expected timeframe (15 to 25 years) for field scale valley fill discharges to fall below current levels of regulatory concern for SC (e.g. 350 µs/cm). However, the fact that the deeper spoils in the COP experiment still appeared to be only slightly weathered after > 30 years demands that such estimates be made with caution.

If funds are available for a final fourth year (2019/2020), we will complete more detailed lab analyses on C forms (humus vs. coal vs. carbonates) on COP samples from 1982, 2008 and 2016 to quantify organic matter accumulation (C-sequestration) rates. This would also allow us to complete full statistical comparisons of our recent data sets (2008 and 2016 sampling) against the original primary 1982-1984 data. Similarly, if funding is available for 2019/2020, we will continue to monitor and summarize results from the TDS leaching mesocosms at the VTRC. However, we do plan to complete as much of the C-fractionation work as possible over the summer of 2019, regardless of the availability of future funding.

Introduction and Background

The Surface Mining Control and Reclamation Act (SMCRA) of 1977 contained a number of contentious provisions including return to original contour (AOC), long-term liability bonding periods, and return to "equal or better" post-mining land use conditions. However, one of the more important provisions was SMCRA's allowance for use of pre-selected overburden materials as topsoil substitutes when (A) the native A+E horizon materials are less than 6 inches (15 cm) thick, and (B) the physical and chemical properties of the proposed substitute spoil materials are deemed suitable for such use. Since native topsoil layers throughout the Appalachian coalfields are usually less than six inches thick, and removing them from steep slopes is difficult and expensive, the vast majority of coal mined lands in the region have employed topsoil substitutes.

In 1982, the USDI Office of Surface Mining and the Powell River Project (PRP) co-funded the installation of the Controlled Overburden Placement (COP) experiment to objectively assess the viability of the topsoil substitute concept and to determine whether or not organic amendments would be beneficial. In one component of the COP experiment we are directly comparing five mixes of sandstone:siltstone (SS:SiS) overburden while in a separate experiment we are following the effects of topsoil return, sawdust addition and four incremental loading rates of biosolids. All treatments are replicated four times and the plots are split between herbaceous (dominantly tall fescue) and forest (red oak following pine) vegetation. We intensively monitored those two side-by-side experiments through the mid 2000's and our results can be reviewed at the PRP web site and at http://landrehab.org. The original installation and early results are summarized by Roberts et al. (1988 abc) and Haering et al. (1993) reported on the initial development of soil morphology as observed from soil pits. More recently, Nash (2012) sampled the surface and subsoil layers in both experiments and reported on long-term changes in chemical and physical properties along with an initial attempt to quantify actual rates of C-sequestration. In summary, we have found that (A) properly selected and placed spoil materials provided an outstanding soil medium for tall fescue production and allowed vigorous invasion of native herbaceous species; (B) higher pH spoils such as the siltstone strata employed were deleterious to pine tree growth; and (C) higher rates of biosolids amendments drove high fescue production while suppressing the pines. The COP experiment remains the longest intact and continuously monitored study of mine soil genesis in the world. Follow-up studies by various PRP researchers at other sites in the 1990's and 2000's also characterized the wider effects of biosolids applications and the nature of inherent variability in mine soil properties in the Research & Education Center area (Haering et al., 2004).

Over the past several decades, the concept of topsoil substitution has been directly and indirectly criticized from a number of perspectives. First of all, advocates of the return of Appalachian mined lands to native forest covers have pointed to the lack of topsoil salvage and the inclusion of higher pH unweathered spoils as directly inhibiting effective reforestation. Secondly, the fact that relatively unweathered spoils (such as those employed in the COP study) release significant total dissolved solids (TDS) loads to drainage waters over time has been implicated as a component of mining related surface water degradation under both low and moderate pH conditions. Very few studies have been published to date that detail the expected variations in TDS due to spoil type and age/leaching regime since placement. Finally, the ability of these mine soils to accumulate organic matter, maintain a stable and viable microbial biomass and available nutrient pools, and overall productivity potentials beyond the requisite five-year performance liability period is also questioned by many.

Progress to Date and Future Research Plans

This program was originally proposed and funded by PRP in 2016/2017 as a one-year intensive project with the expectation that beyond that initial year would not be available. However, PRP was fortunate to receive an additional allocation of funds for the past year (2017/2018) and we were extended our efforts and objectives as described below. During the 2016-2017 project year, we completed the detailed morphological description of soil profiles from three selected treatments in the rock mix experiment and five treatments from the surface amendment experiment. Bulk soil/rock samples were taken from all morphological horizons and then every 10 cm with depth. Our interpretations of overall morphology and mine soil weathering processes were summarized in last year's report and we completed all initial physical and chemical analyses of those soil samples as reported in this year's annual report.

During the past project year (2017/2018), we also developed a new column leaching protocol to evaluate differences in TDS leaching potentials on original samples archived from the pre-treatment May 1982 plots vs. 2016 rock samples extracted from the upper 25 cm of selected treatments. We utilized a small portion of these funds to continue the limited long-term monitoring of the field spoil leaching mesocosms at the Virginia Tech Turfgrass Research Center (VTRC) which were described in previous reports and by Ross (2015). We were also fortunate to receive funds for the current project year (2018/2019), which will allow us to complete essential analyses on samples from multiple depth increments in the COP pits along with archived bulk density samples and to manually transcribe historic/archived data sets from the early 1980's into electronic records. We will also continue periodic monitoring of pH and SC from the leaching mesocosms at the VTRC.

If funds are available for a final fourth year (2019/2020), we will complete more detailed lab analyses on C forms (humus vs. coal vs. carbonates) on samples from 1982, 2008 and 2016 to quantify organic matter accumulation (C-sequestration) rates. Similarly, if funding is available for 2019/2020, we will continue to monitor and summarize results from the TDS leaching mesocosms at the VTRC. This would also allow us to complete full statistical comparisons of our recent data sets (2008 and 2016 sampling) against the original primary 1982-1984 data. However, we do plan to complete as much of the C-fractionation work as possible over the summer of 2019, regardless of the availability of future funding.

Once all study components are completed, we will combine data sets from all 30+ years of the experiment to produce a model of long-term soil development. In parallel, the combined TDS leaching data from our lab columns (on COP samples) and the VTRC mesocosms will allow us to confirm and validate our recent literature predictions (Daniels et. al, 2016; Evans et. al, 2014) on the temporal pattern of TDS release. Finally, we will combine our findings to predict the ability of selected overburden materials to weather and transform into mine soils suitable for the support of native hardwoods and hayland/pasture vegetation, and to estimate their rate(s) of transformation.

Thus, by a combination of direct and differential analyses, we are currently working to meet the following objectives:

Research Objectives

1. To determine the long-term (30+ years) effects of overburden rock type and surface treatments on important mine soil morphological, physical, and chemical properties.

2. To measure the net TDS elution potential of a range of fresh, partially weathered and well-weathered topsoil substitute materials.

3. To estimate the actual rate of organic matter accumulation (C-sequestration) in these mine soils and to compare the properties of these now relatively well-developed mine soils to local native soils.

4. To predict the ability of selected overburden materials to weather and transform into mine soils suitable for the support of native hardwoods and hayland/pasture vegetation, and to estimate their rate(s) of transformation.

Methods and Procedures

This project is focused on the analysis of a combination of current and past data sets and mine soil samples from the Controlled Overburden Placement (COP) experiment established in 1982. For the results reported here, we excavated, sampled and described three pedons in late

September 2016 from each of the pure SS, 1:1 SS:SiS, and pure SiS treatments in the Rock Mix experiment along with three pedons each from the control (2:1 SS:SiS), topsoil, 50 T/Ac (112 Mg/ha) sawdust, and 25 T/Ac + 50 T/Ac (56 and 112 Mg/ha) biosolids plots in the Surface Treatment experiment.

At each pit location we carefully described mine soil morphology, rooting features, and spoil packing/settling patterns using standard soil survey protocols. We took photographs and at a later date, we will superimpose a grid to allow better volumetric quantification of rock amount/size, coarse rooting and other important features. We then incrementally sampled the mine soils with depth by morphological horizon (e.g. ^A-^Bw-^C), in 10 cm increments from 0 to 50 cm, and then again from 50 to 75 cm and 75 to 100 cm to allow quantification of changes in physical and chemical properties with depth. Finally, representative rock fragments were sampled from the upper 0-25 cm, 50-75 cm and from the lowest portion (~1.5 m) of each pit for future TDS related studies.

Figure 1. Soil observation and sampling pit being excavated by Dan Early in a pure siltstone (SiS) plot in the Rock Mix Experiment in September 2016. Excavator traffic was limited to the alleyways between plots and the soil pit face was aligned to allow for optimal photography.

A total of 370 separate samples were collected for laboratory analysis. These samples were air-dried in our greenhouse at Virginia Tech and then rock fragments (> 2 mm) were separated away from soil fines for each bulk sample. This was an extremely laborious process and took approximately three months to complete. The fine earth fraction (< 2 mm) was then transported to our laboratories where the following analyses are being performed over time:

pH and total titratable/exchangeable acidity
Saturated paste electrical conductance and soluble salts species (cations + anions)
Total organic carbon and Walkley-Black organic matter
Total-N
Exchangeable cations
Dilute acid extractable nutrients and metals
Extractable Fe- and Mn-oxides
Calcium carbonate equivalence
% Rock fragments
Particle size analysis
Bulk density on intact clods (taken from cohesive subsoil layers from pits)
Moisture desorption/water holding capacity on < 2mm fractions

Over the past project year, we completed the vast majority of the laboratory analyses listed above with the exception of the intact clod bulk density procedure and several of the more intensive chemical analyses (e.g. C forms and Fe-oxides). All remaining lab analyses will be completed in 2018/2019. Over the past year, we also completed the TDS column leaching experiment as described below and continued the long-term monitoring of the spoil leaching mesocosms at VTRC.

2018 COP Column Leaching Protocol

Objectives:

1. Determine long-term effects of weathering and leaching on TDS elution potential on mixed sandstone (SS) and siltstone (SiS) overburden.

2. Compare differences in TDS elution potential as influenced by crushing rocks per original Orndorff et al. (2015) protocol vs. non-crushed rocks on both weathered and non-weathered spoils.

Materials:

Original May 1982 bulk rock/spoil samples were sorted by treatment to match 2016 samples specified below (n = 4 each). This generated large composite samples of ~1:1 SS:SiS etc. to match against 2016 pit samples. These materials ranged in size from 4.75 mm to 3.80 cm. Larger fragments were excluded.

2016 Soil Pit samples were taken by Dan Johnson et al. from the field soil pits in October.

- 100% SS, 100% SiS, 1:1 SS:SiS and 2:1 Controls from Surface Treatment Exp. (n = 3 plots/pedons each); were all combined into large bulk composite samples.

- We used rock fragments from upper ^A horizons, 0-10 cm and bulk 0-25 cm samples to form composite samples that had similar size consist to the May 1982 samples.

- Loose fine soil was brushed and cleaned off of rock fragments before crushing and/or final bulk sample composites were formed.

Methods:

1. The overall design was simple with four main treatments:

- 1982 uncrushed spoils > 4.75 mm, but < 3.8 cm (1.5")
- 2016 uncrushed spoils cm > 4.75 mm, but < 3.8 cm.
- 1982 crushed spoils (from > 3.8 cm fraction) crushed down to < 1.25 cm
- 2016 crushed spoils (from > 3.8 cm fraction) crushed down to < 1.25 cm

2. All four materials were loaded into our "standard columns" which were 7.5 cm in diameter x 40 cm long and run via the unsaturated leaching protocol outlined in Orndorff et al. (2015). All treatments were run with n = 3 replications for the primary uncrushed (U) vs. crushed (C) material comparisons and n = 2 for the larger diameter columns described below.

3. We also constructed a parallel set of columns (n=2) that were 2x the diameter of the standard columns (15 cm) and the same length. These were be run on uncrushed (U) material with the same protocol and allowed us to evaluate if macropore flow was an issue or not vs. the smaller diameter standard columns. This added 4 more columns and were labeled as "UL".

4. Our standard leaching protocol (2.54 cm "simulated acid rain – pH 4.6" at 2x per week for 40 cycles). SC and pH were determined on every leachate. Solution ions were analyzed on leach #2 and every five leaches thereafter. Only the pH and SC data are presented in this report.

Results and Discussion

Overall Mine Soil Morphology and Interpretations of Pedogenesis

In last year's report, we focused on the morphological properties of these soils as described in September 2016 and we are repeating that content here to complement the balance of mine soil physical and chemical data provided in the next section. The morphology of these 30+ year-old mine soils was striking and varied widely among rock types and surface treatments as discussed in more detail below. This soil pit sampling was the first since 1989 (Haering et al., 1993), and significant changes in overall horizon development and associated pedogenesis were obvious in all profiles. In particular, overall ^A horizons were deeper and more distinct. Similarly, the subsoils had differentiated into moderately well-developed ^Bw horizons in all pedons while only certain treatments (e.g. sawdust) contained ^Bw horizons in 1989. Representative profile descriptions (Tables 1 – 5) for five pedons from September 2016 along with images (Figures 2 – 6) of each are provided below along with summary commentary in their captions.

Table 1. Soil profile description for Plot 2 (1:1 SS:SiS) in Controlled Overburden Placement Experiment. Described and sampled in late September, 2016.

Described and Sampled by: D. Johnson, J. Buckwalter, K. Haering; Parent Material: 1:1 Sandstone:Siltstone.

Vegetation: Mostly multiflora rose (*Rosa multiflora*) and *Solidago altissima* var. altissima. Also native ferns, red maple (*Acer rubrum*) and elm (Ulmus sp) seedlings, *Erigeron sp., Carex* sp, tall fescue (*Schedonorus arundinaceus*), broomsedge (*Andropogon virginicus*). Northern red oak (*Quercus rubra*) in overstory.

Horizon	Depth	Description
	--cm--	
O	3-0	Partially decomposed mixed leaf litter.
^A	0-9	Very dark grayish brown (10YR 3/2) gravelly loam; moderate granular structure; friable; many (5) coarse, common (4) very fine and (3) fine roots; 15% rock fragments by volume (15% gravel); low relative bulk density; no packing voids; clear smooth boundary.
^Bw	9-30	Dark yellowish brown (10YR 3/6) stony loam, with common (10%) dark yellowish brown (10YR 4/6) lithochromic color variegations; weak subangular blocky structure; friable; many (6) fine and common (3) coarse roots; 20% rock fragments by volume (20% stones); medium relative bulk density; no packing voids; clear wavy boundary.
^C1	30-84	Dark yellowish brown (10YR 4/4) extremely stony loam, with common (19%) dark gray (10YR 4/1) lithochromic color variegations; structureless massive structure; friable; common (2) very fine and (1) fine roots; 65% rock fragments by volume (50% stones, 15% gravel); high relative bulk density; no packing voids; clear irregular boundary.
^C2	84-125+	Dark gray (10YR 4/1) very stony clay loam, with many (25%) dark yellowish brown (10YR 3/6) lithochromic color variegations; structureless massive structure; firm; few (0.8) coarse roots; 50% rock fragments by volume (40% stones, 10% gravels); medium relative bulk density; no packing voids.
Remarks:		Lower ^Bw and ^C1 are quite compact due to “settling” and possibly migration of fines downward over time.

Figure 2. Soil profile from Plot #2, 1:1 Sandstone:Siltstone (SS:SiS) mine soil after 34 years of development. Note well-developed ^A horizon due to organic matter incorporation over time and ^Bw horizon delineated based on > 50% by volume of weak to moderate structural development. The lower portion of the ^Bw and the C1 were quite compact and root limiting, even though the spoils were loosely end-dumped and excluded from traffic.

Table 2. Soil profile description for Plot 15 (SiS) in Controlled Overburden Placement Experiment. Described and sampled in late September, 2016.

Described and Sampled by: D. Johnson, J. Buckwalter; Parent Material: 100% Siltstone

Vegetation: (~75% cover), *lespedeza cuneata*, Allegheny blackberry, tall fescue, some *Acer rubrum* seedlings. Willows (*Salix sp*.) and Northern red oak (*Quercus rubra*) in overstory. Large Autumn olive over pit

Horizon	Depth	Description
	--cm--	
O	3-0	Partially decomposed mixed leaf litter.
^A	0-12	Very dark grayish brown (10YR 3/2) gravelly silt loam; moderate granular structure; friable; many (7) very fine and common (3) fine and (1) coarse roots; 22% rock fragments by volume (20% gravels, 2% stones); low relative bulk density; no packing voids; clear smooth boundary.
^Bw	12-32	Very dark grayish brown (10YR 3/2) gravelly loam; weak subangular blocky structure; friable; common (3) fine, (2) very fine, and (1) coarse roots; 32% rock fragments by volume (30% gravels, 2% stones); medium relative bulk density; few packing voids; gradual wavy boundary.
^BC	32-58	Dark grayish brown (10YR 4/2) very gravelly loam; weak subangular blocky structure; friable; common (3) very fine and few (0.5) coarse roots; 45% rock fragments by volume (30% gravels, 10% cobbles, 5% stones); medium relative bulk density; few packing voids; gradual smooth boundary.
^CB	58-86	Dark gray (10YR 4/1) extremely cobbly loam; weak subangular blocky structure; friable; common (2) very fine and very few (0.1) coarse roots; 75% rock fragments by volume (35% gravels, 25% cobbles, 10% stones, 5% boulders); medium relative bulk density; few packing voids; gradual wavy boundary.
^C	86-125+	Dark grayish brown (10YR 4/2) very gravelly clay loam; structureless massive structure; very friable; few (0.5) coarse and (0.5) fine roots; 75% rock fragments by volume (35% gravels, 25% cobbles, 10% stones, 5% boulders); medium relative bulk density; common packing voids.
Remarks:		Plot 15 siltstone is much coarser/rockier than plot 14 and plot 9 siltstone. B horizons in siltstone plots are less developed than other rock mixes overall.

Figure 3. Soil profile from Plot #15, Siltstone mine soil after 34 years of development. This pedon was considerably higher in rock fragments than the other two pure SiS profiles, but still exhibits significant physical weathering effects relative to its original rock content (>80%) in 1982. Subsoil compaction was not as notable in this particular profile.

Table 3. Soil profile description for Plot 25 (112 Mg/ha sawdust over 2:1 SS:SiS) in the Controlled Overburden Placement Experiment. Described and sampled in late September, 2016.

Described and Sampled by: D. Johnson, J. Buckwalter; Parent Material: 2:1 Sandstone:siltstone amended with 112 Mg/ha sawdust.

Vegetation: Little veg (<40% cover). Allegheny blackberry, some *Lespedeza cuneata*, native ferns. Lots of Autumn olive in overstory, plus *Quercus rubra*.

Horizon	Depth	Description
	--cm--	
O	2-0	Partially decomposed mixed leaf litter.
^A	0-12	Very dark brown (10YR 2/2) loam; moderate granular structure; friable; many (6) very fine and (6) fine and common (3) very coarse roots; 10% rock fragments by volume (10% gravels); low relative bulk density; no packing voids; clear smooth boundary.
^BA	12-25	Dark yellowish brown (10YR 3/4) gravelly loam; weak subangular blocky structure; very friable; common (7) fine roots; 15% rock fragments by volume (15% gravels); low relative bulk density; no packing voids; clear smooth boundary.
^Bw	25-50	Dark yellowish brown (10YR 3/6) very gravelly loam; moderate subangular blocky structure; friable; common (2) fine roots; 35% rock fragments by volume (20% cobbles, 15% gravels); medium relative bulk density; no packing voids; gradual wavy boundary.
^BC	50-90	Dark brown (10YR 3/3) very gravelly sandy loam; weak subangular blocky structure; very friable; common (2) fine roots and few (0.5) coarse roots; 35% rock fragments by volume (20% gravels, 10% cobbles, 5% stones); medium relative bulk density; no packing voids; gradual smooth boundary.
^C	90-125+	Dark yellowish brown (10YR 3/4) very gravelly sandy loam; structureless massive structure; friable; common (2) fine roots; 35% rock fragments by volume (20% gravels, 10% cobbles, 5% stones); medium relative bulk density; no packing voids.
Remarks:		Much lower rock content than most other profiles with only moderate subsoil compaction. Significant rooting throughout profile.

Figure 4. Soil profile from Plot #25; 112 Mg/ha sawdust added to 2:1 SS:SiS. Rock content was lower in this soil and subsoil compaction was not as notable in this particular profile, but the subsoil ^Bw was considerably more compact than observed in 1989 by Haering et al. (1993).

Table 4. Soil profile description for Plot 31 (112 Mg/ha biosolids over 2:1 SS:SiS) in the Controlled Overburden Placement Experiment. Described and sampled in late September, 2016.

Described and Sampled by: D. Johnson, J. Buckwalter; Parent Material: 2:1 Sandstone:siltstone amended with 112 Mg/ha sewage sludge biosolids.

Vegetation: Very little herbaceous veg (20% cover). Allegheny blackberry, native ferns (2 species), poison ivy, *Lespedeza cuneata*. Mostly autumn olive in overstory.

Horizon	Depth	Description
	--cm--	
O	5-0	Partially decomposed mixed leaf litter.
^A	0-10	Very dark grayish brown (10YR 3/2) very gravelly silt loam; moderate granular structure; friable; many (5) very fine, common (3) fine and (1) coarse, and few (0.5) very coarse roots; 45% rock fragments by volume (25% gravels, 10% cobbles, 10% stones); low relative bulk density; no packing voids; clear smooth boundary.
^Bw	10-29	Very dark grayish brown (10YR 3/2) extremely gravelly sandy loam, with many (35%) dark yellowish brown (10YR 4/6) lithochromic color variegations; weak subangular blocky structure; friable; common (2) fine and (1) very fine and few (0.2) coarse roots; 65% rock fragments by volume (35% gravels, 20% cobbles, 10% stones); medium relative bulk density; few packing voids; gradual wavy boundary.
^C1	29-75	Brown (10YR 4/3) extremely gravelly sandy loam, with many (40%) yellowish brown (10YR 5/6) lithochromic color variegations; structureless massive; friable; few (0.8) medium and (0.2) very fine roots; 70% rock fragments by volume (40% gravels, 20% stones, 10% cobbles); high relative bulk density; no packing voids; clear irregular boundary.
^C2	75-125+	Yellowish brown (10YR 5/6) very cobbly sandy loam, with common (15%) brown (10YR 4/3) lithochromic color variegations; structureless massive; very friable; common (1) medium roots; 50% rock fragments by volume (30% gravels , 20% cobbles); medium relative bulk density; few packing voids.
Remarks:		Several large stones across top of pit face.

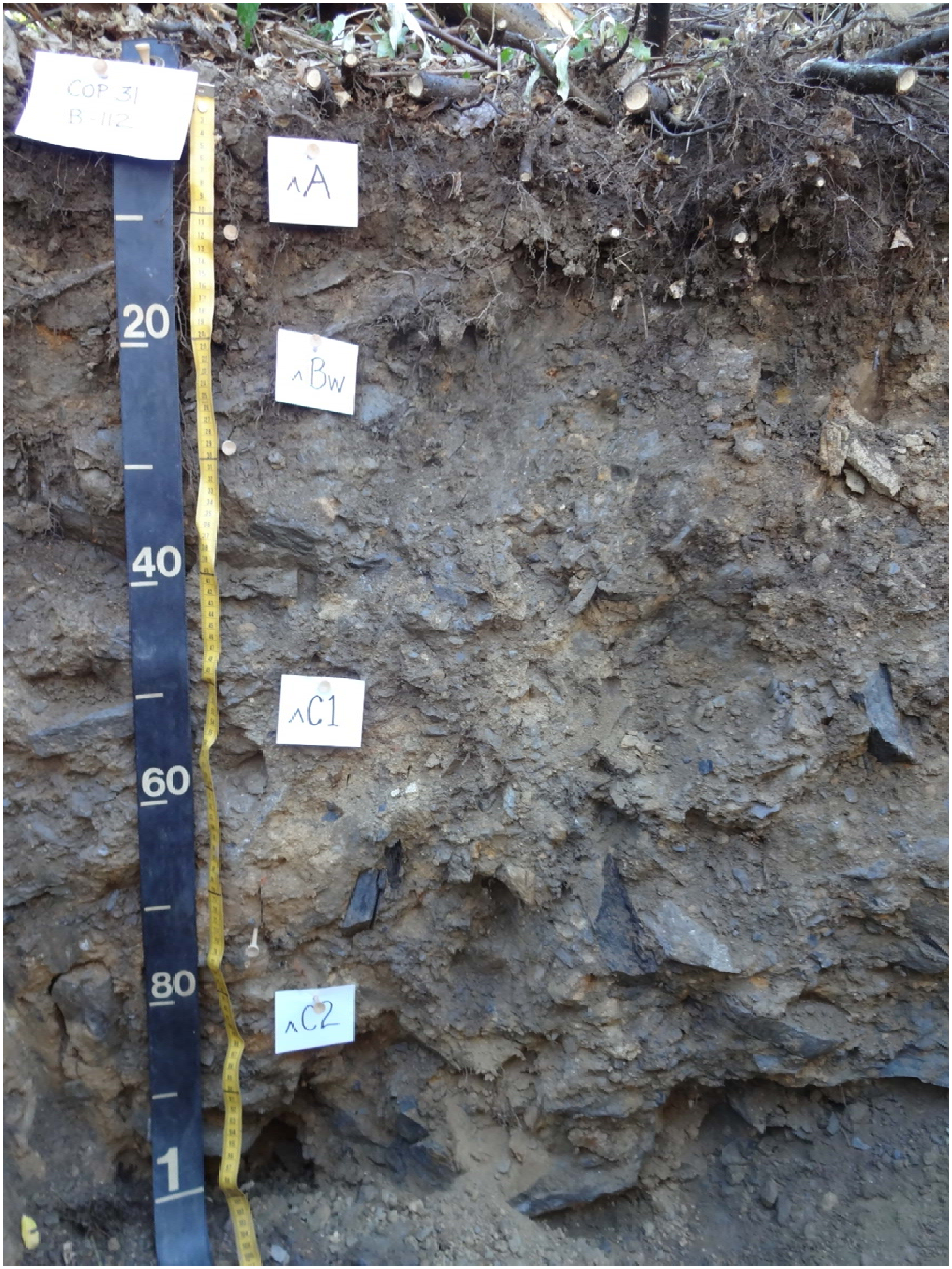

Figure 5. Soil profile from Plot #31, 112 Mg/ha biosolids added to 2:1 SS:SiS. Both ^C horizons were quite compact and root limiting. Note the dark, thick and well-aggregated ^A horizon with heavy rooting concentration.

Table 5. Soil profile description for Plot 46 (30 cm topsoil 2:1 SS:SiS) in the Controlled Overburden Placement Experiment. Described and sampled in late September, 2016.

Described and Sampled by: D. Johnson, J. Buckwalter; Parent Material: 2:1 Sandstone:siltstone amended with 30cm of topsoil

Vegetation: *Solidago altissima var altissima, Lespedeza cuneata,* Allegheny blackberry, some poison ivy and *Clematis virginiana*. Northern red oak (*Quercus rubra*) in overstory a little away from plot.

Horizon	Depth	Description
	--cm--	
O	7-0	Partially decomposed mixed leaf litter.
^A1	0-7	Brown (10YR 4/3) gravelly loam; moderate granular structure; friable; many (5) very fine, common (1) medium, and few (0.5) very coarse roots; 20% rock fragments by volume (20% gravels); low relative bulk density; no packing voids; clear wavy boundary.
^A2	7-15	Yellowish brown (10YR 5/4) very gravelly sandy loam, with many (40%) brown (10YR 4/3) and few (1%) yellowish brown (10YR 5/8) lithochromic color variegations; moderate subangular blocky structure; friable; common (4) very fine and few (0.3) medium and (0.1) very coarse roots; 44% rock fragments by volume (34% gravels, 5% cobbles, 5% stones); low relative bulk density; no packing voids; clear wavy boundary.
^Bw	15-40	Brown (10YR 4/3) extremely gravelly sandy loam, with common (10%) brown (10YR 4/3) lithochromic color variegations; weak subangular blocky structure; friable; common (1) very fine and few (0.1) coarse roots; 75% rock fragments by volume (50% gravels, 20% cobbles, 5% stones); high relative bulk density; few packing voids; clear irregular boundary.
^BC	40-74	Very dark grayish brown (10YR 3/2) extremely gravelly sandy loam, with few (1%) yellowish brown (10YR 5/8) and (1%) dark grayish brown (10YR 4/2) lithochromic color variegations; weak subangular blocky structure; friable; few (0.5) very fine and (0.1) coarse roots; 76% rock fragments by volume (40% gravels, 20% cobbles, 15% stones, 1% boulders); medium relative bulk density; common packing voids; clear irregular boundary.
^C	74-125+	Brown (10YR 4/3) extremely gravelly sandy loam, with common (5%) very dark grayish brown (10YR 3/2) lithochromic color variegations; structureless massive; very friable; many (4) very fine roots; 60% rock fragments by volume (35% gravels, 20% cobbles, 5% boulders); medium relative bulk density; few packing voids.
Remarks:		Large flat stone covering 1/2 of pit face at surface. ^A2 horizon shows signs of physical mixing. 1% carboliths in ^Bw horizon.

Figure 6. Soil profile from Plot #46, 30 cm topsoil over 2:1 SS:SiS. The ^Bw horizon was quite compact and root limiting. The ^A1 and ^A2 horizon still showed dominant yellowish brown coloration of the original mixed A-B-C horizon materials that were added as “topsoil” in 1982. The ^Bw horizon was quite dense and root limiting.

Overall, profound physical x chemical weathering of the rock spoils was noted in all treatments relative to observations made in the late 1980s, particularly in the higher siltstone spoils. Well aggregated ^A horizons have formed to depths > 10 cm (Tables 6 and 7) in most treatments and all pedons contained moderately well-developed cambic ^Bw horizons, with many containing deeper transitional BC horizons. In 1989, only certain treatments (e.g. sawdust) contained cambic horizons and most profiles were described with simpler A-AC-C horizon morphology.

Table 6. Controlled Overburden Placement Rock Mix soil profiles in 2016 (mean of 3 pits/treatment).

Treatment	Depth of A	Depth to bottom of Bw
Sandstone (SS)	9b*	41a
1:1 SS:SiS	10ab	38a
Siltstone (SiS)	12a	36a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Table 7. Controlled Overburden Placement Surface Amendment soil profiles 2016 (mean of 3 pits/treatment).

Treatment	Depth of A	Depth to bottom of Bw
Control (2:1 SS:SiS)	8c*	39a
Topsoil (30 cm)	17a	48a
Sawdust (112 Mg/ha)	12b	45a
Biosolids (56 Mg/ha)	10bc	43a
Biosolids (112 Mg/ha)	10bc	45a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

The long-term influence of sawdust and biosolids additions in the surface treatment experiment is still apparent in darker overall colors and stronger aggregation than noted in the untreated control plots. In 1989, average A horizon depth across most treatments was 7 cm while most treatments supported ^A horizons $\geq$ 10 cm in thickness in 2016.

Perhaps our most surprising observation in this study is the apparent development of compacted subsoil layers in the lower B and C horizons. Since all vehicle traffic has been excluded, we can only hypothesize that these layers are being formed by either (a) net physical illuviation and sorting of finer textured soil sized materials downward over extended periods of time, or (b) physical weathering and slaking of larger rock fragments leading to “collapse” of original open bridging voids. The only similar reports of this latter phenomenon are by Haigh and Sansom (1999) and related work in much different (slaking mudstones and shales) spoils and coal refuse in Wales. However, they do report a very similar process and resultant formation of subsoil compacted layers. In this study, these highly compacted layers were not observed in our previous pit studies in 1989, and we had previously attributed (e.g. Haering et al., 1993, 2004) similar layers to relict effects of compaction from rubber-tired haulers and excessive final dozer grading. That being said, Haering et al. (1993) did not that deeper rooting appeared to be more limited than observed in the early 1980's and some profiles did exhibit modest levels of subsoil compaction. While we still believe those mechanisms are major reasons for root-limiting compaction in Appalachian mine soils, these results clearly indicate that natural pedogenic and/or simple long-term settling processes may be active in forming these limiting layers as well.

Mine Soil Physical and Chemical Properties

Soil pH and Electrical Conductivity (EC)

Mine soil pH and EC for matching depth increments in the Rock Mix Experiment are reported in Tables 8 and 9, respectively. As expected, pH after 30+ years of leaching was higher in the SiS treatment and increased with depth to original 1982 levels of 6.4 (SS) to 8.25 (SiS) depending on rock mix treatment. As reported in earlier articles by Roberts et al. (1988b) and Haering et al. (1993), EC was higher in the surface layer of the higher SS treatments due to cycling and concentration of base cations by the vegetation, but this effect was not evident in the much higher pH/base cation containing pure SiS plots. Subsoil EC levels in the SS and 1:1 SS:SiS treatments were also considerably lower in 2016 than in the early to mid-1980s. Taken together, these data indicate that while weathering and leaching have clearly depleted the upper portions of these mine soils of soluble salts, the lack of pH depression in the deep subsoils and relatively high remaining EC in the SiS plots in all depths indicates that this is overall weathering and depletion of soluble constituents has been largely limited to the surface soil layers.

Table 8. Saturated paste pH by depth in the Controlled Overburden Placement Experiment Rock Mix soil pits described and sampled in September, 2016.

Treatment	**------------------------ Depth in cm ------------------------**						
	0-10	**10-20**	**20-30**	**30-40**	**40-50**	**50-75**	**75-100**
Sandstone (SS)	5.73b*	5.55a	5.57c	5.98b	5.98c	6.10b	6.41b
1:1 SS:SiS	5.76b	5.82b	6.49b	7.26a	7.42b	7.56a	7.58ab
Siltstone (SiS)	6.66a	7.75b	8.07a	8.03a	8.15a	8.19a	8.25a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Table 9. Saturated paste electrical conductivity (dS/cm) by depth in in Controlled Overburden Placement Rock Mix soil pits 2016.

Treatment	**------------------------ Depth in cm ------------------------**						
	0-10	**10-20**	**20-30**	**30-40**	**40-50**	**50-75**	**75-100**
Sandstone (SS)	0.26a*	0.12a	0.07b	0.08b	0.10b	0.10b	0.10b
1:1 SS:SiS	0.29a	0.16a	0.10b	0.13b	0.18ab	0.18ab	0.21a
Siltstone (SiS)	0.26a	0.26a	0.27a	0.24a	0.25a	0.27a	0.26a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Similar results for mine soil pH and EC from the Surface Treatment Experiment (Tables 10 and 11) confirm a similar long-term temporal response in the uniform 2:1 SS:SiS spoils, but with some surface modifications by treatment. For pH, the higher biosolids treatments actually depressed pH vs. the control, presumably due to long-term organic matter turnover and associated acidification processes. In contrast, the EC of the sawdust and biosolids treatments appeared to be elevated above the control and topsoil plots, but the variance was high and these numerical differences were not different via the normal theory statistics applied. We will analyze these data further using a non-parametric contrasts in the future to further analyze and confirm any differences.

Table 10. Saturated paste pH by depth in in Controlled Overburden Placement Surface Amendment soil pits sampled in September, 2016.

Treatment	------------------------ Depth in cm ------------------------						
	0-10	**10-20**	**20-30**	**30-40**	**40-50**	**50-75**	**75-100**
Control (2:1 SS:SiS)	5.69a*	6.43a	7.56a	8.08a	7.99a	7.83a	7.73a
Topsoil (30 cm)	5.26ab	6.23a	6.98a	7.26a	7.21a	7.63a	8.25b
Sawdust (112 Mg/ha)	5.19ab	5.31a	7.01a	6.86a	7.21a	7.59a	7.79a
Biosolids (56 Mg/ha)	5.04b	5.64a	7.59a	7.54a	7.59a	7.80a	7.89a
Biosolids (112 Mg/ha)	5.15b	5.91a	6.99a	7.07a	7.45a	7.87a	7.81a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Table 11. Saturated paste electrical conductivity (dS/cm) by depth in Controlled Overburden Placement Surface Amendment pits 2016.

Treatment	------------------------ Depth in cm ------------------------						
	0-10	**10-20**	**20-30**	**30-40**	**40-50**	**50-75**	**75-100**
Control (2:1 SS:SiS)	0.76a*	0.18b	0.13a	0.12a	0.15a	0.11a	0.13a
Topsoil (30 cm)	0.65a	0.17b	0.14a	0.16a	0.14a	0.15a	0.16a
Sawdust (112 Mg/ha)	1.12a	0.38a	0.13a	0.12a	0.11a	0.12a	0.13a
Biosolids (56 Mg/ha)	1.14a	0.32ab	0.17a	0.16a	0.14a	0.14a	0.14a
Biosolids (112 Mg/ha)	1.21a	0.28ab	0.16a	0.14a	0.14a	0.14a	0.14a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Texture and Chemical Properties of Morphological Horizons

Important physical and chemical properties for the larger bulk morphological horizon properties from the Rock Mix Experiment are presented in in Tables 12 and 13. The strong influence of rock type on texture, exchangeable bases and pH was still evident after 30+ years with the SS dominated mine soils. Surface weathering appears to have shifted the texture of the ^A vs. underlying ^Bw horizons, although these layers were not statistically contrasted. The ^A horizon total C levels are relatively high (> 3%) and reflect the influence of geogenic C from coal fragments which also leads to higher "apparent levels" than would be expected in the underlying ^Bw horizons. Other notable differences include much higher exchangeable and acid-extractable cations in the ^A vs. ^Bw horizons due to long term bioaccumulation processes. We are still analyzing these data sets and will report on further insights next year.

Table 12. Properties of ^A horizons in Controlled Overburden Placement Rock Mix pits sampled in October, 2016.

Treatment	1:1 pH	C	N	Mehlich-1 extractable										Sand	Silt	Clay
				P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	Al			
		---- % ----		---------------------------------- mg/kg ----------------------------------										--------- % ---------		
Sandstone (SS)	5.62b*	3.48b	0.23a	18b	138a	890a	227b	3.7b	39a	0.9a	46a	0.3a	118a	66a	23b	11a
1:1 SS:SiS	5.76b	4.62ab	0.31a	20b	95a	1196ab	314ab	4.7ab	39a	1.3a	39a	0.3a	98a	59ab	28b	13a
Siltstone (SiS)	6.16a	5.17a	0.34a	39a	78a	1622a	388a	5.3a	56a	1.9a	36a	0.6a	94a	43b	43a	14a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Treatment	---------------- Exchangeable ---------------							ECEC	CEC	Base Saturation
	Ca	Mg	K	Na	Acidity	Al	Bases			
	---------------------------- cmol + / kg soil ----------------------------									---- % ----
Sandstone (SS)	4.10a*	2.01b	0.30a	0.03a	0.00a	0.18a	6.43a	6.61a	6.43a	100.0a
1:1 SS:SiS	5.36a	2.72ab	0.30a	0.03a	0.00a	0.15a	8.40a	8.55a	8.40a	100.0a
Siltstone (SiS)	7.76a	3.62a	0.27a	0.02a	0.00a	0.06a	11.67a	11.74a	11.67a	100.0a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Table 13. Properties of ^Bw horizons in Controlled Overburden Placement Rock Mix pits 2016.

Treatment	1:1 pH	C	N	Mehlich-1 extractable										Sand	Silt	Clay
				P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	Al			
		---- % ----		---------------------------------- mg/kg ----------------------------------										--------- % ---------		
Sandstone (SS)	5.86c*	0.97b	0.04b	15b	31a	319b	138b	1.3b	19c	2.0b	32a	0.1b	74a	73a	16c	11a
1:1 SS:SiS	6.82b	1.76a	0.06a	69a	35a	619b	191b	2.2a	30b	2.7a	41a	0.1b	68a	58b	29b	13a
Siltstone (SiS)	8.18a	2.09a	0.07a	54a	40a	1713a	551a	2.3a	52a	1.1ab	39a	0.2a	68a	37c	49a	14a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Treatment	---------------- Exchangeable ---------------							ECEC	CEC	Base Saturation
	Ca	Mg	K	Na	Acidity	Al	Bases			
	---------------------------- cmol + / kg soil ----------------------------									---- % ----
Sandstone (SS)	1.37b*	1.13b	0.10a	0.02a	0.00a	0.48a	2.62c	3.10b	2.62c	100.0a
1:1 SS:SiS	2.28b	1.56a	0.10a	0.02a	0.00a	0.01b	3.96b	3.97b	3.96b	100.0a
Siltstone (SiS)	3.70a	1.62a	0.11a	0.02a	0.02a	0.02b	5.45a	5.48a	5.47a	99.7a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Similar summary data for the morphological ^A and ^Bw horizons from the Surface Treatment Experiment are presented below in Tables 14 and 15. As expected, the ^A horizons of the biosolids treatments were significantly higher in C and N than the topsoil treatment and higher in N than the control plots (Table 14). The lack of difference in C levels is due primarily to the fact that the control treatment ^A horizons were much thinner; we assume that mass C levels in the biosolids plots with depth are still much higher, but we have not confirmed that on this data set.

Topsoil plots were higher in sand content due to differences in original pre-weathered and resistant nature of the weathered materials applied. This difference was not apparent in the 1982-1984 data (Roberts et al., 1983b), which indicates that sands in the control plots have been weathering down to silt+clay while the pre-weathered topsoil materials were more resistant to weathering. Higher sand content in the biosolids treated A horizons is due to the inclusion of significant amounts of quartz sand in those original amendments. Effective CEC and individual cation levels were not strongly influenced by treatment and are similar to levels from 1984, other than for the organic treatments (sawdust and biosolids) which were much lower in 2016. Biosolids treatments have also imparted a clear "chemical signature" on these mines soils after 30+ years as seen in the acid extractable P, Cu, Fe and Zn data (Table 14).

As expected, the data for the ^Bw horizons (Table 15) revealed fewer (if any?) differences in texture or chemical properties due to surface-applied treatments. In general, the ^Bw horizons were much lower in C, N and extractable/exchangeable bases than the ^A horizons above them, but this was not statistically evaluated. We will run depth contrasts on these data during the current project year. The subsoil layers (^Bw) were also higher in pH and lower in base saturation due to the long-term leaching and surface acidification processes associated with organic matter accumulation and turnover described earlier.

Per earlier comments, we are still analyzing and developing this very large and important data set and will report on further insights and conclusions next year. In particular, we have access to the original COP plot-by-plot data from Roberts et al. (1988c) and will use that to rigorously contrast results over time.

Table 14. Properties of ^A horizons in Controlled Overburden Placement Surface Amendment pits 2016.

Treatment	1:1 pH	C	N	Mehlich-1 extractable										Sand	Silt	Clay
				P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	Al			
		---- % ----		----------------------------------- mg/kg ------------------------------------										--------- % ---------		
Control (2:1 SS:SiS)	5.47a*	3.86a	0.20bc	34b	49b	982ab	228ab	3.8b	36a	1.8bc	51bc	0.3a	99b	59c	29a	12a
Topsoil (30 cm)	5.17a	2.84b	0.18c	26b	64ab	780b	208b	2.7b	32a	1.0c	35c	0.2a	86b	69a	20b	11a
Sawdust (112 Mg/ha)	5.12a	4.63a	0.32a	24b	86a	1292a	297a	5.5b	42a	1.4bc	51bc	0.3a	125b	58c	30a	12a
Biosolids (56 Mg/ha)	5.11a	3.91a	0.27ab	38b	63ab	1083ab	232ab	10.6b	28a	2.5b	85ab	0.2a	160b	63b	25a	12a
Biosolids (112 Mg/ha)	5.22a	3.92a	0.27ab	91a	50b	1087ab	202b	20.6a	24a	4.1a	100a	0.3a	242a	61bc	26a	13a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Treatment	---------------- Exchangeable ---------------							ECEC	CEC	Base Saturation
	Ca	Mg	K	Na	Acidity	Al	Bases			
	----------------------------- cmol + / kg soil -----------------------------									---- % ----
Control (2:1 SS:SiS)	3.66b*	1.75b	0.14b	0.01a	4.50a	0.05a	5.02a	5.06a	9.52a	63.9a
Topsoil (30 cm)	3.55b	1.63b	0.19ab	0.01a	4.57a	0.26a	4.88a	5.14a	9.45a	53.3a
Sawdust (112 Mg/ha)	5.28a	2.36a	0.26a	0.02a	6.23a	0.09a	6.26a	6.36a	12.50a	58.9a
Biosolids (56 Mg/ha)	4.10ab	1.80ab	0.18ab	0.04a	9.13a	0.11a	6.12a	6.23a	15.25a	40.1a
Biosolids (112 Mg/ha)	3.88ab	1.48b	0.16b	0.04a	4.53a	0.23a	4.05a	4.28a	8.58a	51.1a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Table 15. Properties of ^Bw horizons in Controlled Overburden Placement Surface Amendment pits 2016.

Treatment	1:1 pH	C	N	Mehlich-1 extractable										Sand	Silt	Clay
				P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	Al			
		---- % ----		----------------------------------- mg/kg ------------------------------------										--------- % ---------		
Control (2:1 SS:SiS)	6.80a*	2.13a	0.06a	55a	27a	562a	188a	2.4a	25a	1.9a	45a	0.06a	62a	61a	28a	11ab
Topsoil (30 cm)	7.18a	1.62ab	0.05ab	46a	28a	607a	198a	2.6a	27a	1.7a	44a	0.09a	79a	65a	24a	10b
Sawdust (112 Mg/ha)	6.60a	1.70ab	0.05ab	37a	31a	502a	186a	2.3a	26a	1.8a	40a	0.08a	73a	65a	24a	11ab
Biosolids (56 Mg/ha)	7.29a	1.42b	0.04b	39a	27a	558a	182a	2.4a	21a	1.7a	38a	0.07a	67a	66a	24a	11b
Biosolids (112 Mg/ha)	7.04a	1.78ab	0.05ab	39a	33a	563a	202a	3.3a	18a	2.1a	37a	0.08a	64a	61a	26a	13a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Treatment	---------------- Exchangeable ---------------							ECEC	CEC	Base Saturation
	Ca	Mg	K	Na	Acidity	Al	Bases			
	----------------------------- cmol + / kg soil -----------------------------									---- % ----
Control (2:1 SS:SiS)	1.74a*	1.38a	0.08a	0.01a	1.57a	0.00a	3.35a	3.73a	4.92a	71.38a
Topsoil (30 cm)	2.01a	1.41a	0.08a	0.01a	1.30a	0.02a	3.50a	3.52a	4.80a	73.32a
Sawdust (112 Mg/ha)	1.92a	1.51a	0.12a	0.11a	1.64a	0.01a	3.29a	3.30a	4.93a	70.33a
Biosolids (56 Mg/ha)	2.02a	1.36a	0.07a	0.01a	1.57a	0.00a	3.46a	3.46a	5.03a	68.72a
Biosolids (112 Mg/ha)	2.19a	1.49a	0.10a	0.02a	0.27a	0.02a	3.72a	3.73a	3.98a	93.42a

*Column means followed by different letters are significantly different ($p \leq 0.05$, Fisher's LSD).

Effects of 35 Years of Weathering on TDS Release Potentials

As discussed earlier, the presumed long-term emission of TDS by active and reclaimed coal mines in the Appalachian region has presented the industry with a significant regulatory challenge. Our recent work (Evans et al., 2014; Daniels et al., 2016) indicates that TDS potentials are clearly related to rock type and extent of pre-mine overburden weathering and that initially high levels should decline over time. However, the actual time that decline will take to occur under field scale mining and valley fill conditions remains debatable. Evans et al. (2014) predicted that this decline could occur at actual valley fills in the field to SC levels lower than 500 μs/cm over several decades. Our lab column studies (Orndorff et. al, 2014; Daniels et al., 2016) have indicated that TDS decreases could occur for a given thickness of spoil within 10 to 15 unsaturated leaching cycles, but those results are difficult to extrapolate to field bulk spoil leaching conditions. Here, reported for the first time, we offer collaborating evidence based upon application of our leaching protocol to similar sized and processed unweathered rock samples collected from the COP research plots in May of 1982 vs. rock fragments extracted from the upper 25 cm of the weathered field profiles in October 2016.

The effects of 30+ years of weathering and leaching have clearly depressed pH in both crushed (C) and uncrushed (U) spoils, with the 2016 leachate pH values consistently 1.0 to 1.5 SU lower throughout the 40 unsaturated leaching cycles (Fig. 16). Interestingly, the larger columns containing uncrushed spoils (UL) produced significantly higher pH results than the same crushed materials (C), most likely due to a lower ratio of preferential flow pathways to spoil mass, allowing them to more effectively neutralize the pH 4.6 acid precipitation utilized. Crushing and fragment size essentially had no effect on leachate pH in for the unweathered May 1982 samples (Fig. 16).

Similar to other nearby SW Virginia mine spoils we have analyzed for SC behavior, initial leachate SC in the unweathered 1982 materials was $\geq$ 1000 μs/cm (Fig. 17; ~ leach cycles 3-4), and then fell to < 500 μs/cm by leach cycle 20. In stark contrast, all weathered 2016 spoil treatments, regardless of fragment or column size, started at < 250 μs/cm and fell to < 100 μs/cm (Fig. 17). For some undetermined reason, longer-term leaching of the uncrushed (U) 1982 spoils in the standard (7.5 cm) columns produced slightly lower SC than the larger columns (UL), while the crushed (C) columns remained somewhat higher as expected.

Taken together, these results indicate that fragment crushing/size and column size had little influence on the unweathered 1982 samples due to a dominance of freshly exposed and highly reactive surfaces in all treatments. In contrast, the 2016 materials had undergone > 30 years of field oxidation, weathering and leaching, and had clearly been depleted of reactive components that could generate TDS. The extent of this depletion is surprising, particularly since crushing the larger uncrushed materials down to pass a 1.25 cm screen had little influence on initial or long term SC. This indicates that these hard rock spoils had been strongly weathered and leached throughout their mass and not just on/in external surface rinds.

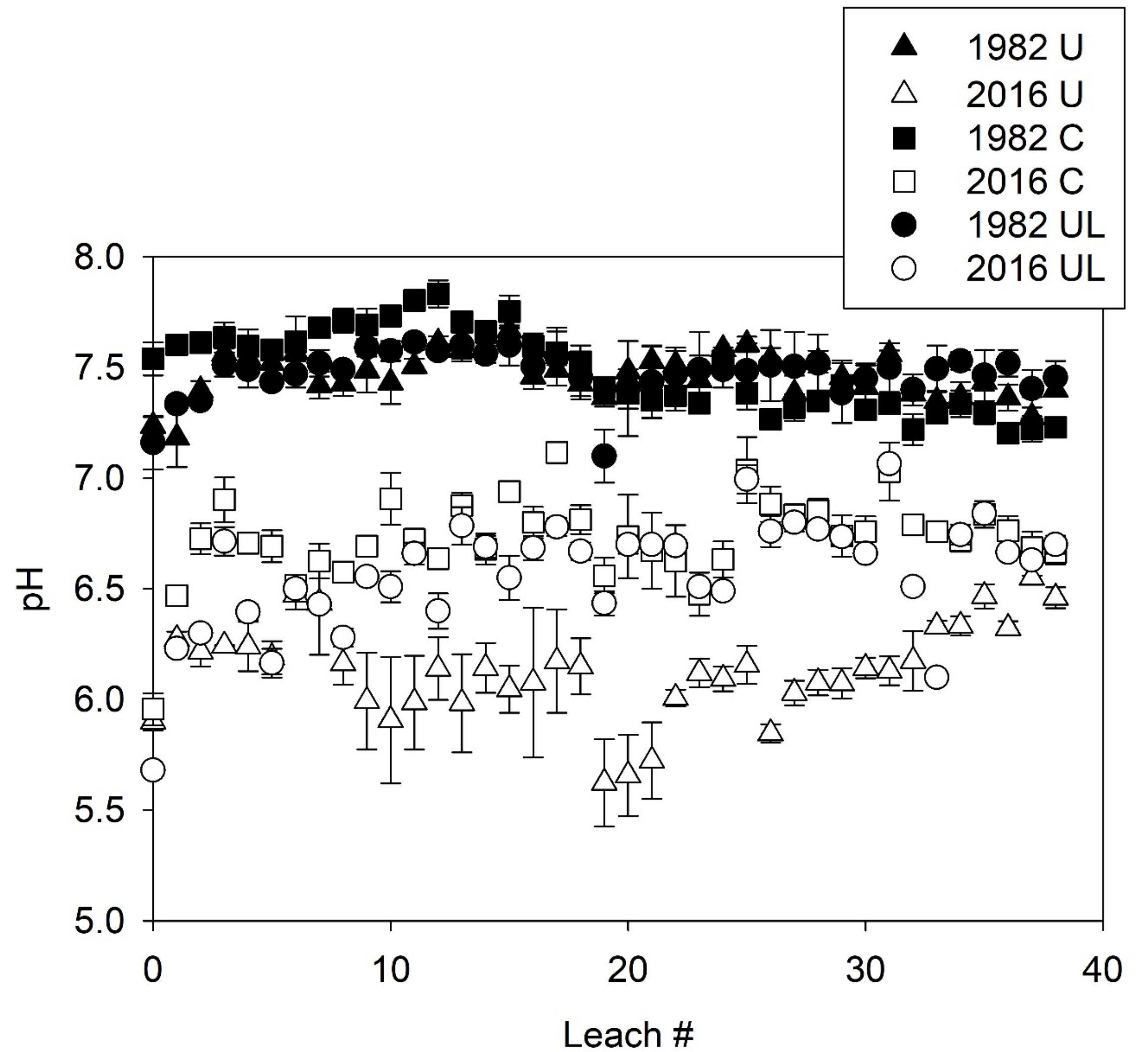

Figure 15. Effects of rock fragment weathering extent (1982 vs. 2016) on leachate pH over 40 leaching cycles in unsaturated 7.5 cm diameter columns. Leaching water was simulated (pH 4.6) acidic precipitation. Materials were evaluated as is (uncrushed – U; 4.75 mm to 3.8 cm) vs. crushed (C; < 1.25 cm). A parallel set of uncrushed materials was run in larger columns (UL; 15 cm) to evaluate effects of column sizing on potential for enhanced preferential flow in the standard 7.5 cm columns.

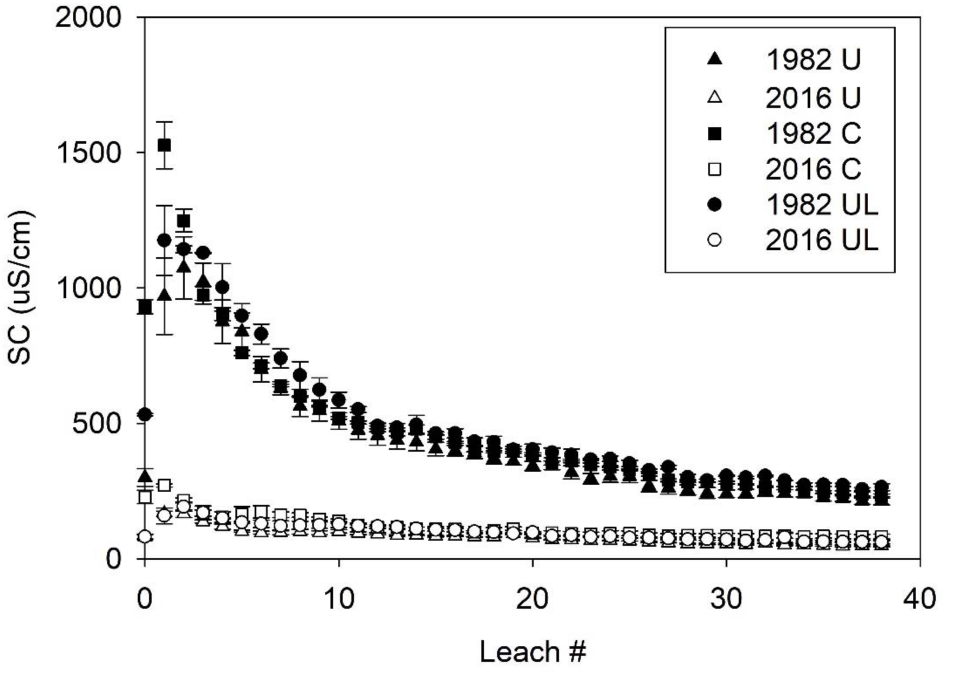

Figure 16. Influence of weathering/age, crushing and column size on leachate specific conductance (linear scale) over 40 leaching cycles with simulated acidic rainfall.

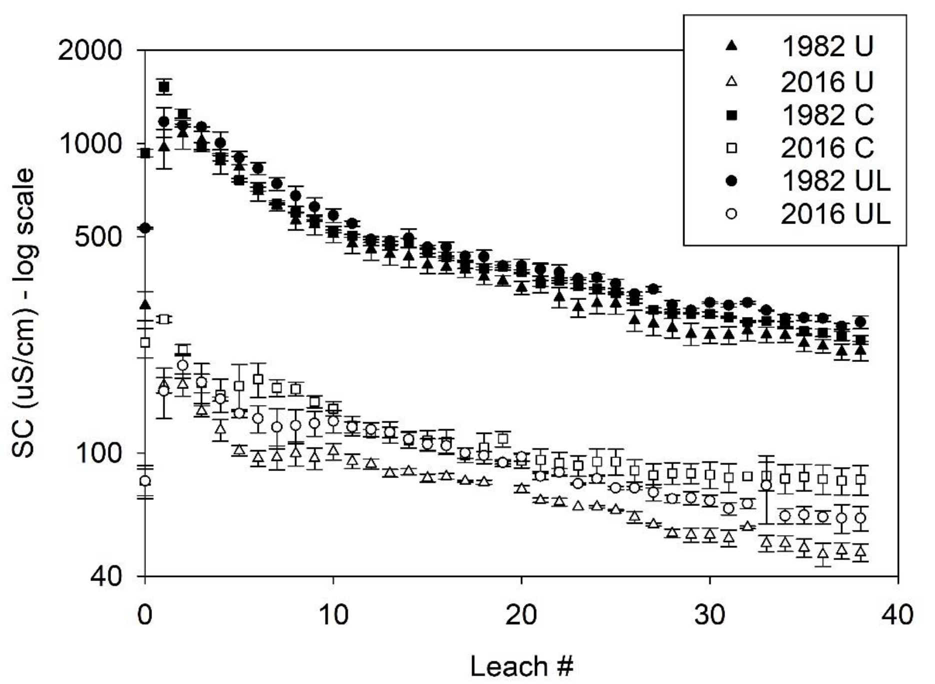

Figure 17. Influence of weathering/age, crushing and column size on leachate specific conductance (log scale) over 40 leaching cycles with simulated acidic rainfall.

TDS Release Over Time by a SW Virginia Sandstone Spoil – Mesocosm Results

In December of 2012, we initiated a field mesocosm study (Ross, 2015) focused on determining the multi-year TDS elution behavior of a typical SW Virginia sandstone mine spoil (Harlan Fm.) in comparison to our column leaching method prediction method (Orndorff et al., 2015). To accomplish this, we constructed large "leaching tanks" (mesocosms; see Fig. 18) at the VTRC in Blacksburg and filled them bulk fresh mine spoil collected from the Harlan Formation collected from the Red River Coal active mine above the Powell River Project field site. This stratum is similar to the unweathered SS component originally utilized for the COP experiment, but occurs higher in the stratigraphic column. The bulk spoils were loaded into the mesocosms and barrels (Fig. 18) to assess the relative influence of size consist on TDS leaching behavior vs. original column predictions (see Figs. 19 and 20). Materials placed into the barrels were ≤ 15 cm, while all materials up to ~50 cm in diameter were loaded into the mesocosms. Leachates were drained from below the mesocosms into separate belowground receiving containers and sampled monthly during the winter leaching season and/or following major precipitation events during the growing season. Local rainfall was also collected for analysis. All samples were analyzed for pH and SC in our labs within several hours of field collection.

In general, leachate pH produced by the lab columns matched up well against that observed in the field from both the barrels and mesocosms (Fig. 19). Similar to many SW Virginia unweathered spoils, these materials are high in pH, most likely due to trace carbonates and other reactive alkaline weathering components like feldspars and metamorphic lithic fragments (Clark et al., 2018). The pH vs. time behavior for the mesocosms (Fig. 20) reveals a strong seasonal effect with pH (and presumably total alkalinity) increasing in the cooler winter months, most likely due to the slight but positive effect of decreasing temperature on pH, CO_2 partial pressures, and the associated carbonate/bicarbonate equilibrium. The drop in pH over time of the local rainfall (labeled as "blank" in figures) is notable and more than likely indicates that some neutralization must have occurred in the first year due to an unknown interaction with the plastic barrels utilized. The longer term rainfall pH ranged from 4.5 to 6.5 as expected.

The influence of leaching scale/method on measured SC (Fig. 21) indicates that while the lab column method did predict the overall shape and initial high vs. longer term SC elution behavior of this spoil, it did not concur with the first winter's seasonal spike as noted in the field barrels and mesocosms (Figs. 21 and 22). The longer-term data set here indicates that (a) leachate EC/SC fell to ~ 300 µs/cm by the end of the second full year of leaching, but that (b) the seasonal winter increase continued to occur for over five years, with lower amplitude each year. The relatively large increase in SC over the first full winter leaching season (2013/2014) may indicate that mechanisms other than simple CO_2 partial pressure and carbonate/bicarbonate equilibrium may be involved. It is likely that highly reactive feldspars and other reactive mineral surfaces generated reaction salts that accumulated over the drier preceding summer months that then dissolve and are flushed from the system under much wetter winter leaching conditions. This would also account for the diminishing "winter flush" observed over longer periods of time as highly reactive phases are consumed. Regardless, these collective data sets again confirm our hypotheses regarding the temporal decline in TDS elution potential for mine spoils over time.

Figure 18. Harlan spoil leaching mesocosms (left) and barrels (right foreground) at Virginia Tech Turfgrass Research Center (VTRC) in November 2012. Leachates were collected monthly or following significant precipitation events and analyzed for pH and specific conductance. Ion composition was also monitored periodically (not reported here).

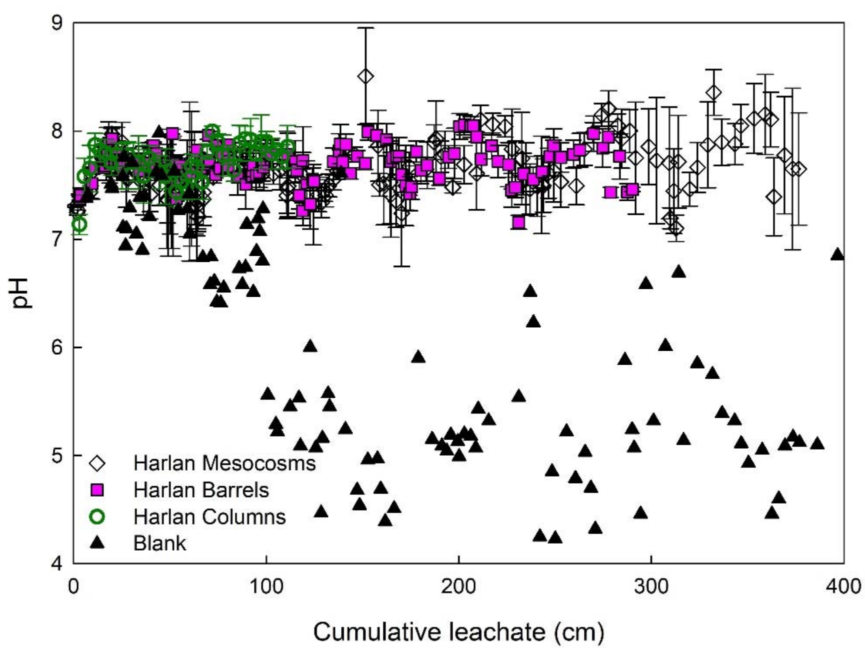

Figure 19. Leachate pH vs. cumulative volume for Harlan mesocosms, barrels and columns. Column technique only evaluates 40 leaching cycles. Blank refers to onsite presumably clean barrel collecting ambient rainfall.

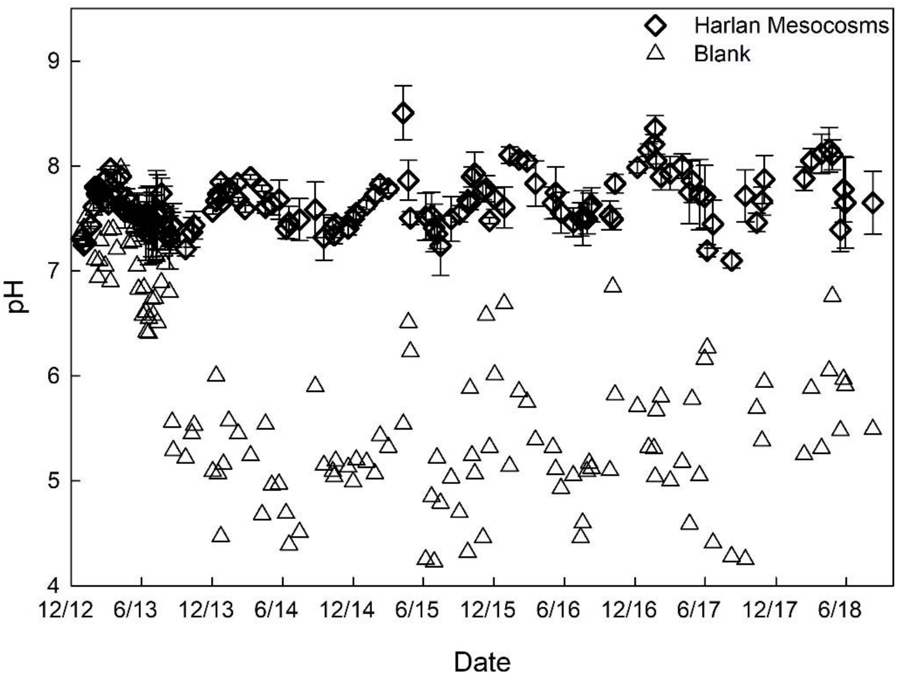

Figure 20. Leachate pH vs. time for Harlan mesocosms. Note the strong seasonal signature of increasing pH in the cooler winter months.

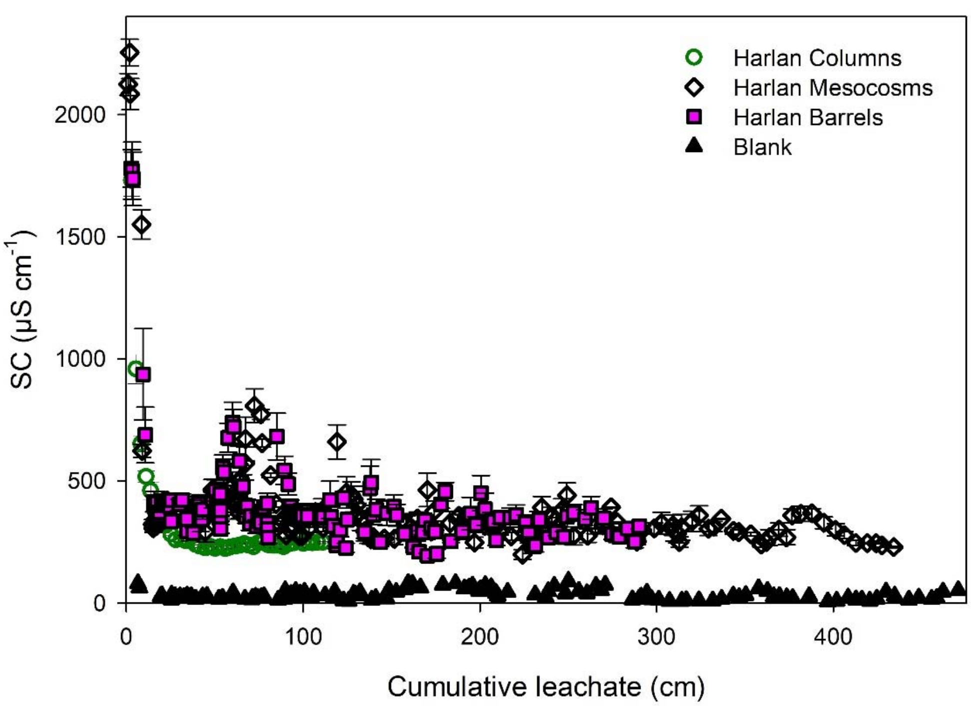

Figure 21. Leachate specific conductance (SC) vs. cumulative leachate for the Harlan mesocosms, barrels and spoils.

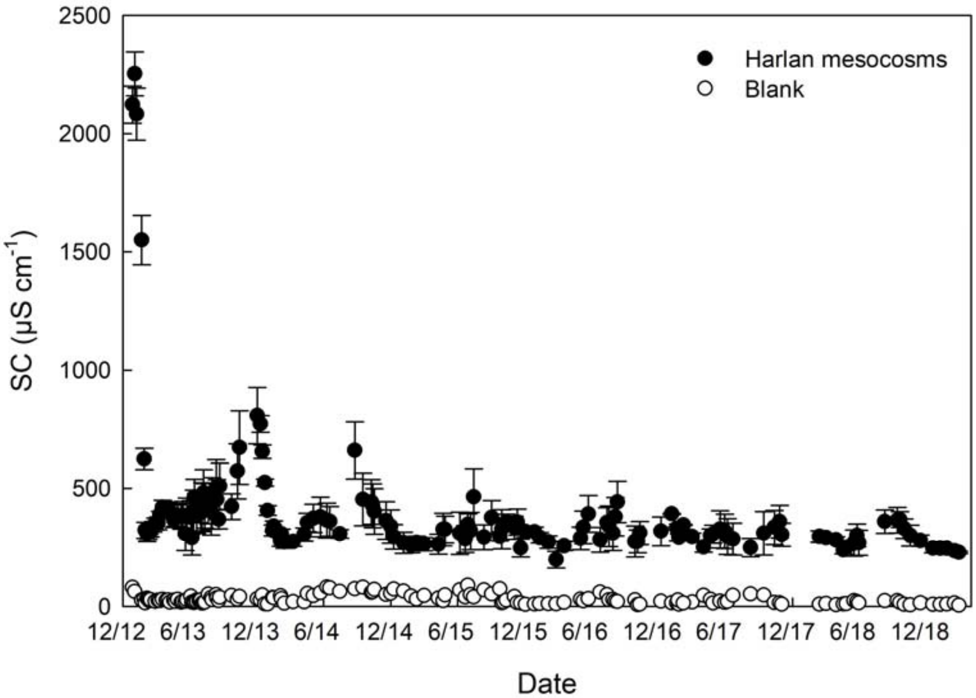

Figure 22. Leachate specific conductance (SC) vs. time for the Harlan mesocosms. Note the significant increase in EC over the first two winter leaching seasons.

Overall Summary and Conclusions

Once we have completed all final physical and chemical analyses on the primary morphological horizon and depth increment samples, we will statistically evaluate them to reconfirm the extent of chemical and physical weathering in these materials over the past 30+ years. However, our detailed morphological studies, coupled with physical and chemical lab analyses to date, clearly indicate that significant pedogenesis has occurred over a relatively short period in these mine soils, resulting in well-developed profiles, including readily discernible cambic (^Bw) subsoil horizons. Thus, while the vast majority of these soils were classified as Entisols by U.S. Soil Taxonomy in the 1980s, they would now all be classified as Inceptisols.

The long-term influence of varying surface treatments (topsoil, sawdust and biosolids) is still readily apparent in the surface ^A horizons of these mine soils, but does not appear to have consistently affected subsoil morphology or physical/chemical properties. While the influence of long-term weathering and leaching on the surface horizons is clear, deeper (e.g. > 75 cm) spoil materials appear to be very similar to original 1982 unweathered spoil properties.

The finding that significant compact and root-limiting subsoil layers appear to be forming in these mine soils via combined pedogenic processes is an important and novel finding. To our knowledge, this has not been reported in the USA scientific literature to date, but has been noted in a different mining/spoil environment in Wales (UK). Recognizing this process may be important for developing management practices (e.g. ripping for forest establishment) on older mined lands, even where rough grading and other initial soil reconstruction practices to limit compaction were followed.

The combined results from the COP column leaching studies and the long-term (6-year) Harlan spoil leaching mesocosms confirm that while our lab column protocol appears to be a relatively accurate predictor of peak vs. long-term leachate specific conductance (SC; proxy for TDS), it probably under-predicts peak seasonal ion release events in younger reactive materials. The dramatic differences in SC production between the 1982 and 2016 spoil samples from the COP experiment clearly demonstrate that we can expect a significant drop in TDS risk for a given "leaching increment" of a spoil over a decadal timeframe and generally support our earlier predictions (Evans et. al, 2014) of the expected time (15 to 25 years) for field valley fill discharges to fall below current levels of regulatory concern (e.g. 350 µs/cm). However, the fact that the deeper spoils in the COP experiment still appeared to be only slightly weathered after > 30 years demands that such estimates be made with caution.

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