Analysis of Reconstructed Mine Soils on Reclaimed Coal and Mineral Sands Mined Lands in Virginia

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ABSTRACT (ACADEMIC)

Post-mining land use potentials are greatly influenced by mine soil properties. I analyzed and classified coal mine soils in SW VA and mineral sands mine soils in SE VA to aid development of appropriate post-mining land use interpretations. For coal mine soils, long-term pedogenesis was assessed in sandstone (SS) and/or siltstone (SiS) spoils with and without surface amendments. For mineral sands mined lands, I evaluated their spatial variability with respect to underlying relic mining influences and rowcrop productivity. Coal mine subsoils densified as root-limiting layers formed that were not observed initially and all soils had weak pedogenic development (^Bw; cambic horizons), particularly SS derived soils. Initial rock spoil type strongly influenced coal mine soils over time (i.e., SS had coarser textures and lower subsoil pH vs. SiS). However, most soil chemical properties (e.g., pH, EC, CEC) became similar in ^A horizons over time. Fe-oxides increased, and extractable-P decreased with weathering, raising concerns for long-term P-availability. Organic amendments applied to rock spoil surfaces sustained higher total-N (sawdust and biosolids) and extractable P (biosolids). Soil carbon sequestration rates did not differ among rock types or amendments (0.16 to 0.28 Mg ha yr^{-1}). Further, mineral sands mine soils were limited by densic contacts and short-range variability of important properties (texture) appeared related to underlying relic mining features (pits and berms). Yields in reclaimed soils were more variable than in adjacent undisturbed farmland, but mean yields were only slightly reduced for soybean in 2020. Coloration and Fe-oxide spectral indices had weak to moderate negative correlations with yield. Berm positions supported better soybean growth (three out of five sites), while pit positions were redder/darker (one out of five sites). Current *Soil Taxonomy* conveys anthropogenic origins at the family (e.g., spolic) and subgroup (e.g., Anthroportic) levels. Existing taxa and proposed Artesols order criteria both acknowledge effective soil depth x compaction limitations (Anthrodensic subgroup), but Artesols more effectively recognizes pedogenesis (Inceptic subgroup) and acknowledges mine soils at the highest level. The biggest management limitation for both mine soil types is root-limiting compaction; thus, future efforts should focus on defining depth ranges and taxonomic interpretations for densic contacts.

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ABSTRACT (GENERAL AUDIENCE)

Surface mining results in drastic disturbances to the original soil, land, and water features. Actual impacts vary due to local site conditions and methods used for mineral extraction and reclamation. Advancing reclamation science requires an understanding of the resulting mine soil properties and how they vary spatially and develop over time. This research program involved two very different mining scenarios and resultant mine soil types in Virginia that were both evaluated in terms of soil properties, taxonomic placements, and land use interpretations. First, I assessed Appalachian coal mine soils in southwestern Virginia following 34 years of soil development in sandstone (SS) and/or siltstone (SiS) derived overburden with and without surface amendments. Over time, rocky mine spoils transformed into weakly developed soil profiles, commonly with four to five total distinct layers (horizons), along with apparent "self-compacted" layers at depth. SS soils were coarser textured with somewhat better subsoil structure, while SiS soils were finer textured and had higher subsoil pH. However, many chemical properties were similar in the soil surface. Organic amendments and topsoil return imparted only subtle differences over time. A secondary objective was to assess mineral sands mine soils, which originate from recombined Coastal Plain sediments. Due to the nature of their wet deposition during final reclamation, these mine soils exhibited high variability across local landforms. Soil profiles over former berm positions were composed mostly of sandier materials, while pit positions had more variable materials and features. Reclaimed rowcrop yields were moderately correlated with bare soil remotely sensed variables. Soils in pit positions were redder in color due to higher clay. While yields were variable, especially in drier years, berms appeared to support better soybean growth, but results were inconsistent across fields. For both mine soil types, root-limiting compaction is their biggest impediment to productive use. Forestry is the predominant post-mining land use on former coal mines, while rowcrop production is becoming more common on former minerals sands mines. Since these two different post-mining environments present unique challenges for correctly interpreting their post-disturbance land-uses, it is important to convey their special properties (e.g., densic contacts) and limitations in their classification.

Dedication

I dedicate this work to my parents, Glenna and Patrick Angel. You helped me up the ladder of success, emphasizing the journey more than the destination, and now as I continue to excel in my profession and life. I am forever blessed by your love and steadfast support.

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1. Introduction

1.1. General Background of Studies

The overall process of modern surface mining involves disturbing land to recover raw mineral commodities. Associated mining impacts to surrounding stream and wetland areas may also occur, but these impacts should be mitigated by federal and state compliance requirements as later discussed (Zipper 2000). Broadly defined, reclamation after mining is the process of rebuilding and revegetating drastically altered landscapes (Nieman and Merkin 2000). Soil, rock, and earthen materials – referred to by the mining industry as "overburden" or "spoil" – are uncovered to access underlying mineral deposits and are usually returned to the original site and revegetated. Methods of surface mining vary regionally and include open pit mining, area or strip mining, mountaintop removal mining, contour mining, dredging, and hydraulic mining (Paone et al. 1978). In the United States, surface mining gained momentum in the late 1950s to early 1960s as society's growing industrial sector and technological advances made the excavation of natural resources, namely coal, more efficient and profitable to greater depths compared to historical underground mining methods (Plass 2000; Shover et al. 1986). Prior to this era of expansion, surface mining occurred to a lesser extent, likely where deposits were shallow and more accessible (Plass 2000). Due to the widespread historical significance of coal mining in the USA, much of the regulatory framework and reclamation technology employed at non-coal mines evolved from surface coal mining operations and related environmental laws passed in the1960s and 1970s. Enactment of state and federal legislation coupled with advancements in reclamation science and technology over the last 50 years has greatly improved the overall post-mining environment (Sobek et al. 2000; Zipper and Skousen 2021). Regardless, reclaimed mine soils are complex systems that continue to present unique challenges based on local site and mining conditions. Thus, continued research efforts are necessary to advance the initial quality and sustained productivity of reconstructed mine soils and their associated post-mine landscapes.

Area surface mining methods are prevalent in regions where topography is flat to gently rolling, whereas contour and mountaintop removal mining operations are commonly used methods in mountainous regions (Paone et al. 1978). In Virginia, surface mining for coal and heavy mineral sands has created large-scale disturbances in the southwestern and southeastern regions,

respectively. Coal mining in the Appalachian Plateau of Virginia occurs in steep, deeply dissected terrain and drastically alters the pre-mine topography, imparting noticeable differences in the post-mining landscape. In the Virginia Coastal Plain, mineral sands mining occurs on landscapes that are relatively flat, resulting in reclaimed areas that are physically similar to unmined landscapes supporting agricultural land uses. These two surface mining methods leave behind very different post-mining landscape aesthetics and land use potentials, but the primary principles and objectives of reclamation for returning and stabilizing both types of lands are fundamentally related (e.g., erosion and sedimentation control, and establishment of desired plant communities) (Vogel 1981).

Most reclaimed coal and mineral sands mine soils are readily capable of supporting vegetation following reclamation (Orndorff et al. 2011; Zipper et al. 2011) and exhibit changes in soil morphological properties, or evidence of pedogenesis, over a relatively short period of time (Daniels and Amos 1981; Haering et al. 2004; Haering et al. 1993; Meredith et al. 2008). Underpinning recent studies of the unique properties of these two different mine soils is an emphasis on improving current soil classification systems and potential land-use management decision making systems regarding human-altered and human-transported (HAHT) materials. While their basic reclamation needs are similar, coal and mineral sands mining occur in two distinct physiographic regions in Virginia with contrasting climate, parent materials, mining methods, and pre-mine soil and site conditions. Hence, the nature of certain mining and reclamation processes create unique soil, site, and vegetation challenges that limit our understanding of sustained productivity and the return of overall ecosystem functions on these reclaimed lands.

Surface coal mining has been ongoing in Virginia since the 1800s and over 28,000 ha of land had been disturbed between the 1940s and passage of the Surface Mining Control and Reclamation Act in 1977 (Daniels and Amos 1981). The larger spatial extent of surface mining after federal regulatory legislation (i.e., from 1977 to present) greatly increased the total area of land disturbed. The intensely dissected topography, mining methods used, and weathering of geologic overburden materials in the Appalachian coalfields region have generated serious environmental issues (e.g., high soil acidity, erosion, poor water quality), which have largely been addressed by federal and state laws (see Section 2.1.1. for more details). Regarding Appalachian coal mine soils derived from sedimentary rock, many studies have indicated significant differences

in physical, chemical, and mineralogical properties directly related to the parent material rock type, coupled with both the initial degree of and subsequent weathering (Daniels and Amos 1981; Emerson et al. 2009; Miller et al. 2012; Wilson-Kokes et al. 2013). Appalachian coal mine soils have been noted for plant growth limiting morphological characteristics (e.g., densic layers) common to mining and reclamation processes (e.g., equipment grading), rapid A horizon development (Haering et al. 2004; Haering et al. 1993), along with the potential for weak Bw (cambic) horizon development in mine soils within 10 to 20 years (Daniels and Amos 1981; Haering et al. 1993). Studies in Pennsylvania reported similar results with respect to pedogenesis in somewhat older (> 15 years) mine soils (Ciolkosz et al. 1983; 1985).

For mineral sands mining in the Upper Coastal Plain of Virginia, reclamation procedures typically result in highly variable mine soil physical, chemical, and morphological properties at multiple scales, but their spatial distribution and effects on post-mining soil productivity are not well understood (Daniels et al. 2012). While pedogenic subsoil horizons are capable of re-forming in mineral sands mine soils in < 10 years (e.g., cambic Bw horizons), it is unclear if and how these processes are limited by extreme short-range variability observed in soil properties following reclamation (Orndorff et al. 2005). The fundamental relationships between extreme spatial variability and initial revegetation success and subsequent rowcrop soil productivity potentials are also poorly understood. For land-use interpretation and management purposes, a clearer understanding is needed regarding temporal changes of coal mine soil development along with the spatial characteristics of mineral sands mine soils. Additionally, little effort has been made to update their soil classification criteria accordingly to support modern mined land soil mapping and interpretation development. Thus, this research program aims to address and synthesize these topics in greater detail across two very different mine soils in Virginia.

1.2. Research Objectives

The goal of my dissertation research was to investigate soil forming processes and important properties associated with the initial construction, pedogenesis, and classification of mine soils on reclaimed coal and mineral sands mines in Virginia. To address this goal, four research objectives outlined below are addressed in Chapters Three through Six. Chapter Two provides a literature review for coal and mineral sands mining and reclamation, including topics

important to the detailed objectives below such as mine soil genesis and classification. The seventh and final chapter broadly summarizes and contrasts morphological development, associated pedogenic processes, taxonomic classification, and management recommendations for coal and mineral sands mine soils based on my collective findings.

i. Evaluate long-term (> 30 years) pedogenesis and soil taxonomic classification of coal mine soils with and without surface amendments reclaimed from sedimentary hard rock overburden in southwestern Virginia.
ii. Model the spatial characteristics of mineral sands mine soils related to initial soil reconstruction practices and evaluate their potential effects on rowcrop productivity in the Virginia Coastal Plain.
iii. Describe the soil morphological properties and taxonomic classification of mineral sands mine soils in southeastern Virginia.
iv. Compare and contrast the properties, soil classification, and associated land-use interpretations of these two differing types of mine soils and post-mining landscapes.

1.3. References

Ciolkosz, E., R.L. Cunningham, G.W. Petersen and R.C. Cronce. 1983. Characteristics, interpretations and uses of Pennsylvania minesoils. Pennsylvania. Agricultural Experiment Station. Progress Report No. 381.

Ciolkosz, E.J., R.C. Cronce, R.L. Cunningham and G.W. Petersen. 1985. Characteristics, genesis, and classification of Pennsylvania minesoils. Soil Science 139: 232-238. doi:10.1097/00010694-198503000-00007.

Daniels, W.L. and D.F. Amos. 1981. Mapping, characterization and genesis of mine soils on a reclamation research area in Wise county, Virginia. p. 261-265. In: Proc. Symp. Surf. Mining Hydrol., Sedimentol., and Reclamat., Lexington, KY. 7-11 December. Office Eng. Serv., College Eng., Univ. Kentucky, Lexington, KY.

Daniels, W., C. Stilson and C. Zimmerman. 2012. Development of effective rehabilitation protocols for mineral sands mining in Virginia, USA. 97-103. In: Life-Of-Mine Conference, Brisbane, Qld, 10 - 12 July. Australian Inst. of Mining & Metallurgy.

Emerson, P., J. Skousen and P. Ziemkiewicz. 2009. Survival and growth of hardwoods in brown versus gray sandstone on a surface mine in West Virginia. J Environ Qual 38: 1821-1829. doi:10.2134/jeq2008.0479.

Haering, K.C., W.L. Daniels and J.A. Roberts. 1993. Changes in mine soil properties resulting from overburden weathering. Journal of Environment Quality 22: 194-200. doi:10.2134/jeq1993.00472425002200010026x.

Haering, K.C., W.L. Daniels and J.M. Galbraith. 2004. Appalachian mine soil morphology and properties. Soil Science Society of America Journal 68: 1315-1325. doi:10.2136/sssaj2004.1315.

Meredith, K., W. Daniels, Z. Orndorff, M. Alley and C. Teutsch. 2008. The influence of soil reconstruction techniques on mineral sands mine soils in Virginia. p. 700-719. In: R.I. Barnhisel (Ed.), Proc., 2008 Nat. Meeting Amer. Soc. Mining and Reclamation, Richmond, VA, June 14-19. Published by ASMR, 3134 Montavesta Rd., Lexington, KY. doi:10.21000/JASMR08010700.

Miller, J., C. Barton, C. Agouridis, A. Fogel, T. Dowdy and P. Angel. 2012. Evaluating soil genesis and reforestation success on a surface coal mine in Appalachia. Soil Science Society of America Journal 76: 950-960. doi:10.2136/sssaj2010.0400.

Nieman, T. and Z. Merkin. 2000. Pre-mining planning for post-mining land use: applying principles of comprehensive planning and landscape architecture to reclamation. p. 667-686. In: Reclamation of Drastically Disturbed Lands. .

Orndorff, Z.W., W.L. Daniels and J.M. Galbraith. 2005. Properties and classification of mineral sands mine soils in southeastern Virginia. In: R.I. Barnhisel (Ed.), Proc., 2005 Nat. Meeting Amer. Soc. Mining and Reclamation, Breckenridge, CO, June 19-23. Published by ASMR, 3134 Montavesta Rd., Lexington, KY, 40502. doi: 10.21000/JASMR05010842.

Orndorff, Z.W., W.L. Daniels, K.R. Meredith, M.M. Alley and A.F. Wick. 2011. Effects of prime farmland soil reconstruction methods on post-mining productivity of mineral sands mine soils in Virginia. p. 504-518. In: R.I. Barnhisel (Ed.), Proc. Nat. Meeting Amer. Soc. Mining and Reclamation, Bismarck, ND, June 11-16. Published by ASMR, 3134 Montavesta Rd., Lexington, KY, 40502. doi:10.21000/JASMR11010504.

Paone, J., P. Struthers and W. Johnson. 1978. Extent of disturbed lands and major reclamation problems in the United States. p. 11-22. In: Reclamation of Drastically Disturbed Lands. ASA, CSSA, SSSA, Madison, WI.

Plass, W.T. 2000. History of Surface Mining Reclamation and Associated Legislation. In: R. I. Barnhisel, R. G. Darmody and W. L. Daniels, editors, Reclamation of Drastically Disturbed Lands. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. p. 1-20.

Shover, N., D.A. Clelland and J. Lynxwiler. 1986. Enforcement or negotiation: Constructing a regulatory bureaucracy. SUNY Press.

Sobek, A.A., J.G. Skousen, S.E. Fisher and R. Barnhisel. 2000. Chemical and physical properties of overburdens and minesoils. Agronomy 41: 77-104. doi:10.2134/agronmonogr41.c4.

Vogel, W.G. 1981. Guide for revegetating coal minesoils in the eastern United States. Forest Service, Broomall, PA (USA). Northeastern Forest Experiment Station.

Wilson-Kokes, L., P. Emerson, C. DeLong, C. Thomas and J. Skousen. 2013. Hardwood tree growth after eight years on brown and gray mine soils in West Virginia. Journal of Environmental Quality 42: 1353-1362. doi:10.2134/jeq2013.04.0113.

Zipper, C.E. 2000. Chapter 7: Coal mine reclamation, acid mine drainage, and the Clean Water Act. In: Reclamation of Drastically Disturbed Lands. Agronomy Monograph no. 41. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. Madison, WI 53711, USA. 169-191 p.

Zipper, C.E., J.A. Burger, J.G. Skousen, P.N. Angel, C.D. Barton, V. Davis et al. 2011. Restoring forests and associated ecosystem services on Appalachian coal surface mines. Environmental management 47: 751-765. doi:10.1007/s00267-011-9670-z.

Zipper, C.E. and J. Skousen. 2021. Coal's legacy in Appalachia: Lands, waters, and people. The Extractive Industries and Society. 21 p. doi:10.1016/j.exis.2021.100990.

2. Literature Review

2.1. Mining and Reclamation in the Central Appalachian Coalfields

2.1.1. History and Regulation

Surface mining for coal is noted for its historical economic significance and environmental impacts, particularly in the central Appalachian region (KY, OH, PA, TN, VA, WV) (Zipper and Skousen 2021a). Formed during the Carboniferous period, high-rank bituminous coal (e.g., low sulfur and high C contents) has been extensively mined throughout Appalachia, with highest-rank anthracite coal occurring to a much lesser extent (Ferm and Weisenfluh 1989). Historically, surface mining impacts and research in the United States have been largely focused on coal due to its extensive geographic range, total extent, and high energy demand, with most of the historic coal production occurring in eastern regions (Shover et al. 1986). Prior to the 1970s, surface mining in the central Appalachians generated negative public scrutiny due to the environmental effects associated with mining in steep terrain (e.g., slope instability), lack of sedimentation controls, and excavation of geologic strata containing pyrite (FeS_2) in both surface- and deep-mines, which has impacted local waterways by production of acid mine drainage (AMD) (Nordstrom 1982). Environmental concerns were accompanied by human safety and socioeconomic issues that burdened many Appalachian coal mining communities. In contrast, western and midwestern coal mining regions involved lower risk of unearthing acid materials and encountering surface instability due to regional differences in geology and topography in comparison to the coalfields of Appalachia (Toy and Daniels 1998). Despite early research and planning efforts from industry, there were no uniform federal regulations for surface coal mining and subsequent land reclamation before 1977; thus, many mined sites were abandoned following coal removal. Thirty-eight states enacted state legislation between 1939 and 1975, including the state of Virginia (Grim and Hill 1974). Despite state intervention, adverse environmental and socioeconomic effects of surface mining, especially in Appalachia, continued throughout the mid-and late-1900s, and the industry was widely criticized by environmental organizations, state and federal governments, citizens' groups, and academic institutions (Shover et al. 1986).

Prior to 1977, early Appalachian surface coal mining involved contour or "strip mining", which involves removing overburden along a linear outcrop on a sideslope or across narrow mountain ridges to access coal seams (Zipper and Skousen 2021b). Once coal was removed, the excess loose mine spoil was pushed laterally or over the outslope below the mine bench. The excavated surface above was left as a flat to gently rolling mined bench below a vertical rock wall or "highwall". The overall set of practices described above, collectively referred to as "shoot and shove" mining, produced severe surface stabilization and water quality issues throughout the region. Increased pressure from the public eventually translated into the passage of the federal Surface Mining Control and Reclamation Act (SMCRA) in 1977 and resultant creation of its enforcement agency, the U.S. Office of Surface Mining, Reclamation and Enforcement (OSMRE) (SMCRA 1977). The SMCRA operates as a federal-state oversight system, like other environmental legislation, where state agencies or tribes are granted primacy to enforce compliance of SMCRA performance standards with an equal or greater level of rigor to the federal law, while under supervision of OSMRE (Zipper 2000). Four decades have passed since SMCRA became law and reformed industry practices in terms of controls on environmental degradation (e.g., sedimentation ponds, revegetation, water quality monitoring) and pre-mining and reclamation planning and permitting (Zipper and Skousen 2021a).

Two important mandates set forth by SMCRA to enforce environmental regulation of mining were blocking permits altogether and the use of performance standards. SMCRA Section 515 (b) lists and describes numerous "Environmental Protection Performance Standards" for all mining and reclamation activities (SMCRA 1977). Performance standards are general criteria for protecting land, soil, and water resources during and after mining, and restoring post-mining land uses; however, specific measures regarding how these standards will be achieved are decided by the industry with federal and state approval. To comply with SMCRA's performance standards, surface mines were required to adjust their methods of operations, i.e., returning mined lands to their approximate original contour (AOC), or pre-mine topography (Daniels and Zipper 1988) in most instances and where feasible. The AOC provision required contour surface mines to eliminate highwalls by backfilling spoil on mined benches to reconstruct landforms similar to the original

surface. Unlike shoot and shove mining, post-SCMRA spoil was to be maintained on the footprint of the mine site or placed into adjacent stable landforms (e.g., valley fills).

Other important SMCRA performance standards include meeting long-term reclamation goals by strategic handling and placement of materials (e.g., controlled overburden placement), establishment of permanent self-sustaining vegetation, and maintaining productive post-mining land uses. A particularly important performance-based enforcement standard is the requirement for mine operations to set forth prior to mining a monetary bond equal to an amount necessary for reclaiming lands under the "worst-case scenario" (Toy and Daniels 1998) of early mine abandonment. Bond funds are progressively released to surface mine operators who have achieved various levels of land stability (e.g., final grades, erosion, and sedimentation control). Final performance bond release occurs when post-mining water quality and vegetation for the designated land use have been maintained for five full years for regions where average annual rainfall is greater than 66 cm or ten years if annual rainfall is lower (SMCRA 1977). This revegetation performance period begins when all reclamation site preparation and vegetation treatments are complete and must be reset if significant areas (> 10%) receive augmented treatments (lime, fertilizer, seed, etc.).

2.1.2. Environmental Issues and Land Use Concerns

The evolution of larger earth-moving equipment in the 1970s and beyond resulted in larger mine footprints and increased cuts into deeper unweathered overburden materials (Zipper and Skousen 2021b). Simultaneous mining of multiple seams became commonplace. Surface coal mining prior to SMCRA generated numerous environmental concerns, arising mainly from uncontrolled placement of overburden materials that posed direct and severe water pollution hazards (i.e., erosion and sedimentation, acid mine drainage) (Vogel 1981). Selective overburden placement procedures are mandated by SMCRA to avoid environmental degradation by exposure of toxic materials (e.g., acid-forming pyrite) and as a mechanism for selecting favorable overburden materials as "substitutes" for topsoil when native sources are inadequate for revegetation. The use of topsoil substitutes was initially controversial and spurred a range of research investigations into best available substrates for plant growth; however, this approach is

ideal since the salvage of native topsoil is often logistically complicated and costly on steep slopes returned to AOC (Daniels and Zipper 1988). Despite AOC provisions, mine sites generate excess volume of spoil due to natural swelling (15 to 25%) of excavated hard rock derived materials. Disposal fills created in valleys adjacent to mining are called "valley fills" and are commonly built as V-shaped structures that hold excess spoil or rock (e.g., durable rock fills), varying in size and design based on local topography (Clark et al. 2018).

Inversion of deep geologic rock strata creates higher risks for generating acidity and salts due to rapid oxidation and leaching driven weathering processes (Zipper and Skousen 2021b). Avoidance of this was difficult before the modern era, even in mine backfills, because it involved reducing contact of toxic materials with infiltrating waters and oxygen. With rigorous overburden analyses and pre-mine planning as set forth by SMCRA, previous research focused on the prevention of toxic strata placement near the final reclamation surface (e.g., Sobek et al. 2000). For example, prediction of the maximum total potential for a certain rock stratum to produce acidity (e.g., pyritic materials) and alkalinity (e.g., carbonates, exchangeable bases) includes a detailed procedure called acid-base accounting (Grube et al. 1973; Knabe 1973; Skousen et al. 1997; Skousen et al. 2002; Smith et al. 1976; Sobek 1978). Extensive research regarding pre-mine identification and management of acid-forming and acid-neutralizing (mainly from carbonates) materials in fresh mine spoils has resulted in drastic improvements in the net environmental quality impacts of surface mining for coal.

The original emphasis placed upon mixing net alkaline- and acid-generating strata in mining backfills and valley fills was to limit AMD production (Daniels et al. 2016). However, over the past decade, regulatory attention has shifted away from acid generation on Appalachian coal mines because it has been thoroughly documented and addressed since the implementation of SMCRA. The major environmental and regulatory focus currently surrounding Appalachian coal mining is now focused on limiting the bulk release of total dissolved solids (TDS) into post-mining headwater streams. Generating and leaching high levels of soluble ions is the inevitable result of using hard rock overburden to reconstruct landforms. TDS production occurs when fresh geologic materials are exposed to a surface environment and undergoes rapid chemical weathering processes (Herlihy et al. 1990; Orndorff et al. 2015). Release of circumneutral TDS has major

implications for local water quality and aquatic biota (Agouridis et al. 2012; Clark et al. 2018; Daniels et al. 2013; Orndorff et al. 2010). Studies have found elevated TDS in post-mining drainage comparable to native reference streams, which was negatively correlated with impaired biotic communities, particularly macroinvertebrates (Cormier et al. 2013; Pond et al. 2008; Timpano et al. 2015).

Within the 5-year post-mining performance period, surface mine operators are also required to comply with Clean Water Act (CWA) permit criteria regarding surface water quality standards for post-mine drainage (i.e., effluent limitations). State agencies enforce CWA permits under supervision of the U.S. Environmental Protection Agency (USEPA) (Zipper 2000). While pH and toxic metals have USEPA water quality standards, TDS generation is not clearly defined since it is indirectly measured (i.e., as specific conductance) and applicable numerical criteria have not been approved to date. However, benthic fauna assessments are used as a proxy in presumed TDS affected watersheds. While current literature has identified several reliable predictors of high TDS producing rock strata (e.g., fine/unweathered materials, high total sulfur content), there is continued interest in TDS generation based on the temporal variability associated with weathering processes and reactions (e.g., feldspar hydrolysis, carbonate dissolution), leaching cycles, and scaling to field conditions over extended periods of time (Daniels et al. 2016).

2.1.3. Reclamation of Coal Mined Lands

Coal mined land reclamation improved following SMCRA through implementation of requirements for installing erosion and sedimentation controls, establishment of permanent self-sustaining vegetation, routine pre-mine geochemical characterization of overburden to limit acid production, and development of comprehensive pre-mine and reclamation planning protocols (Nieman and Merkin 2000; Zipper and Skousen 2021b). Selective placement of suitable overburden materials ahead of mining operations is an allowable practice under SMCRA when native topsoil (A and E horizons) is less than 15 cm thick and/or cannot be adequately or safely salvaged for reclamation (SMCRA Section *515 b 5*) (Zipper et al. 2013). In the central Appalachian coalfields, properly selected hard rock overburden materials can provide a sufficient growth medium for plants and are more commonly utilized as the final revegetation medium than the often

shallow and acidic natural topsoil or mixed subsoil (B and C horizons) materials (Daniels and Amos 1985). Rock derived plant growth substrates have been shown to improve tree productivity, especially when amended with native Appalachian forest topsoil where available (Showalter et al. 2010). Topsoil substitutes are commonly used as the final veneer layer over bulk reclaimed coal mines regionally and are an integral part of pre-mining and reclamation planning processes. Mixed overburden materials have also been successfully utilized as plant growth media alternatives on lignite surface coal-mined areas in the Gulf Coastal Plain when chemical and physical properties of overburden are superior to native topsoil, which is highly weathered and acidic (Angel 1973; Feagley and Hossner 2000; Hons 1978). Mine operators in western and midwestern U.S. regions can usually salvage and store topsoil for reclamation because native sources are generally of sufficient depth and fertility, unlike in the central Appalachian coalfields (Darmody et al. 2002). Where available for salvage, topsoil is ideal because it provides sources of native seed banks and microbial communities, but proper storage is critical for these beneficial properties to remain intact and viable (Ghose 2001; Hall et al. 2010). Thus, proper planning and selection of rock strata for use as Appalachian topsoil substitutes is an important reclamation priority for the intended post-mining land use.

Most coal mining reclamation practices in the USA were largely redefined by the passage of SMCRA, which led to shifts in reclaimed plant communities, mine soil properties, and landform reconfiguration, i.e., the creation of highwall backfills in contour mining, plateaus in mountaintop removal, and widespread excess spoil disposal fills (Zipper and Skousen 2021b). Distinct differences in mining practices prior to and following the implementation of SMCRA are also evident in reclaimed coal mine soil properties. Haering et al. (2004) showed that differences in mine soil morphological properties between pre- and post-SMCRA mine soils were often inherited from contrasting degrees of weathering from parent rock materials. Mine soils prior to SMCRA often developed in previously weathered overburden that originated from shallower cuts (i.e., 6 to 12 m below surface) common during this time (Grube et al. 1982). Weathered and oxidized rocks resulted in finer (less rocky) and lower pH soils compared to post-SMCRA mine soils, which often developed in deeper, less weathered overburden (Haering et al. 2004; 2005). Thus, increasingly deeper mining cuts into unoxidized overburden post-SMCRA influenced bulk mine soil properties

and development. Further, the shift to AOC reclamation created relatively homogenous mine soil landforms compared to pre-SMCRA landforms with their highly variable bench-highwall post-mining landscape (Haering et al. 2005). In addition to changes observed in reclaimed mine soils pre-and post-SMCRA, aboveground differences were reflected in vegetation. In the 1950s and 60s, regulatory laws in midwestern states such as Illinois, Indiana, and western Kentucky required the "strike-off" reclamation method, which resulted in a relatively uncompacted mine soil growth medium (Sweigard et al. 2007a). When soil chemical limitations were addressed or avoided under these conditions of minimal grading, reclamation success was higher. More specifically, survival and growth of woody plants was readily achieved due to favorable mine soil physical properties (e.g., lower soil bulk density) (Ashby et al. 1991; Burger et al. 1998; Pope 1989; Rodrigue et al. 2002; Rodrigue and Burger 2004). These results are supported by later research experiments that showed increased tree performance on loosely graded mine spoils (Angel et al. 2006; Conrad et al. 2002; Torbert and Burger 1990), or on conventionally reclaimed mine soils later ameliorated with deep ripping and other soil tillage techniques (Dunker et al. 1995; Sweigard et al. 2007b).

Surface mine reclamation can be defined as returning landforms to conditions that mimic original topography and plant communities (Toy and Daniels 1998). SMCRA requires that surface mines be reclaimed to a condition that equals or exceeds pre-mining land use capabilities. However, achieving similar productivity for certain land uses was challenging and encouraged alternative land uses, which were much different than the pre-mining condition. For example, one post-SMCRA transition that became widely accepted was to stabilize sites by smoothly grading final reclamation surfaces with multiple passes using heavy, earth-moving equipment, resulting in flatter landscapes on sites that had been previously mined and did not have to be returned entirely to AOC (Burger and Zipper 2002). The focus on slope stability and erosion control under SMCRA created a new perception of reclamation that promoted excessive grading and compaction and quick establishment of vegetative cover (Zipper et al. 2011). Post-SMCRA revegetation schemes commonly included non-native highly competitive grasses, trees, and shrubs because they performed well on harsh sites (Zipper et al. 2011). This planting regime often resulted in vast acreage of highly competitive/invasive sericea lespedeza (*Lespedeza cuneata*), which was usually mixed with another aggressive species, tall fescue (*Festuca arundinacea* L.) (Wolf et al. 2018).

The combined effects of compaction and herbaceous competition discouraged reforestation on mined lands, whether by intentional tree plantings or via natural forest succession (Burger 2002). Trees show poor growth and survival in thick herbaceous ground cover, especially when the two are planted together (Ashby et al. 1988). Technical knowledge necessary to overcome issues of poor mine soil physical properties while maintaining ground cover for erosion control was limited. Coal operators were further discouraged from planting trees by a lack of economic incentives and productivity standards for commercial forest lands to meet SMCRA's "higher or better" mandate for post-mining land uses (SMCRA Section *515 b 2*) (Burger and Zipper 2002). Thus, historically common post-mining land uses were hayland/pasture, unmanaged forest, or wildlife habitat, which typically declined in productivity over time, particularly with respect to forest seedling growth (Burger 2002). To address the above issues, research focused on achieving successful mined land reforestation flourished and resulted in the formation of the Forestry Reclamation Approach (FRA) (Andrews et al. 1998; Angel et al. 2008; Burger and Zipper 2002; Emerson et al. 2009; Skousen et al. 2009; Torbert and Burger 1990).

Once potential risks of acid generation are addressed, the next important step in successfully achieving the intended post-mining land use is selecting the best quality growth media and site preparation for planting. Early coal mine reclamation research focused on improving revegetation success and analysis of mine soil growth media (Bengtson et al. 1973; Chapman 1944; Croxton 1928; Grube et al. 1973; Limstrom 1960; Maloney 2015; Tyner et al. 1948). Much of the research in the 1980s and 90s focused on matching tree growth to various overburden mixes and many of these earlier studies were conducted using *Pinus* spp. (Andrews et al. 1998; Angel et al. 2008; Showalter et al. 2007; Torbert et al. 1988). Appalachian overburden rock materials vary greatly in physical (e.g., percent soil fines and rock fragments), chemical (e.g., pH, soluble salts), and mineralogical properties (Zipper et al. 2013). Numerous studies have documented superior growth of trees when planted in brown sandstone or other geochemically weathered rock overburden (Showalter et al. 2010; Skousen et al. 2009; Torbert et al. 1990; Torbert et al. 1988). Trees at all growth stages prefer a rooting medium consisting of lower levels of rock fragments, moderately acidic pH (5.0 to 6.5), and low soluble salt content, which are characteristic of weathered rock overburden such as sandstone (Preve et al. 1984; Rodrigue and Burger 2004;

Torbert et al. 1988) as well as natural soils. In contrast, most grasses and forages are more competitive in unoxidized gray overburden materials because of their more alkaline pH (Skousen et al. 2009) and higher base cation levels. Pure siltstones and shale materials with finer soil sized particles tend to form surface crusts and are more likely to become compacted, though they would also generally exhibit higher cation exchange capacity (CEC) levels (Casselman et al. 2006; Daniels and Amos 1981). Weathered sandstones are more likely to contain lower plant available nutrients versus unweathered sandstones due to longer exposure to pre-mine weathering and leaching processes. Skousen et al. (2010) found no differences, however, in particle size fractions and nutrient (Ca, Mg, K, P) release between weathered brown and unweathered gray sandstones. Mixing of different rock types and weathering status of these materials helps combat the above potential limitations. Young mine soils derived from less weathered materials, especially parent rocks rich in feldspars and micas, usually contain appreciable amounts of P, K, Mg, and Ca comparable to native soils (Howard et al. 1988; Roberts et al. 1988abc; Sobek et al. 2000). However, supply of P may be limited to plants due to P-fixation by Fe-rich mineral phases (e.g., goethite) and in older or pre-weathered overburden materials that have undergone oxidation processes (Howard et al. 1988), further encouraging the mixing of rock types. Burger et al. (2007) showed that mixed sandstone and siltstone strata created a superior plant growth medium for northern red oak (*Quercus rubra* L.) trees and increased survival compared to pure mixes of each rock material.

Despite some soil nutritional benefits inherited from rock overburden, fertilizer additions of essential plant nutrients (N, P, K) are important for vegetation establishment since overburden is initially devoid of soil organic matter and typically low in several plant-available nutrients (Mays et al. 2000). Fertilization and other site preparation techniques (e.g., liming, hydroseeding) became routine practice and were easier to implement following SMCRA due to smoother topography, with more intense prescriptions required for coal refuse and abandoned mine areas (Mays et al. 2000; Stewart and Daniels 1992). For hayland/pasture land uses, it is recommended to plant a mix of grasses (e.g., *Festuca* spp.) and legumes (e.g., *Trifolium* spp.), including a nurse crop such as cereal rye (*Secale cereal*) or foxtail millet (*Setaria italica*) to stabilize the site and condition the mine soil for slower-growing perennial species (Skousen and Zipper 2010). A self-

sustaining plant community, whether forest or hayland/pasture, will persist if overburden materials are carefully selected, handled, placed, and amended in a way that fosters pedogenic development, organic matter accumulation, and recovery of nutrient cycling processes. Nitrogen (N) is particularly important in mine soils because it is derived from atmospheric inputs (e.g., N-fixation by *Rhizobia*) and not from rock sources, unless it is directly supplied via chemical and/or organic additions (Bradshaw 1983). Li and Daniels (1994) measured N-accumulation in a mine soil chronosequence that spanned 30-years. When accounting for indigenous N (i.e., combination of original rock spoil and native topsoil), they found that N-accumulation increased with time and as expected, was highest in the surface (0-5 cm) with an annual accumulation rate of 23.4 kg ha^{-1}. They also noted the importance of establishing and managing a robust community of legumes, which provide a mechanism for rebuilding N levels in mine soil via biological fixation (Li and Daniels 1994; Macdonald et al. 2015). Legumes become the main supplier of N to vegetation not receiving fertilizer additions after several growing seasons (Bendfeldt et al. 2001).

Soil fertility strongly influences early revegetation productivity, but studies suggest soil chemical properties become less important for sustaining that goal over time as mine soil systems stabilize with respect to nutrient availability and cycling (Roberts et al. 1988c). Physical properties, however, also control short- and long-term productivity of mine soils and may be a major impediment regardless of soil chemistry (Sobek et al. 2000). Bussler et al. (1984) found that coal mine soil chemical properties (e.g., pH, exchangeable nutrients, electrical conductivity) were similar to unmined reference soils in southwestern Indiana, whereas mine soil physical properties (i.e., bulk density, micro-and macro porosity, permeability) were inferior relative to unmined sites and inadequate for plant growth. Poor mine soil physical properties commonly include high rock fragment content/size, low percent soil fines, high bulk density, lack of macroaggregates and structure, and reduced permeability and water holding capacity (Skousen et al. 1998). To avoid soil physical limitations, selection of the best available growth medium for the intended post-mining land use is crucial. Handling and placement of overburden materials is also important. Minimal grading of mine soils using alternative techniques (e.g., rough or loose grading) is recommended to avoid compaction, especially for forestry post-mining land uses (Sweigard et al. 2007a). On a coal mine site in southern Illinois, graded overburden exhibited limiting bulk

densities in the range of 1.60 to 1.90 g cm^{-3} even when minimal grading was employed (Ashby et al. 1988). Minimizing equipment traffic is encouraged on reclaimed mine surfaces to improve soil and plant productivity (Darmody et al. 2002).

2.2. Heavy Mineral Sands Mining and Reclamation in the Mid-Atlantic USA

2.2.1. World Overview of Industry

Heavy mineral sands are characterized by their high particle density (≥ 4.0 g cm^{-3}) relative to host sands (mainly quartz at a density of ~2.65 g cm^{-3}) and their dominant dark coloration (Brooks 2000). Ilmenite ($FeTiO_3$), rutile (TiO_2), zircon ($ZrSiO_4$), and leucoxene ($Fe_2Ti_3O_9$) serve as excellent opaquing (as TiO_2) and refracting agents and are used in metallurgical applications due to the high strength of titanium bearing minerals. Heavy mineral sands weather from igneous, metamorphic, or sedimentary rock materials, are transported by wave action, separated from lighter minerals and concentrated as placer deposits in a wave-worked beach or alluvial environment, but may also be re-deposited locally by wind (Brooks 2000). Thus, placer deposits of heavy mineral sands are commonly found near beaches, in alluvial fans, buried under relict beaches, or in coastal dune formations (Lynd and Lefond 1983; Shepherd 1986). Industrial use of heavy mineral sands first occurred in the 19th century in New Jersey, USA, where smelting of ilmenite ores occurred, and in Niagara Falls, where the first titanium metal alloy factory began production (Morley 1981). Economic interest emerged in Australia in the 1920s due to their abundance of mineral sands deposits, and following World War II, increasing demand of minerals such as rutile become a priority of national importance and spurred industry development in several countries (Brooks 2000). Historically, Australia has been the leading world producer of heavy mineral sands, mainly rutile and zircon derived from rich, economically valuable deposits in the east (Brooks 1989).

Fluvio-marine sediment deposits rich in heavy mineral sands occur in several states across the Atlantic Coastal Plain, USA (Carpenter and Carpenter 1991), along the coast of southwestern Oregon (Peterson et al. 1987), and on the North Shore of the St-Lawrence River in Quebec, Canada (Cunningham et al. 2005). Mining facilities operated in Florida beginning in the 1940s, and other operations have occurred in Georgia, New Jersey, North Carolina, Virginia (Brooks 2000) and

Oregon (Peterson et al. 1987). The largest deposit in Virginia, named Old Hickory, is positioned on relict fluvio-marine terrace landforms of Pliocene and Miocene age. A similar but smaller deposit occurs in Greensville County, Virginia and is known as the Brink Deposit. These deposits in Virginia generally contain 2 to 8% heavy mineral sands in the soils and sediments, but thin locally concentrated zones contain around 60% mineral sands, which are economically valuable (Berquist and Bailey 1998).

2.2.2. Virginia Specific Requirements

While countries such as the USA and Australia utilize different regulatory frameworks for the mineral sands mining industry, government supervision is employed to some degree. For example, non-coal mining regulations in the USA vary from state-to-state and are often less stringent than the regulations coal mines must comply with under SMCRA (Section 2.1.1) and delegated state legislation. The state regulatory authority for mineral sands mining and reclamation in Virginia is the Virginia Division of Mineral Mining (VDMM), which is a part of the Virginia Energy Agency. Mine permits and reclamation closure plans are reviewed and approved by VDMM under regulations that apply to all non-coal mined lands (Daniels 2005). For the permits involved in this study (Iluka Resources), the post-mining land use is required to be returned to self-sustaining hayland/pasture vegetation for a bond period of at least two full growing seasons (Daniels 2005). Following successful bond release, landowners may convert the land to different uses if desired. After 2004, native topsoil was redefined for Iluka's operations as the A and E horizons in permits due to local conditional zoning language rather than "suitable geologic materials." This followed public scrutiny over the lack of its proper protection and return of topsoil during mining and reclamation procedures (Daniels 2005). In contrast, regulations in Australia allow more flexibility in terms of preparing mining and reclamation plans. Methods of operation are specifically formulated based on local environmental conditions and expected impacts, and often require return of native plant communities (Brooks 1989) along with approval by native indigenous people's communities. Companies then propose an environmental management system to the government for approval (Brooks 1989). Standards for success are high as this country has developed a robust mining sustainability framework for the industry.

Placer deposits of heavy mineral sands often concentrate on beach shores after high intensity storms and were beach mined or "scraped" in the early years of mining mineral sands. In Australia, this dates to 1870 when gold concentrates were also scraped from east coast beaches (Brooks 2000). As the country allocated more resources toward the growing industry, technology for mining and separation procedures were developed and provided a model for other operations. Heavy mineral sands mining is a relatively clean process because pyrites are rarely encountered, and the mining and processing operations generally do not produce chemical contaminants since no reagents are necessary for separation processes. More specifically, mineral sands are efficiently separated from host materials (e.g., quartz) simply by centrifugal processes (spirals) due to their high specific gravity. The only waste that is generated are soil sized materials (e.g., host sands, silt, clay) after mineral processing, which require time for settling, and any potential environmental issues would stem from high turbidity, improper discharge, etc. Mining and reclamation processes differ depending on regional site conditions, size of the mine site, and nature of the ore body (Luscombe 1986). The main constraint faced by most mineral sands mining operations, and extractive industries that utilize similar processes (e.g., phosphate mining, dredging), is managing the separated mineral waste materials (e.g., sand tailings and silt/clay slimes) following processing. Some native host soils that contain high amounts of humate or cemented organic and ironstone materials (e.g., Bhs horizons in Florida), or high percentages of clay and silt (e.g., Virginia) are more challenging to reclaim following mining.

During the mining process in Virginia, vegetation is cleared away and the upper 15 cm of natural A and E horizons (i.e., topsoil) are temporarily stockpiled. Native subsoils and deeper mineral enriched Coastal Plain sediments are then excavated and screened, and then pumped to a wet processing plant, or "wet mill", where they undergo wet spiral separation to isolate heavy mineral sands. Sands in Virginia are mined using a dry method which utilizes auxiliary equipment such as track-hoe excavators and bulldozers to excavate ore bodies following lowering of the local water table via temporary pumping. Wet mining methods, such as those used in east Australia and Florida where large gently sloped sand masses occur, use dredge ponds and associated submersible bucket-wheel excavators to recover mineral sands (Brooks 1989). After the wet separation process, mineral sands are sent to a "dry mill" for refining and separation into differing products. Rejected

materials from the dry mill are then hauled back to the mining site and are disposed of in dedicated fill under at least 1 m of cover.

At the wet mill, waste materials, or processed host soils and deeper sediments, which include fine (silt, clay, and very fine sand, or "slimes") and coarse (quartz sand, or "tailings") textured components, are pumped as a 25-35% solids slurry to large pits where they "dewater" to allow dry conditions to occur in preparation for re-grading (Zimmerman et al. 2008). Active pits, also called "mine cells", serve as disposal sites for processing waste (slimes and tailings) and are capped with coarse tailings or regraded dike walls (aka berms) once pits are sufficiently dried out, which usually occurs over several months or up to several years. Water from active pits is decanted using internal cross-dikes and flashboard risers located at various discharge points to separate and release clear water from sediments. Final installation of internal pit "rim ditches" just inside the dike walls helps with further dewatering.

The area designated for active pits is constructed based on the shape and size of the ore body, generally about 70 x 200 m and somewhat round to rectangular in shape (Meredith 2007). Constructed walls, also called "berms" or "dikes" as mentioned earlier, surround the pits to hold in saturated slimes and tailings and prevent losses to local surface waters. They are generally constructed with barren subsoil and saprolite materials of low quality and may be up to 4 m high above grade. Some are used as roadbeds. Topsoil is stockpiled away from the active pits in separate berms and replaced by haulers and bulldozers upon pit closure. One issue at Virginia mineral sands mined sites is the naturally high clay content in these weathered soils which creates challenges during pit dewatering because of the segregation of highly contrasting textural materials (Meredith et al. 2008) and the fact that the materials experience net "swell" versus original intact volumes. Several methods have previously been employed at these mines to help with segregation of slimes and tailings, which include using track hoes to physically mix high pockets of slimes with coarser materials after the pit dewaters, periodically relocating discharge points of pumps, and using long-chain polymers to flocculate clays during recombination efforts (Daniels et al. 2003a). Current protocols (since ~2010) now also include constructing smaller pit sizes, using rim ditches just inside of berm walls to accelerate dewatering rates, and "dipping and spreading" of slimes from local pockets back over sandier tailings. These dewatered former mine pits are then usually capped

with additional materials bulldozed or hauled from the surrounding berms to generate a final gently sloping convex post-mine topography. Topsoil return completes the soil placement process, followed by deep ripping and soil amendments.

2.2.2. Prime Farmland Reclamation

Prime farmlands, as defined by the USDA, are in regions receiving ample rainfall and sufficient growing seasons, and support highly productive food, fiber, and oil crops due to their superior soil chemical and physical properties (Grandt and Hossner 1988). It has been estimated that 1 to 1.5 million ha of prime farmlands overlie economically viable coal deposits in the USA, most of which occur in Illinois and other midwestern states (Dunker and Barnhisel 2000). SMCRA has more stringent requirements for reclamation of prime farmlands due to their optimum soil qualities (Section 2.1.1). Thus, coal mines occurring on prime farmlands must return the land to the same use following mining and reclamation to achieve or exceed pre-mining capabilities. There is some flexibility in these standards as SMCRA allows state regulatory authorities to develop standards of productivity for reaching pre-mining target yields, which must be met for a certain period (Dunker et al. 1992). For example, the state of Illinois developed a method of measuring productivity called the Agricultural Land Productivity Formula (ALPF), which estimates soil productivity indices based on county weather data and high levels of management for optimum yields (Spindler et al. 1992). Crops managed on reclaimed mined lands not previously designated as prime farmlands do not have to abide by these special SMCRA provisions. Likewise, prime farmlands occurring on non-coal mines are not legally required to be restored to pre-mining capabilities unless specifically required by state regulations and/or local permit conditions. Regarding the mineral sands mining region in southeastern Virginia, the majority (~2/3) of lands mined to date are designated as prime farmlands.

Mining clearly disrupts many natural soil properties, complicating the return of valuable prime farmland soils. Reclamation research on prime farmlands and croplands has been well documented in the USA, particularly on coal mined lands in Illinois, Iowa, and western Kentucky (Dunker and Barnhisel 2000). To achieve former production of croplands following surface mining, it is important to model reconstruction of mine soils after natural soils to better understand

how to achieve target yields derived from reference sites (Dunker et al. 1992). Thus, reconstructing mine soils in a way that mimics natural horizonation is important. SMCRA requires that soil must be replaced to the original approximate contour with the A horizon and subsoil materials segregated separately and then returned at least 1.2 m deep (Daniels et al. 1992). However, it is allowable and sometimes necessary to use subsoil or B horizon substitutes to return prime farmland soils when certain subsoil properties (e.g., texture, pH) are favorable. An example of this is mixing substratum materials with B horizons to improve physical and chemical properties (Jansen and Dancer 1981; Mcsweeney et al. 1981). Additionally, liming and P fertilization are often necessary to maintain performance of rowcrops that require pH levels above 5.5 (Dunker and Barnhisel 2000) and moderate levels of plant-available P. Powell et al. (1985) found that prime farmland soils in western Kentucky required only 76 cm return of subsoil materials to bury toxic strata when adequately limed and ripped for sites supporting high-water demanding crops such as corn (*Zea mays* L.). Dunker et al. (1987) showed that topsoil return over mine spoil materials (replaced via dragline) produced significantly higher corn yields six out of eight years compared to non-topsoil return treatments and were comparable to undisturbed croplands for five out of seven years. Soybean [*Glycine max* (L.) Merr.] yields that received topsoil over replaced mine spoil or over replaced B horizon subsoil were significantly higher for six out of seven years compared to non-topsoil return treatment yields.

While topsoil return and/or use of an organic amendment is an effective practice, studies have reported varied results with different replacement methods (e.g., direct haul versus stockpiling) (Powell et al. 1985; Van Gorp and Erskine 2011). Ultimately, the end goal is to protect the physical, chemical, and biological integrity of topsoil. Additionally, adequate soil fertility is essential for maintaining crop productivity. Plant-available nutrient levels may be affected by several different mine soil chemical, physical, and biological properties (e.g., SOM, compaction, soil pH) (Dunker and Barnhisel 2000). Of particular importance is plant-available P, which was studied by Semalulu et al. (1992) in a greenhouse experiment. They mixed topsoil with increasing percentages of subsoil using a silt loam soil from prime farmland in western Kentucky, applied varying P rates, and exposed mixtures to simulated wetting/drying cycles. Available P decreased as a function of increased subsoil contents, which contained lower P levels, and higher P adsorption

was noted with more acidic subsoils. An estimated 25% additional P fertilizer was required to maintain available P levels.

Furthermore, studies have shown that topsoil thickness is important in producing higher corn yields, which is notably one of the more difficult crops to manage on prime farmlands (Jansen and Dancer 1981). However, no matter the depth of topsoil, if the growth medium is compacted during soil replacement, root systems will be stressed and productivity will plummet, especially during drought years (Darmody et al. 2002). Subsurface tillage is important for ameliorating poor soil physical properties and should be implemented during optimal soil moisture, usually late summer to fall (Darmody et al. 2002). Deep ripping on a reclaimed prime farmland coal mine in southeastern Kansas was successful at reducing the effects of compaction on scraper replaced mine soils by improving surface drainage in extremely wet years and significantly increasing grain sorghum yields during a drought year compared to non-ripped plots (Caldwell et al. 1992). Soil reconstruction must also consider rubber-tired equipment methods that generate locally high traffic loads, which usually result in high strength mine soils (Dunker and Darmody 2005). Hooks et al. (1992) found higher corn yields on treatments with limited traffic after replacement by haul-trucks, while treatments replaced by scraper pans produced yields below the target. These studies show the importance of reconstructing prime farmland soils in a way that optimizes soil physical and chemical properties throughout the replaced surface and subsurface of mine soil horizons.

2.2.3. Reclamation of Mineral Sands Mined Lands

Early reclamation efforts of mineral sands mined lands occurred in Australia, which included surface erosion control on mined coastal dunes by planting grasses and trees, assembling brush fences, and leveling dunes (Brooks 2000). As with overall industry practices in mining, Australia led the way with developing reclamation technologies (Daniels et al. 1991). Reclamation efforts transformed over the decades from land stabilization goals to restoring post-mining land uses such as native heathlands in the Eneabba region, recreating wetland landforms, and improving productivity of reclaimed farmlands for grazing (Brooks 2000). The basic concepts of these early reclamation practices are similar to non-coal mine lands and have similarly been adopted by reclamation of mineral sands mines in the mid-Atlantic USA. Virginia and Florida have been the

leading producers of mineral sands in the USA. Based on the site and soil conditions, each of these two mining locations have had unique challenges arise during reclamation procedures. Issues occur in mineral separation and dewatering processes in Florida deposits because of the high organic slimes (i.e., spodic Bhs horizons) common in the region (Brooks 2000). In the Upper Coastal Plain of Virginia, segregation of highly contrasting textural materials as dewatering occurs makes it difficult to achieve mine soil that is homogeneous (Daniels et al. 2003a). While most slimes in Virginia are kaolinite clay, some less weathered deposits contain hydroxy-interlayered vermiculite and 2:1 smectite clays which complicate slimes flocculation (Daniels et al. 2003c). These clay minerals tend to repel each other due to their physiochemical states (high charge, interlayer water, etc.), which discourages flocculation and reduces natural mixing activities (VanWormhoudt 1993). The earliest research related to mineral sands mine reclamation in the USA involved a mine soil genesis chronosequence study on reclaimed mined land in Florida (Daniels et al. 1992). Their goal was to gain a better understanding of the long-term effects of mineral sands mining on chemical, physical, and morphological soil properties.

Virginia Coastal Plain soils in the mineral sands mining region (Upper Coastal Plain) have subsoil (Bt horizon) clay contents ranging from 17% to greater than 50%, creating high volumes of slimes in addition to sandy tailings which are pumped together with slimes back to final reclamation pits. During the active reclamation process, differential deposition rates of these two highly contrasting textural materials that are pumped out in a cyclic process causes high lateral and vertical segregation across dewatering pits (Schroeder et al. 2010). The highly trafficked dikes that separate pits, grading of former dike materials over dewatered pits, as well as varying levels of salvaged topsoil return from the dikes over pit areas further adds to this variability (Orndorff et al. 2005). The challenges of high spatial variability and grading related compaction in mine soils translates to variability in crop yields and overall limited plant productivity (Daniels et al. 2003a).

Researchers have focused efforts on improving reclamation practices to restore the pre-mining land use, much of which was highly productive prime agricultural farmland (Daniels et al. 1991). Schroeder et al. (2010) designed a pilot mining pit experiment to assess mine soil morphology and properties and determine crop yields. The authors studied the effects of topsoil return and incorporation of compost as treatments applied to simulated tailings and slimes mine

soils in two test field scale mining pits. High variability was apparent in mine soil properties (i.e., water holding capacity, texture, bulk density, chemical properties) that would likely limit crop yields in years of water stress. The authors concluded that in an actual mining and reclamation scenario, moderate levels of rowcrop productivity might be achieved with addition of organic materials but would likely not meet or exceed unmined prime farmland productivity. A follow-up study to this work showed reduced yields of wheat (*Triticum aestivum* L.), soybeans, corn, and cotton (*Gossypium hirsutum* L.) by 23%, 3%, 27%, and 20%, respectively, during the four-year cropping sequence and as compared to similar data on directly adjacent unmined prime farmlands (Daniels et al. 2003a). Over the years, improvements in pit dewatering methods were implemented as discussed earlier (i.e., re-mixing, internal cross-diking to minimize segregation; Daniels et al. 2007). Despite improvements in Virginia mineral sands mine soil reconstruction practices over time, short-distance variability among mine soil pedons and extreme vertical changes within pedons are still observed (Meredith et al. 2008; Orndorff et al. 2011; Daniels et al. 2018). However, some studies suggest that lateral spatial differences in mine soil properties may diminish as soils develop over time (e.g., rooting, shrink/swell, aggregate formation) (Schroeder et al. 2010; Wick et al. 2013).

Soil compaction is a densification process that increases the unit weight of soil and decreases air and water spaces (Schroeder 1975). When mine sites are reclaimed using scraper pans or combined haulers and bulldozers, deep soil tillage techniques (e.g., dozer ripping) are recommended to alleviate poor soil physical properties (Dunker et al. 1995; USDA Forest Service 1979). After topsoil return and final grading, severe surface and subsoil compaction that limits rooting and water percolation has been documented, particularly on finer textured mineral sands mine soils (Daniels et al. 2003b; Daniels et al. 2003c). The most significant advancements in Virginia mineral sands mined land reclamation have been the addition of deep ripping/tillage of compacted mine soils and increasing soil organic matter through application of surface amendments (e.g., biosolids, compost) (Daniels et al. 2012). Stolt et al. (2001) also noted improved plant growth with yard-waste compost versus topsoil alone, both of which were amended over highly flocculated (via polymer additions) well-mixed tailings and slimes in an experimental pit at the Brink mine (near Emporia, Virginia) in the mid-1990s.

The importance of properly salvaging and returning native topsoil to rebuild disturbed lands is widely recognized (Ghose 2001; Grant et al. 2007; Smith et al. 2000; Tacey and Glossop 1980; Van Gorp and Erskine 2011; Wright and Blaser 1981), and for mineral sands mined lands topsoil return is critical for rowcrop productivity and compliance with state law unless a "topsoil variance" is granted (Daniels and Orndorff 2013). Typical chemical and physical site preparation techniques after final grading of dewatered slimes and tailings include deep ripping (90 cm depth), liming (4 to 8 Mg ha^{-1}) and applying P fertilizer (350 kg ha^{-1} as P_2O_5) to the subsoil, and then returning natural topsoil (15 cm depth) (Meredith et al. 2008). Additional lime and N-P-K fertilization of the topsoil may be necessary depending on soil testing results and selected plant species requirements. Phosphorus application is particularly important on these highly weathered soils because the abundant iron oxide coatings on slimes particles increases P-fixation sites, reducing plant availability of this essential nutrient (Daniels et al. 1996). The earliest work conducted in Virginia was a greenhouse experiment in barrels to assess simulated mineral sands mine soils (Daniels et al. 1996; Daniels et al. 1991). The authors found sufficient plant growth in mixed slimes and tailings when limed and fertilized with heavy P (> 300 kg ha^{-1} as P_2O_5) and moderate N and K applications. Following site preparation as described above, mined lands are seeded to hayland/pasture for a period of at least two full years as required by the state regulator (VDMM) to demonstrate successful reclamation and for soil rebuilding purposes. After that time, it is decided by the landowner if lands are to be managed for rowcrops, which for the region include varying rotations of peanuts (*Arachis hypogaea* L.), cotton, soybeans, corn, and tobacco (*Nicotiana tabacum* L.). Landowners often transition back to rowcrops due to interest in returning lands to historically high levels of prime farmland crop production (Daniels 2005).

Studies have shown that use of mechanical site preparation and/or organic amendments on reclaimed mineral sands mined land improved rowcrop productivity with yields generally meeting or exceeding five-year average yields on unmined farmland in the surrounding counties (Meredith et al. 2008; Orndorff et al. 2011; Stolt et al. 2001). However, the county averages used to compare crop yields by Meredith et al. (2008) and others do not represent the highest possible productivity associated with prime farmlands in the mining area and are based on combined areas of irrigated and non-irrigated lands for a given crop x county. Furthermore, direct comparisons showed that

measured crop yields on reclaimed mined lands were ~15 to 30% less productive than measured crop yields on nearby unmined prime farmlands under similar soil/crop and irrigation management practices (Daniels et al. 2003a; Meredith et al. 2008). Daniels and Orndorff (2013) discuss long-term yield results on similar sites and indicate that ameliorating compaction and incorporating an organic amendment such as biosolids is crucial for reclaimed rowcrop productivity, although a 20% yield reduction is to be expected relative to the highest producing prime farmlands in the area (Daniels et al. 2018). Over time, it is possible that rowcrops could potentially reach ~90% of pre-mining productivity as surface soils and subsoils develop further with respect to aggregation and water holding (Daniels and Orndorff 2013), but this conclusion is speculative. Wick et al. (2013) measured soil organic matter pools over six years (2005 to 2011) at various depths and for tilled and non-tilled treatments (biosolids, topsoil, and lime/fertilizer) on reclaimed mineral sands mine soils in Virginia. After six years treatment effects were noted for microaggregate and mineral-bound soil fractions with higher C and N pools occurring in biosolids treatments versus control and topsoil treatments. The highest total aggregate C was observed in macroaggregates across all treatments. Treatments that were conventionally tilled contained higher C, likely due to incorporation of surface organic crop residues. There were no differences in crop yields among treatments after six years, but in earlier years (less than four years), biosolids treatments were superior. Results indicated that mine soils are recovering over time in terms of soil stable C and N, especially with biosolids applications.

2.2.4. Spatial Evaluation Using Classical and Geostatistical Techniques

Given the short-range variability of reconstructed mine soils, analysis of spatial attributes on mined lands is an important component of reclamation science (Dollhopf 2000), and especially relevant to mineral sands mined lands in southeastern Virginia given their high vertical and lateral variability in soil texture as discussed earlier. Variations in soil physical, chemical, and morphological properties occur at multiple spatial scales, interacting and forming relationships with one another and other natural attributes to create highly variable systems (Campbell 1979). The inherent variation of soils must be carefully considered when measuring, describing, and predicting soil characteristics or vegetation. Several sampling schemes and statistical applications

are designed to account for spatial variability as necessary for useful representation of data (Webster and Oliver 1990). Classical statistical theories aim to categorize data using standard unbiased sampling schemes, estimating separately three sources of variation (total, within-class, among-class) for a whole population, and evaluating the possible significance of different levels (or contrasts) among the observed classes (Webster and Oliver 1990). This approach is called analysis of variance (ANOVA) and was introduced in the 1920s by statistician R.A. Fisher. While this method of analysis is useful for classical field experiments, these normal theory statistics assume data points are independent of one another, generally follow a near-normal data distribution, and that groups being compared (contrasted) have similar variance estimators. Thus, these conventional statistical approaches commonly do not provide accurate modeling of spatial variation within some soil datasets because there is no association of estimated variances of observations to their spatial coordinates (Webster 1985).

In contrast, the field of geostatistics focuses on the spatial properties of variables, or their relative position on earth's surface, and is based on the *Theory of Regionalized Variables* introduced by Matheron (1963) and other statisticians. Unlike traditional techniques that rely on assumed frequency distributions for contrasting or analyzing data observations, geostatistics spatially links variances of measurements by considering the distances between them (Vieira et al. 1981). For example, "kriging" is a technique that produces averages from the data weighted in a way that is unbiased and minimizes the variance (Webster and Oliver 1990). Kriging interpolates values for unsampled locations and relies on autocorrelation or the spatial dependence of values at different locations, which is provided by a semivariogram. A semivariogram models the average rate of change for a regionalized variable (i.e., semivariance) against the separation or "lag" distance between variables. Semivariograms are based on X and Y coordinates at each sample location of the measurement and generally present three model components: 1) *Sill:* Represents the semivariance value on the y-axis when the model shows zero spatial dependence. Put another way, the semivariance increases to a point where it has no relation to lag distance and the graph plateaus; 2) *Range:* Samples are spatially dependent within the range or zone of influence on the x-axis, or the lag at which the model reaches its maximum (the sill variance); and 3) *Nugget:* Represents random error as indicated by some positive semivariance value at lag zero (Warrick et

al. 1986). As the separation distance between samples increases, the correlation of samples decreases until spatial dependence is zero (Warrick et al. 1986). Kriging is only valid when the semivariogram model indicates autocorrelation is present (Vieira et al. 1981). Autocorrelation is calculated by the *autocorrelation coefficient* which ranges from 1 and -1 at certain lag distances. When variables are purely correlated (i.e., values are identical), the coefficient is equal to one. This value decreases as dissimilarity of values increases which usually occurs at longer lags.

In a field setting, soil variability may be purely random among locations or related positively or negatively to neighboring attributes (Campbell 1979). As variability of soil properties increases, the number of samples required to adequately characterize soil variation and form meaningful observational data sets also increases (Dollhopf 2000). Co-kriging, often used in soil surveys, uses additional spatially correlated variables to improve kriging estimates, mapping, and sampling schemes. McBratney and Webster (1983) found that by adding variables of subsoil silt and subsoil sand, they improved estimation of topsoil silt compared to using only topsoil silt in their kriged estimates. The authors optimized sampling strategies based on interpretation of kriged maps for choosing an appropriate precision level at minimum sampling costs. Vieira et al. (1981) assessed spatial variation of infiltration rates over a relatively uniform agricultural field. Semivariograms showed spatial dependence at distances less than 50 m and kriged estimates improved the precision of contour maps of predicted infiltration rates by reducing interpolation errors for the polynomial function. Davidson and Csillag (2003) assessed spatial variation of grasslands using two statistical approaches. They found that the geostatistics employed were not ideal for landscape scale analyses as their semivariograms lacked spatial structure. These authors noted the importance of minimizing lag distances and understanding landscape features when assessing variability.

Another geospatial approach, trend surface analysis, gained much attention in the field of geology and soil science in the 1980s and 1990s as a method for modeling spatial coordinates of data using regression techniques (Webster 1985). Zacharias et al. (1997) assessed soil properties including texture, moisture content, and pH to explore spatial variability trends across a 48 x 32 m agricultural field in the Virginia Coastal Plain. Using trend surface analysis, they found that variations occurred at small spatial scales and did not fit appropriate semivariograms due to a

strong nugget effect (other sources of variation). They recommended detailed assessment of sites prior to conducting spatial analyses. The coefficient of variation (CV) (i.e., quotient of standard deviation and mean expressed as a percentage) can also be used as an estimate of variability but does not consider sampling distances (Campbell 1978; Dollhopf 2000). Cambardella et al. (1994) characterized different levels of spatial dependence for 28 soil properties (e.g., bulk density, organic C, total N) based on the ratio of nugget to total semivariance: <25% as strong; 25-75% as moderate; and >75% as weak. Varying extrinsic (e.g., tillage, fertilization) and intrinsic (e.g., texture) factors likely affected levels of spatial dependence. Thus, a number of authors have concluded that semivariograms may be useful for sites with similar conditions within the same spatial scale but may not be appropriate in other circumstances (Cambardella et al. 1994).

Historically, imagery data were analyzed using visual methods until computer technology evolved to more advanced systems of image processing of remotely sensed data (Cox and Witter 1978). Imagery derived from satellite or airborne sensors captures and records energy from the electromagnetic radiation (EMR) spectrum that is reflected or emitted from earth surfaces (Cox and Witter 1978). Soil, vegetation, water, and other land features display different patterns or signatures due to their varying range of physical and chemical properties. The most widely used segments of the EMR spectrum are visible and near infrared (NIR) (Cox and Witter 1978). Reflectance from plants is high in the infrared region and variations in plants due to their environment (i.e., water stress, stunted growth, poor nutrition) are related to changes in their normal reflectance patterns and surfaces. Remotely sensed data may also be analyzed using a geostatistical approach. Curran and Atkinson (1998) provide an example of applying a semivariogram to a transect of pixels from a remotely sensed image at various lag distances. Several applications of vegetation indices (VI's) have been developed over the last few decades, largely in agronomic systems (Hatfield et al. 2008; Maresma et al. 2016). Vegetation indices combine spectral wavebands and other components of the EMR spectrum to leaf and plant signals (Hatfield et al. 2008). The Normalized Difference Vegetative Index (NDVI) is the most commonly used because of its strong correlation to crop yields (Hatfield et al. 2008; Ma et al. 2001). Several studies have also correlated measured crop yield and soil properties using a combination of spatial and conventional statistical analyses (Kravchenko and Bullock 2000; Miller et al. 1988).

Remote sensing techniques such as calculation of VI's may be used to assess soil-landscape variability and can help optimize sampling for soil and/or vegetation ground data (Davidson and Csillag 2003; Rogovska and Blackmer 2009). Rogovska and Blackmer (2009) successfully correlated the green NDVI of soybean canopies to soil pH, which is often highly variable for the region (USA Corn Belt) at the field scale. Their results showed the significance of using remotely sensed data to help guide soil sampling decisions. One limitation of using remotely sensed data to calculate VI's is the inability to determine the definite cause(s) for observed variations in plant biomass estimations (Hatfield et al. 2008). One strategy for increasing the efficiency of estimation procedures is to utilize additional variables in concert with image data to produce co-kriged estimates, which may also help optimize field sampling strategies. For example, remotely sensed data such as NDVI may serve as a useful secondary interpolation attribute as it overlays and is often correlated with intrinsic soil characteristics (Curran and Atkinson 1998). In one such study, Tola et al. (2017) found that soil texture was strongly correlated with NDVI for Rhodes grass (*Chloris gayana* L.). Another limitation of using remotely sensed imagery is the spatial scale of the field or landscape of interest versus the resolution of the sensor itself; thus, there must be a balance between these two scales to accurately detect spatial patterns (Davidson and Csillag 2003). Additionally, obtaining source imagery at the appropriate time and frequency for a given plant species may be challenging, especially with satellite imagery (Davidson and Csillag 2003).

2.3. Genesis and Classification of Mine Soils

2.3.1. Soil Forming Factors

Human impacts on the environment increased in extent and scale several thousand years ago during the Holocene epoch as a result of advancing human civilization settlement, forest clearing, cultivation, and water management systems (Certini and Scalenghe 2011). Landscapes have been and continue to be manipulated by humans for reasons including agriculture, urbanization, and extraction of raw materials such as fossil fuels (Ruddiman 2003). Soils often preserve records of the past, including anthropogenic influences. On relatively stable landscapes, human influenced soils can persist over millennia, giving rise to anthropogenic soil properties which commonly include high accumulation of organic matter and nutrients (particularly P),

compacted soil layers, mixed materials, evidence of plowing, and artifacts (Certini and Scalenghe 2011). The degree and rate at which soil formation, or genesis, occurs is a function of five factors: parent material, topography, biota, climate, and time (Jenny 1980). Parent materials (e.g., consolidated and unconsolidated rock, organic materials) transform into soils over time as they undergo pedogenic changes by exposure and reaction to climactic, biotic, and topographic factors. Following natural or human-caused drastic disturbances, modified parent materials are reset to time zero and exposed to a new set of environmental conditions that ultimately shape the genesis of resulting soil profiles (Ciolkosz et al. 1989). Drastic anthropogenic disturbances may influence the classical model of soil formation in the following ways (Bidwell and Hole 1965): 1) *Parent Material:* New parent materials created or existing materials altered by an earth-moving disturbance; 2) *Topography*: Altering the original topography (e.g., land-leveling, fills); 3) *Biota*: Destroying and/or altering native biotic communities (e.g., native forest topsoil losses), and planting new vegetation; 4) *Climate*: Changing temperature and moisture regimes above and within the soil environment (e.g., perched saturated layers due to mechanical compaction); and, 5) *Time*: Surface mining resetting or halting soil development of new or altered parent materials (e.g., overburden placement vs. burial of undesirable/excess spoil materials).

2.3.2. Mine Soil Genesis Studies

Pedogenesis, or soil development, increases with soil age, but is initially the most prominent in surface horizons of mine soils (Gorman and Sencindiver 1999; Pedersen et al. 1978). Most mine soil genesis studies published to date occur on surface coal mined lands and span a short period of time and/or involve a chronosequence of different coal mine sites (Ciolkosz et al. 1985; Clayton et al. 2009; Daniels and Amos 1981; Gonzalez-Sangregorio et al. 1991; Haering et al. 2004; Schafer et al. 1980; Sena et al. 2021; Sencindiver 1977; Sweeney 1979; Wood and Pettry 1989). Fewer study areas have documented mine soil genesis over the longer-term (> 10 years) (Nash et al. 2016; Shukla et al. 2004). Mine soils that have undergone repeated sampling at one site are ideal candidates for assessing long-term trends in pedogenesis because all soil forming factors (i.e., vegetation, climate, topography, parent material) except for time are assumed to be relatively constant since reclamation. Parent rock materials play a dominant role in early pathways

of coal mine soil genesis in Appalachia. Over time, as geologic materials are influenced by climate and vegetation (i.e., percolating rainwaters and organic acid production), physical and chemical weathering rates increase precipitously (Carroll 1970). The mineralogical and physiochemical properties of overburden along with the degree of previous weathering have profound effects on mine soil development (Haering et al. 1993; Howard 1979; Sena et al. 2014). Physical disintegration, leaching, carbonate dissolution, trace pyrite oxidation, and organic matter accumulation/decomposition often occur rapidly after overburden placement (Daniels and Amos 1985; Pedersen et al. 1978).

The effects of heavy reclamation equipment on soil health and quality greatly influences pedogenic processes, making it difficult to predict mine soil properties over the long-term (Haering et al. 1993). Mine soils are particularly susceptible to mechanical compaction. Haering et al. (2004) observed root-limiting, massive soil structures within 70 cm of the surface C horizon for half of the observed pedons in their study (n=30) in SW Virginia. Interestingly, these features were not observed by Daniels et al. (1983) in 14 initial pit descriptions made within several years after placement. Limitations associated with high levels of coarse rock fragments typical of coal mine soils (e.g., low water holding capacities) may be overcome with sufficient rooting depth (Daniels and Amos 1981). However, compacted layers formed by equipment, whether in shallow or deep mine soils, typically lead to perched water tables and poor internal drainage characteristics, which have been commonly observed for mine soil profiles due to the nature of routine reclamation procedures (Atkinson et al. 1998; Haering et al. 2004).

In addition to human-made (e.g., machinery) overloads, soils may become severely compacted from the applied weight of natural forces (e.g., glaciers). In contrast, fragipans (Bx horizons) in the southeastern United States have formed in the absence of glacial compaction. This natural process is partially based upon the theory of self-weight collapsed sediments. For example, it is theorized that subsoil compaction in loess deposits (i.e., silt loam textures) in Mississippi originated from sediments collapsing under their own weight following repeated wetting and drying events (Bryant 1989). Likewise, reconstructed mine soils may naturally self-compact over time due to gradual densification processes of settling and downward fine earth migration rather than via applied force from machinery. Rock spoil type itself has a major effect on settling rates

with finer textured spoil materials producing greater volume losses and potentially leading to densified layers in the subsoil (Haigh 1992b; Haigh and Sansom 1999; Miller et al. 2012).

Furthermore, adverse chemical properties can also limit mine soil revegetation efforts. Davidson et al. (1988) found that acid barren spots (aka low pH "hot spots") severely limited growth of vegetation on 6 and 12-year-old mined sites (primarily pre-SMCRA), whereas on a 36-year-old site, soil pH had significantly increased, and the site recolonized with acid tolerant plants. The authors indicated that highly acidic mine soils re-equilibrated to approach pre-mining soil pH levels over decades due to Al buffering processes. Physical limitations are currently the biggest impediment to mine soil development since SMCRA has significantly improved soil chemical properties per rigorous overburden testing and selection procedures to exclude acid materials. While mine soils are capable of stabilizing from undesirable conditions, the question remains as to how routine reclamation practices and resulting mine soil properties affect the rate of soil genesis over time and overall site productivity potentials relative to reference sites.

Organic matter plays an important role in soil structure development, as well as in many other pedogenic soil processes and associated ecosystem functions (Birkeland 1974). Mining inevitably leads to degradation of pre-existing native soil organic carbon (SOC), although mined lands can serve as a large C sink once they are reclaimed and supporting rapid pedogenic processes, particularly A horizon formation (Maharaj et al. 2007; Wick et al. 2009). Loose, well aggregated mine spoil enhances plant rooting and development of soil structure. Avera et al. (2015) found that along a chronosequence (5-, 11-, 21-, and 30-year-old stands) of coal mined lands, aboveground tree C accounted for the largest C pool and was like forests on unmined lands for the older mined stands. Further, ecosystem soil organic carbon (SOC) increased over time (e.g., 0.7 Mg/ha/year for the middle-aged stand). They also found that mineral soil N was highly corrected with ecosystem carbon, particularly soil organic and tree C, in reforested mine soils. This is not surprising since carbon allocation in forests in largely controlled by N availability. Over time the inorganic N fraction was consistent, but total and active microbial biomass were higher in older sites and much higher overall in unmined sites. However, the oldest reclaimed site (21-years-old) was not different in total microbial biomass from the unmined site. Despite an initial lack of SOC and total N, following mine land reforestation the ecosystem begins bio-cycling and colonization

of a microbial community.

Determination of SOC on reclaimed coal mined lands is complicated by geogenic carbon (e.g., coal and fossil-C fragments, various carbonate species) (Jacinthe et al. 2009; Ussiri and Lal 2008). Previous studies have used a wide range of approaches to separate various C fractions in coal mine soils (Akala and Lal 2001; Amichev et al. 2008; Avera et al. 2015; Chatterjee et al. 2009; Chaudhuri et al. 2013; Chaudhuri et al. 2012; Lorenz and Lal 2007; Maharaj et al. 2007; Nash et al. 2016; Rumpel et al. 2003; Shukla and Lal 2005; Ussiri et al. 2006). Without direct and precise fractionation of geogenic versus recently accumulated SOC, over-estimates may be reported (Ussiri et al. 2014). Since SOC distributions and soil forming processes have subsequent effects on soil physical and chemical properties, accurately assessing detailed morphology of mine soil profiles over time helps infer rates of system recovery and stabilization and can improve predictions of future properties and land uses.

Morphological properties of mine soils in the central Appalachian region typically include, but are not limited to, the following features: 1) High percentage of coarse and disordered rock fragments (≥70% in some cases); 2) large open bridging voids between rock fragments; 3) subsurface ^AC or weak ^Bw (cambic) horizons or a complete lack of subsurface pedogenic horizons; 4) dense and massive horizons due to natural or anthropogenic processes; 5) carbolith rock fragments; and, 6) a dominance of unweathered rock fragments (Ammons and Sencindiver 1990; Ciolkosz et al. 1985; Daniels and Amos 1981; Haering et al. 1993; Roberts et al. 1988a; Thomas et al. 2000; Thurman and Sencindiver 1986). These distinct features coupled with various overburden placement and soil reconstruction regimes may create variable and distinct soil chemical and physical properties throughout the soil profile and landscape, which may complicate field mapping of mine soil units and associated development of usable soil interpretations (Schafer 1979). Mine soil pH may not serve a useful purpose in mine soil classification and mapping if pH ranges are highly variable and often are not limiting to plant growth (Daniels and Amos 1981). Haering et al. (2004) observed contrasting low chroma colors within the clearly weathering and oxidized matrix of mine soil profiles, and that contrasting spoil parent materials appeared to strongly influence major soil properties (e.g., color, texture, and/or rock content) among pedons.

Appalachian coal mine soil genesis and classification was first studied in detail by Sencindiver (1977) throughout a range of coal producing states including West Virginia, western Kentucky, southern Indiana, southern Illinois, and central and western Missouri. This research showed that all mine soil profiles – primarily 5 to 10 years old – exhibited rapid surface horizon development (2.5 to 10 cm depth), with increased thickness where topsoil was added. Subsequent regional studies observed increased thickness in surface A horizons and improved aggregate stability as a function of mine soil age (Haering et al. 1993; Thomas and Jansen 1985; Thomas et al. 2000). In fact, Thomas et al. (2000) found that mine soils had thicker A horizons than unmined lands, which was attributed to the extensive rooting of planted herbaceous vegetation versus native soil being dominated by thin O and A horizons and likely impacted by previous logging activities. Of the 24 mine soil profiles they observed, only one (23-years-old) had a ^Bw horizon and was classified within the Inceptisol soil order.

In a midwestern study (Illinois), a chronosequence of mine soils ages 5 to 64 years old were all classified as Entisols (Thomas and Jansen 1985), but it was unclear whether these authors rigorously attempted to fit their profiles against Mollisol criteria or not. Ciolkosz et al. (1985) observed that 5 out of 24 mine soil profiles in Pennsylvania met the full *Soil Taxonomy* criteria for a Bw horizon in mine soils ranging from 3 to 29 years old. Six ^Bw horizons were also observed in Haering et al. (2004) in a range of profiles in southwestern Virginia, and cambic features (i.e., structural development, browner/redder coloration, slight increases in clay content) were more pronounced in 20-year-old mine soils; however, the majority of profiles delineated showed A-C or A-AC-C horizons. This study showed that development of structure was more strongly influenced by finer soil particle sizes (fine silt and clay) and rooting depth rather than age since reclamation. Haering et al. (2004) also observed decreases in the size of bridging voids (mostly < 15 cm diameter) in the lower C horizon of older mine soils, which appeared to result from mechanical reworking and in-filling of finer particles migrating downward over time.

For mineral sands mined lands, the pathways of pedogenic development in mine soils are somewhat different than for coal mine soils, particularly due to differences in parent materials, degree of pre-weathering of the materials, and the reclamation methods employed. Mineral sands deposits are found in the upper 15 to 30 meters of Virginia Coastal Plain capping overlying

Piedmont residuum (metamorphic and igneous rock saprolites). Thus, unlike hard rock overburden in coal mining scenarios, mineral sands mine soils are forming from unconsolidated and frequently highly weathered sediments. Hodges et al. (1997) mapped pre-mining soil series at a 1:12,000 scale to better understand and predict how mining would influence reclaimed mine soils. They described and correlated twenty-five soil series and found that surface soils consisted primarily of Coastal Plain sediments with limited surface outcrops of Piedmont residuum. Some soils had also formed in local colluvium with a mix of these two parent materials. The native pre-mining soils generally showed loamy sand to sandy loam Ap horizons with thick and very well-developed acidic and argillic Bt horizons.

VanWormhoudt (1993) assessed the mineralogy of twenty-eight soil pedons on the pre-mining landscape from differing locations, geomorphologic positions, and drainage classes. She found two very different soil parent material effects from Piedmont versus Coastal Plain sources with different ages of exposure and thus weathering extent. The limited number of dominantly Piedmont profiles exhibited finer soil textures (clay and silt size fractions), lower mica, gibbsite minerals and clay-sized quartz, and very high kaolinite contents. Coastal Plain derived soils had much coarser soil textures in subsurface horizons and approached similar mineralogy to Piedmont soils when they occurred above a presumed relicts transgressive/regressive scarp which separated a much older (higher) landform from a somewhat younger landscape to the east. The primary mica was higher in Coastal Plain soils, particularly surface horizons, which was hypothesized to be a result of eolian redeposition of fluvial deposits. Poorly drained Coastal Plain soils showed characteristics of reduced weathering activity and were much higher in intergrade mica:vermiculite and smectite clays. In a very different mining environment, mineral sands mine soil morphology was assessed by Daniels et al. (1992) in Florida. They found that older mine soils (> 13 years) exhibited stronger development and had similar subsoil morphological (e.g., incipient Bhs horizons) and chemical properties to local native soils (Orthods and Aquods). Compaction due to natural and/or man-made sources (i.e., wet settling, heavy equipment) was observed in subsoil horizons.

There have been limited studies focused on mineral sands mine soil properties and subsequent classification (Orndorff et al. 2005). In Virginia, weak subsoil horizon development

(^Bw cambic) and buried ^Ab horizons were observed in some mine soil profiles, but the dominant horizonation was described as ^Ap-^C, and commonly included the following morphological properties: 1) Highly contrasting particle-size differences between adjacent horizons; 2) strong color changes; 3) thin bands of slimes/tailings; 4) thin bands of heavy minerals; 5) overturned or "convoluted" bands of slimes, tailings, and/or heavy minerals due to grading; and, 6) inclusions of clayey Piedmont saprolites or Coastal Plain substratum within a matrix of coarser textured materials (Meredith et al. 2008; Orndorff et al. 2005). Higher CEC, pH, and OM in surface horizons reflected liming, fertilization, and topsoil return practices (Orndorff et al. 2005). This study also observed densic conditions (i.e., root-limiting layers) formed by heavy machinery in loamy and clayey horizons. The authors discussed how densic layers and abrupt textural changes were both quite common in these mine soil profiles and likely result in reduced root penetration and internal drainage. Ultimately, such mechanically induced compaction will lead to a slower rate of mine soil structural development and associated macroporosity over time.

As noted earlier, most soil morphological descriptions and classification of reclaimed prime farmlands has occurred on coal mined sites in the mid-eastern USA (Sencindiver and Ammons 2000). Soil morphological, physical, and chemical properties typical of prime farmlands on coal mined lands were also assessed by Bell (1994). The author described 72 soil profiles of one to two-year-old reclaimed sites in western Pennsylvania. They found that mining destroyed natural structure and mine soil were severely compacted, limiting downward root growth. Soils that are trafficked by heavy equipment, especially rubber-tired equipment, are subject to increases in bulk density, reduced micro- and macro-pore spaces, and loss of natural structure (Indorante et al. 1981). The rate of mine soil genesis is directly hindered by severe compaction in the upper mine soil profile (Daniels and Amos 1981). Soil morphological properties may be altered by mining and reclamation procedures in many ways such as mixing of materials to create variable color and texture patterns (Thomas and Jansen 1985) and artificial development of soil structure by certain types of overburden transport and handling equipment (McSweeney and Jansen 1984). The latter study was one of the first on mine soil morphology and they discovered that "fritted" soil structure (i.e., round aggregates formed in mine soils transported on belts and then loosely graded using a bucket wheel-conveyor-spreader system) improved soil physical properties as well

as corn and soybean yields comparative to crop yields on undisturbed soils. Thus, in some scenarios, the presence of weak to moderate subsurface structural development in mine soils may be due to effects of mining and reclamation equipment rather than due to pedogenic processes.

2.3.3. Systems of Soil Classification

The modern concepts of soil formation were developed by V.V. Dokuchaev and other Russian scientists who framed soil as independent natural bodies representing a collection of soil characteristics within genetic horizons, or layers created by soil forming factors (Glinka and Marbut 1927). Early work by Dokuchaev has been modified by other soil scientists over the decades (Jenny 1941). Throughout the early 1900s, taxonomic classification schemes in the USA placed emphasis on the complete soil system with much focus on parent materials and whole soil morphology; however, these classification principles have shifted toward the categorization of measurable soil properties related to pedogenesis, rather than based solely on soil forming processes (Bockheim et al. 2005; Soil Survey Staff 1975; Soil Survey Staff 2014). The value and necessity of soil classification has been summarized as providing nomenclature and descriptions of soil characteristics for the purposes of relating soils to the environment, each other, and soil forming processes so to predict their behavior and provide public information regarding soil management and land use capabilities (Kellogg 1960; Marbut 1922). The soil classification system that is used in the USA and some other countries, *Soil Taxonomy*, was initially proposed in 1960 and offered a more detailed, quantitative assessment (e.g., OM, horizon type and thickness, base saturation, moisture and temperature regimes, etc.) of entire soil profiles compared to the old system, which was developed primarily by C.F. Marbut and depended largely on qualitative interpretation of the influence of soil forming factors (Birkeland 1974). *Soil Taxonomy* includes a multi-categorical hierarchy serving many diverse purposes but was created primarily for the use of mapping and interpreting soils using soil surveys (Soil Survey Staff 1975; Soil Survey Staff 2014). This classification system is based on six hierarchical levels. These are in level of generality from broad to most specific: Order, suborder, great group, subgroup, family, and series. The broader level categories reveal information about a soil's origin and subsequent genesis, while lower-level categories are organized based on environment and local site conditions, which largely

influence soil properties and subsequent land use suitability and planning (Soil Survey Staff 2014).

Soil mapping criteria for coal mined lands have greatly improved since the 1970s when there were no efforts made to define and distinguish mine soil mapping units (Ammons and Sencindiver 1990). Up to that point in time, virtually all eastern USA mine soils were simply classified as Typic Udorthents or "mined lands." Sencindiver (1977) originally proposed the Spolent suborder to aid in the classification and subsequent interpretation of coal mine and other disturbed soils. The author's rationale behind Spolents was because existing suborders within the Entisols soil order (e.g., Orthents) do not adequately represent common morphological characteristics of coal mine soils, which has been a challenge faced in other studies (Sweeney 1979). The focus of the Spolents proposal was that rock type was dominant since coal mine soil development is drastically affected by chemical and physical properties of rock materials in which they are derived from. Subsequent levels such as great group, subgroup, etc. would then more easily follow existent *Soil Taxonomy* criteria or classes could be added as appropriate (e.g., family map phases such as slope and stoniness) (Daniels and Amos 1981).

The Spolents suborder concept was successfully applied to mine soils in WV on a research trial basis (Ammons and Sencindiver 1990). Thurman and Sencindiver (1986) found that this proposed classification system was useful in grouping mine soils at the family level and identified several important properties limiting to land use and future planning (e.g., site topography and low hydraulic conductivities, high levels of rock fragments, low pH, and doughtiness of mine soils). In a subsequent study in southern WV, Sweeney (1979) found that while distinct pedogenic horizons were evident in 5 and 10-year-old mine soils, it was difficult to place mine soils within otherwise suitable categories due to strict control section depth requirements in *Soil Taxonomy*. Sweeney (1979) disputed the control section used in Sencindiver (1977) — between 25 and 100 cm for mine soils without topsoil — because many shallow mine soils less than 25 cm were observed, but still indicated pedogenic changes over time. Sweeny suggested a different approach to the Spolent suborder, where *Soil Taxonomy* would adjust depth and thickness requirements to include mine soil conditions within multiple soil orders. As discussed earlier, most eastern USA coal mine soils were classified as Typic Udorthents until 2014, but several researchers observed

mine soils classifiable within the Inceptisol soil order (Ciolkosz et al. 1985; Daniels and Amos 1981; Grube et al. 1972; Haering et al. 2005; Pedersen et al. 1978; Sweeney 1979).

Anthropogenic soils such as urban, landfill, mine, and dredged soils have been widely studied in the USA since 1965 (Capra et al. 2015). Taxonomic classification of anthropogenic soils has provided some challenges due to their inherent differences relative to natural soils. Early attempts of classifying mine soils occurred primarily on coal mined lands, which accounted for the largest acreage of mining disturbance in the USA, by state and federal agencies such as the Soil Conservation Service (currently NRCS) and Soil Survey Staff (Sencindiver 1977). These efforts were for mapping and interpretation purposes, like natural soils, and focused on features such as pH, rock content, parent material, and slope. Despite the apparent need for classifying mined lands, these early mapping efforts did not translate into separate taxa designations within *Soil Taxonomy*. Mine soils often exhibit distinct features such as high bulk densities (i.e., densic layers), high levels of coarse fragments and associated "bridging voids", and low water holding capacities and infiltration rates relative to unmined soils (Haering et al. 2005; Pedersen et al. 1980; Thurman and Sencindiver 1986). Most mine soils in the USA have previously been classified at the highest hierarchical level as within the Entisol and Inceptisol orders (Sencindiver and Ammons 2000), with a few instances of mine soils meeting the criteria for Mollisols (Schafer 1979). Several researchers have proposed taxonomic classification of mine soils at the family level (Ammons and Sencindiver 1990; Haering et al. 2005; Thurman and Sencindiver 1986) and series level (Barnhisel and Gray 2000; Haering et al. 2005; Indorante and Jansen 1984). These systems were only suggestions, however, as properties unique to mine soils (e.g., layered or mixed materials) were at the time difficult to place in pre-existing groups within *Soil Taxonomy*. Numerous soil series have been and continue to be developed and approved for coal mine soils (Ciolkosz et al. 1985; Sencindiver and Ammons 2000; Zipper and Skousen 2021a). However, series level classification and mapping may pose challenges for highly variable mined lands or young mine soils that are undergoing rapid transformations within a few years' time (Sencindiver 1977).

The World Reference Base for Soil Resources (WRB), an international soil classification system, includes two Soil Reference Groups, Anthrosols and Technosols, which encompass various anthropogenic horizons and diagnostic properties such as anthric properties, which show

influences of long-term surface amendments (Food and Agriculture Organization of the United Nations 2014). Other countries (Russia, China, and Australia) have addressed the importance of recognizing human influenced soils at higher levels (e.g., order) of their differing systems (Certini and Scalenghe 2011). The broad variety of human-altered and human-transported (HAHT) soils motivates the need for proper taxonomic classification in the USA (Galbraith and Ditzler 2006). The first public release version of *Soil Taxonomy* (7th approximation) discussed the importance of recognizing new or modified soil horizons and properties created by human disturbances (Soil Survey Staff 1975), although it did not provide any separate taxa designations for anthropogenic soils. Since the late 1970s, there was a push toward modifying *Soil Taxonomy* (Soil Survey Staff 2014) to improve the criteria for describing and classifying HAHT soils, which included reclaimed mine soils (Galbraith 2004; Schafer et al. 1980; Sencindiver 1977; Sencindiver and Ammons 2000; Thurman and Sencindiver 1986).

The rationale for including HAHT diagnostic properties in *Soil Taxonomy* is that these designated taxa additions would help guide and increase the capacity for mapping, land use planning, and development of appropriate interpretations and management practices. Based on several recommendations, the newest edition of Keys to Soil Taxonomy (12th edition; Soil Survey Staff 2014) has incorporated seven new subgroups (Table 1) and one new family category class to help better distinguish the unique properties of HAHT soils (Galbraith 2012; Soil Survey Staff 2014). The 12th edition Keys to Soil Taxonomy also improved the definition for the anthropic epipedon and described several characteristics that are diagnostic for HAHT soils and artificial landforms (e.g., constructional anthropogenic landforms and microfeatures). Updating the taxonomic classification of mine soils becomes critical as information on their soil physical, chemical, and morphological properties potentially change over time. Two new subgroups (i.e., Anthrodensic and Anthroportic) in the 12th edition Keys to Soil Taxonomy are particularly applicable to the mine soils examined in this research program (i.e., coal and mineral sands mine soils) since they deal exclusively with human-transported materials or such materials that have been severely compromised by mechanical compaction (Table 2.1).

Table 2.1. Most recent subgroup modifiers (extragrades) for HAHT soils in the 12th edition Keys to Soil Taxonomy (2014).

Subgroup	Description
1. Anthraquic	Soils with anthric saturation such as flooded rice paddies.
2. Anthrodensic	Soils with a densic contact via mechanical compaction in > 90% of the lateral pedon within 100 cm of the mineral soil surface.
3. Anthropic	Soils with anthropic epipedons (i.e., contain artifacts or midden material).
4. Plaggic	Soils with plaggen epipedons (i.e., formed by continued manuring).
5. Haploplaggic	Soils that meet a plaggen epipedon requirements except for thickness.
6. Anthroportic	Soils formed in 50 cm + human-transported material (e.g., dredged soils, mine spoil, urban soils).
7. Anthraltic	Soils formed in 50 cm + human-altered material. Mostly used for excavated and replaced areas (e.g., trenches) or for deeply tilled soils.

Since the Keys to Soil Taxonomy was updated in 2014, the ICOMANTH (International Committee for Anthropogenic Soils) has recognized the need to include higher taxa for distinguishing HAHT soils and landforms by proposing a new soil order, Artesols. The goal of this new order is to improve the classification, interpretation, and management of HAHT soils as they grow in extent and as scientists gather new data and knowledge on their behavior over time. Many of the mine soils unique to coal and mineral sands surface mined lands within the Artesols soil order would classify at the great group level as Portortharts followed by a wide selection of subgroup extragrades, which are based on soil limitations or other features. An important advantage of the taxonomic criteria within Artesols is that they recognize the pedogenic pathways of some anthropogenic soils with the use of the "Inceptic" subgroup. While the 12th edition Keys to Soil Taxonomy recognizes HAHT soils through the addition of new subgroups (e.g.,

Anthroportic), these new taxa have not yet been added for the Inceptisol soil order, thus overlooking the anthropogenic source and nature of parent material in such developing soils (e.g., coal mine soils). The two modes of classification —the 12th edition Keys to Soil Taxonomy and new proposed Artesols order – will be discussed later in Chapter 7 in the context of their relevancy and helpfulness in interpreting the use and management of reclaimed mine soils.

2.4. Overall Summary

This literature review discusses surface mining and reclamation on coal and mineral sands mined lands in southwestern and southeastern Virginia, respectively, as related to my research sites. Coal mined lands are regulated by state legislation under federal oversight by the 1977 Surface Mining Control and Reclamation Act (SMCRA). Following SMCRA, post-mining environments greatly improved via rigorous overburden analyses and performance standards related to environmental protection, etc. Appalachian mine soils are primarily formed in hard rock overburden (e.g., siltstones, sandstones) used as topsoil substitutes (a.k.a. controlled overburden placement). Most reclamation research on coal mined lands post-SMCRA investigated the effects of overburden rock types, particularly on tree survival and growth which has been severely limited by the excessive grading and revegetation schemes (i.e., aggressive non-native grasses/legumes) common on post-SMCRA mine sites (Zipper et al. 2011).

In contrast to coal mined lands, mineral sands mining and reclamation is not regulated by SMCRA, but rather by delegated state legislation. Most lands within the Virginia mineral sands mining region are designated as prime farmlands and may be converted back to rowcrops following two years in hayland/pasture as required by the Virginia Division of Mineral Mining. Reclaimed crop yields have shown ~15-30% reductions compared to nearby unmined prime farmlands (Daniels et al. 2003a). While long-term productivity of intensive reclaimed agricultural lands is unclear, deep tillage and topsoil return (or use of organic amendments) is crucial for plant growth.

In regard to pedogenic pathways, coal mine soil morphology is largely influenced by parent rock materials, while mineral sands mine soils form in highly weathered unconsolidated sediments and their morphological properties are shaped largely by routine reclamation procedures. To

classify these mine soils in the USA, *Soil Taxonomy* (Soil Survey Staff 2014) is used. Until 2014, there were no separate taxa designations within the Keys to Soil Taxonomy for HAHT soils, which greatly complicated classification and mapping efforts (Sencindiver and Ammons 2000). Table 2.1 above lists and describes the new subgroups for anthropogenic soils in the current edition of the Keys. The new proposed soil order, Artesols, deals exclusively with anthropogenic soils and their classification.

2.5. References

Agouridis, C.T., P.N. Angel, T.J. Taylor, C.D. Barton, R.C. Warner, X. Yu et al. 2012. Water quality characteristics of discharge from reforested loose-dumped mine spoil in eastern Kentucky. J Environ Qual 41: 454-468. doi:10.2134/jeq2011.0158.

Akala, V.A. and R. Lal. 2001. Soil Organic Carbon Pools And Sequestration Rates In Reclaimed Minesoils In Ohio. Journal of Environmental Quality 30: 2098-2104. doi:10.2134/jeq2001.2098.

Amichev, B.Y., J.A. Burger and J.A. Rodrigue. 2008. Carbon sequestration by forests and soils on mined land in the midwestern and Appalachian coalfields of the U.S. Forest Ecology and Management 256: 1949-1959. doi:10.1016/j.foreco.2008.07.020.

Ammons, J. and J. Sencindiver. 1990. Minesoil mapping at the family level using a proposed classification system. Journal of Soil and Water Conservation 45: 567-571.

Andrews, J.A., J.E. Johnson, J.L. Torbert, J.A. Burger and D.L. Kelting. 1998. Minesoil and site properties associated with early height growth of eastern white pine. Journal of Environment Quality 27: 192. doi:10.2134/jeq1998.00472425002700010027x.

Angel, P.N. 1973. A soil analysis of the strip mine spoil bank at Fairfield, Texas. M.S. Thesis, Stephen F. Austin State University, Nacogdoches, Texas.

Angel, P.N., D.H. Graves, C. Barton, R.C. Warner, P.W. Conrad, R.J. Sweigard et al. 2006. Surface mine reforestation research: evaluation of tree response to low compaction reclamation techniques. p. 45-48. In: Proc. National Meeting of the American Society of Mining and Reclamation. doi:10.21000/JASMR06020045.

Angel, P., C. Barton, R. Warner, C. Agouridis, T. Taylor and S. Hall. 2008. Forest establishment and water quality characteristics as influenced by spoil type on a loose-graded surface mine in eastern Kentucky. p. 28-65. In: Proceedings America Society of Mining and Reclamation. doi:10.21000/JASMR08010028

Ashby, W.C., M.R. Norland and D.A. Kost. 1988. Establishment of trees in herbaceous cover on graded lenzburg minesoil. p. 48-53. In: Mine Drainage and Surface Mine Reclamation Conference Proceedings, Pittsburg, PA.

Ashby, W.C., W. Oaks and J. Bowden. 1991. Surface mine tree planting in the Midwest pre-and post-public law 95-87. p. 617-623. In: Proc. National Meeting of the American Society for Surface Mining and Reclamation, Durango, CO. doi:10.21000/JASMR91020617.

Atkinson, R.B., W. Daniels and J. Cairns Jr. 1998. Hydric soil development in depressional wetlands: A case study from surface mined landscapes. p 170-182. In: Ecology of wetlands and associated habitats. Pennsylvania Academy of Science, Philadelphia.

Avera, B.N., B.D. Strahm, J.A. Burger and C.E. Zipper. 2015. Development of ecosystem structure and function on reforested surface-mined lands in the Central Appalachian Coal Basin of the United States. New Forests 46: 683-702. doi:10.1007/s11056-015-9502-8.

Barnhisel, R.I. and R.B. Gray. 2000. Changes in morphological properties of a prime land soil reclaimed in 1979. p. 511-519. In: Proceedings of the Annual Meeting of the American Society for Surface Mining and Reclamation, Tampa, Fl. Amer. Soc. Surf. Mining Rec. doi:10.21000/JASMR00010511.

Bell, J.C. 1994. Morphological characteristics of reconstructed prime farmland soils in western Pennsylvania. Journal of environmental quality 23. doi:10.2134/jeq1994.00472425002300030016x.

Bendfeldt, E.S., J.A. Burger and W.L. Daniels. 2001. Quality of amended mine soils after sixteen years. Soil Science Society of America Journal 65: 1736-1744. doi:10.2136/sssaj2001.1736.

Bengtson, G., D. Mays and J. Allen. 1973. Revegetation of coal spoil in northeastern Alabama: effects of timing of seeding and fertilization on establishment of pine-grass mixtures. p.

208-214. In: Research and Applied Technology Symposium on Mined Land Reclamation, Pittsburg, PA.

Berquist, C. and C. Bailey. 1998. Late cenozoic reverse faulting in the fall zone, southeastern Virginia. p.1-126. In: Geological Society of America, 1998 Annual Meeting, Abstracts with Programs.

Bidwell, O. and F. Hole. 1965. Man as a factor of soil formation. Soil Science 99: 65-72.

Birkeland, P.W. 1974. Pedology, weathering, and geomorphological research. Oxford University Press, Inc.

Bockheim, J.G., A.N. Gennadiyev, R.D. Hammer and J.P. Tandarich. 2005. Historical development of key concepts in pedology. Geoderma 124: 23-36. doi:10.1016/j.geoderma.2004.03.004.

Bradshaw, A.D. 1983. The reconstruction of ecosystems. Journal of Applied Ecology 20: 1-17. doi:10.2307/2403372.

Brooks, D.R. 1989. Reclamation in Australia's heavy mineral sands industry. p 11-26. In: D.G. Walker et al. (eds). Proceedings of the America Society of Mining and Reclamation. doi:10.21000/JASMR89010010.

Brooks, D.R. 2000. Reclamation of lands disturbed by mining of heavy minerals. p 725-754. In: R.I Barnhisel, R.G. Darmody, W.L. Daniels (eds). Reclamation of Drastically Disturbed Lands. Agron. Monogr. 41. ASA and SSSA, Madison, WI.

Bryant, R. 1989. Physical processes of fragipan formation. In: N.E. Smeck, E.J. Ciolkosz (eds). Fragipans: their occurrence, classification, and genesis. 24: 141-150. doi:10.2136/sssaspecpub24.c8.

Burger, J.A., D.L. Kelting and C.E. Zipper. 1998. Maximizing the value of forests on reclaimed mined land. Virginia Cooperative Extension Publ. No. 460-138. Virginia Polytechnic Institute and State University.

Burger, J. 2002. Achieving forestry goals on mined land: mine site conditions, species composition, and stand development of economically viable hard-woods forests. p. 1-12. In: Market-based approaches to mined land reclamation and reforestation: a technical interactive forum: US Office of Surface Mining, Mid-Continent Region.

Burger, J.A. and C.E. Zipper. 2002. How to restore forests on surface-mined land. Virginia Cooperative Extension Publication 460-123. p. 1-20.

Burger, J.A., D. Mitchem, W.L. Daniels and R. Barnhisel. 2007. Red oak seedling response to different topsoil substitutes after five years. p. 132-142. In: 24th Annual National Conference of The American Society of Mining and Reclamation. Lexington, KY. doi:10.21000/JASMR07010132.

Bussler, B.H., W.R. Byrnes, P.E. Pope and W.R. Chaney. 1984. Properties of minesoil reclaimed for forest land-use. Soil Science Society of America Journal 48: 178-184. doi:10.2136/sssaj1984.03615995004800010033x.

Caldwell, W., D. Whitney, R. Lamond, J. Hickman, G. Kilgore and R. Dunker. 1992. Reconstructed soil depth for rowcrop production on reclaimed prime farmland in southeast Kansas. p. 43-49. In: R.E. Dunker et al. (ed) Proc. of the Natl. Symp. on Prime Farmland Reclamation. Dept. of Agron., Univ. of IL, Urbana, IL.

Cambardella, C.A., T.B. Moorman, J.M. Novak, T.B. Parkin, D.L. Karlen, R.F. Turco et al. 1994. Field-scale variability of soil properties in central Iowa soils. Soil Science Society of America Journal 58: 1501-1511. doi:10.2136/sssaj1994.03615995005800050033x.

Campbell, J.B. 1978. Spatial variation of sand content and pH within single contiguous delineations of two soil mapping units. Soil Science Society of America Journal 42: 460-464. doi:10.2136/sssaj1978.03615995004200030017x.

Campbell, J.B. 1979. Spatial variability of soils. Annals of the Association of American Geographers 69: 544-556. doi:10.1111/j.1467-8306.1979.tb01281.x.

Capra, G.F., A. Ganga, E. Grilli, S. Vacca and A. Buondonno. 2015. A review on anthropogenic soils from a worldwide perspective. Journal of Soils and Sediments 15: 1602-1618. doi:10.1007/s11368-015-1110-x.

Carpenter, R.H. and S.F. Carpenter. 1991. Heavy mineral-deposits in the upper coastal-plain of North-Carolina and Virginia. Econ Geol Bull Soc 86: 1657-1671. doi:10.2113/gsecongeo.86.8.1657.

Carroll, D. 1970. Rock weathering. Plenum Press, New York.

Casselman, C.N., T.R. Fox, J.A. Burger, A.T. Jones and J.M. Galbraith. 2006. Effects of silvicultural treatments on survival and growth of trees planted on reclaimed mine lands in the Appalachians. Forest Ecology and Management 223: 403-414. doi:10.1016/j.foreco.2005.12.020.

Certini, G. and R. Scalenghe. 2011. Anthropogenic soils are the golden spikes for the Anthropocene. The Holocene 21: 1269-1274. doi:10.1177/0959683611408454.

Chapman, A.G. 1944. Forest planting on strip-mined coal lands with special reference to Ohio. USDA-FS Central States For. Exp. Stn. Tech. Pap. 104. p. 1-25.

Chatterjee, A., R. Lal, R.K. Shrestha and D.A.N. Ussiri. 2009. Soil carbon pools of reclaimed minesoils under grass and forest landuses. Land Degradation & Development 20: 300-307. doi:10.1002/ldr.916.

Chaudhuri, S., E.M. Pena-Yewtukhiw, L.M. McDonald, J. Skousen and M. Sperow. 2012. Early C sequestration rate changes for reclaimed minesoils. Soil Science 177: 443-450. doi:doi10.1097/SS.0b013e318254494d.

Chaudhuri, S., L.M. McDonald, E.M. Pena-Yewtukhiw, J. Skousen and M. Roy. 2013. Chemically stabilized soil organic carbon fractions in a reclaimed minesoil chronosequence: Implications for soil carbon sequestration. Environmental Earth Sciences 70: 1689-1698. doi:10.1007/s12665-013-2256-8.

Ciolkosz, E.J., R.C. Cronce, R.L. Cunningham and G.W. Petersen. 1985. Characteristics, genesis, and classification of Pennsylvania minesoils. Soil Science 139: 232-238. doi:10.1097/00010694-198503000-00007.

Ciolkosz, E.J., W.J. Waltman, T.W. Simpson and R.R. Dobos. 1989. Distribution and genesis of soils of the northeastern United States. Geomorphology 2: 285-302. doi:10.1016/0169-555X(89)90016-0.

Clark, E.V., W.L. Daniels, C.E. Zipper and K. Eriksson. 2018. Mineralogical influences on water quality from weathering of surface coal mine spoils. Applied Geochemistry 91: 97-106. doi:10.1016/j.apgeochem.2018.02.001.

Clayton, H., A. Wick and W. Daniels. 2009. Microbial biomass in reclaimed soils following coal mining in Virginia. p. 227-236. In: Proceedings America Society of Mining and Reclamation.

Conrad, P., R. Sweigard, D. Graves, J. Ringe and M. Pelkki. 2002. Impacts of spoil conditions on reforestation of surface mined land. Mining Engineering 54: 39-47.

Cormier, S.M., G.W. Suter, 2nd and L. Zheng. 2013. Derivation of a benchmark for freshwater ionic strength. Environ Toxicol Chem 32: 263-271. doi:10.1002/etc.2064.

Cox, T. and S. Witter. 1978. Applications of remote sensing technology to disturbed lands In: Reclamation of Drastically Disturbed Lands p. 705-727.

Croxton, W.C. 1928. Revegetation of Illinois coal stripped lands. Ecology 9: 155-175. doi:10.2307/1929352.

Cunningham, C.G., M.L. Zientek, W.J. Bawiec and G.J. Orris. 2005. Geology and nonfuel mineral deposits of Latin America and Canada. Report 1294B, U.S. Geological Survey.

Curran, P.J. and P.M. Atkinson. 1998. Geostatistics and remote sensing. Progress in Physical Geography 22: 61-78. doi:10.1191/030913398667999161.

Daniels, W.L. and D.F. Amos. 1981. Mapping, characterization and genesis of mine soils on a reclamation research area in Wise county, Virginia. p. 261-265. In: Proc. Symp. Surf. Mining Hydrol., Sedimentol., and Reclamat., Lexington, KY. 7-11 December. Office Eng. Serv., College Eng., Univ. Kentucky, Lexington, KY.

Daniels, W.L., J.C. Bell, D.F. Amos and G.D. McCart. 1983. First year effects of rock type and surface treatments on mine soil properties and plant growth. p. 275-282. In: Proc Symposium on Surface Mining, Hydrology, Sedimentology and Reclamation, November, College of Engineering, University of Kentucky, Lexington KY.

Daniels, W.L. and D.F. Amos. 1985. Generating productive topsoil substitutes from hard rock overburden in the southern Appalachians. Environmental geochemistry and health 7: 8-15. doi:10.1007/bf01875045.

Daniels, W.L. and C.E. Zipper. 1988. Improving coal surface mine reclamation in the central Appalachian region. Rehabilitating Damaged Ecosystems 1: 139-162.

Daniels, W.L., L.W. Zelazny, M.M. Alley and K.C. Haering. 1991. The development of restoration strategies for prime agricultural soils following mineral sands mining in the coastal plain of the eastern USA. p. 26-37. In: Proc. 1991 Aust. Mining. Ind. Council Environ. Workshop. AMIC, Dickson, ACT, Australia.

Daniels, W.L., M.H. Genthner and R.L. Hodges. 1992. Soil development in sandy tailings derived from mineral sands mining in Florida. p. 37-47. In: Proceedings of the 9th National Meeting of the American Society for Surface Mining and Reclamation, Duluth, 14–18 June. ASSMR, Lexington, KY. doi:10.21000/JASMR92010037.

Daniels, W., M. Alley, L. Zelazny, Y. Lei, V. Groover and P. Schroeder. 1996. Strategies for rehabilitating prime farmlands following mineral sands mining in Virginia, USA. p. 412-427. In: Proceedings of 3rd International and the 21st Annual Minerals Council of Australia. Environ. Workshop. Vol. 2. 14-18 Oct.

Daniels, W., P. Schroeder, S. Nagle, L. Zelazny and M. Alley. 2003a. Reclamation of prime farmland following mineral sands mining in Virginia. Mining Engineering 55: 42-48. doi:10.21000/JASMR99010146.

Daniels, W., P. Schroeder, S. Nagle, L. Zelazny and M. Alley. 2003b. Reclamation Of Prime Farmland Following Mineral Sands Mining In Virginia. Mining engineering 55: 42-48.

Daniels, W.L., Z.W. Orndorff and P.D. Schroeder. 2003c. Chemical and physical properties of mineral sands mine soils in southeastern Virginia. p. 209-227. In: Proc., 2003 National Meeting of the Am. Soc. of Mining and Reclamation, Lexington, KY. doi:10.21000/JASMR03010209.

Daniels, W.L. 2005. Can we return heavy mineral sands mines in Virginia to productive agricultural uses? p. 7. In: Proceedings of the Heavy Minerals 2005 Conference, Ponte Vedra, Fl.

Daniels, W.L., Z. Orndorff, M. Alley, L. Zelazny and C. Teutsch. 2007. Sustainability indicators for mineral sands mining in Virginia, USA. p. 1-8. In: Proc. 3rd International Conference on Sustainable Development Indicators in the Minerals Industry, June 2007, Milos island, Greece.

Daniels, W., C. Stilson and C. Zimmerman. 2012. Development of effective rehabilitation protocols for mineral sands mining in Virginia, USA. 97-103. In: Life-Of-Mine Conference, Brisbane, Qld, 10 - 12 July.

Daniels, W.L. and Z.W. Orndorff. 2013. Indicators of reclamation success for mineral sands mining in the USA. p. 226-231. In: 6th International Conference on Sustainable Development in the Minerals Industry. Milos Island, Greece.

Daniels, W.L., Z.W. Orndorff, M.J. Eick and C.E. Zipper. 2013. Predicting TDS release from Appalachian mine spoils. p. 275-285. In: Craynon JR (ed.), Proc., Environmental Considerations in Energy Production, April 14–18, 2013, Charleston, WV Soc Mining Met & Explor, Englewood, CO.

Daniels, W.L., C.E. Zipper, Z.W. Orndorff, J. Skousen, C.D. Barton, L.M. McDonald et al. 2016. Predicting total dissolved solids release from central Appalachian coal mine spoils. Environ Pollut 216: 371-379. doi:10.1016/j.envpol.2016.05.044.

Daniels, W.L., Z. Orndorff, C. Stilson, C. Zimmerman, and A. Haywood. 2018. Development of effective rehabilitation protocols for mineral sands mining in Virginia, USA. p. 127 – 133 In: From start to finish: A life-of-mine perspective. Spectrum Series 24. The Australasian Institute of Mining and Metallurgy, Carlton, Victoria, Australia.

Darmody, R., R. Dunker and R. Barnhisel. 2002. Reclamation of prime agricultural lands after coal surface mining: the midwestern experience. Urbana 51: 61801. doi:10.21000/JASMR02010900.

Davidson, A. and F. Csillag. 2003. A comparison of nested analysis of variance (ANOVA) and variograms for characterizing grassland spatial structure under a limited sampling budget. Canadian Journal of Remote Sensing 29: 43-56. doi:10.5589/m02-078.

Davidson, W.H., W.C. Ashby and W.G. Vogel. 1988. Progressive changes in mine soil ph over three decades. p. 89-92. In: Mine Drainage And Surface Mine Reclamation Conference Proceedings. April 19-21, Pittsburg, PA.

Dollhopf, D.J. 2000. Sampling strategies for drastically disturbed lands. Barnhisel, R.I., Darmody, R.G., Daniels, W.L. (eds). p. 21-40. In: Reclamation of Drastically Disturbed Lands. ASA, CSSA, SSSA, Madison, WI. doi:10.2134/agronmonogr41.c2.

Dunker, R., I. Jansen and D. Graves. 1987. Corn and soybean response to topsoil and rooting medium replacement after surface mining. p. 83-89. In: Proceedings, National Symposium on Mining, Hydrology, Sedimentology and Reclamation. Springfield, Illinois. doi:10.2134/agronj1988.00021962008000030005x.

Dunker, R.E., R.I. Barnhisel and R.G. Darmody. 1992. Prime farmland reclamation. p. 284. In: Proc. 1992 National Symposium on Prime Farmland Reclamation. St. Louis. University of Illinois at Urbana-Champaign.

Dunker, R.E., C.L. Hooks, S.L. Vance and R.G. Darmody. 1995. Deep Tillage Effects on Compacted Surface-Mined Land. Soil Science Society of America Journal 59: 192-199. doi:10.2136/sssaj1995.03615995005900010029x.

Dunker, R. and R. Barnhisel. 2000. Cropland reclamation. p. 323-369. In: Reclamation of Drastically Disturbed Lands. American Society of Agronomy.

Dunker, R. and R. Darmody. 2005. Rowcrop response to topsoil replacement on high traffic vs low traffic soil reconstruction systems. p. 302-327. In: Proceedings of the National Meeting of the American Society of Mining and Reclamation, Breckenridge CO, June, 19-23. doi:10.21000/JASMR05010302.

Emerson, P., J. Skousen and P. Ziemkiewicz. 2009. Survival and growth of hardwoods in brown versus gray sandstone on a surface mine in West Virginia. J Environ Qual 38: 1821-1829. doi:10.2134/jeq2008.0479.

Feagley, S. and L. Hossner. 2000. Reclamation of lignite mined lands. p. 415-432. In: Reclamation of Drastically Disturbed Lands. ASA, CSSA, SSSA, Madison, WI.

Ferm, J. and G. Weisenfluh. 1989. Evolution of some depositional models in Late Carboniferous rocks of the Appalachian coal fields. International Journal of Coal Geology 12: 259-292. doi:10.1016/0166-5162(89)90054-2.

Food and Agriculture Organization of the United Nations. 2014. World reference base for soil resources. 2nd Ed. World Soil Resources Reports 106. FAO Rome, Italy. p 193.

Galbraith, J. 2004. Proposed changes to soil taxonomy that may affect mine soil classification. p. 706-719. In: National Meeting of the American Society of Mining and Reclamation and

The 25th West Virginia Surface Mine Drainage Task Force, April 18-24, 2004. ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

Galbraith, J.M. and C. Ditzler. 2006. New terms for describing human-altered and-transported soils. In: 18th World Congress of Soil Science, 9–15 July, Philadelphia.

Galbraith, J. 2012. Proposed revisions to the future 12th edition of keys to soil taxonomy based on: icomanth (international committee for anthropogenic soils). Circular Letter 7. Int. Committee for Anthropogenic Soils.

Ghose, M. 2001. Management of topsoil for geo-environmental reclamation of coal mining areas. Environmental Geology 40: 1405-1410. doi:10.1007/s002540100.

Glinka, K.D. and C.F. Marbut. 1927. Great soil groups of the world and their development. Edward Brothers, Inc. Ann Arbor, Michigan. p 150.

Gonzalez-Sangregorio, M.V., M.C. Trasar-Cepeda, M.C. Leiros, F. Gil-Sotres and F. Guitian-Ojea. 1991. Early stages of lignite mine soil genesis: changes in biochemical properties. Soil Biology and Biochemistry 23: 589-595. doi:10.1016/0038-0717(91)90117-3.

Gorman, J. and J. Sencindiver. 1999. Changes in mine soil physical properties over a nine-year period. p. 245-253. In: Proc. of the Annual Meeting of the American Society for Surface Mining and Reclamation.

Grandt, A.F. and L. Hossner. 1988. Productivity of reclaimed lands-cropland. p. 1321-135. In: L.R. Hossner (ed.) Reclamation of Surface Mined Lands. CRC Press, Boca Raton, FL.

Grant, C.D., S.C. Ward and S.C. Morley. 2007. Return of ecosystem function to restored bauxite mines in Western Australia. Restoration Ecology 15: S94-S103. doi:10.1111/j.1526-100X.2007.00297.x.

Grim, E.C. and R.D. Hill. 1974. Environmental protection in surface mining of coal. National Environmental Research Center, Office of Research and Development.

Grube, E.W., S.M. Richard, J.M. Everett and S.N. Rabindar. 1972. Significance of weathering in a Pennsylvanian sandstone to pollution from strip mines. Nature 236: 70. doi:10.1038/236070a0.

Grube, W.E., R.M. Smith, R.N. Singh and A.A. Sobek. 1973. Characterization of coal overburden materials and minesoils in advance of surface mining. p. 134-151. In:

Proceedings of Research and Applied Technology Symposium on Mined Land Reclamation, NCA/BCR, Pittsburg, PA.

Grube, W., R. Smith and J. Ammons. 1982. Mineralogical alterations that affect pedogenesis in minesoils from bituminous coal overburdens. p. 209-225. In: J.A. Kittrick et al. (ed.) Acid Sulfate Weathering. SSSA Spec. Publ. 10. SSSA, Madison, WI.

Haering, K.C., W.L. Daniels and J.A. Roberts. 1993. Changes in mine soil properties resulting from overburden weathering. Journal of Environment Quality 22: 194-200. doi:10.2134/jeq1993.00472425002200010026x.

Haering, K.C., W.L. Daniels and J.M. Galbraith. 2004. Appalachian mine soil morphology and properties. Soil Science Society of America Journal 68: 1315-1325. doi:10.2136/sssaj2004.1315.

Haering, K.C., W.L. Daniels and J.M. Galbraith. 2005. Mapping and classification of southwest Virginia mine soils. Soil Science Society of America Journal 69: 463-472. doi:10.2136/sssaj2005.0463.

Haigh, M.J. 1992b. Problems in the reclamation of coal-mine disturbed lands in Wales. International Journal of Surface Mining, Reclamation and Environment 6: 31-37. doi:10.1080/09208119208944313.

Haigh, M.J. and B. Sansom. 1999. Soil compaction, runoff and erosion on reclaimed coal-lands (UK). International Journal of Surface Mining, Reclamation and Environment 13: 135-146.

Hall, S.L., C.D. Barton and C.C. Baskin. 2010. Topsoil seed bank of an oak–hickory forest in eastern Kentucky as a restoration tool on surface mines. Restoration Ecology 18: 834-842. doi:10.1111/j.1526-100X.2008.00509.x.

Hatfield, J.L., A.A. Gitelson, J.S. Schepers and C.L. Walthall. 2008. Application of spectral remote sensing for agronomic decisions. Agronomy Journal 100: S-117. doi:10.2134/agronj2006.0370c.

Herlihy, A.T., P.R. Kaufmann, M.E. Mitch and D.D. Brown. 1990. Regional estimates of acid-mine drainage impact on streams in the mid-atlantic and southeastern United-States. Water Air Soil Poll 50: 91-107. doi:10.1007/BF00284786.

Hodges, R., W. Daniels, P. Thomas and M. Genthner. 1997. Soil survey of Old Hickory Project area. Crop and Soil Env. Sci. Dept., Virginia Tech, Blacksburg, VA.

Hons, F.M. 1978. Chemical and physical properties of lignite spoils and their influence upon successful reclamation. Doctoral Dissertation, Texas A&M University College Station, Texas.

Hooks, C., R. Dunker, S. Vance and R. Darmody. 1992. Rowcrop response to truck and scraper hauled root media systems in soil reconstruction. p. 19-23. In: Proc. of the 1992 Natl. Symp. on Prime Farmland Reclamation. Dept. of Agron., Univ. of IL, Urbana, IL. doi:10.21000/JASMR05010302.

Howard, J.L. 1979. Physical, chemical and mineralogical properties of mine spoil derived from the wise formation, Buchanan county, Virginia. M.S. thesis. Virginia Polytechnic Inst. and State Univ. Blacksburg, VA.

Howard, J., D. Amos and W. Daniels. 1988. Phosphorus and potassium relationships in southwestern Virginia coal-mine spoils. Journal of Environmental Quality 17: 695-700. doi:10.2134/jeq1988.00472425001700040029x.

Indorante, S.J., I.J. Jansen and C.W. Boast. 1981. Surface mining and reclamation: initial changes in soil character. Journal of Soil and Water Conservation 36: 347-351.

Indorante, S.J. and I.J. Jansen. 1984. Perceiving and defining soils on disturbed land. Soil Science Society of America Journal 48: 1334-1337. doi:10.2136/sssaj1984.03615995004800060027x.

Jacinthe, P., C. Barton, S. Maharaj and R. Lal. 2009. An evaluation of methodologies for assessing geogenic carbon in mine soils of the eastern United States. 347-363. In: Soil Carbon Sequestration and the Greenhouse Effect, 2nd edition. SSSA Special Publication 57.

Jansen, I. and W. Dancer. 1981. Rowcrop yield response to soil horizon replacement after mining. p. 357-362. In: Proc. of the Symposium on Surface Mining Hydrology, Sedimentation and Reclamation. Louisville, KY. .

Jenny, H. 1941. Factors of soil formation: a system of quantitative pedology. New York. Macgraw Hill.

Jenny, H. 1980. The soil resource: origin and behavior. Springer Science, Verlag, New York, NY. p 377.

Kellogg, C.E. 1960. Soil classification and correlation in the soil survey. Soil Science 89: 62.

Knabe, W. 1973. Development and application of the'Domsdorf Ameliorative Treatment'on toxic spoil banks of lignite opencast mines in Germany. Ecology and reclamation of devastated land 2: 273-294.

Kravchenko, A.N. and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agronomy Journal 92: 75-83.

Li, R.S. and W.L. Daniels. 1994. Nitrogen accumulation and form over time in young mine soils. Journal of Environmental Quality 23: 166-172. doi:10.2134/jeq1994.00472425002300010026x.

Limstrom, G.A. 1960. Forestation of strip-mined land in the central states. USDA Handbook 166. US Dept. Agriculture.

Lorenz, K. and R. Lal. 2007. Stabilization of organic carbon in chemically separated pools in reclaimed coal mine soils in Ohio. Geoderma 141: 294-301. doi:10.1016/j.geoderma.2007.06.008.

Luscombe, A. 1986. Mineral sand mining techniques in western Australia. p. 73-80. In: Australia: A world source of ilmenite, rutile, monazite and zircon. Australian Inst. Mining Metall., Perth.

Lynd, L. and S. Lefond. 1983. Titanium minerals. p. 1303-1362. In: S.J. Lefond (Ed.) Industrial Minerals and Rocks. 5th ed. American Institute of Mining, Metallurgical and Petroleum Engineers. Littleton, Co

Ma, B.L., L.M. Dwyer, C. Costa, E.R. Cober and M.J. Morrison. 2001. Early prediction of soybean yield from canopy reflectance measurements. Agronomy Journal 93: 1227-1234. doi:10.2134/agronj2001.1227.

Macdonald, S.E., S.M. Landhäusser, J. Skousen, J. Franklin, J. Frouz, S. Hall et al. 2015. Forest restoration following surface mining disturbance: Challenges and solutions. New Forests 46: 703-732. doi:10.1007/s11056-015-9506-4.

Maharaj, S., C.D. Barton, T.A.D. Karathanasis, H.D. Rowe and S.M. Rimmer. 2007. Distinguishing "new" from "old" organic carbon in reclaimed coal mine sites using thermogravimetry: ii. field validation. Soil Science 172: 302-312. doi:10.1097/SS.0b013e3180314702.

Maloney, S.M.M. 2015. Revegetation of coal stripped land near Henryetta, Oklahoma. Proceedings of the Oklahoma Academy of Science 22: 123-129.

Marbut, C.F. 1922. Soil classification. Soil Science Society of America Journal 3: 24-32.

Maresma, A., M. Ariza, E. Martínez, J. Lloveras and J.A. Martínez-Casasnovas. 2016. Analysis of vegetation indices to determine nitrogen application and yield prediction in maize (zea mays l.) from a standard uav service. Remote Sensing 8: 973. doi:10.3390/rs8120973.

Matheron, G. 1963. Principles of geostatistics. Economic geology 58: 1246-1266. doi:10.2113/gsecongeo.58.8.1246.

Mays, D., K. Sistani and J. Soileau. 2000. Lime and fertilizer needs for land reclamation. p. 217-240. In: Reclamation of Drastically Disturbed Lands.

McBratney, A. and R. Webster. 1983. Optimal interpolation and isarithmic mapping of soil properties. V. Corregionalization and multiple sampling strategy. European Journal of Soil Science 34: 137-162. doi:10.1111/j.1365-2389.1983.tb00820.x.

Mcsweeney, K., I.J. Jansen and W.S. Dancer. 1981. Subsurface horizon blending - an alternative strategy to b-horizon replacement for the construction of post-mine soils. Soil Science Society of America Journal 45: 794-799. doi:10.2136/sssaj1981.03615995004500040024x.

McSweeney, K. and I. Jansen. 1984. Soil structure and associated rooting behavior in minesoils. Soil Science Society of America Journal 48: 607-612. doi:10.2136/sssaj1984.03615995004800030028x.

Meredith, K.R. 2007. The influence of soil reconstruction methods on mineral sands mine soil properties. M.S. Thesis. Virginia Tech.

Meredith, K., W. Daniels, Z. Orndorff, M. Alley and C. Teutsch. 2008. The influence of soil reconstruction techniques on mineral sands mine soils in Virginia. p. 700-719. In: R.I. Barnhisel (Ed.), Proc., 2008 Nat. Meeting Amer. Soc. Mining and Reclamation,

Richmond, VA, June 14-19. Published by ASMR, 3134 Montavesta Rd., Lexington, KY. doi:10.21000/JASMR08010700.

Miller, M.P., M.J. Singer and D.R. Nielsen. 1988. Spatial variability of wheat yield and soil properties on complex hills. Soil Science Society of America Journal 52: 1133-1141.

Miller, J., C. Barton, C. Agouridis, A. Fogel, T. Dowdy and P. Angel. 2012. Evaluating soil genesis and reforestation success on a surface coal mine in Appalachia. Soil Science Society of America Journal 76: 950-960.

Morley, I.W. 1981. Black sands: A history of the mineral sand mining industry in eastern Australia. University of Queensland Press.

Nash, W.L., W.L. Daniels, K.C. Haering, J.A. Burger and C.E. Zipper. 2016. Long-term effects of rock type on Appalachian coal mine soil properties. J Environ Qual 45: 1597-1606. doi:10.2134/jeq2015.10.0540.

Nieman, T. and Z. Merkin. 2000. Pre-mining planning for post-mining land use: applying principles of comprehensive planning and landscape architecture to reclamation. p. 667-686. In: Reclamation of Drastically Disturbed Lands. .

Nordstrom, D.K. 1982. Aqueous pyrite oxidation and the consequent formation of secondary iron minerals. p. 37-56. In: Acid Sulfate Weathering. SSSA Special Publication 10. .

Orndorff, Z.W., W.L. Daniels and J.M. Galbraith. 2005. Properties and classification of mineral sands mine soils in southeastern Virginia. In: R.I. Barnhisel (Ed.), Proc., 2005 Nat. Meeting Amer. Soc. Mining and Reclamation, Breckenridge, CO, June 19-23. Published by ASMR, 3134 Montavesta Rd., Lexington, KY, 40502. doi: 10.21000/JASMR05010842.

Orndorff, Z., W.L. Daniels, M. Beck and M. Eick. 2010. Leaching potentials of coal spoil and refuse: acid-base interactions and electrical conductivity. p. 736-766. In: Proc. 27th National Meeting of the American Society of Mining and Reclamation. 3134: 736-766. doi:10.21000/JASMR10010736.

Orndorff, Z.W., W.L. Daniels, K.R. Meredith, M.M. Alley and A.F. Wick. 2011. Effects of prime farmland soil reconstruction methods on post-mining productivity of mineral sands mine soils in Virginia. p. 504-518. In: R.I. Barnhisel (Ed.), Proc. Nat. Meeting Amer.

Soc. Mining and Reclamation, Bismarck, ND, June 11-16. Published by ASMR, 3134 Montavesta Rd., Lexington, KY, 40502. doi:10.21000/JASMR11010504.

Orndorff, Z.W., W.L. Daniels, C.E. Zipper, M. Eick and M. Beck. 2015. A column evaluation of Appalachian coal mine spoils' temporal leaching behavior. Environ Pollut 204: 39-47. doi:10.1016/j.envpol.2015.03.049.

Pedersen, T., A. Rogowski and R. Pennock Jr. 1978. Comparison of morphological and chemical characteristics of some soils and minesoils [in Clearfield County, Pennsylvania]. Reclamation Review (USA) (1):143-156.

Pedersen, T., A. Rogowski and R. Pennock. 1980. Physical characteristics of some minesoils. Soil Science Society of America Journal 44: 321-328. doi:10.2136/sssaj1980.03615995004400020024x.

Peterson, C.D., G.W. Gleeson and N. Wetzel. 1987. Stratigraphic development, mineral sources and preservation of marine placers from pleistocene terraces in southern Oregon, U.S.A. Sedimentary Geology 53: 203-229. doi:10.1016/0037-0738(87)90035-2.

Pond, G.J., M.E. Passmore, F.A. Borsuk, L. Reynolds and C.J. Rose. 2008. Downstream effects of mountaintop coal mining: comparing biological conditions using family- and genus-level macroinvertebrate bioassessment tools. Journal of the North American Benthological Society 27: 717-737. doi:10.1899/08-015.1.

Pope, P.E. 1989. Reforestation of minelands in the Illinois coal basin. Department of Forestry and Natural Resources, Agricultural Experiment Station, Purdue University. Station Bulletin 565. p. 12.

Powell, J., R. Barnhisel, W. Thom, M. Ellis, J. Armstrong, F. Craig et al. 1985. Reclamation of prime farmland in Kentucky. p. 12. In: Proc. 2nd Ann. Meet. Am. Soc. Surf. Min. Reclam. Denver, CO, 8–10 Oct. . doi:10.21000/JASMR85010001.

Preve, R.E., J.A. Burger and R.E. Kreh. 1984. Influence of mine spoil type, fertilizer, and mycorrhizae on pines seeded in greenhouse trays Journal of Environmental Quality 13: 387-391. doi:10.2134/jeq1984.00472425001300030013x.

Roberts, J.A., W.L. Daniels, J.A. Burger and J.C. Bell. 1988a. Early stages of mine soil genesis in a southwest Virginia spoil lithosequence. Soil Science Society of America Journal 52: 716-723. doi:10.2136/sssaj1988.03615995005200030023x.

Roberts, J., W. Daniels, J. Burger and J. Bell. 1988b. Early stages of mine soil genesis as affected by topsoiling and organic amendments. Soil Science Society of America Journal 52: 730-738. doi:10.2136/sssaj1988.03615995005200030025x.

Roberts, J.A., W.L. Daniels, J.C. Bell and D.C. Martens. 1988c. Tall fescue production and nutrient status on southwest Virginia mine soils. Journal of Environmental Quality 17: 55-62. doi:10.2134/jeq1988.00472425001700010008x.

Rodrigue, J., J. Burger and R. Oderwald. 2002. Forest productivity and commercial value of pre-law reclaimed mined land in the eastern United States. Northern Journal of Applied Forestry 19: 106-114. doi:10.1093/njaf/19.3.106.

Rodrigue, J.A. and J. Burger. 2004. Forest soil productivity of mined land in the midwestern and eastern coalfield regions. Soil Science Society of America Journal 68: 833-844. doi:10.2136/sssaj2004.8330.

Rogovska, N. and A.M. Blackmer. 2009. Remote sensing of soybean canopy as a tool to map high pH, calcareous soils at field scale. Precision Agriculture 10: 175-187. doi:10.1007/s11119-008-9087-8.

Ruddiman, W.F. 2003. The anthropogenic greenhouse era began thousands of years ago. Climatic change 61: 261-293.

Rumpel, C., J. Balesdent, P. Grootes, E. Weber and I. Kögel-Knabner. 2003. Quantification of lignite-and vegetation-derived soil carbon using ^{14}C activity measurements in a forested chronosequence. Geoderma 112: 155-166. doi:doi.org/10.1016/S0016-7061(02)00302-6.

Schafer, W.M. 1979. Minesoil resources in the northern Great Plains: Characterization, evaluation and potential. PhD Diss. Montana State University-Bozeman, College of Agriculture.

Schafer, W.M., G.A. Nielsen and W.D. Nettleton. 1980. Minesoil genesis and morphology in a spoil chronosequence in Montana. Soil Science Society of America Journal 44: 802-807. doi:10.2136/sssaj1980.03615995004400040029x.

Schroeder, W.L. 1975. Soils in construction. John Wiley & Sons, Inc. Waveland Press.

Schroeder, P.D., W.L. Daniels and M.M. Alley. 2010. Chemical And Physical Properties Of Reconstructed Mineral Sand Mine Soils In Southeastern Virginia. Soil science 175: 2-9.

Semalulu, O., R. Barnhisel and R. Dunker. 1992. Phosphorus availability as affected by topsoil and subsoil mixing. Prime farmland reclamation. p. 93-91. In: Proc. National Symposium on Prime Farmland Reclamation, St. Louis, MO.

Sena, K., C. Barton, P. Angel, C. Agouridis and R. Warner. 2014. Influence of spoil type on chemistry and hydrology of interflow on a surface coal mine in the eastern US coalfield. Water, Air, & Soil Pollution 225: 2171. doi:10.1007/s11270-014-2171-y.

Sena, K.L., K.M. Yeager, C.D. Barton, J.M. Lhotka, W.E. Bond and K.J. Schindler. 2021. Development of mine soils in a chronosequence of forestry-reclaimed sites in eastern Kentucky. Minerals 11: 422.

Sencindiver, J.C. 1977. Classification and genesis of minesoils. Ph.D. Diss. West Virginia Univ., Morgantown (Univ. Micro. 77-22 746).

Sencindiver, J.C. and J.T. Ammons. 2000. Minesoil genesis and classification. In: R. I. Barnhisel, R. G. Darmody and W. L. Daniels, editors, p. 595-613. Reclamation of Drastically Disturbed Lands. ASA, CSSA, SSSA, Madison, WI.

Shepherd, M. 1986. Australian heavy mineral reserves and world trends. Australia: A world source of ilmenite, rutile, monazite and zircon. p. 61-68. In: Australasian Inst. Mining Metallurgy, Perth. .

Shover, N., D.A. Clelland and J. Lynxwiler. 1986. Enforcement or negotiation: Constructing a regulatory bureaucracy. SUNY Press.

Showalter, J., J. Burger, C. Zipper, J. Galbraith and P. Donovan. 2007. Physical, chemical, and biological mine soil properties influence white oak seedling growth: a proposed mine soil classification model. Southern Journal of Applied Forestry 31: 99-107.

Showalter, J.M., J.A. Burger and C.E. Zipper. 2010. Hardwood seedling growth on different mine spoil types with and without topsoil amendment. J Environ Qual 39: 483-491. doi:10.2134/jeq2008.0500.

Shukla, M., R. Lal, J. Underwood and M. Ebinger. 2004. Physical and hydrological characteristics of reclaimed minesoils in southeastern Ohio. Soil Science Society of America Journal 68: 1352-1359. doi:10.2136/sssaj2004.1352.

Shukla, M. and R. Lal. 2005. Temporal changes in soil organic carbon concentration and stocks in reclaimed minesoils of southeastern Ohio. Soil science 170: 1013-1021. doi:doi10.1097/01.ss.0000187354.62481.91.

Skousen, J., J. Renton, H. Brown, P. Evans, B. Leavitt, K. Brady et al. 1997. Neutralization potential of overburden samples containing siderite. Journal of Environmental Quality 26: 673-681. doi:10.2134/jeq1997.00472425002600030012x.

Skousen, J., J. Sencindiver, K. Owens and S. Hoover. 1998. Physical properties of minesoils in West Virginia and their influence on wastewater treatment. Journal of environmental quality 27: 633-639. doi:10.2134/jeq1998.00472425002700030022x.

Skousen, J., J. Simmons, L. McDonald and P. Ziemkiewicz. 2002. Acid–base accounting to predict post-mining drainage quality on surface mines. Journal of Environmental Quality 31: 2034-2044. doi:10.2134/jeq2002.2034.

Skousen, J., J. Gorman, E. Pena-Yewtukhiw, J. King, J. Stewart, P. Emerson et al. 2009. Hardwood tree survival in heavy ground cover on reclaimed land in West Virginia: mowing and ripping effects. J Environ Qual 38: 1400-1409. doi:10.2134/jeq2008.0297.

Skousen, J.G. and C.E. Zipper. 2010. Revegetation Species and Practices. Virginia Cooperative Extension Publication 460-122. p. 1-18.

Skousen, J., P. Emerson and R. Barnhisel. 2010. Release of nutrients from brown and gray sandstone soil substitutes in southern West Virginia. p. 1135-1143. In: Proceedings National Meeting of the American Society of Mining and Reclamation, Pittsburgh, PA. doi:10.21000/JASMR10011135.

SMCRA. 1977. The surface mining control and reclamation act. Public Law 95-87. Federal Register 3. US Congress 445-532.

Smith, R.M., A.A. Sobek, T. Arkle Jr, J. Sencindiver and J. Freeman. 1976. Extensive overburden potentials for soil and water quality. EPA Publ. 600/1-76-184. U.S. Gov. Print. Office. Washington. DC.

Smith, B.M.A., W.A. Loneragan, C.D. Grant and J.M. Koch. 2000. Effect of fire on the topsoil seed banks of rehabilitated bauxite mine sites in the jarrah forest of western Australia. Ecological Management & Restoration 1: 50-60. doi:10.1046/j.1442-8903.2000.00008.x.

Sobek, A.A. 1978. Field and laboratory methods applicable to overburdens and minesoilsEPA Publ. 600/2-78-054. U.S. Gov. Print. Office. Washington. DC.

Sobek, A.A., J.G. Skousen, S.E. Fisher and R. Barnhisel. 2000. Chemical and physical properties of overburdens and minesoils. Agronomy 41: 77-104. doi:10.2134/agronmonogr41.c4.

Soil Survey Staff. 1975. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. Soil Conservation Service USDA. Agricultural Handbook No. 436.US Government Printing Office.

Soil Survey Staff. 2014. Keys to soil taxonomy, 12th Ed. USDA-NRCS. US Gov. Print. Office, Washington, DC.

Spindler, D., P. Ehert, J. Steiner and R. Dunker. 1992. Cropland and hayland productivity restoration on mined land in Illinois. p. 165-168. In: Proc. 1992 Natl. Symp. on Prime Farmland Reclam., St. Louis. 10-14 August. Dep. of Agronomy, University of Illinois, Urbana.

Stewart, B. and W. Daniels. 1992. Physical and chemical properties of coal refuse from southwest Virginia. Journal of environmental quality 21: 635-642. doi:10.2134/jeq1992.00472425002100040018x.

Stolt, M.H., J.C. Baker, T.W. Simpson, D.C. Martens, J.R. McKenna and J.R. Fulcher. 2001. Physical reconstruction of mine tailings after surface mining mineral sands from prime agricultural land. Soil Science 166: 29-37. doi:10.1097/00010694-200101000-00006.

Sweeney, L.R. 1979. Soil genesis on relatively young surface mined lands in southern West Virginia. M.S. Thesis. Virginia Polytechnic Inst. and State Univ. Blacksburg, VA.

Sweigard, R., J. Burger, D. Graves, C. Zipper, C. Barton, J. Skousen et al. 2007a. Loosening compacted soils on mined sites. U.S. Office of Surface Min. Forest Reclam. Advisory No. 4.

Sweigard, R., J. Burger, C. Zipper, J. Skousen, C. Barton and P. Angel. 2007b. Low compaction grading to enhance reforestation success on coal surface mines. U.S. Office of Surface Min. Forest Reclam. Advisory No. 3.

Tacey, W.H. and B.L. Glossop. 1980. Assessment of topsoil handling techniques for rehabilitation of sites mined for bauxite within the jarrah forest of Western Australia. Journal of Applied Ecology: 195-201. doi:10.2307/2402974

Thomas, D. and I. Jansen. 1985. Soil development in coal mine spoils. Journal of Soil and Water Conservation 40: 439-442.

Thomas, K., J. Sencindiver, J. Skousen and J. Gorman. 2000. Soil horizon development on a mountaintop surface mine in southern West Virginia. Green Lands 30: 41-52.

Thurman, N. and J. Sencindiver. 1986. Properties, classification, and interpretations of minesoils at two sites in West Virginia. Soil Science Society of America Journal 50: 181-185. doi:10.2136/sssaj1986.03615995005000010034x.

Timpano, A.J., S.H. Schoenholtz, D.J. Soucek and C.E. Zipper. 2015. Salinity as a limiting factor for biological condition in mining-influenced central Appalachian headwater streams. Journal of the American Water Resources Association 51: 240-250. doi:10.1111/jawr.12247

Tola, E., K. Al-Gaadi, R. Madugundu, A. Zeyada, A. Kayad and C. Biradar. 2017. Characterization of spatial variability of soil physicochemical properties and its impact on Rhodes grass productivity. Saudi journal of biological sciences 24: 421-429.

Torbert, J.L., A. Tuladhar, J. Burger and J. Bell. 1988. Minesoil property effects on the height of ten-year-old white pine. Journal of Environmental Quality 17: 189-192.

Torbert, J.L. and J.A. Burger. 1990. Tree survival and growth on graded and ungraded minesoil. Tree Planters' Notes 41: 3-5.

Torbert, J.L., J. Burger and W. Daniels. 1990. Pine growth variation associated with overburden rock type on a reclaimed surface mine in Virginia. Journal of Environmental Quality 19: 88-92. doi:10.2134/jeq1990.00472425001900010011x.

Toy, T. and W. Daniels. 1998. Reclamation of disturbed lands. Encyclopedia of Environmental Analysis and Remediation. New York: John Wiley: 4078-4101.

Tyner, E.H., R.M. Smith and S.L. Galpin. 1948. Reclamation of strip-mined areas in West Virginia. Journal of the American Society of Agronomy 40: 313-323.

USDA Forest Service. 1979. Mining and reclamation in the West: user guide to vegetation. p. 1-85. Gen. Tech. Rep. INT-64. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Ussiri, D.A., R. Lal and P.-A. Jacinthe. 2006. Post-reclamation land use effects on properties and carbon sequestration in minesoils of southeastern Ohio. Soil science 171: 261-271. doi:10.1097/01.ss.0000199702.68654.1e.

Ussiri, D.A.N. and R. Lal. 2008. Method for determining coal carbon in the reclaimed minesoils contaminated with coal. Soil Science Society of America Journal 72: 231-237. doi:10.2136/sssaj2007.0047.

Ussiri, D.A., P.-A. Jacinthe and R. Lal. 2014. Methods for determination of coal carbon in reclaimed minesoils: A review. Geoderma 214: 155-167. doi:10.1016/j.geoderma.2013.09.015.

Van Gorp, L. and P.D. Erskine. 2011. The influence of topsoil management on stradbroke island sand mine rehabilitation: Implications for ecosystem recovery. p. 377-389. In: Proceedings of the Royal Society of Queensland. The University of Queensland, Centre for Mined Land Rehabilitation, Brisbane, Queensland, Australia.

VanWormhoudt, A. 1993. Soil mineralogy of an upper coastal plain landscape in Virginia. M.S. Thesis. Virginia Tech. .

Vieira, S.R., D. Nielsen and J. Biggar. 1981. Spatial variability of field-measured infiltration rate. Soil Science Society of America Journal 45: 1040-1048. doi:10.2136/sssaj1981.03615995004500060007x.

Vogel, W.G. 1981. Guide for revegetating coal minesoils in the eastern United States. Forest Service, Broomall, PA (USA). Northeastern Forest Experiment Station.

Warrick, A., D. Myers and D. Nielsen. 1986. Geostatistical methods applied to soil science. p. 53-82. In: Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods.

Webster, R. 1985. Quantitative spatial analysis of soil in the field. Advances in Soil Science: 1-70. doi:10.1007/978-1-4612-5090-6_1.

Webster, R. and M.A. Oliver. 1990. Statistical methods in soil and land resource survey. Oxford University Press (OUP).

Wick, A.F., L.J. Ingram and P.D. Stahl. 2009. Aggregate and organic matter dynamics in reclaimed soils as indicated by stable carbon isotopes. Soil Biology and Biochemistry 41: 201-209. doi:doi.org/10.1016/j.soilbio.2008.09.012.

Wick, A., W. Daniels, Z. Orndorff and M. Alley. 2013. Organic matter accumulation post-mineral sands mining. Soil Use and Management 29: 354-364. doi:10.1111/sum.12058.

Wolf, D.D., J.H. Fike and C.E. Zipper. 2018. Conversion of Sericea lespedeza-dominant vegetation to quality forages for livestock use. p. 1-5. Virginia Cooperative Extension Publication 460-119.

Wood, C. and D. Pettry. 1989. Initial pedogenic progression in a drastically disturbed prime farmland soil. Soil Science 147: 196-207. doi:10.1097/00010694-198903000-00006.

Wright, D. and R. Blaser. 1981. Establishment of vegetation on graded road cuts as influenced by topsoiling and tillage. . Soil Science Society of America Journal 45: 419-422. doi:10.2136/sssaj1981.03615995004500020036x.

Zacharias, S., C.D. Heatwole and J.B. Campbell. 1997. Spatial trends in the texture, moisture content, and pH of a Virginia coastal plain soil. Transactions of the Asae 40: 1277-1284. doi:10.13031/2013.21385.

Zimmerman, C., C. Stilson and W.L. Daniels. 2008. Reclamation of mineral sands mine and topsoil replacement study. p. 1429-1446. In: Proceedings America Society of Mining and Reclamation. doi:10.21000/JASMR08011429.

Zipper, C.E. 2000. Coal mine reclamation, acid mine drainage, and the clean water act. p. 169-191. In: Reclamation of drastically disturbed lands.

Zipper, C.E., J.A. Burger, J.G. Skousen, P.N. Angel, C.D. Barton, V. Davis et al. 2011. Restoring forests and associated ecosystem services on Appalachian coal surface mines. Environmental management 47: 751-765. doi:10.1007/s00267-011-9670-z.

Zipper, C.E., J.A. Burger, C.D. Barton and J.G. Skousen. 2013. Rebuilding soils on mined land for native forests in Appalachia. Soil Science Society of America Journal 77: 337-349. doi:10.2136/sssaj2012.0335.

Zipper, C.E. and J. Skousen. 2021a. Appalachia's coal-mined landscapes: Resources and communities in a new energy era. Springer Nature. 351 p. doi:10.1007/978-3-030-57780-3.

Zipper, C.E. and J. Skousen. 2021b. Coal's legacy in Appalachia: Lands, waters, and people. The Extractive Industries and Society. 21 p. doi:10.1016/j.exis.2021.100990.

3. Pedogenic Influences of Rock Type Over 34 Years on Southwest Virginia Coal Mine Soils

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Abbreviations: COPE, Controlled Overburden Placement Experiment; SS, sandstone; SiS, siltstone; RM, rock mix; SA, surface amendment; sbk, subangular blocky; gr, granular; CEC, cation exchange capacity; SOC, soil organic carbon; SOM, soil organic matter; EC, electrical conductivity; Fe, iron; Mn, manganese.

3.1. Abstract

Under SMCRA, blasted rock overburden can be substituted for topsoil plant growth media in lieu of poor quality and thin native soils. While the use of properly selected topsoil substitutes is commonplace across Appalachia, long-term studies are necessary to fully understand their pedogenesis. In 1982, the Controlled Overburden Placement Experiment was constructed in SW Virginia to study the effects of sandstone (SS) and siltstone (SiS) on mine soil properties and plant growth. My objective was to evaluate long-term (> 34 years) effects of rock type – 100% SS, 1:1 SS:SiS, and 100% SiS – on soil morphological, physical, and chemical properties. Evident morphological changes included deeper ^A, transitional ^BC, and ^Bw horizons with SS soils having somewhat stronger subsoil structure. Root-limiting compaction in lower ^B and ^C horizons increased through time, which indicates weathering and collapse of bridging voids and infilling via movement of soil materials from above and presents longer term land use concerns. By the end of the study, the surface soil had lower pH and higher soluble salts, cation exchange capacity (CEC), and metal, carbon, and nutrient (nitrogen and phosphorus) concentrations compared to subsoil horizons. Over time, organic matter (OM) and soil fines (silt + clay) increased in ^A horizons. Sand was higher in SS soils and generally decreased over time, while silt was higher in SiS and increased over time. Increasing clay was associated with increasing CEC. Surface CEC increased, and pH decreased over time due to OM production and turnover, but pH remained relatively stable in the subsurface and higher in SiS. Over time, Fe-oxides increased in the surface and subsurface and were correlated with decreased extractable P, raising concerns for long-term P-availability. Subsurface EC decreased due to leaching but did not change in the surface. Soil ^A horizons sequestered organic-C at ~0.21 Mg ha^{-1} $year^{-1}$ with comparable rates among treatments. Rock type dominated soil texture after 34 years, but many chemical properties (e.g., pH, EC, Fe-oxides) converged in ^A horizons over time. Time periods longer than this study are needed to understand how soils equilibrate across spoil types and within profiles.

3.2. Introduction

In the central Appalachian coal region, over 900,000 ha were surface mined for coal between 1977 to 2015, creating large-scale deforestation and forest fragmentation (Adams 2017). Pre-mining soils within the central Appalachian coalfields are strongly influenced by parent rock material and landscape position (e.g., sandstone capped ridgetops, colluvial footslopes) (Daniels et al. 1984). Sharp changes in sedimentary facies are common within the region's stratigraphy, giving rise to abrupt changes in soil texture across contrasting strata outcrops (Daniels et al. 1984). Per SMCRA, blasted sedimentary rock overburden, also referred to as "spoil", is commonly used as a substitute for native topsoil for the final surface revegetation media due to inadequate supply, salvageability, and quality (e.g., thin, acidic A + E horizons) of pre-mine soils. Land use potential is dictated by selective overburden placement or the use of proper rock strata selection and subsequent placement procedures (Daniels and Amos 1985). While SMCRA's standards resulted in deeper cuts and thicker mine soils vs. pre-law mines, heavy grading often created compacted densic horizons (Haering et al. 2004). Ideal spoil placement (e.g., minimal or no grading) results in a deep (≥ 1.2 m) and uncompacted mine soil conducive to plant rooting (Adams 2017).

Further, an appropriate spoil rock type(s) must be selected for the appropriate revegetation scheme. For example, weathered spoil materials are desirable for forestry post-mining land uses due to lower soluble salt contents, moderately acidic pH, and higher soil fines (> 2 mm) (Andrews et al. 1998; Daniels and Amos 1985; Rodrigue and Burger 2004; Showalter et al. 2007; Torbert et al. 1988). Brown weathered sandstone leads to superior tree growth compared to unweathered sandstones or other unweathered rock types (Angel et al. 2008; Dallaire and Skousen 2019; Sena et al. 2014; Torbert et al. 1990). Mixtures of weathered and unweathered mine spoil materials may serve as a second-best option for reforestation due to their intermediate soil properties and tree growth potentials (Casselman et al. 2007; Sena et al. 2014). Different mine spoil materials have a major influence on soil fertility, pH, and the release and accumulation of soluble salts and other elements over an extended period (Nash et al. 2016; Sena et al. 2021). Since land use productivity potentials are associated with original parent material, it is essential to follow mine soil developmental changes over time in varying spoil types.

Rock mineralogy and particle size are important determinants of initial mine soil chemical and physical properties such as texture, pH, cation exchange capacity (CEC), electrical conductivity (EC), and macro-porosity (Daniels et al. 1983; Gorman et al. 2001; Roberts et al. 1988a; Skousen et al. 1998; Thomas et al. 2001). Early work noted the influence of original parent rock over a chronosequence of site ages in West Virginia (Sweeney 1979). The Controlled Overburden and Placement Experiment (COPE) in southwestern Virginia was the first replicated plot experiment to assess long-term mine soil genesis in response to parent material and vegetation (Haering et al. 1990). Roberts et al. (1988a) reported early findings at the COPE, constructed in 1982 using pure and ratio mixes of sandstone (SS) and siltstone (SiS) spoils. Within three years, rapid chemical weathering occurred (e.g., dissolution, leaching, oxidation). Generally, total nitrogen (N) increased, whereas extractable phosphorus (P) decreased. Siltstone spoils had higher pH, CEC, extractable iron (Fe), and EC levels compared to sandstone spoils. Oxidized and pre-weathered (brown) rock fragments rapidly slaked and disintegrated within two years, increasing the fraction of soil-sized particles (< 2 mm) initially dominated by sands which further weathered into silts. After five years of weathering at the COPE, Haering et al. (1993) found that among spoil types, SiS derived ^A horizons were the most altered and increased in silt, pH, and exchangeable calcium (Ca) and magnesium (Mg) due to continued carbonate cement weathering. Extractable Fe was higher than earlier years, but no differences were found among rock types. Similarly, Miller et al. (2012) found that fine-textured shale mine spoils in Kentucky (KY) had a higher CEC and, based on topographic surveys, settled relatively quickly due to rapid loss of soluble carbonates, whereas unoxidized gray sandstone spoils created alkaline pH (> 8.0) and disintegrated much more slowly. Others also noted disintegration of shales within a few years after placement leading to volume loss and settling (Ciolkosz et al. 1985; Haigh 1992ab; Haigh and Sansom 1999). Nash et al. (2016) conducted a follow-up study on the COPE after 26 years and reported that rock type still had a profound effect on soil texture, pH, and CEC. Physical weathering dominated the system whereas chemical weathering was more notable initially (e.g., < 10 years), indicating that the nature of mine soil transformations differs in the short vs. decadal time frame.

As reforested mine soils mature, an important consideration is the influence of O horizon development and/or incorporation and associated nutrient cycling, which strongly affects soil

chemical properties (e.g., pH, EC, and nutrient levels) (Mudrick et al. 1994; Sweeney 1979). Reclaimed vegetation type also influences soil microclimate and biological properties, thus impacting soil horizon thickness and other morphological features (Gorman et al. 2001; Yarwood et al. 2015). In two to 5-year-old mine soils, Pedersen et al. (1978) reported lower pH in the ^A horizons than deeper horizons due to the contribution of organic acids during decomposition of leaf litter. Overall, they found lower rock fragments and higher clay contents and extractable aluminum (Al) and Fe in natural vs. reclaimed soils due to prolonged solum weathering. Three years following installation of the COPE, Roberts et al. (1988a) found higher CEC and water holding capacity in the surface vs. subsurface, but EC levels were similar. Over a range of mine soil pedons, Ciolkosz et al. (1985) reported EC levels (> 2 mmhos cm^{-1}) that were highest in the ^C horizons (> 1 m depth) and much higher overall than natural soils. Similarly, Schafer et al. (1980) attributed surface accumulation of salts to nutrient cycling effects in mine soils and found overall higher soluble salt contents compared to native soils. Gorman et al. (2001) attributed higher EC values in ^A horizons of reclaimed white pine (*Pinus strobus* L.) plantations to greater ionic concentrations in the surface due to OM turnover. Another contributor of high EC is parent materials that contain particularly high concentrations of sulfate (SO_4^{2-}), potassium (K), sodium (Na), manganese (Mn), Ca, and Mg, and are usually less oxidized and finer textured such as siltstones and other mudrocks. However, freshly blasted brown, gray, or mixed spoils in this region weather to release significant amounts of soluble ions and the order of magnitude is generally as follows: $SO_4^{2-} > Ca > Mg > K = HCO_3^- > Na > Mn$ (Clark et al. 2018; Sena et al. 2014).

Accurately estimating soil organic C (SOC) in mine soils is complicated by several potential sources of error (Jacinthe et al. 2009). Researchers have used various approaches to separate geogenic (coal), carbonate, and pedogenic (organic) sources of C from coal mine soils (Avera et al. 2015; Maharaj et al. 2007; Nash 2012; Sena et al. 2021). For example, total soil carbon (C) via dry combustion or simple loss on ignition does not accurately estimate SOC since both a range of forms including geogenic (coal and carbonates) and accumulated SOC are usually present, but this approach may be useful for making relative comparisons. Generally, Appalachian coal mine soils have irregular depth distributions of total soil C compared to native soils likely due to an assortment of coal and carbonate C sources from the original parent rock (Ciolkosz et al.

1985; Pedersen et al. 1978; Thomas et al. 2001; Thurman and Sencindiver 1986). Schafer et al. (1980) calculated C accumulation rates using total soil C and found that younger coal mine soils in Montana had higher rates compared to older mine soils (1.35 Mg ha^{-1} vs. 0.45 Mg ha^{-1}) likely due to fertilization and seeding of perennial grasses. Overall, C:N ratios were higher in mine soils compared to the more equilibrated native soils and this was inferred to be largely due to higher rates of litter accumulation, reducing N-availability. Wick et al. (2016) working in the same area of this study, found that extent of macroaggregation had the strongest impact on C and N accumulation and storage vs. microaggregates which are generally associated with lower C:N ratios (i.e., complex humic substances). However, C storage was higher in the non-aggregated fine earth fractions. Schafer et al. (1980) observed in western USA mine soils that fine particles of coal (silt + clay sized) contributed to a higher CEC and EC, lower pH, and an erroneously high organic C content (>10%). Daniels and Amos (1982) found similar errors in CEC, acidity, and OM in a study that assessed the effects of relatively unweathered coal fragments of various sizes on mine soil chemical properties. Only very small sized coal fragments (< 0.05 mm) were readily oxidizable, particularly at higher concentrations, during the standard wet acid-dichromate digestion technique for determining OM (Walkley and Black 1934). Ferrous Fe and Mn were also oxidized during the procedure, contributing to positive errors and inflated apparent OM levels.

Since there is no one widely accepted method for measuring SOC accumulation in coal mine soils, researchers have based their SOC estimations on several assumptions and correction factors (Amichev et al. 2008; Shrestha et al. 2009). Using an HCl pre-treatment procedure to remove carbonate-C followed by an isotopic approach to separate out organic C from coal C, Sena et al. (2021) found that SOC generally increased over time and was highest in near surface depths on reclaimed coal mine sites in southeastern KY. Avera et al. (2015) showed similar depth and temporal trends in SOC using a similar C fractionation approach on a coal mine in southwestern Virginia. These two recent studies found reasonably similar SOC accumulation rates—0.9 Mg SOC ha^{-1} $year^{-1}$ at a 19-year-old site (Sena et al. 2021) and 0.7 Mg SOC ha^{-1} $year^{-1}$ at a 11-year-old site (Avera et al. 2015). Nash (2012) estimated non-geogenic SOC in southwestern Virginia based on volumetric samples (0-5 and 5-25 cm) taken in 2008 vs. original samples taken at the same depths in 1982; her estimated SOC accumulation rates (0-25 cm) ranged from 0.5 to 1.1 Mg

SOC ha^{-1} $year^{-1}$ after 26 years. These SOC accumulation rates generally align with those reported by Sperow (2006), who provided a comprehensive review of C sequestration datasets on reclaimed mined lands across seven east-central states.

Over time, mine soil horizons develop and deepen in rocky mine spoils that were not overly compacted during final placement and grading (Thomas et al. 2000). In young Appalachian mine soils, ^A horizons develop quickly due to the initial plant growth and organic matter accumulation in near surface root zones (Gorman and Sencindiver 1999; Pedersen et al. 1978; Sencindiver 1977; Sweeney 1979). Sweeney (1979) reported ^Bw horizons in five-year-old mine soils, but they did not meet the required thickness to be cambic. According to *Soil Taxonomy*, the cambic horizon (Bw) must be at least 15 cm thick and show slight subsoil alterations that indicate pedogenesis such as weak to moderate structure development and change in color (i.e., higher chroma, higher value, or redder hue), or a slightly higher clay content comparative to the underlying or overlying horizon (Soil Survey Staff 2014). Over a chronosequence of sites, Daniels and Amos (1981) observed young (< 5 years) mine soils with poor subsoil differentiation (e.g., A-C), but noted ^Bw horizons in older (> 20 years) mine soils. Within three years of the COPE, Roberts et al. (1988a) observed distinct ^A horizon development, but subsurface horizons were undifferentiated. By the fifth year, ^A horizons were thicker and more distinct and the subsurface began to differentiate (i.e., ^A-^AC-^C1-^C2) (Haering et al. 1993). Ciolkosz et al. (1985) found 10 to 30% less rock fragments in the surface vs. subsurface horizons, and reported several cambic ^Bw horizons, but most did not meet the color criteria. Thomas et al. (2000) found that over a chronosequence of mine sites: 1) Solum thickness of mine soils (^A + ^Bw horizons) increased with age; 2) mine soils had shallower sola (all horizons above the ^C) compared to native soils; and 3) older mine soils (> 20 years) had similar aggregation to native soils at similar depths. Researchers have described evidence of minor clay films in subsoil horizons of mine soils less than 30 years old (Ciolkosz et al. 1985; Gorman and Sencindiver 1999; Gorman et al. 2001). Clay films were patchy, thin, and discontinuous, and likely a contribution of the shale derived parent material more so than clay illuviation. While clay films are not a requirement for the cambic horizon, they indicate pedogenic pathways. Gorman et al. (2001) found several ^Bw horizons in mine soils between 27 to 29 years old based on weak structure and a clay increase of 3% from the overlying ^A horizon.

Both pre- and post SMCRA mined lands have undergone severe compaction by heavy machinery (Daniels and Amos 1981; Haering et al. 2004), and in some cases subsoil densification has been noted from weathering and settling (Haigh and Sansom 1999). Studies have reported high bulk densities in Appalachian coal mine soils and other regions (Bell 1994; DeLong et al. 2012; Gorman and Sencindiver 1999; Gorman et al. 2001; Page-Dumroese et al. 1999; Pedersen et al. 1980; Skousen et al. 1998; Thomas et al. 2000; Thurman et al. 1985). Rock fragments commonly occupy nearly half or more of the total volume of Appalachian mine soils (Miller et al. 2012; Thomas et al. 2000; Thurman and Sencindiver 1986). Thus, measuring mine soil bulk density is complicated by rock fragments, leading to poor estimations. DeLong et al. (2012) underestimated bulk density ($\bar{x}$ 1.35 Mg m^{-3}) using the sand cone method due to large rock protrusions. However, the foam, frame, and radiation methods produced similar and higher bulk densities (1.64-1.76 Mg m^{-3}), though these methods posed time and cost constraints. In lieu of taking measurements on bulk soils, researchers have used individual, intact clods coated with a water-repellent mixture or substance such as paraffin wax or saran resin (Campbell 1994; Tisdall 1951). Pedersen et al. (1980) did not find any differences in PA mine soil surface bulk density between excavation, gamma probe, and clod methods with mean values of 1.81, 1.70, and 1.78 Mg m^{-3}, respectively.

Coal mined lands may achieve short-term reclamation regulatory compliance goals, but beyond SMCRA's five-year performance bond period, long-term evaluation of pedogenic transformations and associated soil properties is poorly documented. Thus, there is interest in characterizing mine soil genesis over several decades following spoil placement to account for changing conditions, weathering processes, recovery of ecosystem functions, and long-term suitability for varying post-mining land uses. Numerous studies have been published to date that evaluated the ability of rock overburden and amended rock spoils at the COPE to transform into productive mine soils capable of supporting herbaceous and woody vegetation (Bendfeldt et al. 2001; Haering et al. 1993; Moss et al. 1989; Nash et al. 2016; Roberts et al. 1988b; Roberts et al. 1988a). Haering et al. (1993) studied mine soil morphology two, four-, and eight-years following COPE installation. Nash et al. (2016) reported on rock type effects in follow-up work at the COPE in 2008, and while they examined some pedogenic soil properties, there have been no published studies since 1989 detailing changes in soil morphology over time, particularly related to horizon

formation and root-limiting layers. This study was conducted with three main objectives: 1) Describe changes in mine soil morphological properties over time, with emphasis on associated pedogenic features and taxonomic implications; 2) compare mine soil chemical and physical properties among rock spoil treatments and mine soil horizons and depths; and 3) evaluate long-term (34+ years) changes in mine soil chemical and physical properties.

3.3. Materials and Methods

3.3.1. Site Description

The COPE study area is located within the coalfields of southwestern Virginia in the eastern portion of the Appalachian Plateau. In this region, mixed mesophytic southern Appalachian forests are underlain by relatively horizontal sedimentary rock strata of Permian and Pennsylvanian ages and to a lesser extent Mississippian (Vogel 1981). The COPE was built in Wise County, Virginia (37º00' N, 82º41' W) on a flat, mined bench within a larger area of land dedicated to the Powell River Project (PRP; https://powellriverproject.org/), a cooperative Virginia Tech reclamation research and outreach program supported by the coal industry, and federal and state agencies. The study site, previously a finger ridge, was contour mined in 1973 and then later abandoned. The COPE was designed and located in late 1981, plot construction was completed in April 1982, and the site was revegetated in mid-May of 1982. Mean annual precipitation for this region is ~125 cm with a humid temperate climate. Common herbaceous and woody revegetation species in the immediate reclaimed areas include tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.], sericea lespedeza [*Lespedeza cuneata* (Dum. Cours.) G. Don], eastern white pine (*Pinus strobus* L.), and black locust (*Robinia pseudoacacia* L.) (Daniels et al. 2004).

Sedimentary rock overburden was used as topsoil substitutes in this study and selected from an adjacent second-cut contour mining operation (Haering et al. 1990). Rock strata in the region (SW VA and E KY) are the Pennsylvanian Pottsville, Alleghany, Conemaugh, and Monongahela groups. Within the Pottsville group, the dominant formations include Lee, Wise, and Harlan formations. The dominant pre-mining soil for Wise County was mapped in 1940 as Muskingum series (fine-loamy, mixed, semiactive, mesic Typic Dystrudepts) with 3 to 60% slopes, but more recent work in and around the experimental site showed that natural profiles differ

from the older survey in terms of thinner A horizons (8-15 cm) and shallower depth to bedrock (< 61 cm), unless formed on coves and toeslopes (Daniels et al. 1984). Within the study area, Haering et al. (2005) relied on recently correlated NRCS mapping and identified two dominant pre-mining soil series which are the deep and very deep colluvial Shelocta series (fine-loamy, mixed, active, mesic Typic Hapludults) and the moderately deep residual Gilpin series (fine-loamy, mixed, active, mesic Typic Hapludults). For full taxonomic classifications, see Section 3.4.1.3.

3.3.2. Experimental Design

The overall experiment contains two separate portions, both with randomized complete block designs (RCBD) consisting of four replicate blocks (see Appendix A1 for plot layout). The rock mix (RM) experiment treatments are derived from pure or ratio mixes of SS and SiS, while the surface amendment (SA) experiment utilized organic amendments and native topsoil applied to the surface of a uniform 2:1 SS:SiS mixture. This chapter reports exclusively on the RM experiment, while Chapter 4 provides results from the SA experiment. Following overburden placement, plots were lightly graded using a D-4 dozer. An initial application of N-P-K fertilizer was used in the RM experiment (Table 3.1). There were a total of 48 plots (20 in RM and 28 in SA), each measuring 3.5 m x 7 m in size with a 3.5 m wide buffer between plots. The final graded plots were approximately 1.3 m above the highly compacted bench. In May 1982, all 48 plots were rototilled (12 cm depth) and hydroseeded with a water slurry composed of Kentucky-31 tall fescue (80 kg ha^{-1}) and wood fiber mulch (840 kg ha^{-1}). The plots were also straw mulched (2300 kg ha^{-1}) to encourage uniform vegetation establishment. Detailed reports of mine soil properties were conducted one, two, five-, and seven-years following plot establishment, and tall fescue biomass production was measured in 1982–1984, 1986, 1987, 1989, and 2008 (Daniels et al. 1983; Daniels et al. 1984; Haering et al. 1990; Haering et al. 1993; Nash et al. 2016; Roberts et al. 1988b; Roberts et al. 1988c; Roberts et al. 1988a). In the early years, biomass production was significantly lower on the pure SiS and 1:2 SS:SiS treatments, but with time rock type effects diminished (Nash et al. 2016). Our study details changes in soil properties with time and not biomass production.

3.3.3. Rock Spoil Treatments

The rock spoils used in this experiment were associated with the Taggart and Taggart Marker coal seams within the Marcum Hollow Sandstone member of the Upper Wise Formation (Daniels et al. 1984). Sandstones and SiS low in total-S (<0.1%) with moderate levels of carbonate cements (2-3%) are common within the Upper Wise Formation and were chosen as the topsoil substitutes placed in the COPE (Daniels et al. 1984). Rock strata were generally <20 m below the surface and were generally gray and unoxidized, but a notable portion of the SS contained Fe-oxide stains and coatings on fracture trace surfaces. The SS spoils were therefore somewhat leached and oxidized, and contained approximately 1/3 unweathered gray clasts, while the SiS was almost entirely reduced, hard, and gray (Figure 3.1). Early in 1982 during experimental plot installation, the SS and SiS bulk rocks were separated into piles and thoroughly mixed with a front-end loader before and as they were placed into individual plots reflecting five different pure or mixed spoils (Table 3.1). Due to the sampling scheme used in 2016, results are presented for only the 100% SS, 1:1 SS:SiS, and 100% SiS spoil treatments.

Table 3.1. Spoil treatments and fertilizer added. Bold font indicates treatments sampled in 2016.

Treatment	Ratio Mixes	Fertilizer†
Sandstone (SS)	100% SS	N, P, K
2:1 SS:SiS	67% SS: 33% SiS	N, P, K
1:1 SS:SiS	50% SS: 50% SiS	N, P, K
1:2 SS:SiS	33% SS: 67% SiS	N, P, K
Siltstone (SiS)	100% SiS	N, P, K

†1120 kg ha^{-1} of 15-30-15 dry fertilizer initially, and 56 kg NH_4NO_3 ha^{-1} annually for three years.

3.3.4. Sampling and Analysis

3.3.4.1. Field Sampling

In August 2016, a total of 24 soil profiles between the RM and SA experiments were described at the COPE for morphological horizons, depth of horizons, rooting density, mine soil settling patterns, color, structure, texture class, relative bulk density, visual estimates of rock fragments, and other details (Appendix A2). Morphological descriptions were conducted

according to USDA-NRCS protocol (Schoeneberger et al. 2012). Three soil pits were dug in each of the 100% SS, 1:1 SS:SiS, and 100% SiS plots in the RM experiment (n=9). Each soil pit in 2016 was photographed on the day of sampling. The 1:2 and 2:1 SS:SiS rock mixes were not described or sampled in 2016. Additionally, a total of 370 individual soil and rock samples were collected from soil test pits and treatments. Samples were collected from each morphological horizon and in 10 cm intervals from 0-50 cm, and then from 50-75 and 75-100 cm, for a total of seven depth increments. Additionally, intact subsoil aggregates or clods were carefully pulled out from the faces of various soil pits, wrapped in soft tissue, and placed in small tins to protect them from shattering. The particle size control section (Soil Survey Staff 2014) for this study is from 25 cm to either a depth of 100 cm or a root-limiting layer, if shallower (i.e., restrictive layers found in ^Bw and/or transitional ^C horizons). At the time of early COPE reports, the caret (^) symbol was not used in *Soil Taxonomy* to denote horizons formed in human-altered and human-transported materials but was adopted by 2016. For consistency, the ^ symbol is used throughout this chapter.

3.3.4.2. Soil Analyses

Bulk samples from the field were air-dried in a greenhouse at Virginia Tech. Soil sized particles were passed through a 2-mm sieve to separate the fine earth fraction from rock fragments. Soil properties for 2016 samples were analyzed by major soil morphological horizons and for incremental depths and are reported in Section 3.4.2. May 1982 archived bulk samples (Figure 3.1) were analyzed for EC and SOC as presented in Section 3.4.3, which reports changes over time for important soil surface (≤ 10 cm) properties among datasets in the spring (May) and fall (October) of 1982 and in 1983, 1984, 1987, 2008, and 2016. If one of these years is not featured in the results, it indicates unavailable data in that year. Subsurface (≥ 20 cm) soil properties were analyzed across time using paired t-tests (Section 3.3.5) due to a lack of available data by year and different subsurface depth range in 2008 (i.e., 5-25 cm). Unless otherwise noted, soil analytical methods outlined below match the methods used for historical COPE datasets in 1982-1984 (Roberts et al. 1988a), 1987 (Haering et al. 1993), and 2008 (Nash et al. 2016). Due to lack of visual field estimates, rock fragment contents in Table 3.2 for 1985 and 1989 were based on laboratory bulk samples in 1984 at 0-5 and 25-30 cm depths, and in 1987 at 0-5 cm, respectively.

Cohesive intact clods were analyzed using a modification of the saran-coated clod method (Shipp and Matelski 1965). Since saran resin is in limited supply, we modified the clod bulk density method by Blake and Hartge (1986) using paraffin wax as the coating substance. Coated clods were immersed in a known density of liquid and clod weights were recorded before and after submersion to determine the volume of the displaced liquid and the displacement weight differential, and thus the clod density. The procedure by Hirmas and Furquim (2006) was used to correct for rock fragments. Clods previously collected from COPE SA plots in 1983 had been partially calculated for bulk density and results were finalized for this study. The 1983 values were numerically compared to 2016 bulk densities.

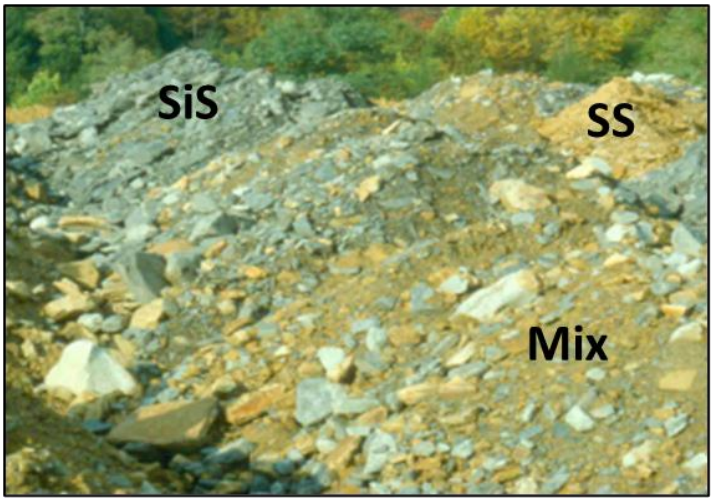

Figure 3.1. Original bulk-blended rock spoils in May 1982. 100% SiS and SS (background) and 2:1 SS:SiS (foreground). Photo by W. Lee Daniels used with permission.

Particle size distribution was determined on the < 2 mm fraction via the pipette method with removal of high OM in certain samples by H_2O_2 (Gee and Bauder 1986). Soil pH and EC data in Section 3.3.3 were analyzed by saturated paste (Rhoades 1996). Soil EC was also determined in a 1:2 soil:water ratio with a conductivity meter calibrated to a standard 0.01 *M* KCl solution for comparison of May 1982 archived bulk and 2016 horizon samples (Rhoades 1996). Extractable P data in Section 3.4.3 were analyzed by 0.5 *M* $NaHCO_3$ at pH 8.5 (Olsen and Sommers 1982). Soil pH data in Section 3.4.3 were measured in a 1:1 soil:water slurry with a glass-calomel combination electrode (McLean 1982). A dilute double-acid extract (Mehlich I) was

used to determine P, K, Ca, Mg, Zn, Mn, Cu, Fe, and B by an Optical Emission Spectrometry Inductively Coupled Plasma (ICP-OES) analyzing unit (Thermo Scientific, USA) (Donohue and Heckendorn 1996). Exchangeable cations (Ca, Mg, K, Na) were extracted by 1 *M* NH_4OAc buffered at pH 7 and analyzed by atomic absorption spectrophotometry (Thomas 1982). Exchangeable Al was determined by extraction with 1 *M* KCl and analyzed by titration with 0.1 *M* NaOH to pH 7 endpoint (Barnhisel and Bertsch 1982). Effective CEC was determined as the sum of exchangeable cations plus Al and percent base saturation was calculated as the quantity of exchangeable bases divided by CEC. Fe-and Mn-oxides were historically extracted using sodium dithionite-citrate-bicarbonate (DCB) and measured by atomic absorption spectrophotometry in early years and ICP-OES in 2008 and 2016 (Mehra and Jackson 1960).

Soil organic matter (SOM) was determined using the Walkley-Black method (Walkley and Black 1934) via wet oxidation (Nelson and Sommers 1996). Total-C and-N were determined using a controllable combustion Elementar^{tm} elemental analyzer (Nelson and Sommers 1996). Inorganic C (carbonates) sources were removed using HCl acid fumigation (Harris et al. 2001) and then total-C was run again. To estimate pedogenic SOC in 2016, we assumed that there was still a significant geogenic error in these mine soils after 34 years due to the recalcitrant nature of high rank bituminous coal. To account for all geogenic (coal and carbonate) sources, we analyzed the bulk (pre-treatment application) May 1982 samples to derive total-C minus carbonate-C, thus representing the "coal-C", assuming the original May 1982 bulk samples were devoid of any initial native accumulated organic C. These coal-C values from 1982 were then subtracted out from the total-C minus carbonate-C in the 2016 ^A horizon samples, thus presumably representing pedogenic SOC in the surface. To scale up corrected C values from percent, or mg kg^{-1}, to mass per area (g C per m^2), we used the 0-5 cm soil fines (g) data by Nash (2012) that were volumetrically sampled using a 0.093 m^2 quadrat given the assumption that there were no appreciable volumetric x mass differences in soil fines between 2008 and 2016. Since the estimated soil fines data by Nash (2012) were collected to a depth of 5 cm in 2008, the 2016 ^A horizons were adjusted on a plot-by-plot basis based on horizon thickness (e.g., fines for 10 cm ^A horizons were doubled). Sequestration rates were calculated by dividing SOC stocks by 34 years, assuming a linear sequestration rate, and reported as Mg C ha^{-1} $year^{-1}$.

3.3.5. Statistical Analyses

The COPE was instated in 1982 as a randomized complete block design (n=4). No block (location) level effects were detected for this experiment. All analyses were performed in JMP Pro software (JMP®, Version 15.1 SAS Institute Inc., Cary, NC, 1989-2019). To verify assumptions of normality and homogeneity of variance, visual and formal diagnostics were used. Significant differences were interpreted using an alpha = 0.05 for all analyses outlined below. Variations in soil properties across rock mix treatments were analyzed using a one-way analysis of variance (ANOVA) followed by Tukey's HSD test for means separation when the overall ANOVA was significant. Due to the inherent variation of spoil materials within plots by treatment (e.g., slightly higher proportion of brown material in some SS plots), we used a paired t-test to determine changes with time at a given depth by plot x treatment and a mixed model that included a random effect for plots to determine differences with depth. The mixed model included major morphological horizon (uppermost ^A, ^Bw, and lowermost ^C) or incremental depth (7 total) as the fixed effect and plot ID as the random effect, followed by Tukey's HSD test.

To analyze the effects of time on surface soil properties by treatment, a mixed model was used, including main effects (year and treatment), an interaction term (treatment x year), and a random effect (plot ID), followed by Tukey's HSD test. For mixed models, missing samples do not pose a problem (Wang and LA Goonewardene 2004), hence this approach was preferred due to limited samples per treatment in 2016 (n=3) vs. previous years (n=4). SigmaPlot was used for curvilinear regression analyses between soil parameters (SigmaPlot®, Version 12.5, Systat Software, Inc.). Due to limited available datasets, paired t-tests were used for time contrasts in subsurface soil properties and for EC contrasts between the 2016 horizon samples and May 1982 bulk samples. Surface (0-5 cm) and subsurface (25-30 cm) soil properties in previous datasets share the same depth intervals, except for the May 1982 bulk samples (Figure 3.1) which reflected the entire profile. Unless otherwise noted, the 2016 morphological ^A horizons (7 to 13 cm) and the 20-30 cm increment samples in 2016 were used for analyzing changes over time. While the 2016 depth intervals did not perfectly match depths used in previous years (i.e., 0-5 and 25-30 cm), they both included the same horizons and therefore we assumed that they were similar enough for time comparison analyses.

3.4. Results and Discussion

3.4.1. Morphological Properties Over Time

3.4.1.1. Horizon Sequences and Associated Properties

The 2016 soil profile descriptions revealed mine soil morphological properties that were different from earlier reports. Figure 3.2 depicts a conceptual model of changes over time using the 100% SiS treatment. Table 3.2 highlights select mine soil pedons from the COPE RM experiment in the years that morphological descriptions were made (1983, 1985, 1989, 2016). For complete and detailed soil profile descriptions, refer to Appendix A2. These original bulk spoils were high in rock fragments, particularly in the SiS spoils ($\bar{x}$ = 79%) due to their massive, hard and non-weathered nature, and as a result showed lower overall water holding capacities (Roberts et al. 1988a). Rapid physical weathering of coarse (> 2 mm) particles into silt and clay occurred across RM treatments within the first year (Daniels et al. 1983). In 1985, after three growing seasons, Roberts et al. (1988a) observed weak granular (gr) structure in ^A horizons tightly associated with grass rooting concentrated between rock fragments. Thickness of ^A horizons was consistent across treatments (0-6 cm). Soil texture was consistent in the SS and 1:1 SS:SiS spoils (sandy loam), while the SiS spoils typically had loam textures. By 1985, readily apparent morphological boundaries were noted in the subsurface (i.e., ^C1 and ^C2 horizons), presumably due to settling and weathering patterns. Also, thin (< 2 cm) Oe horizons comprised of partially decomposed tall fescue litter were evident in a few pedons. Further, Haering et al. (1993) showed that by 1989, ^A horizons were somewhat thicker (5-11 cm) and darker compared to earlier reports, and generally occurred above an ^AC horizon (10-20 cm). Weak to moderate gr and subangular (sbk) structure was observed in ^A and ^AC horizons, respectively. The SS spoil treatment had lower rock fragment contents in 1987 compared to earlier years. Deeper layers were commonly described as ^C2 with less compaction, common open bridging voids, and at least some rooting to the depth of the observed profile (Figure 3.3). Also, in 1989, one pedon was described with a cambic (Bw) horizon, though it likely did not meet the diagnostic criteria in *Soil Taxonomy*, which is discussed below in more detail.

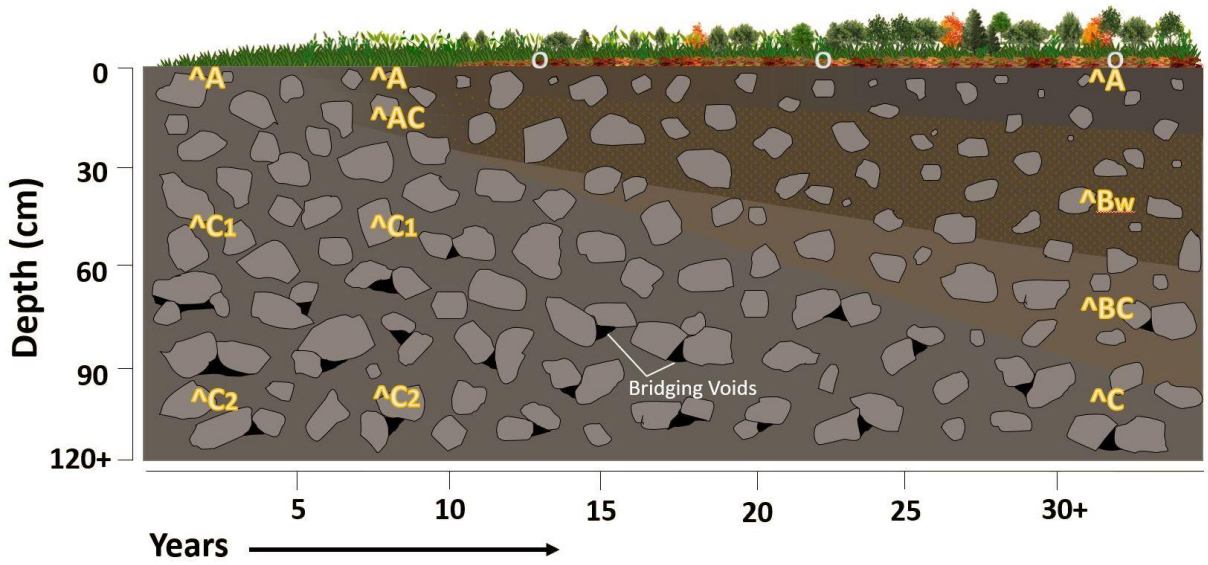

Figure 3.2. Graphical depiction of major morphological horizon development in 100% siltstone (SiS) derived mine soils over time at the COPE. This model is based on detailed soil descriptions made in 1983, 1985, 1989, and 2016 (Appendix A2) and associated laboratory data. Physical settling of spoil was also observed over time but is not depicted here.

There were no detailed soil profile descriptions made between 1989 and 2016. However, Nash (2012) volumetrically sampled coarse and fine fraction weights on all COPE RM and SA plots in 2008, which provided decent estimates of rock fragment contents at 0-5 and 5-25 cm depths. Based on this data, the average 0-5 cm rock fragment contents in the SS, 1:1 SS:SiS, and SiS spoil treatments were 53%, 56%, and 77%, respectively, and the average 5-25 cm rock fragment contents were 54%, 69%, and 71%, respectively. Surface rock fragment contents in 2008 were higher than our recent (2016) field visual estimates in the ^A horizons, which were upwards of 30%. However, our visual rock fragment observations only recognized relatively large rock fragments while the 2008 data were based on lab sieving of all rock fragments greater than 2 mm in relatively large bulk samples. Rock fragment estimates in 2016 were similar among spoil treatments, but generally appeared higher at subsoil depths for the SiS plots (see Appendix A2 for full profile descriptions). Despite some variability due to factors such as different sampling depth, method, and location, we identified below some general trends in changes in mine soil properties over time.

Table 3.2. Select sandstone (SS) and siltstone (SiS) pedons from historical profile descriptions at the RM experiment. Note: The 1:1 SS:SiS is not included here due to the lack of consistent descriptions made over time for plots in this treatment.

Plot No.	Rock Type	Horizons	Depth (cm)	Structure Type[+]	Texture [+]	Rock Frag. †	Color
1983							
1	SS	N/A*	N/A	N/A	N/A	N/A	N/A
4	SS	^A ^C	0-8 8-40+	1 f-m sbk 0 sls	l l	50-60%ł	10YR 4/3 10YR 4/3
9	SiS	^A ^C	0-10 10-75+	1 f-m sbk 0 sls	l/sil l/sil	70-80%ł	10YR 4/1 10YR 4/1
1985							
1	SS	^A ^C1 ^C2	0-5 5-36 36-110+	1 vf-f gr 0 sls/1 f-m sbk 0 sls	sl sl N/A	53% 63% -	10YR 4/4 10YR 4/4 10YR 4/4
4	SS	^A ^C1 ^C2	0-6 6-44 44-105+	1 vf-f gr 0 sls/1 f sbk 0 sls	sl sl N/A	58% 55% -	10YR 4/2 10YR 4/2 10YR 4/2
9	SiS	^A ^C1 ^C2	0-5 5-56 56-98+	1 vf-f gr 2 f-m gr/sbk 0 sls/2 f sbk	sil sil sil	89% 71% -	2.5Y 4/2 10YR 4/1 10YR 4/1
1989							
1	SS	^A ^AC ^C1 ^C2	0-7 7-17 17-51 51+	1 f sbk 1 m sbk 0 sls/1 sbk/pl 0 sls	sl sl sl sl	51% - - -	10YR 4/4 10YR 4/6 10YR 4/6 10YR 4/6
4	SS	N/A	N/A	N/A	N/A	54%	N/A
9	SiS	^A ^AB ^Bw ^C1 ^C2	0-9 9-20 20-36 36-49 49+	1 f gr/1 f sbk 1 m sbk 1 m sbk 0 sls 0 sls	sil sil sil l l	83% - - - -	10YR 3/2 10YR 4/1 10YR 4/1 10YR 4/1 10YR 4/1

Table 3.2. Continued.

2016							
1	SS	Oi	3-0	-	-	-	-
		^A	0-9	2 gr	l	15%	10YR 3/2
		^Bw	9-29	1 sbk	l	36%	10YR 4/4
		^C1	29-65	0 sls/1 sbk	l	55%	10YR 3/4
		^C2	65-125+	0 sls	l	55%	10YR 4/2
4	SS	Oi	4-0	-	-	-	-
		^A	0-7	2 gr	l	6%	10YR 3/2
		^BA	7-15	2 sbk	sl	20%	10YR 4/4
		^Bw	15-60	1 sbk	sl	50%	10YR 4/4
		^BC	60-97	1 sbk	sl	40%	10YR 4/4
		^C	97-125+	0 sls	cl	35%	10YR 4/1
9	SiS	Oi	3-0	-	-	-	-
		^A	0-13	2 gr	l	10%	10YR 3/1
		^Bw	13-41	1 sbk	cl	56%	10YR 3/2
		^BC	41-75	1 sbk	l	68%	10YR 3/2
		^C	75-125+	0 sls	l	53%	10YR 3/2

*Plot not described in that year.
[+]Codes for soil structure (grade, size, class) and texture classes by Schoeneberger et al. (2012).
†1985 values are based on 0-5 and 25-30 cm 1984 bulk samples; 1989 values are based on 0-5 cm 1987 bulk samples.
ŧVisual range estimate for the entire profile.

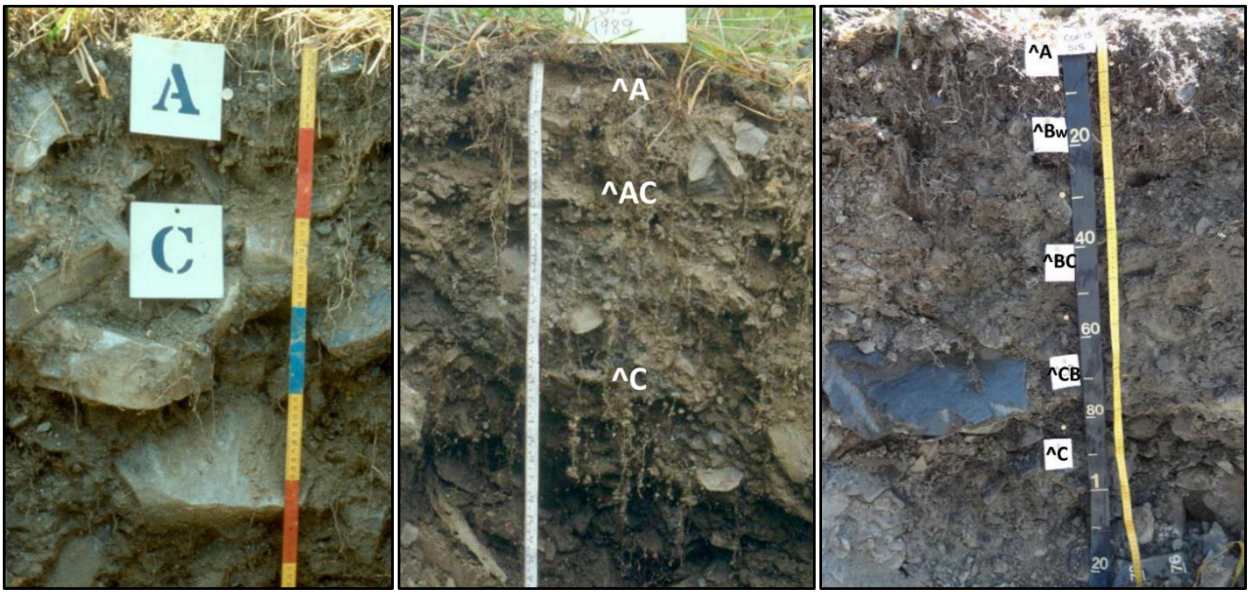

Figure 3.3. From left to right: One year-old 2:1 SS:SiS spoil, seven year-old 100% SiS spoil, and 34 year-old 100% SiS spoil. Photos by W. Lee Daniels used with permission.

In 2016, after a period of 34 years, several major changes in soil morphology were noted across spoil treatments, including: 1) Rock fragments decreased in size and total volume, particularly in the surface; 2) large bridging voids decreased in size and occurrence due to internal spoil self-collapse and weathering; 3) soil structure advanced to stronger grades in both surface and subsurface horizons (e.g., weak sbk progressing into moderate sbk); and, 4) soil color values and/or chromas were generally lower (i.e., darker) in the ^A horizons, and were generally higher (i.e., brighter) in the ^Bw horizons, particularly for SS derived mine soils (Table 3.2; Figs. 3.2 and 3.3; Appendix A2). Several additional new horizons had developed since 1989 within all the described plots and were generally delineated based on soil texture, structure, and color differences (Table 3.2). Changes in soil texture were also apparent over time, as detailed in Section 3.4.3. Deeper ^A horizons, transitional ^BC horizons, and relatively well-developed cambic horizons were delineated in most profiles in 2016. For the SS, 1:1 SS:SiS, and SiS spoil treatments, the average ^A horizon depth was 9, 10, and 12 cm, respectively, and the average depth to bottom of ^Bw horizons was 41, 38, and 36 cm, respectively (Figs. 3.4 and 3.5). Please refer to Appendix A3 for full sized photos of sandstone, 1:1 SS:SiS, and siltstone soil profiles.

All ^Bw horizons met the diagnostic criteria for the cambic horizon, primarily due to moderate structure development in over half of the soil volume. Other diagnostic criteria met by these horizons include the following: thickness of at least 15 cm, soil texture classes finer than very fine sand and loamy very fine sand, and higher chroma, higher value, or redder hue compared to the overlying or underlying horizon (Soil Survey Staff 2014). Sandstone derived mine soils typically had the best strength of peds. Clay films were not evident in ^Bw horizons, presumably due to the low clay content and relatively young age of these mine soils. All soil profiles across rock types had partially decomposed mixed leaf litter (Oi) horizons. There were no O horizons observed for the RM treatment plots in the earlier years that descriptions were made, but some were noted in the SA parallel experiment as discussed in Chapter 4. Additionally, these RM treatment plots, which were originally seeded to tall fescue, underwent plant successional changes as noted by the encroachment of woody shrub, vine, and tree species, many of which are native (Appendix A2). As expected, the soil morphological properties indicate that these rocky mine spoils are continuing to break down, incorporate organic matter, and differentiate a greater number

of overall horizons based on subtle shifts in soil properties. This mixed herbaceous system is at the early end of primary forest succession, which is reflected in the weak to moderate subsoil structural development.

Figure 3.4. Soil ^A horizons in the 100% SS spoil treatment (left) and 1:1 SS:SiS spoil treatment (right) in August 2016. Photos by Dan Johnson used with permission.

Figure 3.5. Soil ^Bw horizons in the 100% SS spoil treatment (left) and 1:1 SS:SiS spoil treatment (right) in August 2016. Photos by Dan Johnson used with permission.

3.4.1.2. Void Filling and Development of Subsoil Root Restrictive Layers

In 2016, compact root-limiting layers were observed within the ^Bw and/or upper transitional ^C horizons of most experimental plots. Root-limiting compaction was not widely observed in earlier years, suggesting that these zones are forming as the result of natural settling, mass flow, or illuviation of finer textured material over time. Some evidence of compaction was noted in 1983, but generally did not influence rooting and was likely a result of grading; however, bulldozer traffic was limited during plot installation. Compacted zones were also noted in 1985 and 1989 but were generally observed for deeper C horizons and were not root-limiting. In 2016, most subsoil horizons (^Bw and ^C) were noted in the field as having a higher bulk density relative to overlying and underlying horizons. Compacted zones were clearly recognizable during pit excavation and via manual probing with a soil knife and a pick. Additionally, overall rooting was restricted in these layers and where it occurred, was concentrated only along fragment faces.

Intact, cohesive clods were collected in subsoil horizons (> 25 cm depth) in 1983 and 2016 clods using similar methods. Clod bulk densities in 2016 were generally higher than clod bulk densities in 1983 when compared numerically on a plot-by-plot basis (Table 3.3). However, a few plots in 1983 showed similar or higher bulk density values vs. 2016. While earlier studies indicated limited subsoil compaction in a few pedons, the compacted layers observed in 2016 were common across most soil pedons. Subsoil bulk densities in 2016 ranged from 1.26 to 1.61 g cm^{-3} across RM and SA plots. For only the SA plots, the average bulk density was 1.45 g cm^{-3} and soil profiles generally contained loam, sandy loam, and to a lesser extent silt loam textures. According to Daddow (1983), sandy loams, loams, and silt loams with bulk density ranges approaching 1.65-1.75, 1.45-1.55, and 1.40-1.45 g cm^{-3}, respectively, are considered root-limiting for most plants, assuming lack of significant structural development and similar moisture conditions. These root-limiting bulk density values are generally in agreement with our observed bulk density values, further confirming the dense and root-restricting layers that were visually observed in 2016.

Table 3.3. Whole soil and fine earth fraction (< 2 mm) subsoil clod bulk densities in 1983 and 2016.

Treatment/ Plot No. ǂ	1983		2016	
	Whole Soil*	**Fine Earth**	**Whole Soil**	**Fine Earth**
	Bulk density (g cm^{-3})			
Sandstone (SS) #1	-	-	2.04	1.34
1:1 SS:SiS #2	-	-	1.99	1.26
Siltstone (SiS) #9	-	-	2.06	1.38
Topsoil #24	-	-	2.00	1.49
Sawdust #25	1.96	1.42	1.93	1.45
Control #26	1.87	1.45	1.97	1.61
BS[+] 56 Mg ha^{-1} #28	1.88	1.27	-	-
BS 112 Mg ha^{-1} #30	-	-	1.98	1.48
BS 112 Mg ha^{-1} #31	-	-	2.05	1.52
BS 112 Mg ha^{-1} #32	-	-	1.91	1.37
BS 56 Mg ha^{-1} #33	-	-	2.04	1.55
BS 56 Mg ha^{-1} #34	1.99	1.68	1.92	1.43
Sawdust #35	-	-	1.80	1.41
Control #36	-	-	2.03	1.39
Topsoil #39	1.88	1.18	1.94	1.37
Control #43	-	-	1.94	1.42
Sawdust #44	-	-	1.82	1.34
Topsoil #46	-	-	2.04	1.39
Bios 56 Mg ha^{-1} #47	-	-	2.09	1.52
Overall Mean†	**1.92**	**1.40**	**1.96**	**1.45**

ǂAverage of two clods per plot in 1983 and a single clod value per plot in 2016;
*Includes soil-sized fraction (< 2 mm) and hard mass rock fragments;
†Mean includes SA experiment only;
[+]BS=biosolids treatment loading rate.

These results align with other studies showing elevated mine soil bulk densities associated with mine spoil materials hauling, placement, and final grading activities that result in poor soil structural development and reduced tree performance over time (DeLong et al. 2012; Skousen et al. 2011). Gorman et al. (2001) measured soil bulk density on intact subsoil clods at a 30-year-old surface mine. Naturally revegetated sites had lower bulk density in ^Bw horizons (1.40 g cm^{-3})

compared to the more graded and manipulated planted sites (1.58 g cm^{-3}), likely due to the comparatively higher rock fragments and less structure development in the planted sites. Gorman and Sencindiver (1999) found that over a nine-year period in West Virginia, mine soil bulk density decreased, and soil structure improved, with the exception of fly ash treated mine soils. However, bulk densities were root-limiting within 8-60 cm for some profiles (i.e., 1.51 g cm^{-3} for clay loam texture; increased rooting along rock fragments). Thurman and Sencindiver (1986) found higher overall mine soil bulk densities (1.55-1.86 g cm^{-3}) and lower porosities compared to native soils. Given that mine soil aggregate formation in the subsoil horizons at the COPE has clearly strengthened over time, the presence of these relatively dense, root-restrictive subsoil layers noted in 2016 was surprising.

Relative to the appearance of root-limiting layers in our study by 1989, it is important to point out that a few other studies have documented mine soil compaction arising from mechanisms other than heavy machinery operations and grading. Haigh and Sansom (1999) observed densification through natural processes in much more fissile and finer textured shale derived coal mine spoils in Britain. Upon near-surface exposure, shale spoils underwent accelerated weathering and disintegrated into high amounts of clay sized particles that were lost to surface runoff or carried downward in soil profiles, accumulating in voids and originally looser fine-earth materials as dense (1.80 g cm^{-3}), concentrated layers that limited water and root movement. We may also find a better understanding of this "self-compaction" phenomenon in a very different pedogenic environment. Fragipans in Mississippi loess and compact glacial till in New York have been theorized to originate from silty or loamy sediments or till via "self-collapse" under their own weight following repeated wetting and shrink-swell events (Bryant 1989). Physical ripening, the main process in self-weight collapse, is based on initial wetting and desiccation (i.e., cracking of soil fabric), followed by repeated cycles of wetting and desiccation (Bryant 1989). Desiccation is accompanied by the illuviation of clays, silts, and/or soluble weathering products into lower-lying cracks during fabric rearrangement (i.e., wetting-desiccation). Eventually this process reaches its final stages as the fabric becomes so dense with close interlocking grain-to-grain contacts that the system resists further rearrangement. Notably, Bryant (1989) was also able to simulate this process in the laboratory for loamy glacial till materials following a relatively short number of wet/dry cycles.

Densification of natural soils may also involve the infilling of large voids such as those created by freeze-thaw cycles in cold climates (Schaetzl and Thompson 2015). Frenot et al. (1995) observed silt translocation as a result of frost heaving, resulting in silt-enriched horizons. Physical transport of silt is presumably less likely to occur than for much smaller colloidal clays via illuviation in percolating waters. Thus, for silt particles to migrate downward, soil macropores must be large enough for preferential flow and mass movement where they accumulate and physically plug pores (Schaetzl and Thompson 2015). Common large "bridging voids", or air-filled conduits between overlapping rock fragments, were documented in earlier (1983 and 1985) profile descriptions at the COPE but were almost entirely absent by 2016 in the upper profile (< 75 cm depths). Densification gradually occurred over the decades likely due to a combination of those processes. Weathering of overlying spoil materials, aided by wet-dry and freeze-thaw cycles, led to the well-documented weathering and slaking of rock fragments into soil sized particles, followed by the preferential flow of mixed particle sizes into bridging voids of lower horizons, leading to eventual self-collapse and settling. We hypothesize that this downward mass movement of fines likely occurred following major precipitation or snowmelt events where ephemeral saturated flow conditions could drive mass slurry flows. Over time, physical settling of spoils presumably reduced the size of bridging voids, while still allowing for the continued infilling and subsequent concentration of finer soil particles in subsoil macropores via percolating waters. Since there were no apparent chemical binding agents (e.g., carbonates) observed in 2016, the limited amount of finer clay sized soil particles along with simple interparticle attraction likely served as physiochemical bridging agents among the tightly packed coarse silt and sand grains. Overall, the resulting soil fabric was relatively dense and root-limiting.

3.4.1.3. Taxonomic Implications

According to *Soil Taxonomy* (Soil Survey Staff 2014), most of these mine soils classify as Dystric Eutrudepts since they meet the diagnostic criteria for the cambic (^Bw) subsurface horizon, have a base saturation percent greater than 60% between 25-75 cm, and do not contain free carbonates. For more detailed information on the taxonomic classification and interpretations of these coal mine soils, refer to Chapter 6. Previous efforts have mapped mine soils in this region

(southwestern Virginia) using the Sewell, Fiveblock, Kaymine, and Cedarcreek series concepts (all Typic Udorthents) for both pre- and post-SMCRA mined lands, which contained differing mine soil parent materials and depth classes due to differences in pre- and post-SMCRA reclamation methods (Haering et al. 2005). They also noted the common occurrence of densic contacts on older mine benches, which typically underwent heavy vehicle traffic. The dense, root-restrictive subsoil layers in the COPE mine soils may potentially impact rooting and overall useful soil depth. Land use suitability impacts such as poor internal drainage may occur due to these compacted zones as reported for other self-compacting shale-derived mine soils (Haigh 1992a; Haigh and Sansom 1999). However, there was no evidence (e.g., redox features) of poor internal drainage in 2016. Given a loam, silt loam, or fine sandy loam texture class for the higher bulk density subsoils (Table 3.3), these pedons would have an estimated moderately low saturated hydraulic conductivity (Ksat) (Schoeneberger et al. 2012) if rock fragment interactions are not considered. In the absence of densic contacts, these mine soils would be interpreted to support higher Ksat classes due to their rock fragment dominated (e.g., loamy skeletal) particle-size class as detailed below (Schoeneberger et al. 2012). *Soil Taxonomy* recognizes densic contacts in mine soils via the Anthrodensic subgroup: "Soils that have a densic contact due to mechanical compaction in more than 90 percent of the pedon (measured laterally) within 100 cm of the soil surface" (Soil Survey Staff 2014). However, this is only currently an option for Entisols and the compacted layers in these mine soils appear to be pedogenic. Current *Soil Taxonomy* includes a soil series differentiating option for densic materials (i.e., noncemented, root-limiting layers), which would be an appropriate series concept for these mine soils.

These mine soils fall within the loamy-skeletal particle size class since they contained rock fragment contents ≥ 35% and clay contents < 35% in the particle control section (Soil Survey Staff 2014) (see Appendix A2 for detailed visual estimations). Additionally, these mine soils include several different texture modifiers such as "very gravelly" since visual evaluations generally reported rock contents between 35% and 60% (Soil Science Division Staff 2017). Texture modifiers are used as phase criteria for soil survey map units (e.g., gravelly silt loam) when surface rock fragments are ≥ 15%, which affects soil management (e.g., ease of cultivation, water holding capacity, rooting depth, and soil-erodibility) (Nichols et al. 1984). Low soil pH is not a concern,

as these soils generally have nonacid reaction classes (≥ pH 5.5 in H_20, 1:1); however, the SiS soils are still approaching a pH of 8.0 at depths >10 cm. Overall, soil physical factors related to large rock fragments and densic layers create most of the nonagricultural land use and management limitations (e.g., building construction, conventional septic fields) (Thurman and Sencindiver 1986). Natural regional soils support forest and farmlands (primarily pastures) with high rock fragment contents, but their steep terrain limits many engineering land uses (Nichols et al. 1984). In contrast, relatively flat mined lands such as the ones the COPE was located on are desirable from an engineering and to a lesser extent agricultural standpoint, but still might be limited by rock fragments and bulk density.

3.4.2. Rock Spoil Treatment and Depth Effects

Particle size distribution

Rock spoil type effects were still apparent for most mine soil chemical and physical properties after 34 years, providing insight into the dominating influence of original SiS and SS spoils over an extended period of time. Here, we detail rock spoil treatment and depth (by horizon or depth increment) effects for the most recent 2016 dataset. Mine soil texture differences by depth (horizon) across spoil treatments are given in Figure 3.6. Generally, SiS soils were silt loam and loam textures, while SS soils were sandy loams and loams. For more details on field estimated texture, refer to Appendix A2. There were no differences with depth (horizon) for spoil treatments, although slight numerical differences were evident. In 2008, Nash (2012) found differences in soil texture between the 0-5 and 5-25 cm depths in several COPE spoil treatments, but the field sampling and analytical procedures used in 2008 to generate those results were different from this study. Overall, clay contents were relatively low (≤ 15%), which is not unusual for mine soils in this region (Miller et al. 2012). Ciolkosz et al. (1985) noted thin clay films primarily in older (> 15 yrs.) mine subsoils in PA, which generally had higher clay contents compared to these COPE mine soils. Those authors also found no consistent trends in clay content across mine soil depths.

Across ^A horizons, SS soils had higher sand content and lower silt content than SiS soils as would be expected. In the ^Bw horizons, sand was also highest and silt was lowest in the SS soils followed by the 1:1 SS:SiS and SiS soils. However, it is interesting to note that in the ^C

horizons, there were no differences in sand content among spoil treatments, but silt content was higher in the 100% SiS vs. SS soils. There were no treatment differences in clay content. Given these results, after 30+ years, differences in sand and silt contents are still strongly linked to the original parent rock materials, even in the fine earth fraction. It is also likely that the coarse fragments (> 2 mm) in these spoils are physically weathering to release more sand and silt sized particles at a faster rate than the release of clay particles or alteration of silt into clay sized minerals. In contrast to these SiS and SS spoils, shale derived spoils would likely weather into much finer soil textures with higher clay content (Miller et al. 2012). Additionally, in terms of relative weathering rates, there may be greater physical weathering occurring within surface horizons of the SS spoil treatments since their original spoil was partially weathered and oxidized materials and therefore less resistant.

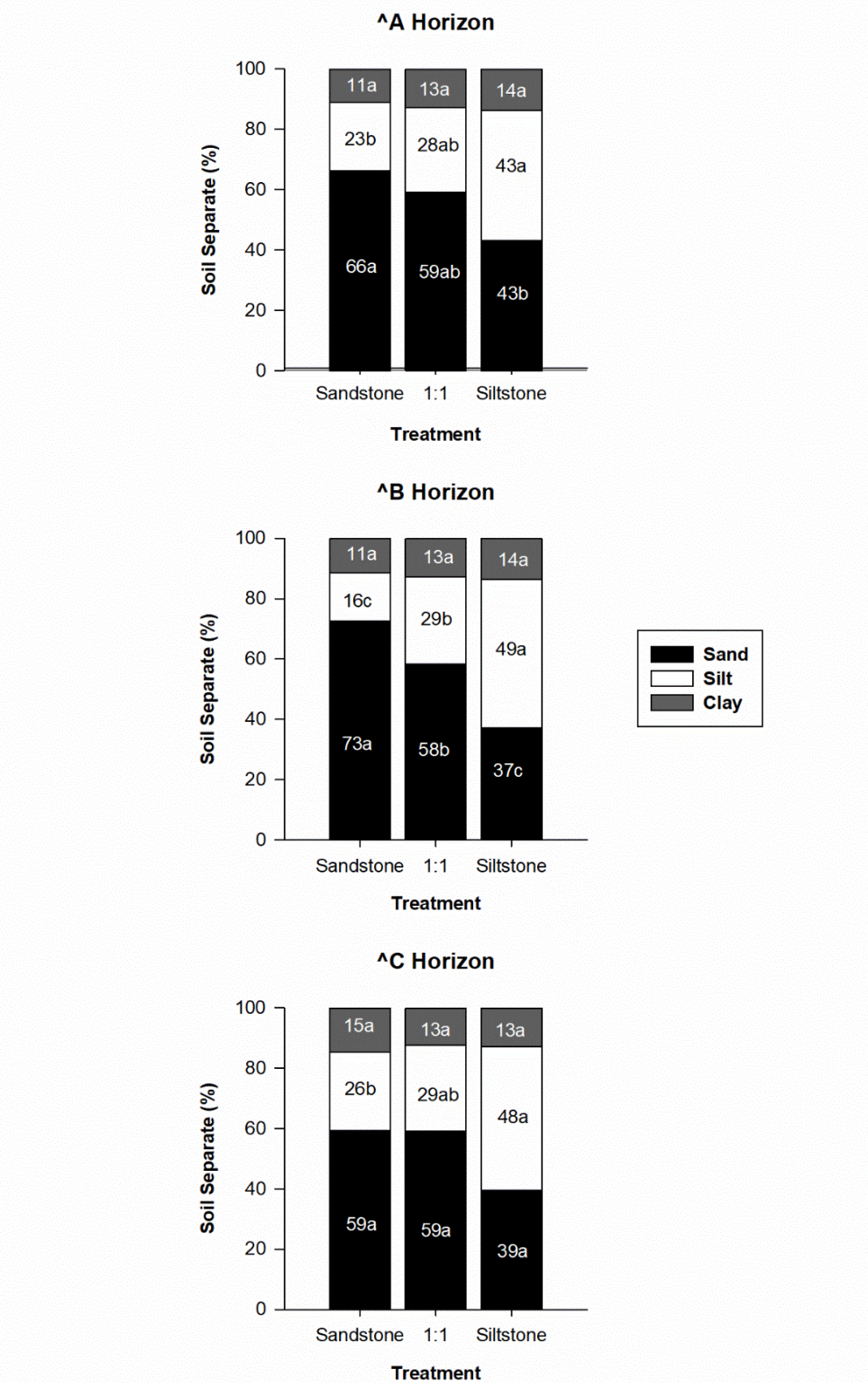

Figure 3.6. Sand, silt, and clay content by treatment and in major morphological horizon in 2016. Letters denote treatment differences across a given horizon ($P \leq 0.05$).

Soil pH

At 0-10 cm, there were no differences in soil pH among spoil treatments, but the SiS was numerically higher (Figure 3.7). Soil pH varied with incremental depth, especially in the 1:1 SS:SiS soils – pH gradually increased with depth, and became similar to the SiS soils after 30 cm. The spoil treatments reflected initial differences in the weathering status and carbonate content of the original parent rocks. Siltstone, being less weathered and much finer in grain size originally, provided higher levels of basic Ca^{2+} and Mg^{2+} via carbonate weathering compared to the SS spoils which were lower in pH originally due to the greater extent of pre-disturbance leaching and oxidation. Furthermore, the pH of SS soils stayed consistent with depth, while SiS soils had lower surface pH (0-10 cm) compared to all lower layers. The 1:1 SS:SiS spoils also had lower pH values in the upper 30 cm compared to lower layers. Over time, weatherable mineral phases rapidly dissolve (carbonates) and oxidize (Fe- and Mn-oxides) in the surface, lowering pH. The subsequent turnover of OM generates carbonic and organic acids that further enhance weathering, leading to the larger pH difference in the surface vs. subsurface for the initially much less weathered and more reactive 1:1 SS:SiS and SiS spoils. The pH of the pure SiS soils remained near 8.0 in the lower layers, indicating that trace carbonates were still present, even after 30+ years of weathering and leaching.

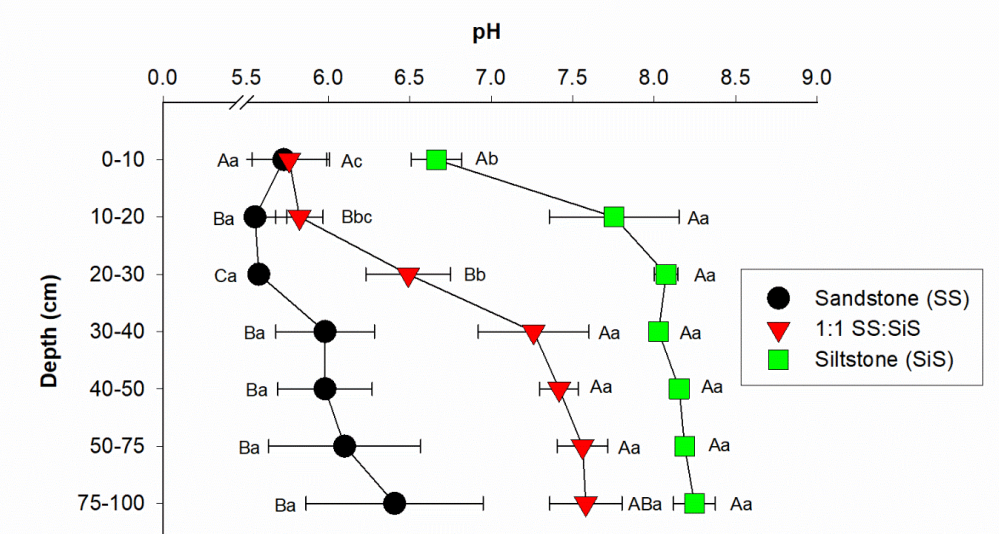

Figure 3.7. Saturated paste pH (mean ± SE) by treatment and depth after 34 years of mine soil weathering. Different uppercase letters denote treatment differences across a given depth and different lowercase letters denote differences among depths within a given treatment ($P \leq 0.05$).

Soil EC

There were no spoil treatment differences in the uppermost surface (0-10 cm) for EC (Figure 3.8). The SiS soils had higher EC levels compared to SS soils for all depths below 10 cm. Under 10 cm, the 1:1 SS: SiS soils varied more with depth than other rock types. The less weathered nature of the SiS soils coupled with their continued release of ions via carbonate dissolution explains lack of differences in EC across depths. Furthermore, the original strong rock spoil treatment differences (Roberts et al. 1988a) in near-surface EC levels have been minimized due to 30+ years of weathering, leaching, and OM accumulation processes. However, it is still clear that combined weathering and nutrient cycling processes have accumulated soluble ions in near-surface horizons of the SS and 1:1 SS:SiS plots. Electrical conductivities here are relatively low when compared to known plant growth limiting levels or leachate water quality issues (TDS drainage; Daniels et al. 2016), and instead reflect nutrient cycling effects, which have been observed in the surfaces of other mine soils (Pedersen et al. 1978; Schafer et al. 1980).

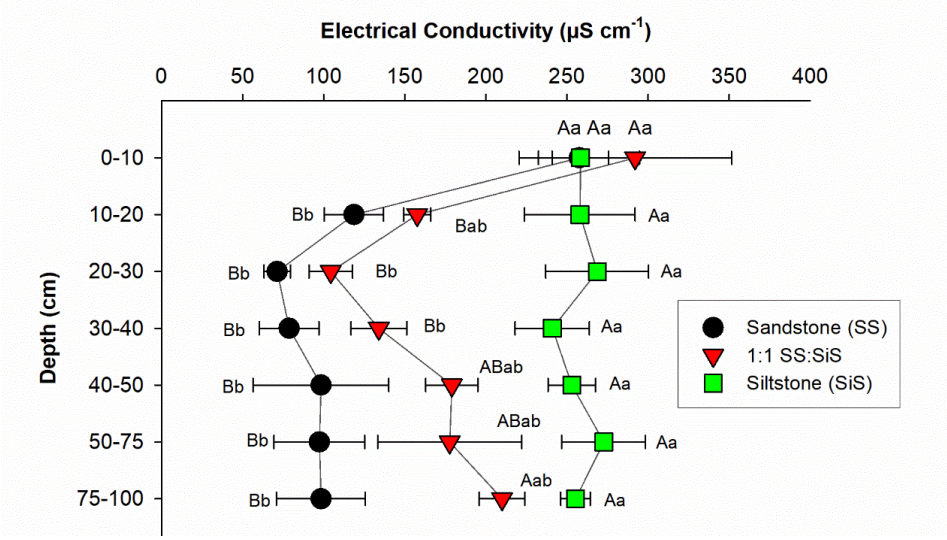

Figure 3.8. Saturated paste EC (mean ± SE) by treatment and depth after 34 years of mine soil weathering. Different uppercase letters denote treatment differences across a given depth and different lowercase letters denote differences among depths within a given treatment ($P \leq 0.05$).

Fe- and Mn-oxides

Extractable Fe- and Mn-oxides by treatment and horizon are presented in Table 3.4, and Fe-oxides data are also depicted in Figure 3.9. Fe-oxides in these sedimentary rock strata

originated primarily from trace pyrite along with cementing agents such as siderite ($FeCO_3$), other more complex carbonates (Howard et al., 1988), and various Fe-oxyhydroxides. Biotite and chlorite also occur in these strata from sand sized metamorphic rock fragments and may have contributed minor amounts of Fe as well (Clark et al. 2018). Over time, Fe-oxides accumulate as secondary weathering or re-mobilized products, primarily in amorphous phases as grain coatings, or are inherited from the parent material via dissolution and reprecipitation (Barrón and Torrent 2013). The mineral goethite (α-FeOOH) is common in the Wise Formation overburden rock strata existing as a single phase or a complex mixture with other minerals such as hematite and magnetite (Howard et al. 1988). In terms of treatment effects, the SS soils had higher Fe-oxides in the ^Bw horizons compared to other rock types, while in the ^A horizons, the SiS soils were higher in Mn-oxides. Higher extractable Fe-oxides were due to its pre-weathered nature as described earlier relative to the gray reduced SiS strata. These differences in Fe-oxides were readily visible in the 2016 soil profiles. For example, the SS derived mine soils contained more vibrant yellowish brown grain coatings compared to other rock spoils. Also, the lack of treatment differences in the surface may in part be a product of Fe-adsorption by OM. Depth effects were only evident in the SS spoils, where ^Bw horizon had higher Fe-oxides compared to the ^A horizons, suggesting that Fe-oxides forming within upper horizons had been translocated downward. Further, the sandier textures of SS spoils may have facilitated the movement of Fe-oxides relative to the much siltier SiS textures.

Table 3.4. Extractable Fe- and Mn-oxides by treatment and in major morphological horizon.

Oxides (%)	**Horizon**	**Rock Mix Treatment**		
		Sandstone (SS)	**1:1 SS:SiS**	**Siltstone (SiS)**
Iron (Fe)	^A	1.81 ± 0.04 Ab*	1.68 ± 0.11 Aa	1.49 ± 0.07 Aa
	^Bw	2.40 ± 0.08 Aa	1.85 ± 0.18 Ba	1.54 ± 0.08 Ba
	^C	2.10 ± 0.13 Aab	1.82 ± 0.25 Aa	1.50 ± 0.07 Aa
Manganese (Mn)	^A	0.05 ± 0.01 Ba	0.07 ± 0.00 ABa	0.08 ± 0.00 Aa
	^Bw	0.06 ± 0.01 Aa	0.06 ± 0.01 Aa	0.08 ± 0.01 Aa
	^C	0.08 ± 0.01 Aa	0.05 ± 0.01 Aa	0.07 ± 0.00 Aa

*****Mean ± SE. Different uppercase letters denote treatment differences across a given horizon and different lowercase letters denote differences among horizons within a given treatment ($P \leq 0.05$).

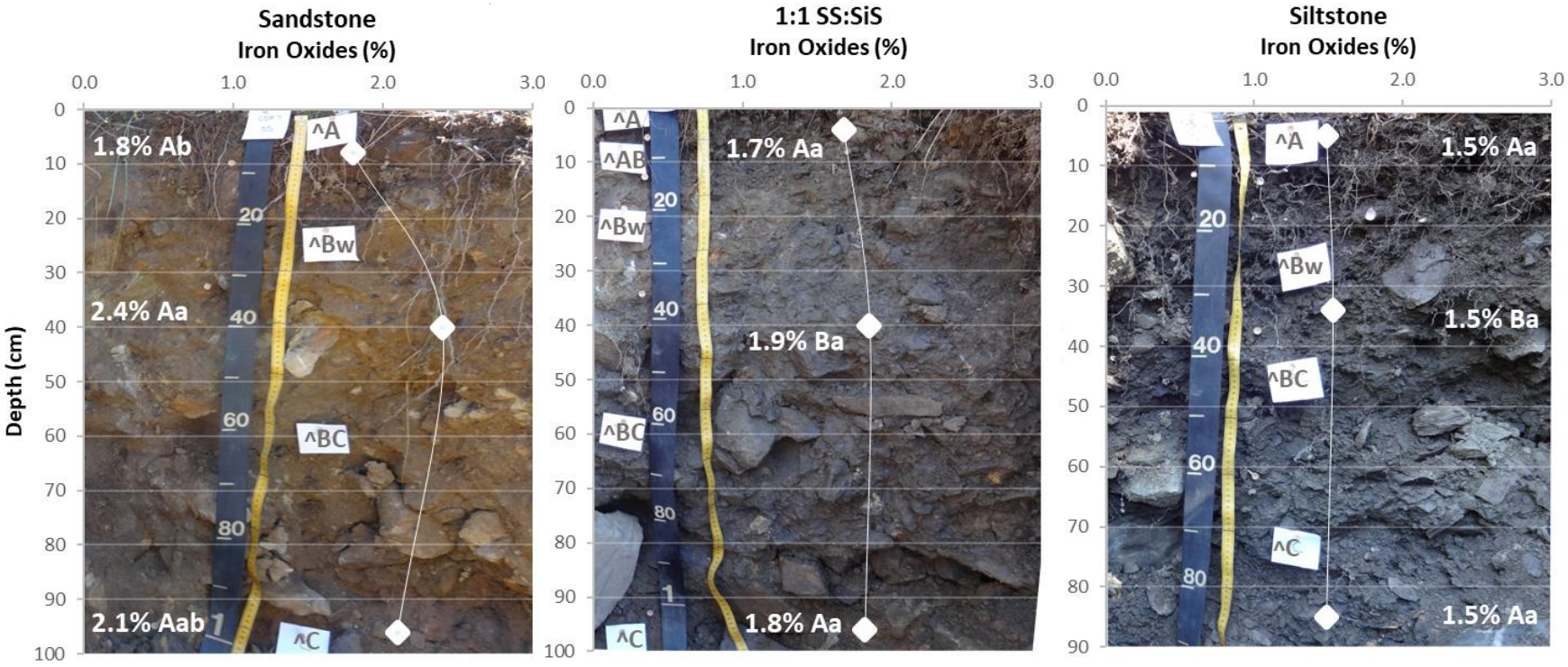

Figure 3.9. Extractable Fe-oxides by treatment and in major morphological horizon. Different uppercase letters denote treatment differences across a given horizon and different lowercase letters denote differences among horizons within a given treatment ($P \leq 0.05$).

With respect to cambic horizon development, the most evident physical alteration in these mine soils was the presence of moderate medium subangular blocky soil structure in at least half of the horizon's soil volume. Additionally, there were slight color differences (e.g., higher value and chroma) in ^Bw horizons vs. underlying or overlying horizons, particularly for the SS spoils. Soil structure was more defined in the ^Bw horizons of SS spoils compared to other spoil types, where Fe-oxides may have improved aggregation. Ciolkosz et al. (1985) found extractable Fe-oxides between 2 and 5% in mine soils ranging from 2 to 29 years old and values were similar to native soils. Generally, the older mine soils (> 20 years) had higher Fe-oxide contents than the 2-year-old mine soil and they did not find any depth effects, nor did Fe-oxides correspond with cambic horizon soil color. Also, the range of Fe-oxide values in their PA study were higher than the COPE mine soils and they noted likely elevated Fe release from weathering of acid-sulfate producing materials in the mine spoils. The COPE mine soils contained low levels (< 0.1%) of pyrite, but it would have oxidized very quickly. Pedersen et al. (1978) generally found higher Fe-oxide contents in native soils compared to mine soils. Free Fe-oxides of native sandstone derived soils (Typic Hapludults; Clymer series) in this region are similar to these mine soils, ranging from 0.8-1.8% on north facing slopes and 1.6-4.3% on southern slopes (Losche et al. 1970). However, the authors used sodium hydrosulphite in a slightly different extraction method.

Extractable nutrients and metals

Variations by treatment in acid extractable nutrients and metals across a given horizon (Table 3.5) were noted for P, Ca, Mg, Mn, Cu, and B, with the SiS soils often showing higher concentrations compared to SS and 1:1 SS:SiS soils. These effects were present in both ^A and ^Bw horizons for P and Mg, but only in ^Bw horizons for Ca, Mn, Cu, and B. No treatment effects were found in the lowermost ^C horizon for any element. Thus, differences in elements by treatment are likely due to sustained weathering release from the parent rock spoils (e.g., Ca, Mg, P are higher in SiS; Daniels and Amos, 1982). Also, the influence of pH, presence of carbonate cements, and rapid increases in Fe-oxides in the weathering spoils are controllers of the availability of certain nutrients and metals, particularly P. For example, low pH (< 6.0) generally decreases P solubility while carbonates and free Fe/Mn oxides will lead to P fixation at high and low pH levels,

respectively (Howard et al. 1988). Generally, nutrients and metals were higher in ^A horizons compared to subsoil horizons, but this varied across treatments. Phosphorus depth effects were present only for 1:1 SS:SiS soils, with higher concentrations in the ^Bw vs. ^A horizon. Potassium was higher in the surface of 1:1 SS:SiS and SiS soils, indicating that K-availability is more so a product of biological cycling rather than weathering release. Calcium and Mg depth effects were present for the 1:1 SS:SiS soils, with highest concentrations in the ^A vs. ^C horizon. Zinc and B were concentrated in the surface across all rock types. Magnesium was higher in the ^A vs. ^C horizon for SS and 1:1 SS:SiS soils. Iron depth effects were present only for the 1:1 SS:SiS soils, with higher concentrations in the ^Bw vs. ^C horizon. Lastly, Al was higher in the surface for 1:1 SS:SiS and SiS soils likely due to lower pH. Overall, these depth effects suggest that accumulation of acid extractable elements is occurring via nutrient cycling and associated OM accumulation in the surface. For these data, it is important to point out that interpretation of conventional soil testing extract data is notoriously difficult for these materials since they tend to dissolve large amounts of P and certain other elements from acid soluble cementing agents and mineral phases that are not "plant available" per se (Daniels & Amos, 1982). Thus, it is difficult to separate whether certain differences noted in this section are due to treatments, pedogenesis, or background weathering and mineral dissolution effects.

Table 3.5. Mehlich I extractable nutrients and metals by treatment and in major morphological horizon.

Element (mg kg^{-1})	Horizon	Rock Mix Treatment		
		Sandstone (SS)	1:1 SS:SiS	Siltstone (SiS)
Phosphorus (P)	^A	18 ± 2 Ba*	20 ± 3 Bb	39 ± 2 Aa
	^Bw	15 ± 11 Ba	54 ± 8 Aa	69 ± 7 Aa
	^C	23 ± 10 Aa	21 ± 4 Aab	30 ± 7 Aa
Potassium (K)	^A	138 ± 53 Aa	95 ± 12 Aa	78 ± 6 Aa
	^Bw	31 ± 3 Aa	35 ± 2 Ab	40 ± 3 Ab
	^C	40 ± 16 Aa	20 ± 11 Ab	42 ± 5 Ab
Calcium (Ca)	^A	890 ± 70 Aa	1196 ± 153 Aa	1622 ± 261 Aa
	^Bw	319 ± 69 Ba	619 ± 53 Bab	1713 ± 255 Aa
	^C	437 ± 187 Aa	335 ± 119 Ab	1861 ± 742 Aa
Magnesium (Mg)	^A	227 ± 21 Ba	314 ± 30 ABa	388 ± 48 Aa
	^Bw	138 ± 14 Ba	191 ± 9 Bab	551 ± 120 Aa
	^C	140 ± 52 Aa	102 ± 42 Ab	510 ± 188 Aa
Zinc (Zn)	^A	3.7 ± 0.1 Aa	4.7 ± 0.3 Aa	5.3 ± 0.7 Aa
	^Bw	1.3 ± 0.2 Ab	2.3 ± 0.3 Ab	2.2 ± 0.1 Ab
	^C	2.0 ± 0.8 Aab	0.9 ± 0.3 Ab	1.9 ± 0.2 Ab
Manganese (Mn)	^A	39 ± 6 Aa	39 ± 3 Aa	56 ± 7 Aa
	^Bw	19 ± 3.7 Cab	30 ± 0.9 Bab	52 ± 0.3 Aa
	^C	16 ± 4.9 Ab	14 ± 4.2 Ab	38 ± 9.3 Aa
Copper (Cu)	^A	0.9 ± 0.1 Aa	1.3 ± 0.4 Aa	1.9 ± 0.4 Aa
	^Bw	1.1 ± 0.2 Ba	2.7 ± 0.5 Aa	2.0 ± 0.2 ABa
	^C	1.7 ± 0.9 Aa	0.8 ± 0.3 Aa	1.6 ± 0.3 Aa
Iron (Fe)	^A	46 ± 2 Aa	39 ± 8 Aab	36 ± 4 Aa
	^Bw	32 ± 9 Aa	41 ± 2 Aa	39 ± 4 Aa
	^C	20 ± 9 Aa	15 ± 6 Ab	33 ± 5 Aa
Boron (B)	^A	0.3 ± 0.0 Aa	0.3 ± 0.1 Aa	0.6 ± 0.1 Aa
	^Bw	0.1 ± 0.02 Bb	0.1 ± 0.00 Bab	0.2 ± 0.01 Ab
	^C	0.1 ± 0.0 Ab	0.1 ± 0.0 Ab	0.1 ± 0.0 Ab
Aluminum (Al)	^A	118 ± 9 Aa	98 ± 9 Aa	94 ± 3 Aa
	^Bw	74 ± 8 Aa	68 ± 1 Aab	68 ± 2 Ab
	^C	49 ± 20 Aa	32 ± 18 Ab	65 ± 5 Ab

*****Mean ± SE. Different uppercase letters denote treatment differences across a given horizon and different lowercase letters denote differences among horizons within a given treatment ($P \leq 0.05$).

Total-C and-N

As expected, total levels of C and N were higher in the ^A horizons vs. the subsurface for all treatments due to OM accumulation (Table 3.6). The C:N ratio was higher in the ^Bw and/or ^C horizon compared to the surface for all spoil treatments, reflecting higher relative levels of geogenic (coal + carbonate forms) C and lower levels of N. Total-C and -N were higher for 1:1 SS:SiS and SiS soils compared to SS soils in the ^Bw horizon. Treatment differences in the subsurface are likely due to higher geogenic forms existing within the 1:1 SS:SiS and SiS soils (Li and Daniels 1994). There were no treatment differences in the C:N ratio across surface and subsurface horizons. Much more detail on the influence of geogenic C and associated complications in interpreting OM levels in these mine soils is provided by Nash (2012) and later in Section 3.4.3.

Table 3.6. Soil total-C and -N and C:N ratio by treatment and in major morphological horizon.

Parameter	**Horizon**	**Rock Mix Treatment**		
		Sandstone (SS)	**1:1 SS:SiS**	**Siltstone (SiS)**
Total-C (%)	^A	3.48 ± 0.33 Aa*	4.62 ± 0.42 Aa	5.17 ± 0.46 Aa
	^Bw	0.97 ± 0.18 Bb	1.76 ± 0.15 Ab	2.09 ± 0.03 Ab
	^C	1.78 ± 0.54 Aab	1.50 ± 0.31 Ab	2.12 ± 0.29 Ab
Total-N (%)	^A	0.23 ± 0.03 Aa	0.31 ± 0.02 Aa	0.34 ± 0.05 Aa
	^Bw	0.04 ± 0.01 Bb	0.06 ± 0.00 Ab	0.08 ± 0.00 Ab
	^C	0.06 ± 0.02 Ab	0.05 ± 0.01 Ab	0.07 ± 0.00 Ab
C:N Ratio	^A	15.21 ± 0.75 Ab	14.95 ± 0.58 Ab	15.65 ± 1.34 Ab
	^Bw	25.73 ± 1.58 Aab	27.68 ± 2.62 Aa	27.93 ± 1.26 Aa
	^C	27.16 ± 0.83 Aa	32.46 ± 2.03 Aa	30.78 ± 2.75 Aa

*****Mean ± SE. Different uppercase letters denote treatment differences across a given horizon and different lowercase letters denote differences among horizons within a given treatment ($P \leq 0.05$).

Exchangeable cations

Exchangeable cations, cation exchange capacity (CEC), and base saturation data are presented in Table 3.7. Treatment effects were only apparent in the ^Bw horizons, where Ca and CEC were higher in SiS soils, Mg was higher in 1:1 SS:SiS and SiS soils, and Al was higher in SS soils. The SiS soils were higher in total bases and CEC in the ^Bw horizons most likely due to the inherently higher silt + clay content and 2:1 minerals in the silt fraction, and the overall less weathered nature of this rock type compared to SS. Also, the 1:1 SS:SiS and SiS soils had moderate pH levels (5.6-6.3) and were likely able to generate comparatively higher pH-dependent charges from accumulating Fe-oxides and OM. However, the higher CEC in SiS soils may be a product of the CEC method used (ammonium acetate) which is known to enhance dissolution of carbonates in the procedure. Furthermore, variations in depth by treatment revealed that CEC was higher in ^A horizons versus ^Bw horizons for SS and 1:1 SS:SiS soils and were driven by Ca (Table 3.7). Surface (^A) K was higher for 1:1 SS:SiS and SiS soils, while Mg was higher in the 1:1 SS:SiS soils. These depth effects were likely due primarily to OM accumulation, but the weathering 2:1 minerals might be a contributing factor. Generally, the ranges for CEC and exchangeable Ca, Mg, K, Na, and Al across horizons and spoil types were similar to values reported in Thomas et al. (2001) and Skousen et al. (1998) for somewhat younger WV mine soils derived from SS and SiS/shale rock strata. Overall differences in soil chemical properties are due to differences in rock spoil mineralogy (e.g., K-bearing minerals) and texture (Thomas et al. 2001), and extent of pre-disturbance weathering. Base saturation is clearly not a limiting factor in these mine soils, which is commonly high in this region across a variety of rock spoil types (≥ 80% base saturation) (Miller et al. 2012).

Table 3.7. Exchangeable bases, Al, and CEC, expressed as $cmol_c\ kg^{-1}$ soil, and percent base saturation by treatment and in major morphological horizon.

Parameter ($cmol_c\ kg^{-1}$)	Horizon	Rock Mix Treatment		
		Sandstone (SS)	1:1 SS:SiS	Siltstone (SiS)
Calcium (Ca)	^A	4.10 ± 0.62 Aa*	5.36 ± 0.60 Aa	7.76 ± 1.80 Aa
	^Bw	1.37 ± 0.20 Bb	2.28 ± 0.13 Bb	3.70 ± 0.48 Aa
	^C	2.81 ± 0.24 Aab	4.02 ± 0.80 Aab	5.94 ± 1.39 Aa
Magnesium (Mg)	^A	2.01 ± 0.29 Aa	2.72 ± 0.17 Aa	3.61 ± 0.70 Aa
	^Bw	1.13 ± 0.12 Ba	1.56 ± 0.06 Ab	1.62 ± 0.04 Aa
	^C	1.70 ± 0.17 Aa	1.73 ± 0.14 Ab	1.78 ± 0.21 Aa
Potassium (K)	^A	0.30 ± 0.07 Aa	0.30 ± 0.05 Aa	0.27 ± 0.04 Aa
	^Bw	0.10 ± 0.02 Aa	0.10 ± 0.01 Ab	0.11 ± 0.01 Ab
	^C	0.12 ± 0.03 Aa	0.11 ± 0.00 Ab	0.13 ± 0.01 Ab
Sodium (Na)	^A	0.03 ± 0.00 Aa	0.03 ± 0.00 Aa	0.02 ± 0.01 Aa
	^Bw	0.02 ± 0.00 Aa	0.02 ± 0.00 Aa	0.02 ± 0.00 Aa
	^C	0.03 ± 0.01 Aa	0.04 ± 0.01 Aa	0.02 ± 0.00 Aa
Aluminum (Al)	^A	0.18 ± 0.05 Aa	0.15 ± 0.07 Aa	0.06 ± 0.01 Aa
	^Bw	0.48 ± 0.18 Aa	0.01 ± 0.01 Ba	0.02 ± 0.02 Ba
	^C	0.03 ± 0.03 Aa	0.02 ± 0.01 Aa	0.02 ± 0.02 Aa
CEC†	^A	6.61 ± 1.00 Aa	8.55 ± 0.72 Aa	11.74 ± 2.53 Aa
	^Bw	3.10 ± 0.11 Bb	3.97 ± 0.20 Bb	5.48 ± 0.48 Aa
	^C	4.69 ± 0.44 Aab	5.92 ± 0.95 Aab	7.87 ± 1.59 Aa
Base Saturation (%)	^A	97.3 ± 0.9 Aa	98.1 ± 1.7 Aa	99.4 ± 0.1 Aa
	^Bw	84.1 ± 11.2 Aa	99.8 ± 0.3 Aa	99.6 ± 0.6 Aa
	^C	99.4 ± 1.1 Aa	99.6 ± 0.3 Aa	99. 6 ± 0.6 Aa

†CEC is estimated as the sum of total exchangeable Ca, Mg, K, Na, and Al.

*****Mean ± SE. Different uppercase letters denote treatment differences across a given horizon and different lowercase letters denote differences among horizons within a given treatment ($P \leq 0.05$).

3.4.3. Changes in Soil Physical and Chemical Properties Over Time

Soil texture, Fe-oxides, P, pH, CEC, and SOM changed significantly with time, but in different ways from each other (Table 3.8). All except P were also significantly affected by rock spoil type. Sand and silt contents, Fe-oxides, pH, and CEC showed treatment x year interaction effects, indicating that the relative effect of time on a given parameter was not consistent across rock types for all years, i.e., the relative effect varied somewhat from year-to-year. Overall treatment x time x interaction effects for all soil parameters by model level are presented in separate tables below.

Table 3.8. Mixed model p-values for selected mine soil properties in the surface.

Model Source	Sand	Silt	Clay	Fe-oxides	P	pH	CEC	SOM
	(%)				mg kg^{-1}		$cmol_c$ kg^{-1}	(%)
Year	**<0.0001***	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Treatment	**<0.0001**	**<0.0001**	**0.0003**	**0.0023**	0.1211	**<0.0001**	**<0.0001**	**0.0001**
Year x Treatment	**0.0242**	**0.0166**	0.2222	**0.0142**	0.4829	**0.0020**	**0.0049**	0.5806

*Bold font represents significant differences by parameter x model level ($P \leq 0.05$).

3.4.3.1. Particle Size Distribution Over Time

Surface (^A) texture varied by treatment for most years (Table 3.9). After October 1982, sand contents were generally lower in the SiS soils compared to other rock types and silt contents were generally higher in SiS soils vs. SS soils. Differences in sand, silt, and clay contents with time were evident, particularly in the SiS soils; however, trends were not dramatic nor consistent (Tables 3.9-3.10). For example, sand contents in the SiS soils fluctuated from year-to-year and did not show a steady increase or decrease over time. Overall time effects across treatments, however, indicated that sand contents decreased, and silt contents increased. Generally, for the SiS soils, the 2008 particle size distribution was different from earlier years, but this was not the case for 2016. Also, there were no sand, silt, and clay content differences between 2008 and 2016. These data indicate that sand and silt liberation from parent rocks greatly influenced particle size distribution.

Table 3.9. Year x treatment (interaction) pairwise differences for certain soil surface properties.

Year	Soil Age (yrs.)	Sandstone (SS)	1:1 SS:SiS	Siltstone (SiS)
		Sand (%)		
May 1982	0	69 ± 1.0 a*	62 ± 1.7 abc	59 ± 4.6 abcd
Oct. 1982	0.5	71 ± 0.9 a	64 ± 3.6 abc	49 ± 2.2 cde
1983	1	65 ± 3.1 ab	60 ± 0.6 abcd	51 ± 7.1 bcde
1987	5	68 ± 1.9 a	60 ± 2.1 abcd	39 ± 1.4 ef
2008	26	62 ± 0.9 abc	50 ± 0.6 bcde	31 ± 1.2 f
2016	34	66 ± 1.4 ab	59 ± 4.2 abcd	44 ± 6.9 def
		Silt (%)		
May 1982	0	22 ± 0.6 g	28 ± 1.6 cdefg	30 ± 3.9 cdefg
Oct. 1982	0.5	20 ± 0.8 g	26 ± 3.1 efg	39 ± 1.7 abcde
1983	1	27 ± 3.2 defg	31 ± 0.45 cdefg	38 ± 6.8 bcdef
1987	5	23 ± 1.6 g	30 ± 1.0 cdefg	48 ± 1.2 ab
2008	26	25 ± 1.4 efg	39 ± 2.0 abcd	52 ± 1.7 a
2016	34	23 ± 1.5 fg	28 ± 2.7 cdefg	43 ± 5.9 abc
		Fe-oxides (%)		
May 1982	0	0.52 ± 0.01 ghi*	0.47 ± 0.02 hig	0.27 ± 0.03 ig
Oct. 1982	0.5	0.35 ± 0.07 hij	0.24 ± 0.00 ij	0.17 ± 0.02 j
1983	1	1.24 ± 0.06 bc	1.08 ± 0.07 cde	0.65 ± 0.10 fgh
1984	2	0.91 ± 0.02 def	0.85 ± 0.06 efg	0.56 ± 0.05 ghi
1987	5	1.19 ± 0.01 bcde	1.20 ± 0.10 bcd	1.03 ± 0.10 cde
2008	26	1.29 ± 0.07 bc	1.31 ± 0.11 bc	1.18 ± 0.08 bcde
2016	34	1.81 ± 0.04 a	1.68 ± 0.11 a	1.49 ± 0.07 ab
		pH		
May 1982	0	5.9 ± 0.4 efg	7.1 ± 0.3 abc	8.0 ± 0.1 a
Oct. 1982	0.5	5.5 ± 0.3 fgh	6.7 ± 0.2 bcde	7.5 ± 0.1 ab
1983	1	5.0 ± 0.4 h	6.2 ± 0.1 cdefg	6.6 ± 0.0 cde
1984	2	5.3 ± 0.1 gh	6.2 ± 0.2 defg	6.3 ± 0.2 cdefg
1987	5	5.4 ± 0.3 fgh	6.6 ± 0.1 bcde	7.1 ± 0.1 bcd
2008	26	5.7 ± 0.1 efgh	6.1 ± 0.1 defg	6.5 ± 0.2 cdef
2016	34	5.6 ± 0.1 efgh	5.8 ± 0.1 efgh	6.1 ± 0.1 cdefg
		CEC ($cmol_c\ kg^{-1}$)		
May 1982	0	3.3 ± 0.3 j	4.2 ± 0.2 hij	5.2 ± 0.2 ghij
Oct. 1982	0.5	5.3 ± 0.5 ghij	7.5 ± 0.4 defg	8.6 ± 0.3 cde
1983	1	3.7 ± 0.3 ij	5.1 ± 0.2 ghij	5.5 ± 0.3 fghij
1984	2	3.7 ± 0.2 ij	5.6 ± 0.1 fghij	7.1 ± 0.2 efgh
1987	5	5.1 ± 0.8 ghij	8.0 ± 0.1 defg	10.1 ± 0.2 bcd
2008	26	7.7 ± 0.5 defg	10.9 ± 0.4 bc	14.2 ± 0.3 a
2016	34	6.6 ± 1.0 efghi	8.6 ± 0.7 bcdef	11.7 ± 2.5 ab

*Mean ± SE. Different letters show differences among years for a given treatment (columns), as well as differences by treatment within a given year (rows) ($P \leq 0.05$).

Overall, as separated by main effects, clay contents in these mine soils generally showed an increasing trend with time and were highest in the SiS soils (Table 3.10). Rock spoils initially contained an assortment of clay minerals, especially mica, followed by kaolinite, vermiculite, and montmorillonite (Daniels et al. 1991). Over much longer periods of time, we expect to see greater clay contents and abundance of pedogenic minerals in the clay fraction as is common in highly weathered native soils (Losche et al. 1970). Johnson and Skousen (1995) did not find soil textural differences across time or profile depths in similarly aged (15-35 yrs.) coal mine soils in WV.

Table 3.10. Main effects (year and treatment) pairwise differences for certain soil surface properties.

Year	Mean ± SE by Year/ All Treatments	Soil Age (yrs.)	Treatment	Mean ± SE by Treatment/ All Years
Clay (%)				
May 1982	9.9 ± 0.4 c*	0	Sandstone (SS)	9.8 ± 0.4 B**
Oct. 1982	10.5 ± 0.6 bc	0.5		
1983	9.4 ± 0.5 c	1	1:1 SS:SiS	10.3 ± 0.5 B
1987	10.5 ± 0.7 bc	5		
2008	13.7 ± 1.1 a	26	Siltstone (SiS)	13.1 ± 0.6 A
2016	12.6 ± 0.7 ab	34		
Extractable P (mg kg^{-1})				
May 1982	4.7 ± 0.7 d	0	Sandstone (SS)	38.6 ± 5.0 A
Oct. 1982	71.8 ± 5.0 a	0.5		
1983	42.8 ± 2.6 b	1	1:1 SS:SiS	32.6 ± 4.6 A
1984	40.4 ± 3.8 b	2		
1987	25.8 ± 2.8 c	5	Siltstone (SiS)	30.0 ± 5.1 A
2008	16.9 ± 1.4 c	26		
SOM† (%)				
May 1982	-	0	Sandstone (SS)	3.9 ± 0.6 C
Oct. 1982	2.3 ± 0.3 d	0.5		
1984	3.1 ± 0.3 d	2	1:1 SS:SiS	5.2 ± 0.7 B
1987	4.5 ± 0.4 c	5		
2008	9.6 ± 0.6 a	26	Siltstone (SiS)	6.9 ± 0.8 A
2016	7.9 ± 0.8 b	34		

*Lowercase letters show overall differences for each year among all treatments ($P \leq 0.05$).
**Uppercase letters show overall differences for each treatment among all years ($P \leq 0.05$).
†As estimated using Walkley-Black method.

There were no differences in subsurface horizon sand and silt contents between May 1982 and 2016 or between 1983 and 2016 (Table 3.11). However, there was an increase in subsurface clay content from 1983 to 2016 for the SS spoils and other temporal trends ($p < 0.10$) were apparent for clay. Thus, 34+ years of weathering is clearly generating soil textural changes, particularly in the surface. However, soil texture changes with time were often inconsistent and complex, especially for sand and silt, indicating that mine soil texture continues to be driven by the original parent material, but is modified by weathering. Sena et al. (2021) found similar fluctuating trends in soil texture over time in eastern KY mine spoils. They found weak relationships in sand, silt, and clay contents across a 19-year chronosequence. Silt and clay had the least complex relationships and generally showed an increasing trend with time. For COPE mine soils, a more apparent shift in overall soil texture is expected to occur after several more decades or perhaps longer. Additionally, illuvial clay in subsoil horizons is notable in developing soils over much longer periods of time (> 100 years) (Hallberg et al. 1978).

3.4.3.2. Soil Chemical Properties Over Time

Extractable Fe-oxides in the surface differed across spoil rock types only in two years—in 1983, the SS and 1:1 SS:SiS soils were higher than the SiS soils, and in 1984, the SS soils were higher than the SiS soils (Table 3.9). Haering et al. (1993) noted that these early treatments effects were likely due to SiS containing less oxidizable Fe compounds in raw spoils. At the beginning of the experiment, Fe-oxides rapidly decreased from May 1982 to October 1982 during initial revegetation, and then steadily increased over time. Fe-oxides were the highest in 2016 compared to previous years for all rock mix treatments. It is important to note that previous reports show elevated total-Fe contents in Wise formation overburden strata (0.5% to upwards of 10%) (Howard 1979), explaining the initial moderate surface concentrations across all treatments. Subsurface Fe-oxides were highest in 2016 compared to October 1982 and 1984 (Table 3.12). These results indicate that oxidation is a sustained chemical weathering response in these mine soils regardless of the initial rock type and extent of spoil pre-weathering (e.g., brown vs. gray).

Table 3.11. Subsurface particle size distribution (mean ± SE), paired t-test delta values, and two-tailed p-values comparing values in a previous year to 2016, therefore an increase over time is shown as a negative delta value.

Treatment	Sand (%)							
	May 1982	**2016**	Δ†	**P > |t|***	**1983**	**2016**	Δ†	**P > |t|***
Sandstone (SS)	68 ± 1.1	71 ± 1.7	-2.3	0.4257	70 ± 1.3	71 ± 1.7	-0.4	0.8670
1:1 SS:SiS	63 ± 2.0	59 ± 5.0	4.3	0.5988	63 ± 0.7	59 ± 5.0	4.0	0.5529
Siltstone (SiS)	59 ± 6.5	40 ± 2.0	18.8	0.1239	50 ± 4.6	40 ± 2.0	10.2	0.1263
	Silt (%)							
Sandstone (SS)	22 ± 0.8	18 ± 1.9	4.1	0.2368	21 ± 1.3	18 ± 1.9	2.7	0.3881
1:1 SS:SiS	27 ± 1.7	28 ± 4.5	-1.3	0.8503	27 ± 2.1	28 ± 4.5	-1.1	0.8756
Siltstone (SiS)	30 ± 5.5	47 ± 1.5	-16.7	0.0931	40 ± 3.3	47 ± 1.5	-6.8	0.2237
	Clay (%)							
Sandstone (SS)	9 ± 0.4	11 ± 0.2	-1.7	0.0803	9 ± 0.1	11 ± 0.2	-2.2	**0.0248**
1:1 SS:SiS	10 ± 0.9	13 ± 0.7	-3.2	0.1120	10 ± 1.5	13 ± 0.7	-3.0	0.0610
Siltstone (SiS)	11 ± 1.0	13 ± 0.8	-2.1	0.3577	9 ± 1.7	13 ± 0.8	-3.4	0.0783

†Mean delta values or the difference in values between two years (e.g., May 1982 - 2016).
*Delta values were used to test the difference in means between years for a given treatment and interpreted by the two-tailed p-value ($\alpha = 0.05$). Bold represents a significant difference.

Table 3.12. Select subsurface chemical properties (mean ± SE), paired t-test delta values, and two-tailed p-values comparing values in a previous year to 2016, therefore an increase over time is shown as a negative delta value.

Treatment	Fe-oxides (%)							
	Oct. 1982	**2016**	Δ†	**P > |t|***	**1984**	**2016**	Δ†	**P > |t|***
Sandstone (SS)	0.28 ± 0.01	1.56 ± 0.02	-1.28	**0.0001**	0.93 ± 0.07	1.56 ± 0.02	-0.63	**0.0076**
1:1 SS:SiS	0.24 ± 0.02	1.64 ± 0.19	-1.40	**0.0150**	0.74 ± 0.04	1.64 ± 0.19	-0.90	**0.0263**
Siltstone (SiS)	0.18 ± 0.05	1.69 ± 0.08	-1.51	**0.0039**	0.72 ± 0.11	1.69 ± 0.08	-0.97	**0.0023**
Treatment	**pH**							
	Oct. 1982	**2016**	Δ†	**P > |t|***	**1984**	**2016**	Δ†	**P > |t|***
Sandstone (SS)	6.3 ± 0.6	6.0 ± 0.3	0.29	0.7199	5.9 ± 0.1	6.0 ± 0.3	-0.08	0.8705
1:1 SS:SiS	7.1 ± 0.4	6.3 ± 0.1	0.78	0.2084	6.2 ± 0.2	6.3 ± 0.1	-0.09	0.6162
Siltstone (SiS)	8.0 ± 0.1	6.8 ± 0.1	1.19	**0.0008**	6.4 ± 0.1	6.8 ± 0.1	-0.48	0.1521
Treatment	**CEC ($cmol_c\ kg^{-1}$)**							
	1983	**2016**	Δ†	**P > |t|***	**1987**	**2016**	Δ†	**P > |t|***
Sandstone (SS)	3.5 ± 0.4	5.5 ± 0.3	-2.00	0.1011	5.4 ± 1.0	5.5 ± 0.3	-0.09	0.9443
1:1 SS:SiS	4.8 ± 0.2	6.7 ± 0.0	-1.97	**0.0069**	8.0 ± 0.1	6.7 ± 0.0	1.24	**0.0036**
Siltstone (SiS)	5.9 ± 0.4	7.0 ± 0.1	-1.10	0.1515	10.2 ± 0.3	7.0 ± 0.1	3.21	**0.0122**

†Mean delta values or the difference in values between two years (e.g., May 1982 - 2016).
*Delta values were used to test the difference in means between years for a given treatment and interpreted by the two-tailed p-value ($\alpha = 0.05$). Bold represents a significant difference.

For surface soil pH, the SiS soils were higher in the beginning of the experiment, but treatment effects diminished by 2008 and 2016 (Table 3.9). Subsurface pH varied little over time, except for SiS spoils with lower pH values by 2016 (Table 3.12). Thus, soil pH changes with time are focused in the surface. Organic acid production from decomposing organic matter in upper layers generated acidity, overcoming initial trace carbonate buffering mechanisms. While surface

pH decreased over time, unmined soils in the local area were reported to have an average pH of 4.3 at 0-5 cm, which is several units lower than these mine soils (Craig 2012). Beyond initial raw spoil values (May 1982), surface CEC differed among spoil rock types in most years, with SiS soils higher than SS soils due to finer texture and the potential for carbonate dissolution in the NH_4OAc extractant (Table 3.9). Over time, CEC increased across all rock spoil treatments, especially compared to initial May 1982 (Table 3.9). It is important to note that the soil surface x time mixed model had treatment differences in 2016, while the one-way ANOVA for the 2016 horizon data did not show differences among treatments (Table 3.7 vs. Table 3.9). The mixed model accounted for additional factors (e.g., plot pairing, year) vs. the one-way ANOVA. Given the clear numerical differences in CEC values among treatments in 2016, there is likely a treatment effect as evident from the mixed model results. Changes in surface CEC over time are likely due to accumulating SOM and possibly increasing silt, clay, and Fe-oxides. As discussed earlier, relative differences in background weathering of carbonates may influence test results. Subsurface CEC did not change over time in SS soils, but the 1:1 SS:SiS and SiS soils were inconsistent in time contrasts (Table 3.12). Differences in subsurface CEC for the 1:1 SS:SiS and SiS soils might be due to slight fluctuations in soil pH. Soil P did not show treatment effects over time but did show a strong decreasing trend over time (Table 3.10) as discussed more later in Section 3.4.3.4.

After 34 years, EC levels in the ^Bw horizons were lower than the original bulk spoils in May 1982 (Figure 3.10). Soil EC levels were highest at the beginning of the experiment due to the chemical weathering of rock spoils, including the release of K, Ca, and Na ions during feldspar hydrolysis which is common in these regional mine spoils (Clark et al. 2018). While EC levels dropped over time in subsoil horizons due to long-term leaching of soluble ions, EC levels in the ^A horizons remained relatively high after 34 years because of organic matter decomposition and subsequent nutrient cycling. In 2016, EC differences by treatment were evident only in the ^Bw horizons, where SiS soils had the highest EC, and this is similar to treatment differences in the early 1980s (Roberts et al. 1988a). Leaching of soluble salts in western mine spoils has also been reported in lower layers, whereas surface layers accumulated nutrients, particularly K (Schafer et al. 1980). They also found that older mine soils had higher EC than native soils, and young mine soils that lacked vegetative cover had lower EC. Similarly, Sweeney (1979) found that EC levels

in ^A horizons diluted rock type effects, but not in the subsoil. Since the soils reported in Figure 3.10 were analyzed for EC in a 1:2 soil:water extract similar to Craig (2012), these data can be compared to local unmined soil values, which ranged from 103-130 µS cm^{-1}, similar to our reported 2016 ^A horizon levels. Initial and long-term EC levels in these mine soils were well below concentrations assumed detrimental for plant growth, although pure shale and siltstone spoils that are reduced, higher pH, and more finely textured (e.g., silty clay) could pose concerns for tree productivity, including *Pinus* species (Andrews et al. 1998; Rodrigue and Burger 2004; Torbert et al. 1988).

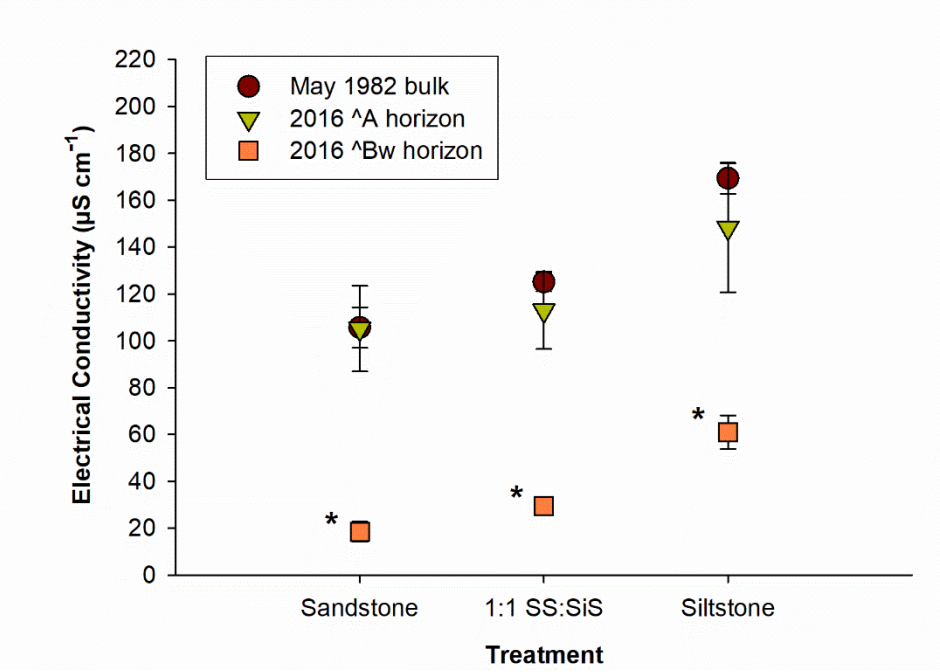

Figure 3.10. 1:2 soil:water EC (mean ± SE) levels in the original May 1982 bulk spoil samples vs. the ^A and ^Bw horizons in 2016. Asterisk (*) = EC lower than May 1982 bulk spoil EC. Delta values were used to test the difference in means between two years for a given treatment and interpreted by the two tailed p-value ($\alpha = 0.05$).

3.4.3.3. Soil Organic Matter and Carbon Over Time

Over time, SOM (Walkley-Black) increased and was highest in the SiS soils followed by the 1:1 SS:SiS soils (Table 3.10). There are inherent errors in using the Walkley-Black method for organic matter in coal mine soils, as coal fragments and Fe and Mn compounds also oxidize during

the process leading to erroneously high values (Daniels and Amos 1982). However, the SOM increases over time point towards the accumulation of organic matter given that values are being compared on a relative basis. Also, the higher SOM in SiS soils is likely due to higher geogenic C and Fe/Mn levels in the original spoils coupled with the concentration of naturally accumulating SOM into a much smaller mass of soil fines in that treatment. Local unmined soils were reported to have an average Walkley-Black SOM of 14.6% at 0-5 cm (including thin O+A), which is at least 5% higher than these mine soils, along with a clear difference in total organic C pools (Craig 2012). In another study, upland Virginia soils had 1.0-2.5% OM in mineral A horizons (Losche et al. 1970).

Surface soil (^A) SOC sequestration rates over 34 years are given in Table 3.13 along with other relevant data. Our estimates (~0.20 to 0.30 Mg ha^{-1} $year^{-1}$) are corrected for assumed background geogenic (coal) and carbonate-C sources. There were no treatment differences for SOC stocks and rates; thus, rock types have comparable sequestration rate potentials. Other Appalachian coal region studies have estimated SOC in mine soils and reported average sequestration rates ranging from 0.4 to 2.1 Mg ha^{-1} $year^{-1}$ (Amichev et al. 2008; Chaudhuri et al. 2012; Fox et al. 2020; Jacinthe and Lal 2007; Lorenz and Lal 2007; Rodrigue 2001; Sena et al. 2021; Shrestha and Lal 2010). The wide gap in SOC rates can be attributed to differences in vegetation type, site quality, soil age, and sampling and analytical methods, as some of these studies included litter layers or deeper sampling intervals and C analytical methods vary as well. Amichev et al. (2008) used a statistical model to predict SOC on Midwestern and Appalachian mine sites (to 1.5 m depth) ranging from 25 to 100 Mg ha^{-1} over 60 years following a pre-SMCRA mining disturbance, but these estimates were dependent on site quality. Sperow (2006) reviewed studies conducted on mined lands and reported an average SOC sequestration rate in KY and WV forested mine soils as 0.58 and 0.56 Mg ha^{-1} $year^{-1}$, respectively, and an average of 1.4 Mg ha^{-1} $year^{-1}$ in reclaimed pasture mine soils for several Appalachian coal states. Unmined SOC pools are usually much higher compared to values reported for coal mine soils, despite similar aboveground C pools, and this suggests a strong potential for mine soil C sequestration given stable site and climatic factors (Amichev et al. 2008; Avera et al. 2015).

Further, Avera et al. (2015) found that within a chronosequence of reclaimed mixed grass and forest stands (5, 11, 21, 30 years) located near the COPE, the 11-year-old forest had the highest SOC accumulation rate at 0.7 Mg ha^{-1} $year^{-1}$. However, the oldest 30-year-old mined stand had a lower SOC rate of 0.33 Mg ha^{-1} $year^{-1}$, which is only slightly higher than our estimated SOC sequestration values (Table 3.13). While the mine site vegetation and spoil rock strata (i.e., sandstone and/or siltstone) in Avera et al. (2015) was similar to the COPE, it is important to note that different sampling depths, volume/mass estimators, and analytical methods were used to derive fine earth mass values and to partition out geogenic C sources; for example, they used an isotopic approach with locally sampled end members for coal and soil humus C. It is also important to point out that the RM experiment plots supported a vigorous stand of tall fescue for their first 10 to 15 years that was replaced by a mixed stand of original and invading annual and perennial species (Nash 2012). Thus, higher rates of C-sequestration would be expected during earlier years for the grass cover type like the higher SOC rates reported for pastures in Sperow (2006). Similar to Avera et al. (2015), the COPE plant-soil system likely accumulated SOC at a faster rate within approximately 10 to 20 years and rates may have lowered by the time of 2016 sampling.

Table 3.13. Soil organic carbon (SOC) and sequestration rates in the surface after 34 years of weathering in rock spoil treatments.

Treatment	**Mean ^A horizon**	**Mean Soil Fines (g)***	**SOC (mean ± SE)**		
			%†	Mg ha^{-1}	Mg ha^{-1} $year^{-1}$
Sandstone (SS)	0-9 cm	2,921	2.01 ± 0.37 Ał	6.71 ± 2.36 A	0.20 ± 0.07 A
1:1 SS:SiS	0-10 cm	3,849	2.42 ± 0.23 A	9.53 ± 2.11 A	0.28 ± 0.06 A
Siltstone (SiS)	0-12 cm	2,834	2.35 ± 0.61 A	5.45 ± 1.41 A	0.16 ± 0.04 A

†Includes a HCl pre-treatment for carbonates and the "coal correction" from the original May 1982 bulk spoils to account for geogenic C sources.

*Based on 2008 soil fines (0-5 cm) per 0.093 m^2 surface area adjusted for 2016 ^A horizon depths (7 to 13 cm).

łLetters denoted differences among treatments ($P \leq 0.05$).

Additionally, the accumulation of SOC after 26 years at the COPE was analyzed on 2008 soil samples and reported by Nash (2012). Total soil C (coal forms) from archived 1982 samples was subtracted from 2008 samples in that study with the assumption that geogenic C remained nonlabile and that carbonates had been leached from the system over the +25 years as the soils acidified to pH < 6.5. The 1982 samples were pre-treated with HCl fumigation to remove carbonates so that all C was assumed to be geogenic coal C. Estimated SOC accumulation rates for 0-25 cm were 0.32 and 0.51 Mg ha^{-1} $year^{-1}$ for SiS and 1:1 SS:SiS treatments, respectively (Nash 2012). However, our more recent analyses treated the ^A horizon samples with HCl to test the assumption that carbonate-C had leached from the soil surface. Results showed that there were still a significant portion of carbonates in the surface in 2016 (data not given). Despite the presence of carbonates and the fact that we used the 0-5 cm soil fines data by Nash (2012) to calculate SOC after adjusting for ^A horizon depths in 2016 (deeper than 5 cm), our SOC sequestration rates in the surface were slightly lower in 2016 compared to 2008 estimates. Thus, differences in exact method (carbonate removal) and sampling depth might attest to the slight differences in sequestration rates between the earlier analysis and ours. We believe that our SOC sequestration values in 2016 are the best estimates given our available data and direct approach for geogenic and carbonate-C corrections.

3.4.3.4. Relationships Between Important Soil Properties

In the beginning of the COPE, fertilization supplied P in the surface of these fresh spoils since parent rock spoils are initially very low in total-P (Roberts et al. 1988a). Historically for COPE mine soil datasets, soil P was extracted using the Olsen bicarbonate method since it correlated well with plants growing in near neutral to alkaline pH conditions (Howard 1979). In the earlier years of the experiment, rapid oxidation increased extractable Fe levels between 1982 and 1983, but then levels decreased between 1983 and 1984 while acid extractable P decreased in the surface between 1982 and 1984 (Roberts et al. 1988a). Thus, it was unclear at the time what the relationship between the two parameters was and further investigation was needed to determine if P-fixation was occurring. Based on historical datasets of extractable Fe and bicarbonate P, there is a moderately strong relationship between the two parameters (Figure 3.11). As Fe-oxides

increased each year, extractable P concentrations decreased. Based on this sustained relationship, it is reasonable to conclude that the rapid oxidation and accumulation of Fe-oxides created a sink for P into relatively insoluble Fe-P complexes in the surface of these mine soils, and potentially lower soil horizons. The P-fixation capacity and mechanisms were thoroughly detailed by Howard et al. (1988), who found a strong negative association of extractable-P and Fe-oxides, particularly goethite. Further, studies in this region have reported P to be a growth limiting factor for trees growing in mine soils based on low foliar concentrations relative to native forests (Showalter et al. 2010; Wilson-Kokes and Skousen 2014). Our results indicate that P nutrient availability for plants is a concern for these mine soils over the long-term unless soils undergo routine fertilization or ferruginous rock strata is avoided for vegetation with high demands for P.

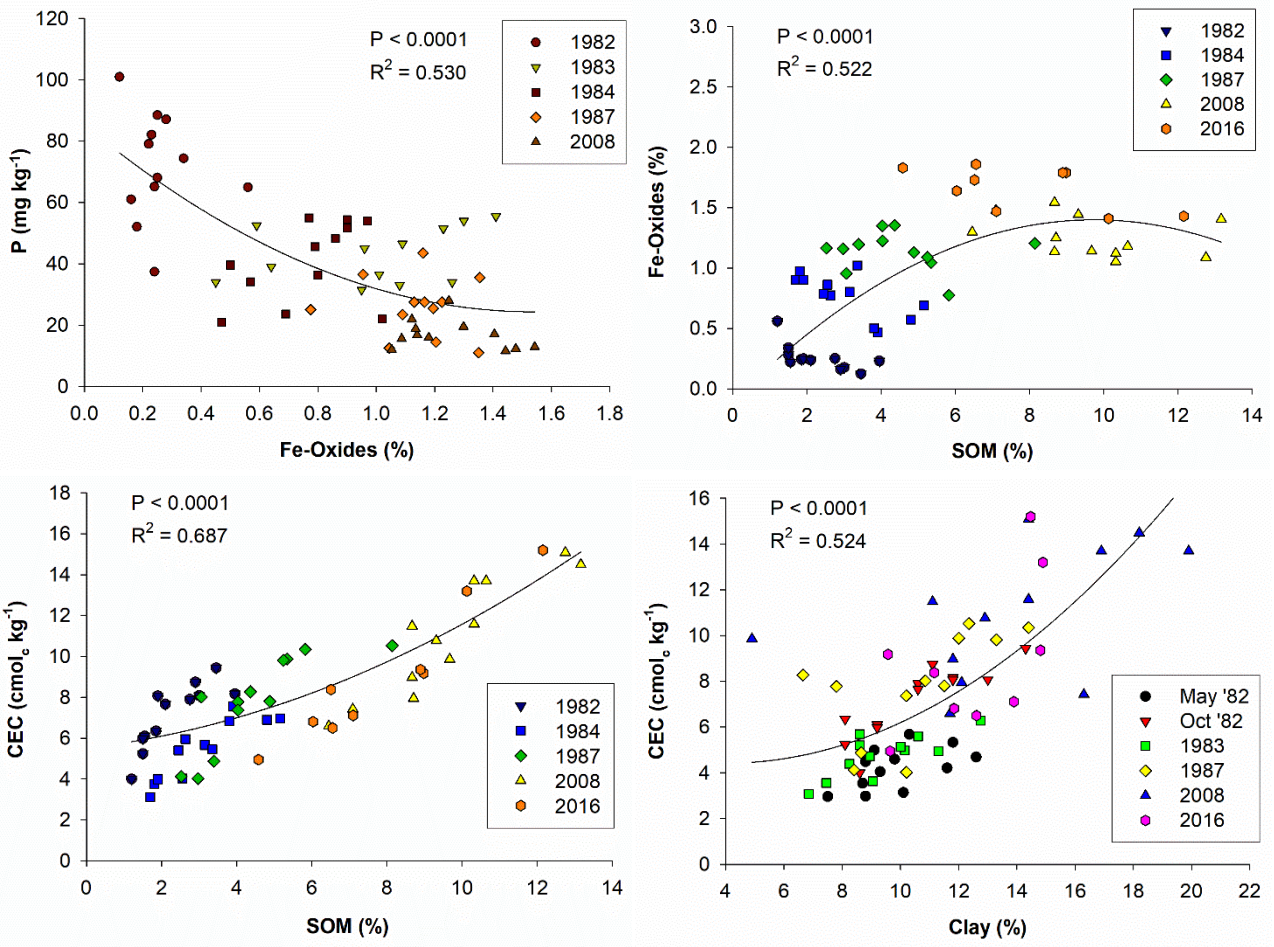

Figure 3.11. Second order regressions for various mine soil parameters in the soil surface.

One possible influence on Fe-oxide accumulation is adsorption by SOM. This may be one explanation for the initial decline in Fe-oxides during 1983 and 1984 (Roberts et al. 1988a). However, these trends are not clear and there are other factors to consider such as SOM turnover rates vs. Fe release and transformations. Additionally, the SOM data are subject to positive errors due to the method (Walkley-Black) used as discussed in the previous section. As expected, there was an increasing trend for CEC as the SOM increased over time and added new cation exchange sites for weathered and biologically cycled nutrients (Figure 3.11). An increase in CEC is expected for surface horizons over time and has been observed in other studies (Chaudhuri et al. 2012). Chaudhuri et al. (2013) found that SOC was positively associated with CEC on older mine sites, whereas clay contents were controlling CEC on the younger site. Overall, it is important to understand how clay minerals will accrue and form over time and affect the mine soil's ability to retain essential nutrients, as well as their contribution to stabilize and protect SOC pools. Additionally, Figure 3.11 depicts the relationship between clay contents and SOM. It is evident that mine soils are generally increasing soil fines over time, but there is a weak correlation of clay content to CEC. Interestingly, it appears that in 2016 the clay contents are dropping off, at least numerically, indicating that clay is possibly relocating or being lost in some fashion. Over additional time periods it is expected that clay minerals will accumulate and have a greater impact on soil chemical properties and SOC accumulation.

3.5. Summary and Conclusions

After 34 years, mine soils at the COPE showed distinct morphological differences compared to the original spoil materials, particularly related to subsoil structural development and overall horizonation. Rock fragment contents still approached half or more of the whole soil volume, particularly at depth, but rock content generally decreased over time, especially in the surface. The original unweathered, gray SiS spoils had much higher rock fragment and lower fine earth fraction vs. SS spoils, but in 2016, rock fragments in SiS soils were similar to SS soils in the surface and only slightly higher at depth. A greater number of well-expressed horizons developed over time. Most notable were diagnostic cambic (^Bw) horizon development in most pedons and deepening of ^A horizons; thus, pedogenic pathways are taking their course across rock types after

only three decades. Interestingly, compacted subsoil layers are forming root-liming zones that may negatively impact post-mining land uses. It is unclear how these compacted layers will evolve over time — will they worsen or improve through continued physical weathering (e.g., freeze-thaw and shrink-swell cycles) and deeper plant rooting? Currently, clod bulk densities are near root-limiting ranges for their loamy textures and this finding was reinforced by visual rooting evaluations. While these compacted layers likely formed by natural settling patterns coupled with fines migration, it is important to document their occurrence and monitor other loose-dumped or lightly graded topsoil substitutes in the region for changes in subsoil physical properties. The dense nature of these subsoils combined with their overall high rock fragment content might limit forest site productivity over time and discourage ecosystem recovery (e.g., reduced soil capillaries and plant available water) (Rodrigue and Burger 2004). If initial reclamation strategies cannot overcome the potential for self-collapse and compaction, site specific management practices such as deep dozer ripping may be employed in areas where compacted layers are limiting tree productivity and rainfall infiltration.

In terms of depth effects in the latest year monitored (2016), soil nutrients, metals, and total-C and-N were typically higher in surface vs. subsurface horizons as a result of litter deposition and rooting additions. The greater biological activity in the ^A horizons significantly influenced pH (lower), soluble salts (higher), and CEC (generally higher). In SiS soils, the CEC did not change across depths, likely due to elevated initial carbonates and persistence with time. A positive correlation was observed between SOM and CEC, as organic matter accrued and provided additional cation exchange sites. The SS soils had higher Fe-oxides in ^Bw horizons, which likely contributed to their somewhat better structural development in these treatments. Regarding changes in the soil surface, clay contents showed overall time and treatment main effects, with clay generally increasing over time and higher in the SiS vs. SS soils. We observed a positive correlation between CEC and clay contents, both of which increased with time as expected. Sand contents generally decreased over time while silt contents increased, but the relative effect of time on each parameter was not consistent across rock types from year to year. Over time, CEC and SOM increased and was higher in SiS vs. SS soils. Soil pH decreased with time and rock type only influenced pH in the earlier years, with higher pH in SiS vs. SS soils. However, in later years, rock

type still influenced subsoil pH. Over time, EC dropped in the subsurface, while the accumulation of OM maintained EC levels in the surface. Extractable Fe-oxides increased in both the surface and subsurface and had strong treatment effects in earlier years (< 1984), with pre-weathered SS highest. A negative correlation was observed between Fe-oxides (increasing) and extractable P (decreasing). For agricultural land uses that support P demanding grasses and legumes, it would be advised but difficult to avoid high ferruginous rock strata. If productivity potentials are impacted by limited P-availability, post-reclamation fertilizer additions might be necessary and/or the selection of plant species that are more adapted to low P environments (e.g., *Pinus* and other native species).

Accurate determination of SOC in mine soils is necessary to monitor SOC storage dynamics over time, e.g., are SOC pools reaching native equilibria, offsetting carbon dioxide emissions, and correlated to other soil and vegetative properties? Natural forested ecosystems in the southern Appalachian Mountains along an elevation gradient showed SOC contents between 14.9 and 50.6 Mg ha^{-1} at 5-20 cm of the mineral soil, and the greatest SOC fraction occurred within protected pools via organomineral complexes (Garten et al. 1999). Forested sites in their study were undisturbed for more than 50, 60, or 100 years. However, mineral soil is only one component of the total carbon sink offered by reclaimed surface mined lands sustaining plant communities. Our data showed that among rock types, SOC stocks and accumulation rates were not different after 34 years. Mean overall SOC sequestration rate across treatments was 0.21 Mg ha^{-1} $year^{-1}$, which is generally lower than other reports in the mine soil related literature, most of which were measured over shorter periods. Higher SOC rates probably occurred in these mine soils within the first 10 to 20 years when net primary productivity and C additions were most rapid. Higher SOC sequestration rates are common in younger mine soils (8 years) despite their overall lower SOC contents compared to native regenerating systems such as clear-cuts, and this is likely due to rapid tree growth, litterfall, and root production (Littlefield et al. 2013). Given the improved aggregate formation and higher soil fines noted after 34 years, these mine soils have the potential to reach unmined SOC levels if ecosystem and soil development progress with time. Future research is needed to understand SOC accumulation for entire profiles and in particular, changes in clay

accumulation among rock types should be measured over longer periods of time, as increased soil fines will likely influence SOC storage potentials.

Rapid changes in mine soil properties were evident at the beginning of the COPE, and while changes were maintained over the long-term primarily in the surface, the relative effect of time on a given soil parameter was typically not consistent across rock types for all years (i.e., differences varied from year to year). From a post-mining land use management perspective, it is essential to understand how different rock-derived soils change and theoretically approach equilibrium over time so that reclamation practitioners can make informed short and long-term decisions, especially given the vast acreage of reclaimed mined lands in this region (i.e., over 900,000 ha from 1977 to 2015; Adams 2017). Soil related information also allows for improved reclamation guidelines, such as the Forestry Reclamation Approach (FRA), which is a set of best management practices that follow the basic concepts of controlled overburden placement (Burger et al. 2005).

Most of the research conducted in Appalachia to date shows that brown weathered SS spoils, either used alone or mixed with salvaged topsoil, produce superior tree growth (Adams 2017). However, Avera et al. (2015) found that a mix of sandstone and siltstone rock strata returned several ecosystem functions and aboveground structural attributes to native forest reference values. Our study shows that a soil chemical property important for tree growth, pH, was still relatively high at depth for SiS soils after 34 years, but soil ^A horizons (~10 cm) were similar in pH across rock types. Since the 1:1 SS:SiS soils provided several intermediate physical and chemical soil properties, some combination or mix of rock types might serve as the next best option to brown weathered SS spoils for the purpose of supporting forestry land uses. However, combining two or more different rock strata may be logistically constrained at a given mine site. Overall, the monitoring of pedogenesis in these mine soils should be extended over longer periods of time to improve our understanding and development of proper management regimes for optimizing productivity potentials, carbon capture, and other ecosystem functions.

3.6. Acknowledgements

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3.7. References

Adams, M.B. 2017. The Forestry Reclamation Approach: guide to successful reforestation of mined lands. Gen. Tech. Rep. NRS-169. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station: 128 p. 169.

Amichev, B.Y., J.A. Burger and J.A. Rodrigue. 2008. Carbon sequestration by forests and soils on mined land in the midwestern and Appalachian coalfields of the U.S. Forest Ecology and Management 256: 1949-1959. doi:10.1016/j.foreco.2008.07.020.

Andrews, J.A., J.E. Johnson, J.L. Torbert, J.A. Burger and D.L. Kelting. 1998. Minesoil and site properties associated with early height growth of eastern white pine. Journal of Environment Quality 27: 192. doi:10.2134/jeq1998.00472425002700010027x.

Angel, P., C. Barton, R. Warner, C. Agouridis, T. Taylor and S. Hall. 2008. Forest establishment and water quality characteristics as influenced by spoil type on a loose-graded surface mine in eastern Kentucky. p. 28-65. In: Proceedings America Society of Mining and Reclamation. doi:10.21000/JASMR08010028

Avera, B.N., B.D. Strahm, J.A. Burger and C.E. Zipper. 2015. Development of ecosystem structure and function on reforested surface-mined lands in the Central Appalachian Coal Basin of the United States. New Forests 46: 683-702. doi:10.1007/s11056-015-9502-8.

Barnhisel, R. and P.M. Bertsch. 1982. Aluminum. p. 275-300. In: Methods of Soil Analysis. Part 2. 2nd ed. Chemical and Microbiological Properties. ASA and SSSA, Madison, WI.

Barrón, V. and J. Torrent. 2013. Iron, manganese and aluminium oxides and oxyhydroxides. Minerals at the Nanoscale 14: 297-336. doi:10.1180/EMU-notes.14.9.

Bell, J.C. 1994. Morphological characteristics of reconstructed prime farmland soils in western Pennsylvania. Journal of environmental quality 23. doi:10.2134/jeq1994.00472425002300030016x.

Bendfeldt, E.S., J.A. Burger and W.L. Daniels. 2001. Quality of amended mine soils after sixteen years. Soil Science Society of America Journal 65: 1736-1744. doi:10.2136/sssaj2001.1736.

Blake, G.R. and K.H. Hartge. 1986. Bulk density. p. 363-375. In: A. Klute (ed.) Methods of Soil Analysis, Part 1. 2nd ed. Madison, Wisconsin. doi:10.1002/gea.3340050110

Bryant, R. 1989. Physical processes of fragipan formation. In: N.E. Smeck, E.J. Ciolkosz (eds). Fragipans: their occurrence, classification, and genesis. 24: 141-150. doi:10.2136/sssaspecpub24.c8.

Burger, J.A., D. Graves, P. Angel, V. Davis and C. Zipper. 2005. The Forestry Reclamation Approach. The Appalachian Regional Reforestation Initiative. Forest Reclamation Advisory No. 2.

Campbell, D. 1994. Determination and use of soil bulk density in relation to soil compaction. Developments in Agricultural Engineering. Elsevier. p. 113-139.

Casselman, C.N., T.R. Fox and J.A. Burger. 2007. Thinning response of a white pine stand on a reclaimed surface mine in southwestern Virginia. Northern Journal of Applied Forestry 24: 9-13.

Chaudhuri, S., E.M. Pena-Yewtukhiw, L.M. McDonald, J. Skousen and M. Sperow. 2012. Early C sequestration rate changes for reclaimed minesoils. Soil Science 177: 443-450. doi:doi10.1097/SS.0b013e318254494d.

Chaudhuri, S., L.M. McDonald, E.M. Pena-Yewtukhiw, J. Skousen and M. Roy. 2013. Chemically stabilized soil organic carbon fractions in a reclaimed minesoil chronosequence: Implications for soil carbon sequestration. Environmental Earth Sciences 70: 1689-1698. doi:10.1007/s12665-013-2256-8.

Ciolkosz, E.J., R.C. Cronce, R.L. Cunningham and G.W. Petersen. 1985. Characteristics, genesis, and classification of Pennsylvania minesoils. Soil Science 139: 232-238. doi:10.1097/00010694-198503000-00007.

Clark, E.V., W.L. Daniels, C.E. Zipper and K. Eriksson. 2018. Mineralogical influences on water quality from weathering of surface coal mine spoils. Applied Geochemistry 91: 97-106. doi:10.1016/j.apgeochem.2018.02.001.

Craig, N. 2012. Properties and potentials of coal mine soils in southwest Virginia 29 years after establishment. M.S. thesis. Virginia Polytechnic Inst. and State Univ. Blacksburg, VA.

Daddow, R.L. 1983. Growth-limiting soil bulk densities as influenced by soil textureWatershed Systems Development Group, USDA Forest Service.

Dallaire, K. and J. Skousen. 2019. Early tree growth in reclaimed mine soils in Appalachia USA. Forests 10: 549. doi:10.3390/f10070549.

Daniels, W.L. and D.F. Amos. 1981. Mapping, characterization and genesis of mine soils on a reclamation research area in Wise county, Virginia. p. 261-265. In: Proc. Symp. Surf. Mining Hydrol., Sedimentol., and Reclamat., Lexington, KY. 7-11 December. Office Eng. Serv., College Eng., Univ. Kentucky, Lexington, KY.

Daniels, W.L. and D. Amos. 1982. Chemical characteristics in some southwest Virginia mine soils. p. 377–381. In: Proceedings of the 1982 Symposium on Surface Mining Hydrology, Sedimentology and Reclamation, Lexington, KY. 6–10 Dec. 1982. University of Kentucky, Lexington.

Daniels, W.L., J.C. Bell, D.F. Amos and G.D. McCart. 1983. First year effects of rock type and surface treatments on mine soil properties and plant growth. p. 275-282. In: Proc Symposium on Surface Mining, Hydrology, Sedimentology and Reclamation, November, College of Engineering, University of Kentucky, Lexington KY.

Daniels, W.L., J. Burger and D.F. Amos. 1984. The effect of controlled overburden placement on mine soil properties and the growth of loblolly pine. p. 1-72. Final Rep. U.S. Off. Surf. Min. Contract # J5120114. Virginia Polytechnic Inst. and State Univ., Blacksburg, VA.

Daniels, W.L. and D.F. Amos. 1985. Generating productive topsoil substitutes from hard rock overburden in the southern Appalachians. Environmental geochemistry and health 7: 8-15. doi:10.1007/bf01875045.

Daniels, W.L., J. Burger and D.F. Amos. 1991. The effects of controlled overburden placement on topsoil substitute quality and bond release: Phase III. p. 1-89. Final Rep. U.S. Off. Surf. Min. Contract # HQ51-GR87-10022. Virginia Polytechnic Inst. and State Univ., Blacksburg, VA.

Daniels, W.L., K. Haering, J. Galbraith and J. Thomas. 2004. Mine soil classification and mapping issues on pre-and post-SMCRA Appalachian coal mined lands. p. 450-481. In: Proceedings America Society of Mining and Reclamation. doi:10.21000/JASMR04010450.

Daniels, W.L., C.E. Zipper, Z.W. Orndorff, J. Skousen, C.D. Barton, L.M. McDonald et al. 2016. Predicting total dissolved solids release from central Appalachian coal mine spoils. Environ Pollut 216: 371-379. doi:10.1016/j.envpol.2016.05.044.

DeLong, C., J. Skousen and E. Pena-Yewtukhiw. 2012. Bulk density of rocky mine soils in forestry reclamation. Soil Science Society of America Journal 76: 1810-1815. doi:10.2136/sssaj2011.0380n.

Donohue, S. and S. Heckendorn. 1996. Laboratory procedures: Virginia Tech soil testing and plant analysis laboratory. Virginia Cooperative Extension Bulletin. 452-881.

Fox, J.F., J.E. Campbell and P.M. Acton. 2020. Carbon sequestration by reforesting legacy grasslands on coal mining sites. Energies 13: 6340.

Garten, C.f., W.M. Post, P.J. Hanson and L.W. Cooper. 1999. Forest soil carbon inventories and dynamics along an elevation gradient in the southern Appalachian Mountains. Biogeochemistry 45: 115-145.

Gee, G.W. and J.W. Bauder. 1986. Particle-size analysis. p. 383-411. In: A. Klute (ed.) Methods of Soil Analysis. Part I. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI. doi:10.1002/gea.3340050110

Gorman, J. and J. Sencindiver. 1999. Changes in mine soil physical properties over a nine-year period. p. 245-253. In: Proc. of the Annual Meeting of the American Society for Surface Mining and Reclamation.

Gorman, J., J. Skousen, J. Sencindiver and P. Ziemkiewicz. 2001. Forest productivity and minesoil development under a white pine plantation versus natural vegetation after 30 years. p. 11. In: Proc National Meeting of the American Society for Surface Mining and Reclamation. doi:10.21000/JASMR01010103.

Haering, K., W.L. Daniels, J. Torbert and J. Burger. 1990. Effects of controlled overburden placement on topsoil substitute quality and bond release: Phase III. p. 1-86. Final

Rep.U.S. Off. Surf Min Coop. Agreement HQ51-GR87-10022. Virginia Polytechnic Inst. and State Univ., Blacksburg, VA.

Haering, K.C., W.L. Daniels and J.A. Roberts. 1993. Changes in mine soil properties resulting from overburden weathering. Journal of Environment Quality 22: 194-200. doi:10.2134/jeq1993.00472425002200010026x.

Haering, K.C., W.L. Daniels and J.M. Galbraith. 2004. Appalachian mine soil morphology and properties. Soil Science Society of America Journal 68: 1315-1325. doi:10.2136/sssaj2004.1315.

Haering, K.C., W.L. Daniels and J.M. Galbraith. 2005. Mapping and classification of southwest Virginia mine soils. Soil Science Society of America Journal 69: 463-472.

Haigh, M. 1992a. Degradation of 'reclaimed' lands previously disturbed by coal mining in Wales: causes and remedies. Land Degradation & Development 3: 169-180.

Haigh, M.J. 1992b. Problems in the reclamation of coal-mine disturbed lands in Wales. International Journal of Surface Mining, Reclamation and Environment 6: 31-37. doi:10.1080/09208119208944313.

Haigh, M.J. and B. Sansom. 1999. Soil compaction, runoff and erosion on reclaimed coal-lands (UK). International Journal of Surface Mining, Reclamation and Environment 13: 135-146.

Hallberg, G.R., N.C. Wollenhaupt and G.A. Miller. 1978. A century of soil development in spoil derived from loess in Iowa. Soil Science Society of America Journal 42: 339-343. doi:10.2136/sssaj1978.03615995004200020028x.

Harris, D., W.R. Horwáth and C. Van Kessel. 2001. Acid fumigation of soils to remove carbonates prior to total organic carbon or carbon-13 isotopic analysis. Soil Science Society of America Journal 65: 1853-1856. doi:10.2136/sssaj2001.1853.

Hirmas, D. and S. Furquim. 2006. Simple modification of the clod method for determining bulk density of very gravelly soils. Communications in soil science and plant analysis 37: 899-906.

Howard, J.L. 1979. Physical, chemical and mineralogical properties of mine spoil derived from the wise formation, Buchanan county, Virginia. M.S. thesis. Virginia Polytechnic Inst. and State Univ. Blacksburg, VA.

Howard, J., D. Amos and W. Daniels. 1988. Phosphorus and potassium relationships in southwestern Virginia coal-mine spoils. Journal of Environmental Quality 17: 695-700.

Jacinthe, P.-A. and R. Lal. 2007. Carbon storage and minesoil properties in relation to topsoil application techniques. Soil Science Society of America Journal 71: 1788-1795.

Jacinthe, P., C. Barton, S. Maharaj and R. Lal. 2009. An evaluation of methodologies for assessing geogenic carbon in mine soils of the eastern United States. 347-363. In: Soil Carbon Sequestration and the Greenhouse Effect, 2nd edition. SSSA Special Publication 57.

Johnson, C.D. and J.G. Skousen. 1995. Minesoil properties of 15 abandoned mine land sites in West Virginia. Journal of Environment Quality 24: 635. doi:10.2134/jeq1995.00472425002400040014x.

Li, R.S. and W.L. Daniels. 1994. Nitrogen accumulation and form over time in young mine soils. Journal of Environmental Quality 23: 166-172. doi:10.2134/jeq1994.00472425002300010026x.

Littlefield, T., C. Barton, M. Arthur and M. Coyne. 2013. Factors controlling carbon distribution on reforested minelands and regenerating clearcuts in Appalachia, USA. Science of the Total Environment 465: 240-247. doi:10.1016/j.scitotenv.2012.12.029.

Lorenz, K. and R. Lal. 2007. Stabilization of organic carbon in chemically separated pools in reclaimed coal mine soils in Ohio. Geoderma 141: 294-301. doi:10.1016/j.geoderma.2007.06.008.

Losche, C., R. McCracken and C. Davey. 1970. Soils of steeply sloping landscapes in the southern Appalachian Mountains. Soil Science Society of America Journal 34: 473-478.

Maharaj, S., C.D. Barton, T.A.D. Karathanasis, H.D. Rowe and S.M. Rimmer. 2007. Distinguishing "new" from "old" organic carbon in reclaimed coal mine sites using thermogravimetry: ii. field validation. Soil Science 172: 302-312. doi:10.1097/SS.0b013e3180314702.

McLean, E.O. 1982. Soil pH and lime requirement. p. 199-223. In: A. Klute (ed.) Methods of Soil Analysis, Part 2. 2nd ed. Madison, WI.

Mehra, O. and M. Jackson. 1960. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. 317-327 p. 7th National Conference on Clays and Clays Minerals, Washington. Committee on Clay Minerals of the National Academy of Sciences-National Research Council, Washington, USA.

Miller, J., C. Barton, C. Agouridis, A. Fogel, T. Dowdy and P. Angel. 2012. Evaluating soil genesis and reforestation success on a surface coal mine in Appalachia. Soil Science Society of America Journal 76: 950-960. doi:10.2136/sssaj2010.0400.

Moss, S., J. Burger and W. Daniels. 1989. Pitch× loblolly pine growth in organically amended mine soils. Journal of Environmental Quality 18: 110-115. doi:10.2134/jeq1989.00472425001800010020x.

Mudrick, D.A., M. Hoosein, R.R. Hicks Jr and E.C. Townsend. 1994. Decomposition of leaf litter in an Appalachian forest: effects of leaf species, aspect, slope position and time. Forest Ecology and Management 68: 231-250.

Nash, W.L. 2012. Long-term effects of rock type, weathering and amendments on southwest Virginia mine soils. M.S. Thesis. Virginia Polytechnic Inst. and State Univ. Blacksburg, VA.

Nash, W.L., W.L. Daniels, K.C. Haering, J.A. Burger and C.E. Zipper. 2016. Long-term effects of rock type on Appalachian coal mine soil properties. J Environ Qual 45: 1597-1606. doi:10.2134/jeq2015.10.0540.

Nelson, D.W. and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. p. 961-1010. In: Methods of Soil Analysis Part 3. Chemical Methods. ASA and SSSA, Madison, WI.

Nichols, J.D., P.L. Brown and W.J. Grant. 1984. Erosion and productivity of soils containing rock fragments. SSSA Special Publication Number 13. Soil Science Society of America, Madison, WI.

Olsen, S. and L.E. Sommers. 1982. Phosphorus. p. 403-430. In: Page, A.L., (eds.), Methods of Soil Analysis Part 2 Chemical and Microbiological Properties, American Society of Agronomy, Soil Science Society of America, Madison, WI.

Page-Dumroese, D.S., R.E. Brown, M.F. Jurgensen and G.D. Mroz. 1999. Comparison of methods for determining bulk densities of rocky forest soils. Soil Science Society of America Journal 63: 379-383.

Pedersen, T., A. Rogowski and R. Pennock Jr. 1978. Comparison of morphological and chemical characteristics of some soils and minesoils [in Clearfield County, Pennsylvania]. Reclamation Review (USA) (1):143-156.

Pedersen, T., A. Rogowski and R. Pennock. 1980. Physical characteristics of some minesoils. Soil Science Society of America Journal 44: 321-328. doi:10.2136/sssaj1980.03615995004400020024x.

Rhoades, J. 1996. Salinity: Electrical conductivity and total dissolved solids. In: Methods of Soil Analysis: Part 3 Chemical Methods: p. 417-435.

Roberts, J.A., W.L. Daniels, J.A. Burger and J.C. Bell. 1988a. Early stages of mine soil genesis in a southwest Virginia spoil lithosequence. Soil Science Society of America Journal 52: 716-723. doi:10.2136/sssaj1988.03615995005200030023x.

Roberts, J., W. Daniels, J. Burger and J. Bell. 1988b. Early stages of mine soil genesis as affected by topsoiling and organic amendments. Soil Science Society of America Journal 52: 730-738. doi:10.2136/sssaj1988.03615995005200030025x.

Roberts, J.A., W.L. Daniels, J.C. Bell and D.C. Martens. 1988c. Tall fescue production and nutrient status on southwest Virginia mine soils. Journal of Environmental Quality 17: 55-62. doi:10.2134/jeq1988.00472425001700010008x.

Rodrigue, J.A. 2001. Woody species diversity, forest and site productivity, stumpage value, and carbon sequestration of forests on mined lands reclaimed prior to the passage of the surface mining control and reclamation act of 1977. M.S. Thesis. Virginia Tech.

Rodrigue, J.A. and J. Burger. 2004. Forest soil productivity of mined land in the midwestern and eastern coalfield regions. Soil Science Society of America Journal 68: 833-844. doi:10.2136/sssaj2004.8330.

Schaetzl, R.J. and M.L. Thompson. 2015. Soils: genesis and geomorphology. Second editionCambridge University Press. New York, NY.

Schafer, W.M., G.A. Nielsen and W.D. Nettleton. 1980. Minesoil genesis and morphology in a spoil chronosequence in Montana. Soil Science Society of America Journal 44: 802-807. doi:10.2136/sssaj1980.03615995004400040029x.

Schoeneberger, P.J., D.A. Wysocki and E.C. Benham. 2012. Field book for describing and sampling soils, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Sena, K., C. Barton, P. Angel, C. Agouridis and R. Warner. 2014. Influence of spoil type on chemistry and hydrology of interflow on a surface coal mine in the eastern US coalfield. Water, Air, & Soil Pollution 225: 2171. doi:10.1007/s11270-014-2171-y.

Sena, K.L., K.M. Yeager, C.D. Barton, J.M. Lhotka, W.E. Bond and K.J. Schindler. 2021. Development of mine soils in a chronosequence of forestry-reclaimed sites in eastern Kentucky. Minerals 11: 422.

Sencindiver, J.C. 1977. Classification and genesis of minesoils. Ph.D. Diss. West Virginia Univ., Morgantown (Univ. Micro. 77-22 746).

Shipp, R.F. and R. Matelski. 1965. Bulk-density and coarse-fragment determinations on some Pennsylvania soils. Soil Science 99: 392-397.

Showalter, J., J. Burger, C. Zipper, J. Galbraith and P. Donovan. 2007. Physical, chemical, and biological mine soil properties influence white oak seedling growth: a proposed mine soil classification model. Southern Journal of Applied Forestry 31: 99-107.

Showalter, J.M., J.A. Burger and C.E. Zipper. 2010. Hardwood seedling growth on different mine spoil types with and without topsoil amendment. J Environ Qual 39: 483-491. doi:10.2134/jeq2008.0500.

Shrestha, R.K., R. Lal and P.-A. Jacinthe. 2009. Enhancing carbon and nitrogen sequestration in reclaimed soils through organic amendments and chiseling. Soil Science Society of America Journal 73: 1004-1011. doi:10.2136/sssaj2008.0216.

Shrestha, R.K. and R. Lal. 2010. Carbon and nitrogen pools in reclaimed land under forest and pasture ecosystems in Ohio, USA. Geoderma 157: 196-205.

Skousen, J., J. Sencindiver, K. Owens and S. Hoover. 1998. Physical properties of minesoils in West Virginia and their influence on wastewater treatment. Journal of environmental quality 27: 633-639. doi:10.2134/jeq1998.00472425002700030022x.

Skousen, J., C. Zipper, J. Burger, C. Barton and P. Angel. 2011. Selecting materials for mine soil construction when establishing forests on Appalachian mine sites. US Office of Surface Mining, Appalachian Regional Reforestation Initiative Advisory: 6.

Soil Science Division Staff. 2017. Soil survey manual. US Department of Agriculture. Handbook No. 18.

Soil Survey Staff. 2014. Keys to soil taxonomy, 12th Ed. USDA-NRCS. US Gov. Print. Office, Washington, DC.

Sperow, M. 2006. Carbon sequestration potential in reclaimed mine sites in seven east-central states. Journal of environmental quality 35: 1428-1438. doi:10.2134/jeq2005.0158.

Sweeney, L.R. 1979. Soil genesis on relatively young surface mined lands in southern West Virginia. M.S. Thesis. Virginia Polytechnic Inst. and State Univ. Blacksburg, VA.

Thomas, G. 1982. Exchangeable cations. p. 159-165. In: Method of Soil Analysis. Part 2. 2nd ed. Agronomy Monograph 9. ASA and SSSA, Madison, WI. doi:10.1002/gea.3340050110

Thomas, K., J. Sencindiver, J. Skousen and J. Gorman. 2000. Soil horizon development on a mountaintop surface mine in southern West Virginia. Green Lands 30: 41-52.

Thomas, K., J. Sencindiver, J. Skousen and J. Gorman. 2001. Chemical properties of minesoils on a mountaintop removal mine in southern West Virginia. p. 448-456. In: S.A. Bengston et al., editors, Proceedings of the American Society for Surface Mining and Reclamation, Albuquerque, NM. 3–7 June. Am. Soc. Min. Reclam., Champaign, IL.

Thurman, N., J. Sencindiver, J. Ammons and D. Adamo. 1985. Physical properties of minesoils and their effects on root growth. Proceedings, Fifth better reclamation with trees conference. Southern Illinois University, Carbondale, IL: 194-208.

Thurman, N. and J. Sencindiver. 1986. Properties, classification, and interpretations of minesoils at two sites in West Virginia. Soil Science Society of America Journal 50: 181-185. doi:10.2136/sssaj1986.03615995005000010034x.

Tisdall, A. 1951. Comparison of methods of determining apparent density of soils. Australian Journal of Agricultural Research 2: 349-354.

Torbert, J.L., A. Tuladhar, J. Burger and J. Bell. 1988. Minesoil property effects on the height of ten-year-old white pine. Journal of Environmental Quality 17: 189-192. doi:10.2134/jeq1988.00472425001700020004x.

Torbert, J.L., J. Burger and W. Daniels. 1990. Pine growth variation associated with overburden rock type on a reclaimed surface mine in Virginia. Journal of Environmental Quality 19: 88-92. doi:10.2134/jeq1990.00472425001900010011x.

Vogel, W.G. 1981. Guide for revegetating coal minesoils in the eastern United States. Forest Service, Broomall, PA (USA). Northeastern Forest Experiment Station.

Walkley, A. and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science 37: 29-38. doi:10.1097/00010694-193401000-00003.

Wang and Z. LA Goonewardene. 2004. The use of MIXED models in the analysis of animal experiments with repeated measures data. Canadian Journal of Animal Science 84: 1-11. doi:10.4141/A03-123.

Wick, A.F., W.L. Daniels, W.L. Nash and J.A. Burger. 2016. Aggregate recovery in reclaimed coal mine soils of SW Virginia. Land Degradation & Development 27: 965-972. doi:10.1002/ldr.2309.

Wilson-Kokes, L. and J. Skousen. 2014. Nutrient concentrations in tree leaves on brown and gray reclaimed mine soils in West Virginia. Science of the Total Environment 481: 418-424. doi:10.1016/j.scitotenv.2014.02.015.

Yarwood, S., A. Wick, M. Williams and W.L. Daniels. 2015. Parent material and vegetation influence soil microbial community structure following 30-years of rock weathering and pedogenesis. Microbial ecology 69: 383-394. doi:10.1007/s00248-014-0523-1.

4. Pedogenic Influences of Surface Amendments Over 34 Years on Southwest Virginia Coal Mine Soils

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Abbreviations: COPE, Controlled Overburden Placement Experiment; SS, sandstone; SiS, siltstone; SA, surface amendment; RM, rock mix; sbk, subangular blocky; gr, granular; CEC, cation exchange capacity; SOC, soil organic carbon; SOM, soil organic matter; EC, electrical conductivity; Fe, iron; Mn, manganese.

4.1. Abstract

Properly selected hard rock overburden commonly serves as a substitute for native topsoil (A + E horizons) on mine sites in the Appalachian coalfields. Salvaged topsoil and organic amendments have increased initial productivity and soil quality in rock-derived topsoil substitutes, but it is unclear how these amendments sustain important soil properties and functions over time. At a SW Virginia coal mine, we assessed the long-term (34+ years) effects of surface amendments (control, topsoil, 112 Mg ha^{-1} sawdust, and 56 and 112 Mg ha^{-1} biosolids) applied to a 2:1 sandstone:siltstone spoil on soil surface morphological, physical, and chemical properties. Over time, transitional horizons (^BA, ^AB) and deeper ^A horizons developed in all treatments. The sawdust and biosolids imparted a somewhat thicker and darker ^A horizon over the control and topsoil. Subsurface cambic (^Bw) horizons had weak to moderate structure and root-limiting layers were present in lower ^B and ^C horizons due to natural settling and infilling processes. Treatment differences were not present for surface soil texture, except for higher sand and lower silt contents with time in topsoil. Silt and clay contents generally increased over time, while sand content decreased. Soil pH decreased over time, while electrical conductivity (EC) at the surface was maintained by plant cation cycling. In later years, treatment effects diminished for pH and EC, likely due to organic matter (OM) accumulation and cycling. Iron oxides increased over time, while extractable phosphorus (P) decreased, likely due to P-fixation. Both biosolids rates sustained higher long term available P levels and had higher trace element concentrations in 2016 compared to other treatments. Most extractable nutrients were concentrated in the surface, particularly in the sawdust treatment. Cation exchange capacity was similar among treatments and generally increased over time due to OM accumulation. Total nitrogen (N) was generally higher in the sawdust and biosolids. Across treatments, total N was much higher in the surface. Surprisingly, soil organic carbon (SOC) accumulation rates (0.19 to 0.23 Mg ha^{-1} $year^{-1}$) did not differ among treatments. Biosolids were superior in terms of soil fertility and may better sustain essential nutrients. However, SOC and texture were not impacted by treatments during this 34-year time frame.

4.2. Introduction

The advent of larger earth-moving equipment on Appalachian coal surface mines allowed for excavation of rock strata at greater depths (> 20 m) and on more steeply sloping terrain (Haering et al. 2004; Zipper and Skousen 2021). With this evolved the use of a wider range of weathered and/or unweathered sedimentary rocks as an appropriate plant growth media alternative to native Appalachian topsoil (i.e., usually the A + E horizons) (Daniels and Amos 1985). Local, natural sources of topsoil are ideal for the primary growth media material since it incorporates native propagules and microorganisms directly back to the disturbed site (Hall et al. 2010). However, topsoil return in the Appalachian coal fields is complicated because native topsoil is difficult to salvage and generally low in physical and chemical quality (e.g., thin and acidic), often outweighing the potential benefits of its use (Daniels and Amos 1985). However, best management practice guidelines still recommend topsoil incorporation into rock spoil alternatives where feasible (Adams 2017; Hall et al. 2010). Productive and healthy revegetated communities can help rebuild soil organic matter (SOM) and plant available nutrients (Zipper et al. 2013). One way of enhancing soil quality and thus plant productivity on disturbed lands is through the application of organic soil amendments (e.g., biosolids, pulp and paper-mill sludge, livestock manures, crop residues, and wood residues) (Haering et al. 2000; Larney and Angers 2012; Slick and Curtis 1985; Wijesekara et al. 2016). For example, biosolids, or treated municipal sewage sludge, provide organic matter and large amounts of organic nutrients such as nitrogen (N) and phosphorus (P) that mineralize to plant available forms over time (Haering et al. 2000). Sustained release of mineralizable nutrients may be provided from a range or mix of amendments and depend on many different factors such as decomposition rates (Larney and Angers 2012).

Initial mine soil properties are directly inherited from parent materials, particularly mineral content and soil texture, rock fragment content, and packing structure, and may be further affected by reclamation placement and grading practices (e.g., low plant available water and fertility, lack of aggregates) (Ammons and Sencindiver 1990; Haering et al. 1993; Roberts et al. 1988a; Skousen et al. 2011). Organic materials have been shown to ameliorate unfavorable mine soil conditions by reducing bulk density, increasing aggregate stability and water holding capacity, and improving soil fertility (Hinesly et al. 1982; Shrestha and Lal 2006). Some of the earliest regional work on

the application of surface organic amendments on mined lands occurred at the Controlled Overburden Placement Experiment (COPE) established in 1982 on a coal mine in southwestern Virginia (Daniels et al. 1983; Daniels et al. 1991). At this site, surface amendment treatments (i.e., fertilized rock spoil control, topsoil, sawdust, and four rates of municipal biosolids) were applied to a 2:1 sandstone:siltstone (SS:SiS) overburden mix. Several years later, Roberts et al. (1988c) showed initial improvements in tall fescue biomass production over three years in biosolids amended treatments vs. fertilized control plots, while Moss et al. (1989) showed that higher rates of biosolids (112 and 224 Mg ha^{-1}) increased electrical conductivity (EC) or soluble salt levels and appeared to induce Mn deficiencies in these mine soils relative to pine (*Pinus rigida* x *taeda*) seedling survival and growth. They also found that sawdust additions (112 Mg ha^{-1}) greatly improved soil water retention, increasing seedling growth. These studies emphasized the importance of balancing N and P supply along with appropriate pH conditions on reforested sites.

In addition to the improved short-term (3-year) growth of tall fescue in amended rock spoils, Roberts et al. (1988b) found that the biosolids treatments were superior in enhancing soil organic matter (SOM) and plant available N and P, and providing a higher CEC, while the sawdust treatment produced higher water holding capacity and exchangeable K levels. On an acidic abandoned mine site, Pichtel et al. (1994) evaluated soils amended with biosolids, composted paper-mill sludge, fly ash, and limed topsoil over a period of 10 years and found that biosolids and paper-mill sludge treatments were generally comparable to the limed topsoil in terms of vegetation productivity and soil nutrient and pH levels. Fly ash was the least effective due to its relatively lower pH (5.1). As follow-up research, Bendfeldt et al. (2001) assessed the long-term effects of surface amendment treatments at the COPE on mine soil physical and chemical properties and SOM. Sawdust and biosolids treatments led to pronounced differences in soil properties such as SOM, total-N, plant-available P, and aggregate stability over five years compared to control and topsoil treatments. After 16 years these properties were similar across treatments, except for total and mineralizable N, which was greatest in the 112 Mg ha^{-1} biosolids rate, as well as extractable P levels, which were much higher in the 56 and 112 Mg ha^{-1} biosolids. The authors attributed the lack of long-term treatment effects for other soil parameters to the stabilization of aboveground

vegetation productivity. After 26 years, it was clear that the higher rates of biosolids had long-term soil fertility benefits, e.g., higher extractable-P compared to other amendments (Nash 2012).

Pools of soil organic carbon (SOC) are influenced by carbon (C) turnover rates, aggregate formation, interactions with the silt and clay fractions, plant and microbial community shifts, seasonality, and microclimate (Six et al. 2002; Trumbore 2000; Wick et al. 2009). Restoring soil organic carbon pools on mined lands contribute to healthy and productive plant communities and operate as a potential sink for atmospheric CO_2, thus offsetting anthropogenic emissions. Distinguishing between pedogenic and geogenic C sources is necessary to accurately estimate SOC accumulation in coal mine soils (Jacinthe and Lal 2007). Since rock-derived mine soils are naturally devoid of native SOM, amending freshly blasted rock mine spoil is of interest for enhancing SOC potentials. Chaudhuri et al. (2013) found that, across a chronosequence of rock-derived mine soils in WV, SOC fractions at older sites were associated with the humin fraction (i.e., biochemically stable or non-labile) compared to younger sites where SOC was largely controlled by labile and mineral-bound fractions, indicating that older soils have greater stability and protection of SOC. The ability for organic amendment materials to enhance SOC sequestration potential long-term has been questioned due to their easily decomposable nature, unless composed of higher sources of recalcitrant C such as lignin rich wood residues (Shrestha and Lal 2006). After 27 years at the COPE, Wick et al. (2010) found no significant differences in soil aggregate associated C and N concentrations among treatments owing to the high variability among plots; however, numerically, the 22 and 56 Mg ha^{-1} biosolids treatments were relatively higher.

While organic amendments are beneficial for mined land reclamation with respect to revegetation potentials (Hinesly et al. 1982; Pichtel et al. 1994; Roberts et al. 1988b), only a handful of studies have monitored changes in amended Appalachian mine soils over longer periods of time (> 10 years) (Bendfeldt et al. 2001; Craig 2012; Nash 2012). Longer term experiments have shown beneficial soil outcomes (e.g., higher SOM) for certain organic amendments, but were conducted on unmined managed crop lands (Odell et al. 1984; Paustian et al. 1992; Rasmussen et al. 1980). The initial goals of the COPE were to monitor changes in vegetation and soil properties from 1982 to 1987, focusing on the five-year performance bond period, but the experiment subsequently served to assess mine soil genesis and soil fertility in amended topsoil substitutes

over a much longer (> 30 years) period of time. Our objectives in this study included: 1) Assess mine soil morphology changes over time, emphasizing the surface layer or zone of original treatment application; 2) compare mine soil chemical and physical properties among native topsoil vs. organic amendment treatments and major morphological horizons; and 3) evaluate changes in mine soil surface chemical and physical properties over a 34-year period.

4.3. Materials and Methods

4.3.1. Study Site and Design

The surface amendment (SA) experiment was constructed as a component of the Controlled Overburden Placement Experiment (COPE) in May 1982 on a surface coal mine in Wise County, Virginia (37º00' N, 82º41' W). For detailed information on the study background, location, and site conditions (e.g., geology, climate, soils, vegetation), refer to Section 3.3.1, which focuses on the parallel rock mix (RM) experiment. The SA experiment was also arranged in a RCBD (n=4) and compared a range of surface amendments applied to a 2:1 sandstone:siltstone (SS:SiS) rock mixture, including the following treatments: fertilized control, native topsoil, sawdust, and four rates of biosolids (Table 4.1; Appendix A1 for plot layout). Since all SA and RM experimental plots were similarly installed, refer to Section 3.3.2 for details on plot dimensions and installation.

4.3.2. Surface Amendment Treatments

Surface amendment application rates and initial N-P-K fertilizer and/or lime rates are given in Table 4.1. Greater detail on the methodology and amendments is provided by Roberts et al. (1988bc). Select treatments were sampled (n=3 each) and described in 2016, which included the control, topsoil, sawdust, and two biosolids rates (56 and 112 Mg ha^{-1}) and results are presented for these five treatments. The 2:1 SS:SiS base rock spoils were mixed in a similar fashion to the RM experiment. Local topsoil (all horizons to ^Cr saprolite contact) and organic amendments (sawdust and biosolids) were hauled to the site and applied using a tractor-mounted front-end loader. Application rates for amendments were based on their measured density and the volume of the front-loader. Additionally, the sawdust treatment plots received additional fertilizer N to

counteract anticipated immobilization effects, and the topsoil treatment plots were limed due to their initial low pH (~4.5). Finally, all plots were mixed with a rototiller (to ~12.7 cm depth) and then mulched and seeded in the same fashion as the RM experiment (refer to Section 3.3.2).

4.3.3. Soil Sampling and Analysis

4.3.3.1. Field Sampling

In August and September of 2016, three soil test pits were dug in each of the control, topsoil, sawdust, and 56 and 112 Mg ha^{-1} biosolids plots (n=15). Sampling and profile description schemes were the same as the RM experiment and were conducted using standard NRCS protocols (Schoeneberger et al. 2012) (see Section 3.3.4.1 for additional details). The caret symbol (^) is used for all years to denote horizons formed in human-altered and human-transported materials.

Table 4.1. Surface amendment treatments and additives applied to a 2:1 sandstone:siltstone SS:SiS rock mixture. Bold font indicates treatments sampled in 2016.

SA Treatment	Rock Mix	Other Additions
Control (No Amendment)	67% SS: 33% SiS	N, P, K‡
Topsoil* (30 cm)	67% SS: 33% SiS	N, P, K + 7.8 Mg ha^{-1} Ag lime
Sawdust (112 Mg ha^{-1})	67% SS: 33% SiS	N, P, K + 336 kg ha^{-1} IBDU†
Biosolids (22.4 Mg ha^{-1})	67% SS: 33% SiS	None
Biosolids (56 Mg ha^{-1})	67% SS: 33% SiS	None
Biosolids (112 Mg ha^{-1})	67% SS: 33% SiS	None
Biosolids (224 Mg ha^{-1})	67% SS: 33% SiS	None

‡1120 kg ha^{-1} of 15-30-15 dry fertilizer, and 56 kg NH_4NO_3 ha^{-1} annually for three years.
*Includes a mixture of A, E, B, C, and Cr native soil horizons.
†Isobutyldiene Diurea, a slow-release N fertilizer.

4.3.4. Soil and Statistical Analyses

4.3.4.1. Laboratory Methods

The 2016 soil samples reported in Section 4.4.2 were analyzed by treatment and major morphological horizon (uppermost ^A, ^Bw, and lowermost ^C). Soil samples were processed and analyzed in the laboratory according to the detailed methods outlined in Section 3.3.4.2. However,

one notable difference is that in this current chapter we report the 2016 soil depth x treatment data for a 1:2 soil:water EC (Rhoades 1996) and 1:1 soil:water pH (McLean 1982) using the horizon samples, whereas in Chapter 3 the 2016 soil depth x treatment data were reported for saturated paste EC and pH using incremental depth samples (Section 3.3.4.2). For the time series analysis (May 1982 - 2016) of soil properties by treatment, bulk soil samples collected at 0-5 cm were used for the 1982 - 1987 datasets (Roberts et al. 1988b; Roberts et al. 1988c) and 2008 data (Nash 2012), and the ^A horizon bulk samples were used for the 2016 data. All soil laboratory methods outlined in Section 3.3.4.2 are the same methods used in this current chapter, with the addition of Kjeldahl total-N (Bremner and Mulvaney 1982) for the 1987 vs. 2008 paired t-test. Like Chapter 3, we estimated SOC accumulation rates via simple subtraction of the original May 1982 rock spoil coal error (percent total organic C-carbonates) from the C data in 2016 (percent total C-carbonates). The appropriate scale conversions for SOC accumulation rates were estimated using 0-5 cm soil fines data collected from Nash (2012) in 2008, which were scaled to a deeper depth ratio using our measured ^A horizon depths in 2016. Greater detail on the SOC methodology is outlined in Section 3.3.4.2. Also, we reiterate that the SOC accumulation rates we calculated for Chapter 3 and 4 include our best available estimations and may have been complicated since these very rocky spoils reduce the accuracy of fine soil (< 2 mm) mass per unit volume measurements. Since we used soil fines data collected in 2008 by Nash (2012), we assumed that these data did not substantially change over time and reflected 2016 mass soil fines per surface m^2 expression.

4.3.4.2. Statistics

All analyses were performed in JMP Pro software (JMP®, Version 15.1 SAS Institute Inc., Cary, NC, 1989-2019). Visual comparisons and formal diagnostics were used to assess for and test normality and homogeneity of variance. All significant differences were interpreted using an alpha = 0.05. Variations in soil properties by treatment in 2016 were analyzed using a one-way analysis of variance (ANOVA) followed by Tukey's HSD test for means separation when the overall ANOVA F-test was significant. A mixed model was used to determine differences with depth in 2016 and included major horizon as the fixed effect and plot ID (location) as the random effect, followed by Tukey's HSD test for treatments. A mixed model was used to analyze the effects of

time (May 1982 - 2016) on soil properties by treatment, including main effects (year and treatment), an interaction term (treatment x year), and a random effect (plot ID), followed by Tukey's HSD test. We also used a paired t-test to determine changes in soil properties (i.e., 1:2 soil:water EC and total N) by treatment between two years (e.g., 1982 and 2016).

4.4. Results and Discussion

4.4.1. Morphological Field Attributes Over Time

Detailed soil profile descriptions for the SA experiment over time (1983, 1985, 1989, and 2016) are given in Appendix A2 and partial descriptions are given for select pedons in Table 4.2. Distinct ^A horizons with weak to fine and medium granular (gr) and subangular blocky (sbk) structure, and common very fine (< 1 mm) and fine (1-2 mm) roots were observed within two years after revegetation (Daniels et al. 1983; Daniels et al. 1991). After three years, Roberts et al. (1988b) observed rapid pedogenesis in ^A horizons, particularly for the sawdust and biosolids treatments, the latter of which produced the highest biomass at higher application rates (≥ 56 Mg ha^{-1} rates). Over a longer time period (34 years), rock fragment contents visibly decreased as the surface ^A horizons thickened, and additional horizons developed, most notably ^Bw (cambic) horizons due to > 50% moderate structural development. Subsoil morphological properties varied across treatments, primarily by color and overall horizonation. Refer to Chapter 3 for a detailed overview of soil morphological features in the subsoil, as well as general taxonomic implications for 34-year-old SS and SiS derived soils. As discussed in Chapter 3, compacted layers formed over time in lower ^B, ^C, and/or transitional horizons. Subsoil bulk densities for select SA plots averaged 1.45 g cm^{-3}. These compacted layers likely resulted from a combination of natural settling and infilling of soil particles into collapsed bridging voids as discussed by Roberts et al. (1988b), who also noted a 0.2 m elevation difference in spoils between 1982 and 1986. Bendfeldt et al. (2001) estimated surface (0-10 cm) fine-earth soil bulk density at the SA experiment in 1998. Native soils had a higher surface bulk density (1.38 Mg m^{-3}). The 112 Mg ha^{-1} biosolids had the lowest soil bulk density (1.09 Mg m^{-3}) and the control had a mean bulk density of 1.24 Mg m^{-3}.

Table 4.2. Select pedons from historical profile descriptions at the SA experiment.

1983							
Plot No.	**Treatment**	**Horizon**	**Depth (cm)**	**Structure Type** [+]	**Texture** [+]	**Rock Frag.** †	**Color**
26	Control	^A ^C	0-4 4-66+	1 f sbk 0 sls	L L	65%ł	10YR 4/3 10YR 4/3
34	56 Mg ha^{-1} Biosolids	^A ^C	0-4 5-65+	1 f-m sbk 0 sls	L L	67%ł	10YR 4/4 10YR 4/4
39	Topsoil	^A ^1C ^2C	0-4 4-12 12-72+	1 f sbk 0 sls 0 sls	L L L	66%ł	10YR 4/4 2.5YR 4/4 10YR 4/4
1985							
26	Control	^A ^C1 ^C2	0-4 4-18 18-100+	1 vf-f gr 1 f-m sbk 0 sls/1-2 sbk	SL SL SL	68% - -	10YR 3/3 10YR 4/3 10YR 4/3
34	56 Mg ha^{-1} Biosolids	Oe ^A ^C1 ^C2	2-0 0-11 11-44 44-92+	- 1 vf-f gr 0 sls/1 m sbk 0 sls	- SL SL SL	- 63% - -	- 10YR 3/2 10YR 5/4 10YR 5/4
39	Topsoil	^A ^C ^2C	0-5 5-15 15-100+	1 vf-f gr 1 vf-f gr/2 sbk 1 f-m sbk/0 sls	SL SL SL	34% - -	10YR 3/3 10YR 5/4 10YR 4/2
1989							
26	Control	^A ^AC ^C1 ^C2	0-9 9-29 29-72 72+	1 f sbk 1 m sbk 0 sls 0 sls	SL SL SL SL	68% - - -	10YR 3/3 10YR 4/3 10YR 4/4 10YR 4/4
34	56 Mg ha^{-1} Biosolids	^A ^AC ^C1 ^C2	0-10 10-25 25-68 68+	1 f gr/sbk 1 m sbk 0 sls 0 sls	SL SL SL SL	56% - - -	10YR 3/3 10YR 4/4 10YR 4/6 10YR 4/6
39	Topsoil	N/A*	N/A	N/A	N/A	-	N/A

Table 4.2. Continued.

2016							
26	Control	Oe ^A ^Bw ^C	5-0 0-7 19-39 105-125+	- 2 gr 1 sbk 0 sls	- SiL SL SL	- 30% 55% 65%	- 10YR 3/2 10YR 3/3 10YR 3/3
34	56 Mg ha^{-1} Biosolids	Oe ^A ^BA ^Bw ^BC ^C	5-0 0-10 10-22 22-40 40-69 69-125+	- 2 gr 2 sbk 1 sbk 1 sbk 0 sls	- L L L SL SL	- 45% 50% 70% 80% 80%	- 10YR 3/1 10YR 3/4 10YR 4/4 10YR 5/4 10YR 4/3
39	Topsoil	Oe ^A ^AB ^Bw ^C	3-0 0-8 8-17 17-44 44-125+	- 2 gr 2 sbk 1 sbk 0 sls	- L SL SL SL	- 40% 45% 75% 80%	- 10YR 3/2 10YR 4/4 10YR 4/3 10YR 3/3

*Plot not described in that year.
[+]Codes for soil structure (grade, size, class) and texture classes by Schoeneberger et al. (2012).
†1985 values based on 0-5 cm 1984 bulk samples; 1989 values based on 0-5 cm 1987 samples.
ŧVisual range estimate for the entire profile.

Across the soil profiles described and sampled in 2016, the uppermost ^A horizons were typically followed by an ^AB or ^BA transitional horizon or an ^A2 horizon as was the case of two topsoil plots. Images of the uppermost surface horizons, cambic horizons, and select soil profiles are given below (Figures 4.1-4.3) and full-size images for each treatment are found in Appendix A3. The sawdust treatment had overall deeper ^A horizons (0-12 cm) followed by the two biosolids treatments, which had similar thickness on average (0-10 cm). The topsoil and control treatments averaged 8 cm deep ^A horizons. Surface ^A horizons were not necessarily thicker or darker than the unamended SS and/or SiS rock mix treatments, which averaged approximately 10 cm and were thickest and darkest in the 100% SiS (refer to Chapter 3). Soil ^A horizon hue, value, and chromas were generally similar among treatments, but some of the sawdust plots were uniquely less gray in color (e.g., 10YR 2/2, very dark brown) compared to other treatments, presumably due to the nature of the organics produced by this substrate. One of the plots for each of the 56 and 112 Mg ha^{-1} biosolids treatments contained the lowest chroma (i.e., 10YR 3/1) recorded among all profiles. Soil ^A horizons clearly deepened and darkened from the

earliest years of sampling to 2016 and immediately underlying subsoils transitioned from ^AC in 1989 into ^BC, ^AB, or ^Bw horizons by 2016. Granular and sbk peds within horizons progressed into stronger grades from earlier observations. Additionally, thin partially decomposed leaf litter (Oi) layers developed across treatments over time.

Figure 4.1. Surface horizons in the control (upper left), topsoil (upper right), sawdust (lower left), and 112 Mg ha^{-1} biosolids (lower right) treatments. Photos by Dan Johnson used with permission.

Figure 4.2. From left to right: topsoil, 56 Mg ha^{-1} biosolids, and sawdust treatment profiles in August 2016. Refer to Appendix A3 for full size profile photos of all SA treatments. Photos by Dan Johnson used with permission.

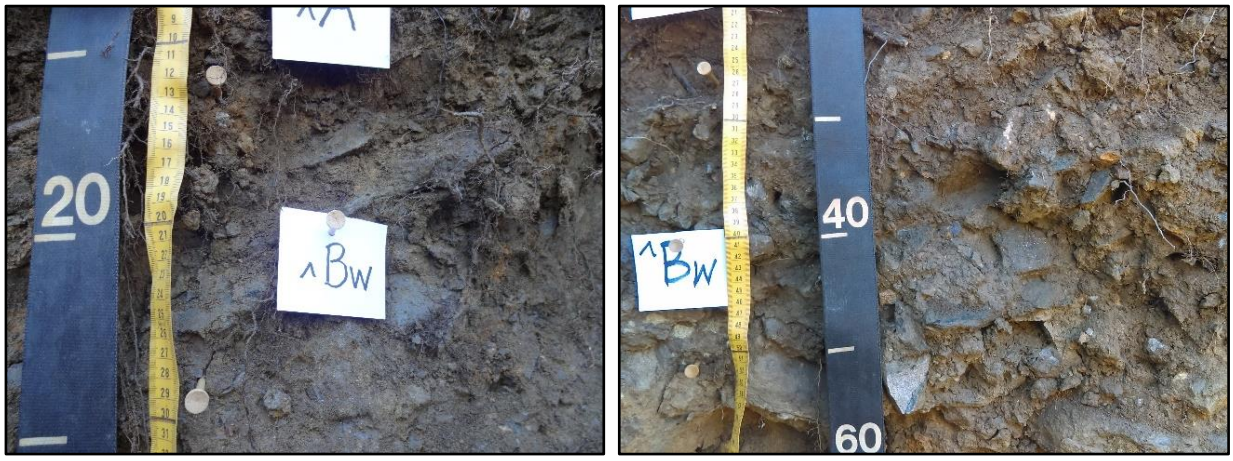

Figure. 4.3. Cambic ^Bw horizons described in 2016 in a 2:1 SS:SiS rock mix or control (left) and the subsoil of a 112 Mg ha^{-1} biosolids treatment (right). Photos by Dan Johnson used with permission.

4.4.2. Surface Amendment Treatment and Depth Effects

Particle size distribution

Sand, silt, and clay contents were similar in the ^Bw and ^C horizons due to the homogenous nature of the original 2:1 SS:SiS rock spoil and limited weathering with depth (Table 4.3). However, in the ^A horizon, topsoil had the highest sand content, reflecting the sandier nature of the native soil materials originally applied. Alternatively, topsoil had a lower silt content compared to the control and sawdust treatments in the ^A horizon. In terms of textural changes with depth, sand, silt, and clay contents were generally uniform across major horizons (Table 4.3). Exceptions included higher sand content in the ^C vs. ^A horizon for the 56 Mg ha^{-1} biosolids treatment and higher clay content in the ^A vs. ^C horizon for the topsoil and 56 Mg ha^{-1} biosolids treatments. These results were inconsistent and likely due to background variability in the 2:1 SS:SiS parent material. Additionally, the particle size analysis was potentially complicated by the high organic matter content of the amended treatments.

Table 4.3. Particle size distribution among treatments and in major morphological horizon.

Soil Separate (%)	Horizon	Surface Amendment Treatment				
		Control	**Topsoil**	**Sawdust**	**Biosolids 56 Mg ha^{-1}**	**Biosolids 112 Mg ha^{-1}**
Sand	^A	59 ± 1.0 Ba*	69 ± 1.0 Aa	58 ± 1.1 Ba	63 ± 1.5 Bb	61 ± 0.9 Ba
	^Bw	61 ± 1.2 Aa	65 ± 1.2 Aa	65 ± 2.3 Aa	66 ± 2.1 Aab	61 ± 1.6 Aa
	^C	64 ± 3.5 Aa	66 ± 0.9 Aa	65 ± 1.9 Aa	68 ± 1.7 Aa	65 ± 2.0 Aa
Silt	^A	29 ± 1.0 Aa	20 ± 1.3 Ba	30 ± 2.7 Aa	25 ± 1.7 ABa	26 ± 0.7 ABa
	^Bw	28 ± 0.9 Aa	24 ± 1.1 Aa	24 ± 2.7 Aa	24 ± 1.6 Aa	26 ± 2.1 Aa
	^C	26 ± 4.0 Aa	25 ± 0.2 Aa	24 ± 1.3 Aa	22 ± 1.0 Aa	25 ± 2.5 Aa
Clay	^A	12 ± 0.2 Aa	11 ± 0.4 Aa	12 ± 1.5 Aa	12 ± 0.7 Aa	13 ± 1.5 Aa
	^Bw	11 ± 0.8 Aa	10 ± 0.3 Aab	11 ± 0.5 Aa	11 ± 0.9 Aab	13 ± 0.6 Aa
	^C	10 ± 1.3 Aa	9 ± 0.7 Ab	11 ± 0.9 Aa	10 ± 0.7 Ab	10 ± 0.5 Aa

*****Mean ± SE. Different uppercase letters denote treatment differences across a given horizon and different lowercase letters denote differences among horizons within a given treatment ($P \leq 0.05$).

Soil pH, EC, and Fe- and Mn-oxides

Soil pH (1:1 soil:water), EC (1:2 soil:water), and extractable iron (Fe) and (Mn) oxides by treatment and major horizons are given in Table 4.4. There were no treatment variations in pH across a given horizon. In terms of depth effects, pH was lower in the ^A horizons compared to the ^Bw and ^C horizons across all treatments, due to the influence of OM decomposition and turnover on pH. Also, the EC levels within a given horizon were not different among treatments but varied by horizon depth within a given treatment. That is, EC was higher in the ^A horizon vs. ^Bw and ^C horizons across all treatments, indicating plant cycling and concentration of base cations and other components in the soil surface.

Table 4.4. Some soil chemical properties among treatments and in major morphological horizon.

Parameter	Horizon	Surface Amendment Treatment				
		Control	**Topsoil**	**Sawdust**	**Biosolids 56 Mg ha^{-1}**	**Biosolids 112 Mg ha^{-1}**
pH	^A	5.5 ± 0.13 Ab*	5.2 ± 0.20 Ac	5.1 ± 0.15 Ab	5.1 ± 0.15 Ab	5.2 ± 0.04 Ab
	^Bw	6.8 ± 0.16 Aa	7.2 ± 0.26 Ab	6.6 ± 0.34 Aa	7.3 ± 0.10 Aa	7.0 ± 0.54 Aa
	^C	7.5 ± 0.30 Aa	7.7 ± 0.23 Aa	7.4 ± 0.20 Aa	7.8 ± 0.12 Aa	7.7 ± 0.06 Aa
EC (µS cm^{-1})	^A	147 ± 26 Aa	199 ± 29 Aa	322 ± 86 Aa	252 ± 28 Aa	208 ± 46 Aa
	^Bw	31 ± 2 Ab	29 ± 3 Ab	30 ± 4 Ab	33 ± 4 Ab	29 ± 6 Ab
	^C	27 ± 5 Ab	29 ± 3 Ab	25 ± 1 Ab	28 ± 1 Ab	28 ± 3 Ab
Fe-oxides (%)	^A	2.18 ± 0.06 Ac*	1.85 ± 0.01 Bb	2.05 ± 0.06 ABa	1.90 ± 0.04 Bb	1.86 ± 0.06 Bb
	^Bw	2.33 ± 0.05 Ab	2.46 ± 0.10 Aa	2.50 ± 0.06 Aa	2.22 ± 0.09 Aa	2.42 ± 0.17 Aa
	^C	2.46 ± 0.03 ABa	2.62 ± 0.08 Aa	2.56 ± 0.15 ABa	2.23 ± 0.01 Ba	2.45 ± 0.03 ABa
Mn-oxides (%)	^A	0.07 ± 0.01 Aa	0.06 ± 0.01 Aa	0.06 ± 0.00 Aa	0.06 ± 0.00 Ab	0.06 ± 0.01 Aa
	^Bw	0.07 ± 0.00 Aa	0.07 ± 0.01 Aa	0.07 ± 0.00 Aa	0.07 ± 0.00 Aa	0.06 ± 0.01 Aa
	^C	0.08 ± 0.00 Aa	0.08 ± 0.00 Aa	0.07 ± 0.00 Aa	0.07 ± 0.00 Aa	0.07 ± 0.00 Aa

*****Mean ± SE. Different uppercase letters denote treatment differences across a given horizon and different lowercase letters denote differences among horizons within a given treatment ($P \leq 0.05$).

Other studies have reported significant differences in soil pH and EC soil levels following a wide range of freshly applied organic materials, but those results reflected short-term analyses (Bonanomi et al. 2019; Nguyen and Marschner 2017). With continued annual litter cycling and rooting additions, the control treatment acidified and bioaccumulated cations at a similar rate to the organic amendment plots. Further, the control had higher Fe-oxides vs. the topsoil and two biosolids treatments in the ^A horizon, which may be attributed to the spoil's relatively unweathered nature and higher degree of oxidation over time (Table 4.4). There were no treatment

differences for Fe-oxides in the ^Bw horizon, but in the ^C horizon, the topsoil was higher than the 56 Mg ha^{-1} biosolids treatment likely due to the inherent variation of the original rock spoil. Except for the sawdust treatment, extractable Fe-oxides were lower in the ^A horizon for all treatments, indicating complex associations with humus or perhaps the loss of Fe-oxides by translocation to lower horizons such as the ^Bw. For Mn-oxides, overall levels were low and there were no treatment differences across the major horizons. Only the 56 Mg ha^{-1} biosolids treatment had a depth effect, with lower Mn-oxides in the ^A horizon vs. subsurface horizons.

Total-C and- N

Levels of total carbon (C) and nitrogen (N) and C:N ratio by treatment and major horizons are given in Table 4.5. In the ^A horizon, sawdust was higher in total-C vs. topsoil presumably due to the sawdust's initially higher baseline OM levels. Sawdust was also higher in total-N vs. the control and topsoil treatments in the ^A horizon, likely owing to the large amount of slow-release fertilizer N added initially to offset anticipated N-immobilization effects due to its very high C:N ratio (Roberts et al. 1988 bc). The control had the highest C:N ratio due to the lack of any organic N amendments versus the presence of geogenic C (coal + carbonate) forms. There were no treatment differences for any parameter in the ^Bw and ^C horizons. For total-C and-N, as expected, the ^A horizons were higher compared to the ^Bw and ^C horizons across all treatments, reflecting the accumulation of OM. However, the ^Bw and ^C horizons had higher C:N ratios across treatments vs. the ^A horizon due to the higher relative levels of geogenic C and lower levels of total-N in the subsurface. While the sawdust stands out in terms of total-N content, it appears that ecosystem function had progressed in the control and topsoil treatments to the point where total-N levels were similar to the biosolids treatments, which were initially much higher in total-N and likely lost N and other elements over extended periods of leaching and/or gaseous losses with time.

Table 4.5. Soil total-C and-N, and C:N ratio among treatments and in major morphological horizon.

Parameter	Horizon	Surface Amendment Treatment				
		Control	**Topsoil**	**Sawdust**	**Biosolids 56 Mg ha^{-1}**	**Biosolids 112 Mg ha^{-1}**
Total-C (%)	^A	3.86 ± 0.50 ABa*	2.84 ± 0.16 Ba	4.63 ± 0.17 Aa	3.91 ± 0.41 ABa	3.92 ± 0.12 ABa
	^Bw	2.13 ± 0.10 Ab	1.62 ± 0.14 Ab	1.70 ± 0.34 Ab	1.42 ± 0.16 Ab	1.78 ± 0.06 Ab
	^C	1.70 ± 0.53 Ab	1.61 ± 0.22 Ab	1.39 ± 0.17 Ab	1.34 ± 0.19 Ab	1.32 ± 0.40 Ab
Total-N (%)	^A	0.20 ± 0.03 Ba	0.18 ± 0.02 Ba	0.32 ± 0.02 Aa	0.27 ± 0.03 ABa	0.27 ± 0.03 ABa
	^Bw	0.06 ± 0.00 Ab	0.05 ± 0.00 Ab	0.05 ± 0.01 Ab	0.04 ± 0.01 Ab	0.05 ± 0.01 Ab
	^C	0.05 ± 0.01 Ab	0.04 ± 0.00 Ab	0.04 ± 0.01 Ab	0.04 ± 0.01 Ab	0.04 ± 0.01 Ab
C:N Ratio	^A	18.9 ± 0.49 Ab	15.8 ± 0.96 ABb	14.7 ± 0.33 Bb	14.4 ± 0.16 Bb	14.7 ± 0.94 Bb
	^Bw	33.1 ± 0.77 Aa	35.4 ± 1.50 Aa	32.6 ± 4.97 Aa	34.3 ± 1.59 Aa	35.0 ± 3.31 Aa
	^C	35.7 ± 2.41 Aa	37.7 ± 1.45 Aa	33.5 ± 1.50 Aa	33.3 ± 0.48 Aa	33.4 ± 4.55 Aa

*****Mean ± SE. Different uppercase letters denote treatment differences across a given horizon and different lowercase letters denote differences among horizons within a given treatment ($P \leq 0.05$).

Extractable nutrients and metals

Mehlich I extractable nutrients and metals by SA treatment and in major horizons are given in Table 4.6. In the ^A horizon, the highest biosolids treatment (112 Mg ha^{-1}) had higher Al, Cu, and Zn compared to the control, topsoil, and sawdust treatments, signifying the effect that biosolids have on supplying trace elements. The 112 Mg ha^{-1} biosolids rate also had higher Fe in the ^A horizon compared to the topsoil. Stehouwer et al. (2006) found that, relative to the quantity applied in the biosolids, leaching losses of Zn were intermediate and much less for Cu, and all trace metals assessed in their study were below U.S. drinking water criteria. Further, our data showed that depth effects for a given element were variable among SA treatments, but generally higher nutrients and metals were found in the ^A vs. ^Bw and/or ^C horizons, particularly for K, Ca, Zn, and B. Both

biosolids treatments had higher Al in the surface vs. subsurface horizons. The sawdust treatment notably had the widest range of nutrients and metals concentrated in the surface vs. subsurface.

Table 4.6. Mehlich I extractable nutrients and metals among treatments and in major morphological horizon.

Parameter (mg kg^{-1})	Horizon	Surface Amendment Treatment				
		Control	**Topsoil**	**Sawdust**	**Biosolids 56 Mg ha^{-1}**	**Biosolids 112 Mg ha^{-1}**
Phosphorus (P)	^A	34 ± 1 Aa*	24 ± 12 Aa	26 ± 2 Aa	38 ± 7 Aa	91 ± 30 Aa
	^Bw	55 ± 3 Aa	46 ± 5 Aa	37 ± 10 Aa	39 ± 4 Aa	39 ± 8 Aa
	^C	46 ± 15 Aa	40 ± 3 Aa	38 ± 5 Aa	30 ± 4 Aa	33 ± 11 Aa
Potassium (K)	^A	49 ± 10 Aa	64 ± 12 Aa	86 ± 13 Aa	63 ± 4 Aa	50 ± 2 Aa
	^Bw	27 ± 1 Aa	28 ± 0 Ab	31 ± 0 Ab	27 ± 4 Ab	33 ± 4 Aa
	^C	36 ± 5 Aa	34 ± 1 Aab	30 ± 2 Ab	32 ± 3 Ab	110 ± 68 Aa
Calcium (Ca)	^A	963 ± 253 Aa	780 ± 91 Aa	1292 ± 34 Aa	1083 ± 152 Aa	1087 ± 105 Aa
	^Bw	562 ± 34 Aa	607 ± 58 Ab	502 ± 58 Ab	558 ± 30 Ab	563 ± 92 Ab
	^C	576 ± 119 Aa	628 ± 63 Ab	511 ± 30 Ab	575 ± 9 Ab	538 ± 95 Ab
Magnesium (Mg)	^A	228 ± 31 Aa	208 ± 21 Aa	296 ± 15 Aa	232 ± 25 Aa	202 ± 20 Aa
	^Bw	188 ± 6 Aa	197 ± 15 Aa	186 ± 10 Ab	182 ± 11 Aa	202 ± 16 Aa
	^C	200 ± 16 Aa	223 ± 25 Aa	176 ± 8 Ab	196 ± 6 Aa	200 ± 7 Aa
Zinc (Zn)	^A	3.8 ± 0.8 Ba	2.7 ± 0.1 Ba	5.5 ± 0.4 Ba	10.6 ± 2.5 ABa	20.6 ± 5.1 Aa
	^Bw	2.4 ± 0.3 Aa	2.6 ± 0.2 Aa	2.3 ± 0.2 Ab	2.4 ± 0.2 Ab	3.3 ± 0.6 Ab
	^C	2.0 ± 0.4 Aa	2.8 ± 0.0 Aa	2.2 ± 0.3 Ab	2.1 ± 0.4 Ab	2.6 ± 0.7 Ab

Table 4.6. Continued.

Manganese (Mn)	^A	36 ± 11 Aa	32 ± 6 Aa	42 ± 2 Aa	28 ± 5 Aa	24 ± 3 Aa
	^Bw	25 ± 2 Aa	27 ± 2 Aa	26 ± 5 Aab	21 ± 2 Aa	18 ± 4 Aa
	^C	19 ± 4 Aa	22 ± 2 Aa	22 ± 4 Ab	15 ± 2 Aa	15 ± 2 Aa
Copper (Cu)	^A	1.8 ± 0.3 Ba	1.0 ± 0.4 Ba	1.4 ± 0.3 Ba	2.5 ± 0.6 ABa	4.1 ± 0.5 Aa
	^Bw	1.9 ± 0.1 Aa	1.7 ± 0.1 Aa	1.8 ± 0.1 Aa	1.7 ± 0.1 Aa	2.1 ± 0.6 Aa
	^C	1.3 ± 0.3 Aa	1.6 ± 0.2 Aa	1.4 ± 0.2 Aa	1.5 ± 0.2 Aa	1.5 ± 0.4 Aa
Iron (Fe)	^A	51 ± 15 ABa	35 ± 4 Ba	51 ± 9 ABa	85 ± 11 ABa	100 ± 16 Aa
	^Bw	45 ± 1 Aa	44 ± 4 Aa	40 ± 7 Aa	38 ± 2 Ab	37 ± 9 Aa
	^C	30 ± 7 Aa	43 ± 2 Aa	39 ± 7 Aa	32 ± 4 Ab	33 ± 9 Aa
Boron (B)	^A	0.3 ± 0.1 Aa	0.2 ± 0.0 Aa	0.3 ± 0.0 Aa	0.2 ± 0.1 Aa	0.3 ± 0.0 Aa
	^Bw	0.1 ± 0.0 Aa	0.1 ± 0.0 Aa	0.1 ± 0.0 Ab	0.1 ± 0.0 Aa	0.1 ± 0.0 Ab
	^C	0.1 ± 0.0 Aa	0.1 ± 0.0 Aa	0.1 ± 0.0 Ab	0.1 ± 0.0 Aa	0.1 ± 0.0 Ab
Aluminum (Al)	^A	99 ± 17 Ba	86 ± 11 Ba	125 ± 13 Ba	160 ± 21 ABa	242 ± 45 Aa
	^Bw	62 ± 4 Aa	79 ± 9 Aa	73 ± 4 Aab	67 ± 5 Ab	64 ± 8 Ab
	^C	57 ± 2 Aa	72 ± 11 Aa	70 ± 6 Ab	65 ± 7 Ab	65 ± 7 Ab

*****Mean ± SE. Different uppercase letters denote treatment differences across a given horizon and different lowercase letters denote differences among horizons within a given treatment ($P \leq 0.05$).

Exchangeable cations

Exchangeable cations, CEC, and base saturation by treatment and major horizons are given in Table 4.7. Treatment differences were evident for Mg in ^A horizons, where the 112 Mg ha^{-1} biosolids rate had higher Mg vs. the sawdust treatment. For base saturation, there were no treatment or depth effects. Most treatments had higher exchangeable bases in the ^A vs. ^Bw and/or ^C horizons, particularly for Ca, Mg, and K. All treatments except for the control had a higher CEC

in the surface (^A) vs. subsurface horizons. CEC was not different among treatments in the surface (^A) horizon, but standard CEC methods (particularly NH_4OAC extracts) are not as accurate for rock-derived mine soils due to the relatively unweathered background carbonate sources, likely increasing sample variability. Further, both biosolids treatments had slightly higher Al in the surface vs. subsurface.

Table 4.7. Exchangeable bases, Al, and CEC, expressed as $cmol_c\ kg^{-1}$ soil, and percent base saturation among treatments and in major morphological horizon.

Parameter ($cmol_c\ kg^{-1}$)	**Horizon**	**Surface Amendment Treatment**				
		Control	**Topsoil**	**Sawdust**	**Biosolids 56 Mg ha^{-1}**	**Biosolids 112 Mg ha^{-1}**
Calcium (Ca)	^A	3.7 ± 0.7 Aa*	3.5 ± 0.2 Aa	5.3 ± 0.4 Aa	4.1 ± 0.5 Aa	3.9 ± 0.6 Aa
	^Bw	1.7 ± 0.1 Ab	2.0 ± 0.1 Ab	1.9 ± 0.2 Ab	2.0 ± 0.2 Ab	2.2 ± 0.2 Ab
	^C	1.9 ± 0.2 Aab	1.8 ± 0.1 Ab	1.8 ± 0.0 Ab	2.2 ± 0.2 Ab	1.8 ± 0.5 Ab
Magnesium (Mg)	^A	1.7 ± 0.2 ABa	1.6 ± 0.0 ABa	2.4 ± 0.3 Aa	1.8 ± 0.1 ABa	1.5 ± 0.2 Ba
	^Bw	1.4 ± 0.0 Aa	1.4 ± 0.0 Ab	1.5 ± 0.1 Ab	1.4 ± 0.1 Ab	1.5 ± 0.1 Aa
	^C	1.4 ± 0.1 Aa	1.4 ± 0.0 Ab	1.3 ± 0.1 Ab	1.4 ± 0.1 Ab	1.2 ± 0.3 Aa
Potassium (K)	^A	0.14 ± 0.0 Aa	0.19 ± 0.0 Aa	0.26 ± 0.0 Aa	0.18 ± 0.0 Aa	0.16 ± 0.0 Aa
	^Bw	0.08 ± 0.0 Ab	0.08 ± 0.0 Ab	0.12 ± 0.0 Ab	0.07 ± 0.0 Ab	0.10 ± 0.0 Aa
	^C	0.08 ± 0.0 Ab	0.09 ± 0.0 Ab	0.10 ± 0.0 Ab	0.10 ± 0.0 Ab	0.11 ± 0.1 Aa
Sodium (Na)	^A	0.01 ± 0.0 Aa	0.01 ± 0.0 Aa	0.01 ± 0.0 Aa	0.04 ± 0.0 Aa	0.04 ± 0.0 Aa
	^Bw	0.01 ± 0.0 Aa	0.01 ± 0.0 Aa	0.11 ± 0.1 Aa	0.01 ± 0.0 Aa	0.02 ± 0.0 Aab
	^C	0.01 ± 0.0 Aa	0.01 ± 0.0 Aa	0.02 ± 0.0 Aa	0.01 ± 0.0 Aa	0.01 ± 0.0 Ab

Table 4.7. Continued.

Aluminum (Al)	^A	0.1 ± 0.0 Aa	0.3 ± 0.2 Aa	0.10 ± 0.0 Aa	0.1 ± 0.0 Aa	0.2 ± 0.1 Aa
	^Bw	0.0 ± 0.0 Aa	0.0 ± 0.0 Aa	0.0 ± 0.0 Aa	0.0 ± 0.0 Ab	0.0 ± 0.0 Ab
	^C	0.0 ± 0.0 Aa	0.0 ± 0.0 Aa	0.0 ± 0.0 Aa	0.0 ± 0.0 Ab	0.0 ± 0.0 Ab
CEC†	^A	5.6 ± 0.9 Aa	5.6 ± 0.0 Aa	8.0 ± 0.7 Aa	6.2 ± 0.6 Aa	5.8 ± 0.8 Aa
	^Bw	3.2 ± 0.1 Aa	3.5 ± 0.1 Ab	3.7 ± 0.4 Ab	3.5 ± 0.3 Ab	3.8 ± 0.2 Ab
	^C	3.4 ± 0.3 Aa	3.3 ± 0.1 Ab	3.2 ± 0.1 Ab	3.7 ± 0.3 Ab	3.1 ± 0.8 Ab
Base Saturation (%)	^A	99 ± 0 Aa	95 ± 3 Aa	99 ± 1 Aa	98 ± 1 Aa	96 ± 1.7 Aa
	^Bw	100 ± 0 Aa	100 ± 0 Aa	100 ± 0 Aa	100 ± 0 Aa	100 ± 0 Aa
	^C	100 ± 0 Aa	100 ± 0 Aa	100 ± 0 Aa	100 ± 0 Aa	100 ± 0 Aa

†CEC is estimated as the sum of total exchangeable Ca, Mg, K, Na, and Al.

*****Mean ± SE. Different uppercase letters denote treatment differences across a given horizon and different lowercase letters denote differences among horizons within a given treatment ($P \leq 0.05$).

4.4.3. Changes in Soil Chemical and Physical Properties Over Time

This section reports on changes over time between 1982 and 2016, with focus on the soil surface where amendments were originally applied. Soil texture, Fe-oxides, P, pH, CEC, and SOM all significantly changed with time (year main effect), but in a different way (Table 4.8). These parameters were also significantly affected by the treatment main effect, except for clay contents. Sand and silt contents, Fe-oxides, pH, CEC, and SOM showed treatment x year interaction effects, indicating that the relative effect of time on a given parameter was not consistent across rock types for all years, or in other words, the relative differences varied from year-to-year (Table 4.8). Details on overall treatment x time x interaction effects for all soil parameters by model level are presented in separate tables below.

Table 4.8. Mixed model p-values for selected mine soil properties in the surface.

Model Source	Sand	Silt	Clay	Fe-oxides	P	pH	CEC	SOM
	(%)				mg kg^{-1}		$cmol_c$ kg^{-1}	(%)
Year	**<0.0001***	**<0.0001**	**0.0007**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Treatment	**<0.0001**	**<0.0001**	0.1199	**0.0035**	**<0.0001**	**<0.0001**	**<0.0001**	**0.0001**
Year x Treatment	**<0.0001**	**0.0014**	0.5203	**0.0072**	**<0.0001**	**<0.0001**	**<0.0001**	**0.0005**

*Bold font represents significant differences by parameter x model level ($P \leq 0.05$).

4.4.3.1. Particle Size Distribution Over Time

Clay contents increased over time in terms of main effects, but there were no overall treatment differences (Table 4.9). The topsoil treatment remained consistently higher in sand contents compared to all other treatments over time, except for the original unamended bulk spoils in May 1982 (Table 4.10). Topsoil also generally had higher silt contents, except in 2016 when the topsoil and biosolids 112 Mg ha^{-1} had similar silt contents. Note that the 56 Mg ha^{-1} biosolids rate was not included in these time x treatment analyses for soil texture because there was limited available data for that treatment. Generally, sand contents decreased over time, but the effect of time on sand was not consistent for all treatments in all years (Table 4.10). Silt contents generally increased over time, but the relative effect of time on silt among treatments also fluctuated from year-to-year. In summary, the topsoil treatment had the only major impact on soil texture initially and over time. Also, temporal changes in particle size distribution were similar to the RM experiment (i.e., sand decreasing and silt + clay increasing), indicating that background weathering of the original 2:1 SS:SiS parent material drove changes in soil texture with time.

Table 4.9. Main effects (year and treatment) pairwise differences for clay contents in the surface.

Year	Mean ± SE by Year/ All Treatments	Soil Age (yrs.)	Treatment	Mean ± SE by Treatment/ All Years
Clay (%)				
May 1982†	9.5 ± 0.2 bc*	0	Control	10.0 ± 0.6 A**
Oct. 1982	9.9 ± 0.4 abc	0.5	Topsoil	9.5 ± 0.3 A
1983	10.6 ± 0.4 abc	1	Sawdust	10.7 ± 0.5 A
1987	9.0 ± 0.5 c	5	Biosolids 56 Mg ha^{-1} ǂ	-
2008	11.5 ± 1.0 ab	26	Biosolids 112 Mg ha^{-1}	11.3 ± 0.5 A
2016	12.0 ± 0.5 a	34	-	-

†Organic amendments were not applied at the time of May sampling.
*Lowercase letters show overall differences for each year among all treatments ($P \leq 0.05$).
**Uppercase letters show overall differences for each treatment among all years ($P \leq 0.05$).
ǂNot enough data available for this analysis.

Table 4.10. Interaction effects (year x treatment) pairwise differences for sand and silt contents in the surface.

Year	Soil Age (yrs.)	Control	Topsoil	Sawdust	Biosolids 56 Mg ha^{-1} ǂ	Biosolids 112 Mg ha^{-1}
		Sand (%)				
May 1982†	0	64 ± 0.9 defg*	64 ± 0.8 defg	65 ± 0.8 bcde	-	62 ± 0.4 efg
Oct. 1982	0.5	62 ± 1.0 efg	73 ± 0.3 a	62 ± 1.4 efg	-	64 ± 1.0 cdef
1983	1	61 ± 0.5 efg	69 ± 1.0 abc	61 ± 0.6 efg	-	59 ± 0.5 g
1987	5	63 ± 0.7 defg	70 ± 0.5 ab	60 ± 1.8 fg	-	60 ± 1.1 efg
2008	26	53 ± 1.5 h	61 ± 1.1 efg	52 ± 1.0 h	-	53 ± 0.9 h
2016	34	59 ± 1.0 fg	69 ± 1.0 abcd	58 ± 1.1 g	-	61 ± 0.9 efg

Table 4.10. Continued.

		Silt (%)				
May 1982	0	27 ± 0.6 cdef	26 ± 0.4 cdef	26 ± 1.0 cdefg	-	28 ± 0.7 cd
Oct. 1982	0.5	28 ± 0.6 cd	18 ± 0.1 h	28 ± 1.3 cde	-	24 ± 1.1 defg
1983	1	28 ± 0.4 cd	22 ± 0.6 fgh	28 ± 0.3 cd	-	28 ± 0.3 cd
1987	5	29 ± 0.5 bcd	22 ± 0.9 efgh	31 ± 1.0 bc	-	29 ± 0.8 cd
2008	26	35 ± 1.8 ab	28 ± 0.2 cd	35 ± 1.1 ab	-	37 ± 3.2 a
2016	34	29 ± 1.0 bcd	20 ± 1.3 gh	30 ± 2.7 bcd	-	26 ± 0.7 cdefg

†Organic amendments were not applied at the time of May sampling.
*Mean ± SE. Different letters show differences among years for a given treatment (columns), as well as differences by treatment within a given year (rows) ($P \leq 0.05$).
ǂNot enough data available for this analysis.

4.4.3.2. Soil Chemical Properties Over Time

Over time, Fe-oxides generally increased while extractable P generally decreased (Table 4.11), and these effects are similar to the unamended SS and SiS in the RM experiment. We can attribute the increase in Fe-oxides to background chemical weathering of the parent rock spoil, while P may be less available due to fixation mechanisms and/or complexed organic forms as SOM levels increased over time (see Section 4.4.3.3). The relative effect of time on Fe-oxides fluctuated in the earlier years of the experiment, but after 1984, Fe-oxides were consistently higher for all treatments in all years. Likewise, the relative effect of time on P was not the same for all treatments in all years. In terms of treatment differences, the topsoil treatment was lower in Fe-oxides in 2008 compared to the control and sawdust treatments. For P, treatment differences were more evident over time, with the 56 and/or 112 Mg ha^{-1} biosolids treatments generally having higher extractable P contents compared to the control and other SA treatments, and these treatment effects notably persisted into the later years (Table 4.11). Roberts et al. (1988c) noted that P tissue concentrations were highest in 1983 for the 56 Mg ha^{-1} biosolids and were also associated with N tissue concentrations, both of which declined after 1984 in relation to lower biomass production.

Table 4.11. Interaction effects (year x treatment) pairwise differences for Fe-oxides and extractable P in the surface.

Year	Soil Age (yrs.)	Control	Topsoil	Sawdust	Biosolids 56 Mg ha^{-1} ǂ	Biosolids 112 Mg ha^{-1}
		Fe-oxides (%)				
May 1982†	0	0.50 ± 0.02 klm*	0.48 ± 0.05 klm	0.58 ± 0.08 ijklm	-	0.53 ± 0.02 jklm
Oct. 1982	0.5	0.43 ± 0.01 klm	0.41 ± 0.08 lm	0.37 ± 0.01 m	-	0.35 ± 0.06 m
1983	1	0.97 ± 0.05 fgh	0.96 ± 0.04 efgh	1.04 ± 0.06 defg	-	0.87 ± 0.07 fghi
1984	2	0.92 ± 0.06 fgh	0.70 ± 0.04 hijkl	0.84 ± 0.03 fghij	-	0.80 ± 0.09 ghijk
1987	5	1.28 ± 0.02 cde	1.00 ± 0.02 defgh	1.31 ± 0.05 cd	-	1.12 ± 0.16 cdef
2008	26	1.38 ± 0.03 c	1.00 ± 0.03 defgh	1.42 ± 0.05 c	-	1.10 ± 0.08 cdef
2016	34	2.18 ± 0.06 a	1.85 ± 0.01 b	2.05 ± 0.06 ab	-	1.86 ± 0.06 ab
		Olsen Extractable P (mg kg^{-1})				
May 1982	0	2.1 ± 0.4 jk	2.0 ± 0.7 k	2.4 ± 0.3 jk	2.4 ± 0.3 jk	2.1 ± 0.4 jk
Oct. 1982	0.5	60.0 ± 6.5 cdefg	38.1 ± 6.5 efghij	24.0 ± 3.2 ghijk	43.2 ± 4.6 defghi	81.0 ± 14.3 bc
1983	1	50.4 ± 0.9 cdefgh	42.0 ± 7.4 efghi	42.1 ± 6.6 efghi	82.4 ± 10.2 bc	120.4 ± 17.1 a
1984	2	25.2 ± 5.6 hijk	29.1 ± 1.7 fghijk	27.3 ± 4.2 ghijk	50.3 ± 9.6 cdefghi	80.0 ± 6.7 bcd
1987	5	27.1 ± 4.5 hijk	28.0 ± 2.9 fghijk	29.0 ± 3.5 fghijk	70.0 ± 8.7 bcde	81.3 ± 8.8 bc
2008	26	16.3 ± 1.0 ijk	16.0 ± 1.9 hijk	20.2 ± 1.7 hijk	64.3 ± 10.5 bcdef	100.1 ± 4.5 ab

†Organic amendments were not applied at the time of May sampling.
*Mean ± SE. Different letters show differences among years for a given treatment (columns), as well as differences by treatment within a given year (rows) ($P \leq 0.05$).
ǂNot enough data available for this analysis for some datasets.

Soil pH generally decreased over time due to the accumulation and turnover of organic matter in the soil surface, with the lowest levels apparent in 2016 (Table 4.12). There were no treatment differences in pH by 2008, but the sawdust treatment was lower in pH than most other

treatments in October 1982, 1983, and 1987. Soil CEC generally increased over time, with higher CEC values in the 56 and/or 112 Mg ha^{-1} biosolids treatments from October 1982 to 1987, but beyond 2008 there were no significant treatment effects (Table 4.12).

Table 4.12. Interaction effects (year x treatment) pairwise differences for surface soil pH and CEC.

Year	Soil Age (yrs.)	Control	Topsoil	Sawdust	Biosolids 56 Mg ha^{-1}	Biosolids 112 Mg ha^{-1}
		pH				
May 1982†	0	7.3 ± 0.1 a*	7.1 ± 0.2 ab	7.2 ± 0.1 a	7.3 ± 0.0 a	7.1 ± 0.1 abc
Oct. 1982	0.5	6.8 ± 0.1 abcde	7.2 ± 0.1 ab	6.1 ± 0.3 fghi	7.3 ± 0.0 a	7.0 ± 0.0 abc
1983	1	6.1 ± 0.1 fghi	6.2 ± 0.1 efgh	5.3 ± 0.0 j	6.4 ± 0.0 defgh	6.4 ± 0.1 efgh
1984	2	6.1 ± 0.1 ghi	6.5 ± 0.2 cdefgh	6.0 ± 0.2 ghi	6.3 ± 0.0 efgh	6.0 ± 0.1 hi
1987	5	6.7 ± 0.0 abcdef	7.0 ± 0.1 abcd	6.1 ± 0.1 fghi	6.7 ± 0.1 abcdef	6.6 ± 0.1 bcdefg
2008	26	6.2 ± 0.1 efgh	6.2 ± 0.1 efgh	6.2 ± 0.1 efgh	6.1 ± 0.1 fghi	6.2 ± 0.1 efgh
2016	34	5.5 ± 0.1 ij	5.2 ± 0.2 j	5.1 ± 0.1 j	5.1 ± 0.1 j	5.2 ± 0.0 j
		CEC ($cmol_c$ kg^{-1})				
May 1982	0	3.7 ± 0.0 pq	3.9 ± 0.2 pq	3.7 ± 0.1 q	4.0 ± 0.2 opq	3.9 ± 0.1 nopq
Oct. 1982	0.5	7.0 ± 0.2 ijklmnopq	7.8 ± 0.2 hijklmno	10.1 ± 0.5 cefghij	12.4 ± 0.9 abcde	15.7 ± 1.8 a
1983	1	4.7 ± 0.0 mnopq	5.2 ± 0.2 mnopq	8.0 ± 0.2 hijklmn	10.6 ± 0.7 bcdefghi	12.6 ± 0.9 abcdef
1984	2	5.0 ± 0.2 mnopq	5.3 ± 0.2 mnopq	7.5 ± 1.0 hijklmnop	8.7 ± 0.5 fghijklm	13.5 ± 1.2 abcd
1987	5	6.4 ± 0.3 jklmnopq	6.8 ± 0.2 ijklmnopq	9.5 ± 0.7 efghijkl	11.3 ± 1.2 bcdefgh	12.2 ± 0.6 bcdef
2008	26	12.1 ± 0.9 abcdefg	10.1 ± 0.6 cdefghijk	13.5 ± 1.2 abd	12.8 ± 0.3 abcde	14.2 ± 1.3 ab
2016	34	5.6 ± 0.9 lmnopq	5.6 ± 0.0 lmnopq	8.0 ± 0.7 ghijklmnop	6.2 ± 0.6 jklmnopq	5.8 ± 0.8 klmnopq

†Organic amendments were not applied at the time of May sampling.
*Mean ± SE. Different letters show differences among years for a given treatment (columns), as well as differences by treatment within a given year (rows) ($P \leq 0.05$).

Furthermore, EC paired contrasts between the original May 1982 unamended spoils and the 2016 ^A and ^Bw horizons are shown below in Figure 4.4. The 2016 ^Bw horizons had lower EC compared to 1982 spoils, indicating that long-term leaching had occurred. Like the RM plots, EC levels have been maintained over time in the surface horizon likely due to plant cycling and surface accumulation of Ca, Mg, and other cations. Surface (^A) horizons in 2016 were not different than the 1982 spoils across treatments ($p < 0.05$), but the topsoil and 56 Mg ha^{-1} biosolids treatments were trending towards higher EC levels (Table 4.13).

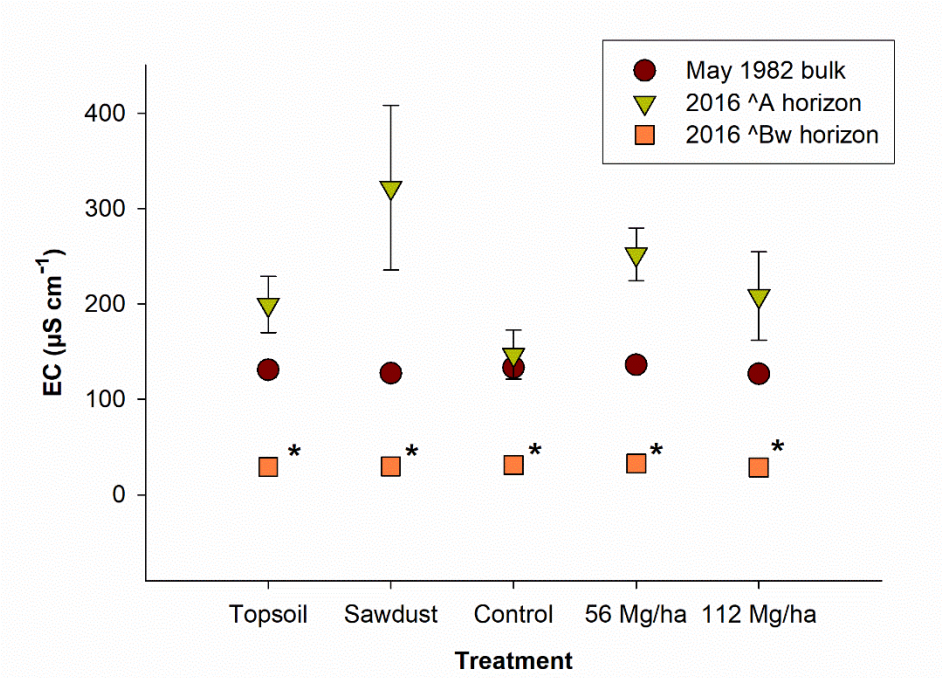

Figure 4.4. 1:2 soil:water EC (mean ± SE) levels in the original May 1982 bulk spoil samples vs. the ^A and ^Bw horizons in 2016. An asterisk (*) = EC was significantly lower than May 1982 EC. Delta values were used to test the difference in means between two years for a given treatment and interpreted by the two tailed p-value ($\alpha = 0.05$).

4.4.3.3. Soil Organic Matter, Nitrogen, and Carbon Over Time

When comparing total-N between 1987 and 2008, levels were similar between the two years except for the control, which was higher in 2008 (Table 4.13). These data indicate that the fertilizer N applied to the control three years following plot installation persisted with time. It is important to note that total-N was determined in 1987 using Kjehldahl digestion and total-N in 2008 was determined via dry combustion. From 2008 to 2016, total-N was similar except for the

highest biosolids treatment, which had lower N in 2016 (Table 4.13), indicating that N is being lost, which has been observed in agricultural systems following high inputs of N from fertilizer and organic amendments (Paustian et al. 1992).

Table 4.13. Subsurface EC and total N (mean ± SE), paired t-test delta values, and two-tailed p-values comparing values in a previous year to a later year, thus an increase = negative delta value.

Treatment	**EC**			
	May 1982 (Bulk)	**2016 (^A horizon)**	Δ†	**P > |t|***
Control	133 ± 3	147 ± 26	-14	0.6409
Topsoil	131 ± 8	199 ± 29	-69	0.0897
Sawdust	127 ± 8	322 ± 86	-195	0.1731
Biosolids 56 Mg ha^{-1}	136 ± 3	252 ± 28	-116	0.0571
Biosolids 112 Mg ha^{-1}	127 ± 7	208 ± 46	-82	0.2537
Treatment	**Total-N (g kg^{-1})**			
	1987 (0-5 cm) ł	**2008 (0-5 cm)**	Δ†	**P > |t|***
Control	1.4 ± 0.1	3.2 ± 0.4	-1.8	**0.0210**
Topsoil	1.0 ± 0.1	3.0 ± 0.7	-1.9	0.1197
Sawdust	2.4 ± 0.2	3.4 ± 0.7	-1.0	0.1709
Biosolids 56 Mg ha^{-1}	3.5 ± 0.6	4.0 ± 0.5	-0.5	0.5237
Biosolids 112 Mg ha^{-1}	3.6 ± 0.1	4.3 ± 0.5	-0.7	0.3077
Treatment	**Total-N (g kg^{-1})**			
	2008 (0-5 cm)	**2016 (^A horizon)**	Δ†	**P > |t|***
Control	3.2 ± 0.4	2.0 ± 0.3	1.1	0.1646
Topsoil	3.0 ± 0.7	1.8 ± 0.2	1.2	0.2901
Sawdust	3.4 ± 0.7	3.2 ± 0.2	0.3	0.7347
Biosolids 56 Mg ha^{-1}	4.0 ± 0.5	2.7 ± 0.3	1.3	0.1621
Biosolids 112 Mg ha^{-1}	4.3 ± 0.5	2.7 ± 0.2	1.6	**0.0380**

†Mean delta values or the difference in values between two years (e.g., May 1982 - 2016).
*Delta values were used to test the difference in means between years for a given treatment and interpreted by the two-tailed p-value ($\alpha = 0.05$). Bold represents a significant difference.
łN method used was Kjehldahl digestion procedure vs. dry combustion used in 2008 and 2016.

Soil organic matter generally increased over time, but the relative effect of time on SOM was not consistent for all treatments in all years (Table 4.14). For example, beyond October 1982 after the plots were amended, SOM levels did not differ in the control and biosolids 112 Mg ha^{-1} treatments until 2008 when SOM levels increased, but by 2016, SOM levels had dropped off again. The drop in SOM may have been due to the difference in the soil depths compared (0-5 cm in 2008 vs. 7-14 cm ^A horizons in 2016). Treatment differences varied in the earlier years; the sawdust and biosolids treatments generally had higher SOM levels compared to the control and/or topsoil treatments. Additionally, higher measures of total-N and SOM do not necessarily translate into higher available forms of nutrients. As reported in the earlier years of this study, fescue tissue N did not correlate to total-N soil levels due to differing rates of mineralization among the amended treatments. However, the biosolids 112 and 224 Mg ha^{-1} treatments led to higher soil N-availability and plant uptake compared to the control and other amended treatments in 1982 through 1984 and this was reflected in the fescue biomass production (Roberts et al. 1988c).

Table 4.14. Interaction effects (year x treatment) pairwise differences for SOM in the surface.

Year	Soil Age (yrs.)	Control	Topsoil	Sawdust	Biosolids 56 Mg ha^{-1}	Biosolids 112 Mg ha^{-1}
		SOM (%)				
Oct. 1982	0.5	2.8 ± 0.6 fgh*	1.3 ± 0.2 h	5.4 ± 1.3 cdefg	3.1 ± 0.3 efgh	5.2 ± 0.7 defg
1984	2	3.1 ± 0.1 efgh	1.9 ± 0.1 gh	8.0 ± 0.9 abcd	5.9 ± 0.4 cdef	7.1 ± 0.8 bcd
1987	5	3.2 ± 0.3 efgh	2.3 ± 0.2 fgh	7.2 ± 1.1 bcd	7.9 ± 1.4 abcd	6.6 ± 0.4 bcde
2008	26	8.9 ± 0.9 abc	7.7 ± 0.4 abcd	8.7 ± 0.3 abcd	10.0 ± 1.1 ab	10.9 ± 0.3 a
2016	34	4.8 ± 0.7 defgh	5.2 ± 0.6 cdefg	7.2 ± 0.6 abcd	6.3 ± 0.8 cdef	6.2 ± 0.6 bcdef

*Mean ± SE. Different letters show differences among years for a given treatment (columns), as well as differences by treatment within a given year (rows) ($P \leq 0.05$).

Accumulation rates for SOC across treatments are reported in Table 4.15 and were derived from a new method we developed to presumably correct for coal and carbonate-C values as described in Sections 3.3.4.2 and 3.4.3.3. Somewhat surprisingly, there were no significant treatment differences in SOC levels after 34 years. Section 3.4.3.3 details the SOC accumulation rates for mine soils in the current literature and for natural Appalachian forests. SOC accumulation levels in our study are slightly lower than what is reported in the literature, but there are several factors to consider such as the faster accumulation rates expected for younger (< 10 years) mine soils that undergo rapid plant growth and OM accrual (Littlefield et al. 2013). Our topsoil and organic amendments did not significantly contribute to higher long term SOC accumulation in later years. Wick et al. (2010), working on this same study, reported numerically higher total aggregate associated C and N concentrations in the biosolids treatments, but results were not significant due to high sample variability. However, the biosolids were significantly higher in microbial biomass C compared to the other treatments. Additionally, in the earlier years of our study, Roberts et al. (1988c) reported higher overall fescue biomass in 1983 vs. 1984 and 1986, indicating that biomass production dropped by 1984. The higher biosolids treatments generally produced superior biomass in earlier years (< 1986) compared to other treatments. Nash (2012) reported no significant differences in biomass production among treatments in 2008. Thus, we can attribute our relatively lower SOC accumulation rates to a lower level or "plateau" in aboveground productivity. Our results also indicate that after 34 years, the fertilized control reached SOC levels similar to amended treatments largely through normal C-sequestration processes, despite the fact that the amended plots received relatively high loadings of organic C when they were built in 1982. Taken together, this indicates potentially significant losses of original biosolids and sawdust C loadings over extended periods of time.

Table 4.15. Soil organic carbon (SOC) and sequestration rates in the surface after 34 years of weathering in surface amendment treatments.

Treatment	Mean ^A horizon	Mean Soil Fines (g)*	SOC (mean ± SE)		
			%†	Mg ha^{-1}	Mg ha^{-1} year^{-1}
Control	0-8 cm	2,846	1.92 ± 0.39 Aǂ	6.60 ± 1.41 A	0.19 ± 0.04 A
Topsoil	0-8 cm	4,506	1.20 ± 0.16 A	6.56 ± 1.54 A	0.19 ± 0.05 A
Sawdust	0-12 cm	3,981	2.12 ± 0.09 A	6.73 ± 1.26 A	0.20 ± 0.04 A
Biosolids 56 Mg ha^{-1}	0-10 cm	3,601	2.18 ± 0.52 A	7.88 ± 2.63 A	0.23 ± 0.08 A
Biosolids 112 Mg ha^{-1}	0-10 cm	3,898	1.71 ± 0.18 A	6.55 ± 1.09 A	0.19 ± 0.03 A

†Includes a HCl pre-treatment for carbonates and the "coal correction" from the original May 1982 bulk spoils to account for geogenic C sources.
*Based on 2008 soil fines (0-5 cm) adjusted for 2016 ^A horizon depths (7 to 14 cm).
ǂLetters denoted differences among treatments ($P \leq 0.05$).

4.5. Summary and Conclusions

Initially treating hard rock spoils with topsoil or organic amendment materials has been shown to improve central Appalachian mine soil quality and productivity potentials in the short-term (Roberts et al. 1988bc). In our study, long-term (34+ years) treatment influences on mine soil morphology were observed in the sawdust and biosolids treatment soils, which were generally a few cm thicker in their ^A horizons compared to the control and topsoil treatments, but not as much as expected. Soil color was generally similar among treatments, but a few of the biosolids plots had darker soil chromas (i.e., 10YR 3/1). Transitional horizons developed over time and were commonly observed in all treatment soil profiles (e.g., ^BA, ^AB, ^A2). Weak to moderate cambic horizon (^Bw) development was common in the subsurface. From a taxonomic and land use management perspective, these mine soils are similar to the RM experiment in terms of rock fragment contents and notably the dense and root-limiting naturally formed layers, which are a concern for long-term aboveground productivity and internal drainage and may provide a rationale for deep ripping at later times following the 5-year performance bond release.

The 2:1 SS:SiS rock spoil (fertilized control) reached levels of soil pH, EC, CEC, SOM, and SOC similar to the topsoil, sawdust, and biosolids amendments after 34 years. Particle size distributions were also similar among treatments except for topsoil, which was originally higher in sand content, and maintained over time. Topsoil was similar to the control for all soil parameters in 2016, except for lower Fe-oxides, which is interesting given the topsoil's highly pre-weathered nature. Sawdust-amended pedons had higher total-N compared to the control and topsoil treatments, and higher total-C compared to the topsoil. However, there were no differences in SOM or SOC per se among treatments. The two biosolids treatment rates (56 and 112 Mg ha^{-1}) did not differ from one another for any reported soil parameter. Both rates of biosolids were consistently higher in extractable P with time compared to all other treatments and were also higher in total-N compared to the topsoil and control. While extractable P and total-N levels over time were in some cases lower than or similar to previous years, the influence of biosolids was still apparent through time. Since there is a close association between N and P-availability, the biosolids treatments may be beneficial over the long-run from a soil fertility standpoint, especially since there is a high capacity for P to be fixed by these ferruginous rock spoils rich in Fe-oxides and complex carbonates (Howard et al. 1988). Additionally, biosolids-amended soils would likely sustain micronutrients for vegetation relative to other treatments in our study. However, the interpretations of total-N and Mehlich I extractable nutrients are complicated in these relatively unweathered rock spoils (Li and Daniels 1994). Our data indicate that the higher initial levels of soil N and P in biosolids treatments likely increased longer term nutrient availability and uptake by the plant and invading legume community, given the close association between N and P.

Further, when assessing changes in surface soil properties over time, the SA experiment reflected much of the findings in the RM experiment (Chapter 3). Sand contents generally decreased, while silt and clay contents increased. Soil pH decreased over time, while EC levels were maintained in the surface likely due to the concentration of base cations and other components via biocycling. Subsurface EC dropped from May 1982 to 2016 due to long-term leaching. For the topsoil and 56 Mg ha^{-1} biosolids treatments, EC was trending higher than the original May 1982 values, although there was high variability for a relatively low number of samples (n=3) in these analyses. Higher EC levels would not be surprising in some of the amended

treatments, particularly for the biosolids which initially had much higher organic nutrient levels. Also, while CEC and SOM increased over time due to organic matter accumulation, there were no long-term treatment differences. In terms of soil carbon capture, there does not appear to be a long-term benefit to the initial surficial biosolids organic amendments. The control plots accumulated SOC at a similar rate while the high organic matter treatments lost C back to the atmosphere along with possible enhanced leaching. After 34 years, sawdust and biosolids applied to raw rock spoils slightly increased soil ^A horizon thickness and maintained higher total levels of N and extractable P soil levels over time. However, Olsen-P was higher in biosolids treatments in 2008, but Mehlich P was only numerically higher in 2016. While amended treatments were beneficial to aboveground productivity in the short-term, we do not recommend the added cost and effort of applying topsoil (if all A-E-B-C horizons) or organic amendments to meet long-term goals based on our data. However, it appears that from a soil fertility standpoint, the sawdust and biosolids treatments used in this study would be superior to the control and topsoil. We recommend future research on long-term essential nutrient levels in relation to aboveground plant uptake rates, particularly for extractable P, which may have limited availability in these Fe rich rocks over time.

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4.7. References

Adams, M.B. 2017. The Forestry Reclamation Approach: guide to successful reforestation of mined lands. Gen. Tech. Rep. NRS-169. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station: 128 p. 169.

Ammons, J. and J. Sencindiver. 1990. Minesoil mapping at the family level using a proposed classification system. Journal of Soil and Water Conservation 45: 567-571.

Bendfeldt, E.S., J.A. Burger and W.L. Daniels. 2001. Quality of amended mine soils after sixteen years. Soil Science Society of America Journal 65: 1736-1744. doi:10.2136/sssaj2001.1736.

Bonanomi, G., T.C. Sarker, M. Zotti, G. Cesarano, E. Allevato and S. Mazzoleni. 2019. Predicting nitrogen mineralization from organic amendments: beyond C/N ratio by 13 C-CPMAS NMR approach. Plant and Soil 441: 129-146. doi:10.1007/s11104-019-04099-6.

Bremner, J. and C. Mulvaney. 1982. Nitrogen-total. p. 595–624. In: A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Chaudhuri, S., L.M. McDonald, E.M. Pena-Yewtukhiw, J. Skousen and M. Roy. 2013. Chemically stabilized soil organic carbon fractions in a reclaimed minesoil chronosequence: Implications for soil carbon sequestration. Environmental Earth Sciences 70: 1689-1698. doi:10.1007/s12665-013-2256-8.

Craig, N. 2012. Properties and potentials of coal mine soils in southwest Virginia 29 years after establishment. M.S. thesis. Virginia Polytechnic Inst. and State Univ. Blacksburg, VA.

Daniels, W.L., J.C. Bell, D.F. Amos and G.D. McCart. 1983. First year effects of rock type and surface treatments on mine soil properties and plant growth. p. 275-282. In: Proc Symposium on Surface Mining, Hydrology, Sedimentology and Reclamation, November, College of Engineering, University of Kentucky, Lexington KY.

Daniels, W.L. and D.F. Amos. 1985. Generating productive topsoil substitutes from hard rock overburden in the southern Appalachians. Environmental geochemistry and health 7: 8-15. doi:10.1007/bf01875045.

Daniels, W.L., J. Burger and D.F. Amos. 1991. The effects of controlled overburden placement on topsoil substitute quality and bond release: Phase III. p. 1-89. Final Rep. U.S. Off. Surf. Min. Contract # HQ51-GR87-10022. Virginia Polytechnic Inst. and State Univ., Blacksburg, VA.

Haering, K.C., W.L. Daniels and J.A. Roberts. 1993. Changes in mine soil properties resulting from overburden weathering. Journal of Environment Quality 22: 194-200. doi:10.2134/jeq1993.00472425002200010026x.

Haering, K.C., W. Lee Daniels and S.E. Feagley. 2000. Reclaiming mined lands with biosolids, manures, and papermill sludges. In: R. I. Barnhisel, R. G. Darmody and W. L. Daniels, editors, p. 615-644. In: Reclamation of Drastically Disturbed Lands. ASA, CSSA, SSSA, Madison, WI.

Haering, K.C., W.L. Daniels and J.M. Galbraith. 2004. Appalachian mine soil morphology and properties. Soil Science Society of America Journal 68: 1315-1325. doi:10.2136/sssaj2004.1315.

Hall, S.L., C.D. Barton and C.C. Baskin. 2010. Topsoil seed bank of an oak–hickory forest in eastern Kentucky as a restoration tool on surface mines. Restoration Ecology 18: 834-842. doi:10.1111/j.1526-100X.2008.00509.x.

Hinesly, T., D. Redborg, E. Ziegler, I. Rose-Innes, W. Sopper, E. Seaker et al. 1982. Effects of chemical and physical changes in stripmined spoil amended with sewage sludge on the uptake of metals by plants. p. 339-352. In: W.E. Sopper et al. (ed.) Land reclamation and biomass production with municipal wastewater and sludge. The Pennsylvania State University Press, University Park, PA.

Howard, J., D. Amos and W. Daniels. 1988. Phosphorus and potassium relationships in southwestern Virginia coal-mine spoils. Journal of Environmental Quality 17: 695-700. doi:10.2134/jeq1988.00472425001700040029x.

Jacinthe, P.-A. and R. Lal. 2007. Carbon storage and minesoil properties in relation to topsoil application techniques. Soil Science Society of America Journal 71: 1788-1795.

Larney, F.J. and D.A. Angers. 2012. The role of organic amendments in soil reclamation: A review. Canadian Journal of Soil Science 92: 19-38.

Li, R.S. and W.L. Daniels. 1994. Nitrogen accumulation and form over time in young mine soils. Journal of Environmental Quality 23: 166-172. doi:10.2134/jeq1994.00472425002300010026x.

Littlefield, T., C. Barton, M. Arthur and M. Coyne. 2013. Factors controlling carbon distribution on reforested minelands and regenerating clearcuts in Appalachia, USA. Science of the total environment 465: 240-247.

McLean, E.O. 1982. Soil pH and lime requirement. p. 199-223. In: A. Klute (ed.) Methods of Soil Analysis, Part 2. 2nd ed. Madison, WI.

Moss, S., J. Burger and W. Daniels. 1989. Pitch× loblolly pine growth in organically amended mine soils. Journal of Environmental Quality 18: 110-115. doi:10.2134/jeq1989.00472425001800010020x.

Nash, W.L. 2012. Long-term effects of rock type, weathering and amendments on southwest Virginia mine soils. M.S. Thesis. Virginia Polytechnic Inst. and State Univ. Blacksburg, VA.

Nguyen, T.T. and P. Marschner. 2017. Soil respiration, microbial biomass and nutrient availability in soil after addition of residues with adjusted N and P concentrations. Pedosphere 27: 76-85.

Odell, R.T., S. Melsted and W.M. Walker. 1984. Changes in organic carbon and nitrogen of Morrow Plot soils under different treatments, 1904–1973. Soil Science 137: 160-171.

Paustian, K., W.J. Parton and J. Persson. 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. Soil science society of America journal 56: 476-488.

Pichtel, J., W. Dick and P. Sutton. 1994. Comparison of amendments and management practices for long-term reclamation of abandoned mine lands. 23: 766-772. doi:10.2134/jeq1994.00472425002300040022x.

Rasmussen, P.E., R. Allmaras, C. Rohde and N. Roager Jr. 1980. Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. Soil Science Society of America Journal 44: 596-600. doi:10.2136/sssaj1980.03615995004400030033x.

Rhoades, J. 1996. Salinity: Electrical conductivity and total dissolved solids. In: Methods of Soil Analysis: Part 3 Chemical Methods: p. 417-435.

Roberts, J.A., W.L. Daniels, J.A. Burger and J.C. Bell. 1988a. Early stages of mine soil genesis in a southwest Virginia spoil lithosequence. Soil Science Society of America Journal 52: 716-723. doi:10.2136/sssaj1988.03615995005200030023x.

Roberts, J., W. Daniels, J. Burger and J. Bell. 1988b. Early stages of mine soil genesis as affected by topsoiling and organic amendments. Soil Science Society of America Journal 52: 730-738. doi:10.2136/sssaj1988.03615995005200030025x.

Roberts, J.A., W.L. Daniels, J.C. Bell and D.C. Martens. 1988c. Tall fescue production and nutrient status on southwest Virginia mine soils. Journal of Environmental Quality 17: 55-62. doi:10.2134/jeq1988.00472425001700010008x.

Schoeneberger, P.J., D.A. Wysocki and E.C. Benham. 2012. Field book for describing and sampling soils, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Shrestha, R.K. and R. Lal. 2006. Ecosystem carbon budgeting and soil carbon sequestration in reclaimed mine soil. Environment International 32: 781-796. doi:10.1016/j.envint.2006.05.001.

Six, J., R.T. Conant, E.A. Paul and K. Paustian. 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant and soil 241: 155-176.

Skousen, J., C. Zipper, J. Burger, C. Barton and P. Angel. 2011. Selecting materials for mine soil construction when establishing forests on Appalachian mine sites. US Office of Surface Mining, Appalachian Regional Reforestation Initiative Advisory. Forest Reclamation Advisory No. 8. p. 1-6.

Slick, B.M. and W.R. Curtis. 1985. A guide for the use of organic materials as mulches in reclamation of coal minesoils in the eastern United States. U.S. Department of Agriculture, Forest Service. Gen. Tech. Rep. NE-98. p. 144.

Stehouwer, R., R.L. Day and K.E. Macneal. 2006. Nutrient and trace element leaching following mine reclamation with biosolids. Journal of Environmental Quality 35: 1118-1126. doi:10.2134/jeq2005.0134.

Trumbore, S. 2000. Age of soil organic matter and soil respiration: radiocarbon constraints on belowground C dynamics. Ecological Applications 10: 399-411. doi:10.1890/1051-0761(2000)010[0399:AOSOMA]2.0.CO;2.

Wick, A.F., L.J. Ingram and P.D. Stahl. 2009. Aggregate and organic matter dynamics in reclaimed soils as indicated by stable carbon isotopes. Soil Biology and Biochemistry 41: 201-209. doi:10.1016/j.soilbio.2008.09.012.

Wick, A., W. Daniels, W. Nash and J. Burger. 2010. Soil aggregate, organic matter and microbial dynamics under different amendments after 27 years of mine soil development. p. 1364-1386. In: National Meeting of the American Society of Mining and Reclamation, Bridging Reclamation, Science and the Community. American Society for Mining and Reclamation, Pittsburgh, PA.

Wijesekara, H., N.S. Bolan, M. Vithanage, Y. Xu, S. Mandal, S. Brown et al. 2016. Utilization of biowaste for mine spoil rehabilitation. Advances in Agronomy 138: 97-173. doi:10.1016/bs.agron.2016.03.001.

Zipper, C.E., J.A. Burger, C.D. Barton and J.G. Skousen. 2013. Rebuilding soils on mined land for native forests in Appalachia. Soil Science Society of America Journal 77: 337-349. doi:10.2136/sssaj2012.0335.

Zipper, C.E. and J. Skousen. 2021. Coal's legacy in Appalachia: Lands, waters, and people. The Extractive Industries and Society. 21 p. doi:10.1016/j.exis.2021.100990.

5. Soilscape Analysis of Reclaimed Mineral Sands Mines in Southeastern Virginia

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Abbreviations: HMS, heavy mineral sands; VDMM, Virginia Division of Mineral Mining; VA, Virginia; UM, unmined; LRS, land reconstruction study; NDVI, normalized difference vegetation index; GNDVI, green normalized difference vegetation index; VI, vegetation indices; DEM, digital elevation model; BI, brightness index; CI, coloration index; IO, iron oxide index; PR, profile surface; PL, planar surface; sbk, subangular blocky; gr, granular; sls, structureless; CEC, cation exchange capacity; CV, coefficient of variation.

5.1. Abstract

Heavy mineral sands mines in southeastern Virginia directly underlie highly productive prime farmlands. Here, reconstructed mine soils are highly variable and their impact on rowcrop variability has not been extensively studied. An observational study was employed at a newly reclaimed site to better understand soils at different surficial landform positions (pits and berms) related to the land reconstruction process. We also conducted a separate study at five additional older (9-14 years) sites to evaluate the variability of rowcrop productivity vs. potential interactions with final reclaimed landforms and underlying relic mining features. Yield was correlated to remotely sensed variables related to vegetation, bare soil, and topographic characteristics. Additionally, we investigated the relationship between remotely sensed variables and surficial landform position. Soil profiles generally resembled expected characteristics at different surficial positions with berms being much sandier and pits having more complex materials. Depth to densic contact appeared to control plant rooting, with higher biomass observed in areas with a greater depth to densic contact. However, densic (^Cd) materials did not correlate with landform position. At the rowcrop sites, yield variability maps illustrated clear yield differences that were more distinct in drier years and appeared consistent across different crops. Reclaimed land yields were numerically similar to or higher than long-term county averages for all fields, but soybeans in 2020 had a 6.8% yield reduction compared with nearby unmined prime farmland yields. Yield was strongly positively correlated to vegetation indices (VI) and weakly to moderately positively correlated with local landform elevation and soil reflectance. Yield was generally negatively correlated with coloration (dark/wet) and iron oxide (clay) indices. Based on the best correlations, remotely sensed properties were compared to underlying landform positions. Three out of five fields had higher VI's on berm surfaces. A smaller number of fields (one out of five) had more elevated berms, and redder and darker pits. Due to these inconsistent results, we recommend collecting actual point soil data on different surficial landform positions to better understand the main drivers of yield variability and to correlate soil properties with spectral and vegetation indices for improved land use planning and management.

5.2. Introduction

Across the world, secondary placer deposits of heavy mineral sands (HMS) are found in relict offshore terrace landforms (e.g., southeastern USA) or in relatively recent beach deposits (e.g., Australia and Japan) (Cunningham et al. 2005). Heavy mineral sands weathered from crystalline rocks are deposited and reworked by wave action and then concentrated due to their high specific gravity (≥ 4.0 g cm^{-3}) relative to other minerals such as quartz sand. Mineral sands ore deposits occur at several locations in the Upper Coastal Plain of southeastern Virginia (VA) and generally contain 8% HMS in soils and sediments, but locally concentrated zones contain around 60% HMS, which are economically valuable (Berquist Jr and Bailey 1998). The depth of HMS deposits in VA ranges from 5 to 20 m within highly weathered coastal sediments, with ilmenite ($FeTiO_3$) being the largest mineral in the suite, followed by rutile (TiO_2), zircon ($ZrSiO_4$), and to a lesser extent leucoxene which is an alteration product of titanium bearing minerals (Daniels et al. 2012). These minerals are economically valuable for many industrial applications due to their high refractive index, durability, and heat resistance (Cunningham et al. 2005). Mineral sands mined lands reclaimed to crop rotation agriculture (i.e., peanuts, cotton, soybeans, corn, and tobacco) in VA have been documented to suffer an average 20 to 25% yield reduction compared to unmined reference prime farmland yields, even when proper reclamation practices are followed, including return of topsoil (or alternative organic materials) and deep ripping to alleviate mechanical compaction via equipment grading (Daniels and Orndorff 2013; Daniels et al. 2018; Meredith et al. 2008). However, these same studies have indicated that it is possible to equal or exceed 5-year county crop yield averages for all soils in production. Since this mining region historically supports prime farmland agriculture, continued research efforts are needed to better understand resulting mine soil properties in relation to intensely managed rowcrop systems.

Prime farmlands possess a beneficial combination of chemical, physical, and environmental properties to produce high-value crops (Grandt and Hossner 1988). Hodges et al. (1997) conducted local pre-mining soil surveys in the HMS region in southeastern VA, describing eleven well-drained prime farmland soils including the Orangeburg (fine-loamy, kaolinitic, thermic Typic Kandiudults) and Faceville (fine, kaolinitic, thermic Typic Kandiudults) series (Soil Survey Staff). During mining and reclamation, highly productive soils are influenced by soil

horizon replacement procedures and selection of the best available spoil materials (Bell et al. 1994; Dunker and Darmody 2005). Federal law requires that mine soils be restored to similar or higher pre-mine rowcrop productivity levels when prime farmland is disturbed by coal surface mining, but there are no federal requirements for non-coal mines (Dunker and Barnhisel 2000). Replacement of natural horizons is required by certain states, particularly A + E horizons (topsoil), which is beneficial for early survival and growth of vegetation and improves crop yields with increasing topsoil quality and thickness (Jansen and Dancer 1981). Regardless of topsoil return, severe mine soil compaction and structure loss has been shown to limit crop productivity (Barnhisel and Gray 1990; Darmody et al. 2002). Horizon replacement using proper material handling techniques and equipment (e.g., truck end-dumped with minimal grading) was the most important factor for successful crop yields on reclaimed coal mine prime farmlands in the Midwest (Hooks et al. 1992). McSweeney et al. (1987) also described well-aggregated "fritted" soil structure created by a wheel-conveyor-spreader system for handling materials. Surprisingly, the artificial fritted structure improved corn and soybean yields. For HMS reclamation on prime farmland, there are no requirements for horizon replacement, but the VA state regulatory authority (VDMM) requires 90% return of the long-term county yield average for a given crop (Daniels et al. 2012) if the post-mine land use is designated as "crop production." However, all HMS reclaimed lands to date (other than research areas) have initially been returned to a hayland/pasture post-mining land use without a specific annual yield requirement. The VA regulations also refer to the potential use of "suitable geologic materials" for the final revegetation surface. However, certain local counties (e.g., Dinwiddie) have conditional zoning criteria that do specify topsoil as being the original A + E horizons. Once these lands are returned to landowners following permit release, certain fields have been returned to rowcrops and were documented in this study.

Historically, successful reclamation has been achieved for a variety of mineral sands post-mining land uses across the world (e.g., forestry, pastures, wetlands, heath shrublands) (Brooks 1989). Early studies in the USA focused on determining soil and crop productivity in VA, soil morphological descriptions in Florida, and simulated tailings (coarse-textured) and slimes (fine-textured) materials in greenhouse and field settings (Daniels et al. 1991; 1992; 1996; 2003a). Re-blended tailings-slimes were considered a suitable plant growth medium given after heavy

phosphorus (P) fertilization to offset P-fixation in the highly pre-weathered VA mine soils (Daniels et al. 1996). Daniels et al. (2003a) subsequently conducted a field scale pilot study in VA and found that topsoil (25 cm) and yardwaste compost (112 Mg ha^{-1}) treatments equally affected crop response, but 23, 3, 27, and 20% yield reductions relative to adjacent prime farmlands plots were still notable for wheat, soybeans, corn, and cotton, respectively, for the first few years following reclamation. Subsequently, the Carraway-Winn Research Farm (CWRF) installed four mine soil treatments (78 Mg ha^{-1} biosolids with and without tillage, control, and topsoil) to assess crop productivity over a nine-year period (Daniels et al. 2018; Meredith et al. 2008; Orndorff et al. 2011; Wick et al. 2013). All treatments were limed, deep-ripped, and fertilized. For the control and biosolids, wheat and corn exceeded long-term county yield averages for all soils in crop production but were 20 to 25% lower than nearby unmined prime farmlands in most years. Soybean yields were variable, equaling prime farmlands under good rainfall conditions, but impossible to harvest in another year due to wet fall soil conditions. Biosolids produced higher initial yields compared to the control and topsoil return treatments, particularly in early years following application. The topsoil treatment suffered lower initial yields due to compaction and surface crusting but recovered following several seasons of remedial tillage (i.e., chisel-plowing).

While organic amendments, deep ripping, and P and liming additions have been shown to improve VA HMS mine soil productivity (Daniels et al. 2003c; Meredith et al. 2008), the mining and reclamation processes result in high short-range vertical and lateral soil variability (Schroeder et al. 2010). Following the removal of existing vegetation and topsoil, mineral-enriched soil is dry excavated using backhoes and pumped in a slurry to the wet mill processing facility, where the HMS are processed from the host materials through size separation and then gravity separation, including sequential steps for cleaning and separating host and ore materials (see Meredith 2007). Since the regional subsoils have high clay contents within sandier sediments, the host materials (non-HMS) include fine-textured secondary clays and silts called “slimes” and coarse-textured materials called “tailings.” After HMS extraction, the combined host materials are thickened and pumped back to the original site in a slurry (~30% solids) that is decanted into mine “pits” surrounded by engineered dike or “berm” features (up to 4 m) constructed mainly from barren Coastal Plain substratum and/or deeper Piedmont saprolite materials (Daniels et al. 2012). As

illustrated in Appendix B, slimes and tailings are returned in sequential layers and dewatered over several months to years; thus, soil lateral and vertical variability results from slimes-tailings segregation due to different rates of settling over multiple depositional events (Zimmerman et al. 2008). Efforts that help homogenize slimes and tailings include: 1) Reduced pit size via smaller internal berm networks; 2) water control measures such as flashboard risers; 3) rotation of discharge point around the pit; and 4) "dipping and spreading" wetter high slimes areas with a long-arm bucket excavator (Zimmerman et al. 2008) followed by dozer regrading. Other factors that create local soil variability occur during pit closure when the final capping layer is fully dewatered, berms are flattened, and the site is graded to meet the appropriate contour grade (Daniels et al. 2003a). Additionally, iron (Fe) coated kaolinite clay minerals that dominate the slimes are discharged close to their zero-point charge (ZPC), so they resist flocculation and natural mixing during settling (VanWormhoudt 1993). These combined factors lead to substantial vertical stratification in settling areas coupled with high short-range lateral variability away from the discharge pipe locations.

Following mineral sands mined land reconstruction, Orndorff et al. (2005) described thirteen soil pedons ranging from 2 to 6 years of age and found that surface soil properties were generally similar in terms of texture, color, and structure, but had variable soil organic matter (SOM), pH, and cation exchange capacity (CEC) due to differential biosolids additions during final reclamation. However, subsurface properties were distinctly variable within and among pedons for texture, color, and other physical features. Most pedons contained multiple ^C horizons, massive structures, and rooting restrictions below 45 cm in the subsoil. While the even distribution of topsoil/organic amendments has previously helped buffer lateral surface variability (Daniels et al. 2003c), researchers have commonly noted the following subsoil characteristics: 1) Strongly contrasting particle-size classes and colors between horizons; 2) thin bands of slimes, tailings, and/or heavy mineral sands within a sandy matrix and are often overturned or deformed due to equipment activity; and, 3) soft mass inclusions of clayey slimes or Coastal Plain saprolite within horizons (Daniels et al. 2003c; Meredith et al. 2008; Orndorff et al. 2005; Schroeder et al. 2010).

The studies cited above were conducted primarily on field plots with associated soil descriptions (Daniels et al. 2003c; Orndorff et al. 2005; Schroeder et al. 2010; Stolt et al. 2001),

but the spatial relationship between field-scale soil variability and associated crop productivity has not been evaluated. Orndorff et al. (2011) observed depressional areas at the CWRF due to landform settling, causing high cotton yield variability and harvesting issues in 2009 and limiting spring/fall routine operations in others. A more recent study assessed 18 soil profiles on berms, pit centers, and berm-pit transitional areas (Orndorff et al. 2015). Subsoil characteristics per landform position included: 1) Berms: thick, uniform profiles of sandy substratum/saprolite materials; 2) pit centers: surficial capping of mixed tailings and slimes followed by various layers of slimes and/or tailings; and 3) transition areas: variable combination of above materials. Generally, the mine soil x presumed landform positions aligned with one another, but a few exceptions were noted, indicating lack of GPS accuracy on the narrow berms or non-typical materials handling practices due to local site conditions or other factors (Orndorff et al. 2015).

Variability of natural soil properties is most strongly correlated to local topography and hydrology, assuming relatively uniform underlying parent materials (Lin et al. 2005). On the other hand, reconstructed mine soil properties are typically quite variable, but in some cases may be homogenous at the local scale depending on mine site-specific reclamation methods (Keck et al. 1993; Stolt et al. 2001). Several studies have assessed spatial properties on mined or degraded lands (Bearden 1984; Boerner et al. 1998; Hossner et al. 1997; Keck et al. 1993; Mummey et al. 2002; Nyamadzawo et al. 2008; Schafer 1979a; Shukla et al. 2007; Wang et al. 2017; Zhou et al. 2017). Generally, these studies, with few exceptions, show that mine soils exhibit much higher short-range variation in most properties than natural soils. Schafer (1979b) found that reconstructed mine soils in SE MT were more variable laterally at < 100 m-spacing compared to natural soils, but at the landscape scale (> 500 m), natural soils were more variable laterally. Hossner et al. (1997) modelled spatial variability of mine soils in TX using an intensive sampling scheme and found high correlation of reduced plant growth and low pH. Other studies noted the importance of using densely gridded soil datasets to accurately represent the degree of spatial variability (Dollhopf 2000; Finke et al. 1992; Keck et al. 1993).

An alternative to intensive field data collection is the use of remotely sensed data variables using satellite or drone imagery, which can be a more precise and practical way to assess field-scale spatial patterns following disturbances (Karan et al. 2016). Remotely sensed vegetation

indices have been shown to correlate strongly with site conditions and soil properties (Ballester et al. 2017; Gao et al. 2018; Hatfield et al. 2008; Karan et al. 2016; Maresma et al. 2016; Zhang et al. 1999). Further, remote sensing may be applied at different spatial scales, providing baseline inventory information for land management and regular assessment of plant productivity over time through vegetation mapping (Cox and Witter 1978; Inman et al. 2008; Karan et al. 2016). Several studies on unmined lands have co-analyzed remotely sensed soil and crop data to improve site-specific management and/or create prediction models for yield or related soil properties (Guo et al. 2012; Hornung et al. 2006; Khanal et al. 2018; Ma et al. 2001; Mandal 2016; Raya et al. 2004). For example, Guo et al. (2012) found that the spectral brightness index derived from bare soil imagery was strongly correlated to soil texture, which was the greatest contributor to cotton yield variability. Georeferenced yield data may also be obtained during field harvest when yield monitors include a GPS unit (Simbahan et al. 2004).

Land use limitations for rowcrop productivity at mineral sands mine operations in VA have previously been attributed to factors such as severe soil compaction, lack of SOM, poorly aggregated surface- and subsoil structure, low water holding and plant-available P, and associated internal permeability issues (Daniels 2003b; Daniels et al. 2003c). Additionally, extensive subsoil variability arises from the differential settling of slimes and tailings during dewatering, final pit closure grading practices, and uneven settling of landforms post-reconstruction (Daniels and Orndorff 2013). However, the spatial distribution of final reclaimed mine soil properties and crop productivity as related to underlying mining influences (pits vs. berms) and landform reconstruction practices has not been studied. These soil-landscape variability issues are further complicated by the fact that HMS ore bodies support highly productive agricultural prime farmlands prior to mining and landowner expectations for post-mining crop productivity are high. Thus, this research included two study components with the following objectives: 1) Relate soil morphological descriptions and associated physical and chemical properties to underlying mine landform positions (pits and berms) at a newly reconstructed site; and 2) characterize the spatial relationships among available crop yield data and remotely sensed vegetative, topographic, and soil variables at several older reclaimed fields in rowcrop production.

5.3. Materials and Methods

5.3.1. Research Area

5.3.1.1. General Background

The research area is in the Upper Coastal Plain of SE VA at the Old Hickory HMS deposit in Dinwiddie and Sussex counties about 100 km south of Richmond, VA (Figure 5.1) (Daniels et al. 1996). The Old Hickory deposit is the largest ore body (2,550 ha) and was leased in the early 1990s by RGC Mineral Sands (USA) and Southeast TiSands Joint Venture (Daniels et al. 1996). These companies later merged into the currently operating mining company, Iluka Resources Inc. (Iluka), an Australian-based company whose name is based on an aboriginal term meaning "of the sea." Active mining for HMS has been ongoing in this region since the mid-1990s, and > 1,500 ha have been disturbed to date. The mines are in the "Fall Zone", or boundary where the Piedmont and Coastal Plain regions converge (Carpenter and Carpenter 1991) and is characterized by Coastal Plain uplands with Piedmont rocks exposed in lower slopes and streams. Here, HMS are highly concentrated along the Orangeburg Scarp in Coastal Plain sediments that overlie weathered thick saprolites of Piedmont bedrock (granites to felsic meta-volcanics) (Newton and Romeo 2006). During the Miocene and Pliocene/Pleistocene epochs, HMS were deposited by transgressive and regressive cycles, and reworked by wind and local erosion. HMS occur from the soil surface down to 10-20 m within the Coastal Plain cap (Stolt et al. 2001).

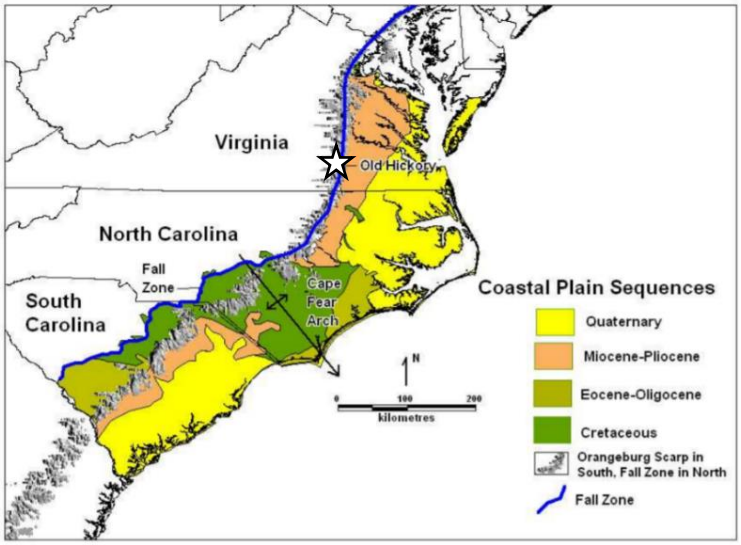


Figure 5.1. Old Hickory mineral sands deposit (see white star). Source: Newton and Romeo (2006).

5.3.1.2. Local Site Characteristics

The study areas, each separately described below, include one newly reconstructed mine site and five reclaimed rowcrop fields, including three unmined reference fields. Local average annual rainfall is 1461 mm with an average high temperature of 20°C and an average annual temperature of 14°C (NOAA 2022). Pre-mining native vegetation commonly includes mixed pine hardwood forests on steeper sideslopes and wetter landscapes or productive prime agricultural farmland with peanuts, cotton, soybean, corn, and tobacco commonly grown in varying rotations (Hodges et al. 1997). For hayland/pasture post-mining land uses, and as required for a full two-year reclamation performance period, cereal rye (*Secale cereal* L.) is typically planted as a cover crop followed by a pasture mix including fescue (*Festuca arundinacea* L.), orchardgrass (*Dactylis glomerata* L.), alfalfa (*Medicago sativa* L.), and clover (*Trifolium pretense* L. and *Trifolium repens* L.). Routine reclamation procedures by Iluka, which began in 2004, include the following sequence: 1) Application and incorporation of lime + P amendment to subsoil; 2) deep ripping (~75 cm depth two ways); 3) topsoil return (15 cm); 4) lime + NPK fertilization of returned topsoil followed by surface disking or chisel-plowing; 5) land-leveling previously ripped subsoil (via tractor-pulled iron bar); and 6) seeding of standard hayland/pasture cover crop and perennial species mix using a drill (see Appendix B for photos). Since 2019, deep ripping has been applied through the topsoil and subsoil following topsoil return and final grading to reverse any "re-compaction" effects. This later protocol also includes incorporation of lime + P fertilizer into the subsoil before topsoil is returned.

5.3.2. Land Reconstruction Study

5.3.2.1. Study Overview

The land reconstruction study (LRS) was an observational study site initiated in 2015 for ground photo-monitoring of the mine reconstruction process to better understand the relationship among landform position (e.g., stored berm materials and returned slimes-tailings in pits), final reconstructed surface, and the resulting mine soil properties and vegetation. This information was expected to aid understanding of important parameters (e.g., materials placement and handling, compaction, infiltration) influencing post-mining productivity potentials. Based on local pre-

mining mapping efforts in 1997, the dominant "pre-mine" soil series at this site was the Slagle series (fine-loamy, siliceous, subactive, thermic Aquic Hapludults) followed by the Emporia series (fine-loamy, siliceous, subactive, thermic Typic Hapludults) and to a much lesser extent, the Uchee (loamy, kaolinitic, thermic Arenic Kanhapludults) and Yemassee (fine-loamy, siliceous, semiactive, thermic Aeric Endoaquults) series (Hodges et al. 1997; Soil Survey Staff). A temporal sequence of satellite images of the LRS site are presented in Figure 5.2 below. Appendices C1 through C3 deal exclusively with the LRS study and document the full time series of final dewatering and landform reconstruction.

5.3.2.2. Data Collection and Analyses

Across three mine cells, quarterly photographs were taken at five different GPS coordinate locations across various fixed azimuths between 2015 and 2021 to document the materials handling and reclamation process (Appendix Fig. C1.1; Table 5.1 below). These photo-monitoring locations were chosen to represent berms, transitional areas, and mine cell centers. Throughout 2020 and 2021, the site supported herbaceous vegetation. Visual observations noted relative aboveground productivity among the three mine cells, which was harder to discern in the low angle photos. In October 2021, a total of ten soil pedons were located based on the surficial positions of underlying mine landforms (i.e., pits vs. berms). A detailed map of these soil pedon locations is found below in Section 5.4.1.1 to aid in the results and discussion (see Figure 5.5; also, in Appendix C1). It is important to note that the underlying pit vs. berm historical features were not clearly expressed at the surface. Thus, the use of the term "landform position" here reflects the presumed underlying former mine structures. Soil pits were excavated using a backhoe, and described for morphological horizons, depth of horizons, rooting density, color, structure, texture class, and other details according to USDA-NRCS protocols (Schoeneberger et al. 2012).

Location and detailed images of each soil profile and their associated land reconstruction photo-sequences are given in Appendix C1. Within each of these ten profiles, bulk soil samples were collected from each morphological horizon to analyze chemical properties according to the Virginia Tech Soil Testing Laboratory (Maguire and Heckendorn 2019), and included the following methods: 1) pH measured in a 1:1 soil/water slurry with a glass electrode; 2) Mehlich I

extractable nutrients; 3) cation exchange capacity (CEC) as the summation of Mehlich I extractable bases (Ca, Mg, and K), plus soil-buffer acidity (H^+ and Al^{+3}); and, 4) percent base saturation as the quantity of exchangeable bases divided by CEC and multiplied by 100. Soil bulk density was determined using the slide-hammer core method (Blake and Hartge 1986) horizontally at three locations within soil profiles (n=3 core reps per horizon): 1) Center of the ^Ap horizon; 2) directly below the ^Ap horizon at the subsoil contact; and, 3) at a depth of approximately 60 cm. Intact bulk density cores were oven-dried to constant weight and calculated as the weight of the oven-dry soil divided by total soil volume.

Table 5.1. LRS spatial coordinates and associated compass bearings and a detailed timeline of significant mining and reclamation activities.

GPS Points	**Latitude (y)**	**Longitude (x)**	**Azimuths**
2-1	36.89787	-77.55510	20º, 35º, 45º, 90º, 280º, 345º
2-2	36.89893	-77.55221	210º, 250º, 280º, 315º, 345º, 355º
2-3	36.90025	-77.55105	0º, 35º, 65º, 95º
2-4	36.89930	-77.55186	165º, 184º, 210º
2-5	36.89783	-77.55255	50º, 85º, 120º
Years	**Timeline Description**		
2007 - 2008	Site cleared and prepared for mining (topsoil removal and stockpiling).		
2009 - 2011*	Active mining pits support excavation of mineral ore.		
2012 - 2016*	Slimes-tailings (host materials) returned to mined pits in varying sequences.		
2017 - 2018	Dewatered pit surfaces are backfilled and graded with bulldozers.		
2019 - 2020	Final reclamation based on standard protocols: 1) *Lime (4-10 Mg ha^{-1} based on soil pH) and 350 kg ha^{-1} P_2O_5* 2) *Topsoil return (~15 cm)* 3) *Additional lime and NPK fertilization based on soil test results* 4) *Surface disking or chisel plowing* 5) *Deep ripping (~75 cm, two passes), followed by land-leveling* 6) *Rye cover crop/pasture mix seeding using a drill*		

*Timeline varies slightly depending on specific site location.

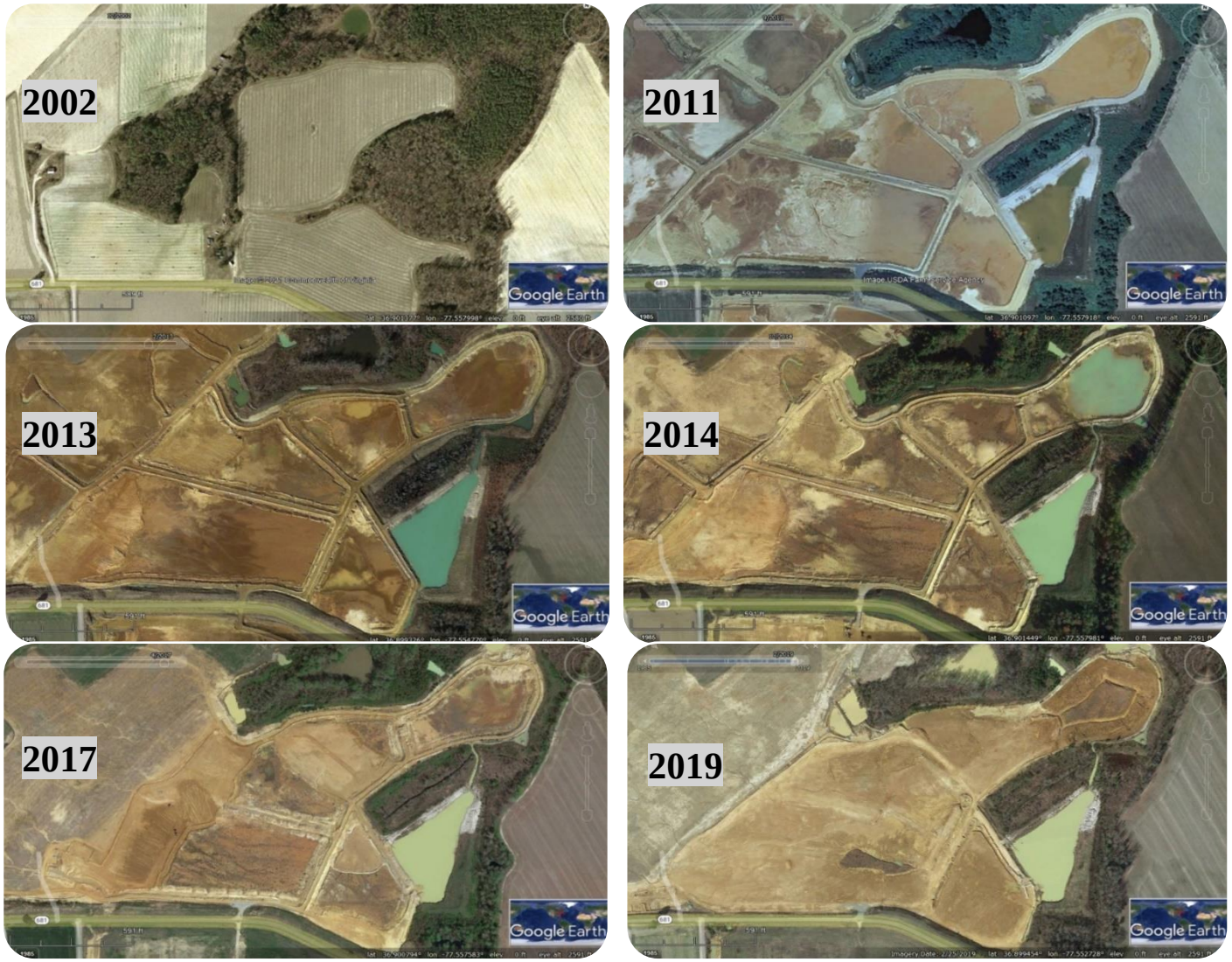


Figure 5.2. Temporal sequence of the active mining and land reconstruction process at the LRS (Source: Google Earth Pro).

5.3.3. Rowcrop Variability Study

5.3.3.1. Study Overview

Following the two-year performance period, reclaimed mine sites are usually released back to the landowners based on forage establishment and persistence over two growing seasons and then later returned to rowcrop production, if desired. Several reclaimed fields were selected for this study component based on available datasets, cropping system, and landowner consent. The major goal for the overall landform reconstruction protocol is to prepare mine soils in a way that can potentially support viable crop productivity comparable to pre-mine levels since the potential to convert to intensive rowcrop production is desired by most landowners (Daniels et al. 2007). On several fields in 2017, pre-harvest soybeans showed a distinct pattern in the crop signatures that directly overlayed original mine pit and berm locations (see below example on Field A; Figure 5.3), leading to the need to evaluate the relationship between reclaimed crop productivity and underlying mining influences. Figure 5.4 below illustrates the field locations, while site details and spatial coordinates for each field are given in Table 5.2. All sites were reclaimed using similar reclamation protocols as described above for the LRS site. Appendix D deals exclusively with the rowcrop variability study.

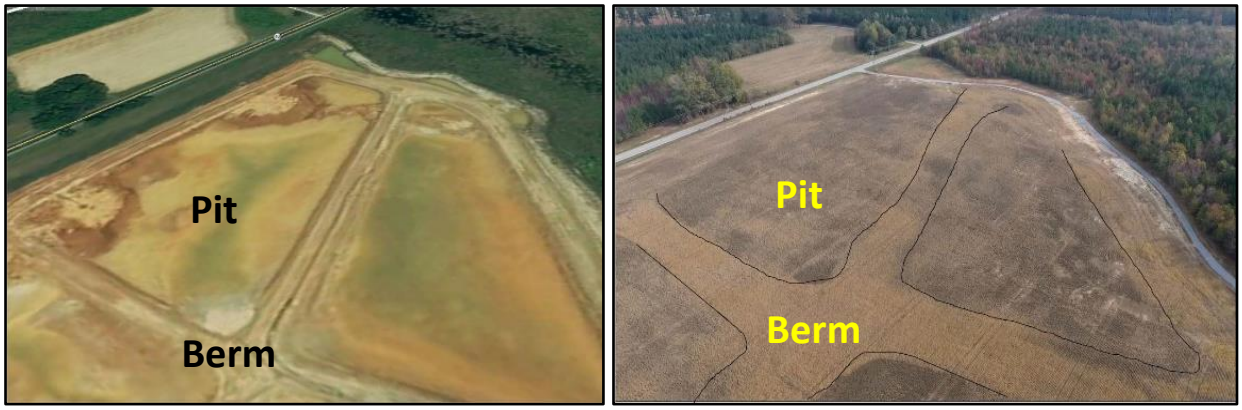


Figure 5.3. Active mine site (left) for reference and the same site reclaimed (right) in 2017 showing dropped soybean leaves on pits vs. retained leaves on berms. Virginia Route 40 is visible in upper left. Photos by Clint Zimmerman (Iluka Resources) used with permission.

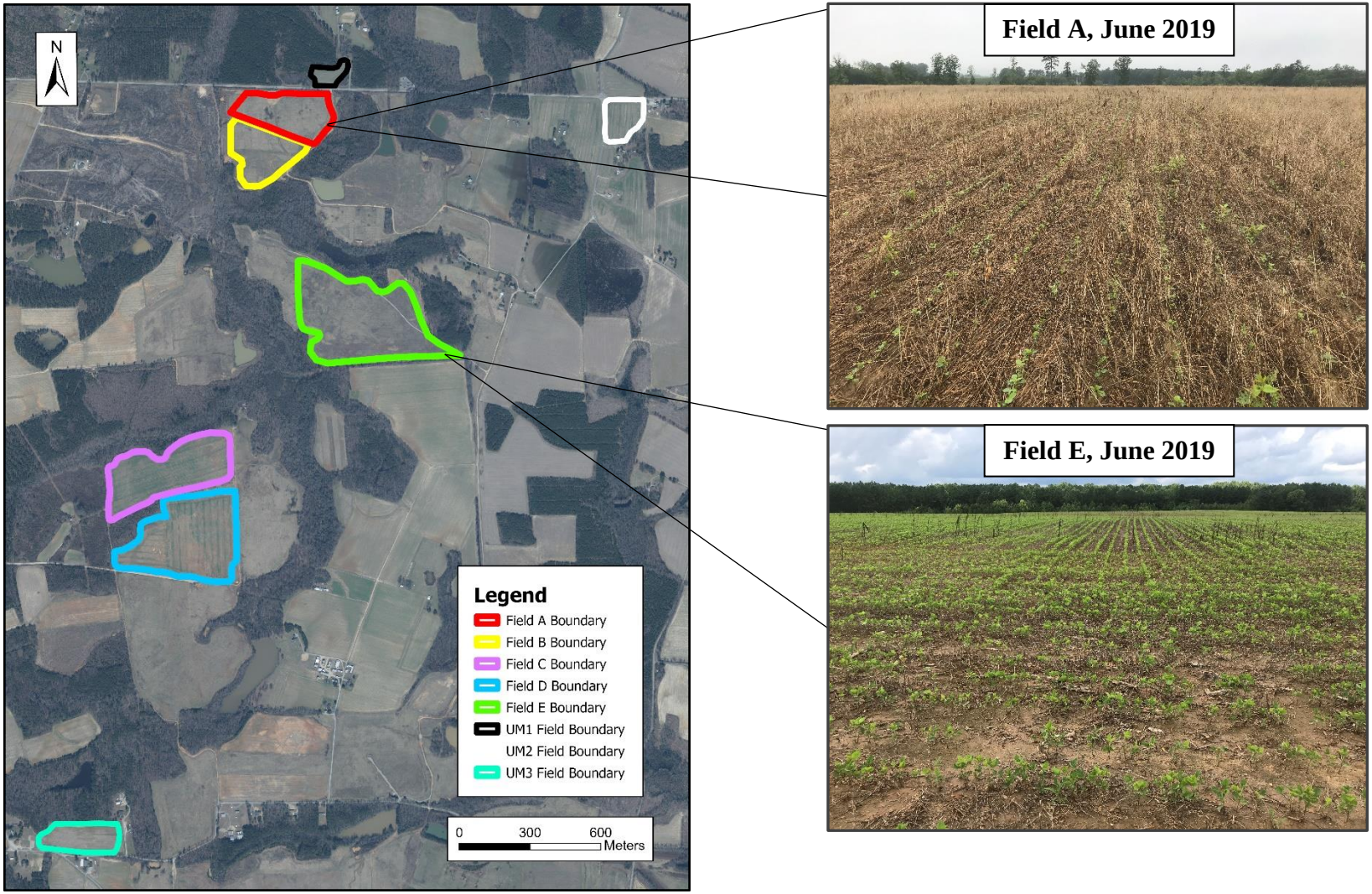


Figure 5.4. Left: Location of reclaimed and unmined (UM) rowcrop fields. Right: Images of Fields A and E planted to soybeans.

Table 5.2. Location and details for each rowcrop study fields. Dashes represent the lack of analyses on certain fields due to limited data availability. See Figure 5.4 above for a visual representation of these locations.

Field (Hectares)	Latitude (y)	Longitude (x)	Year†	Cropping System			
				2018	2019	2020	2021
A (6.2)	36.94526	-77.57274	2012	Double cropped rye-soybean	-	Full season soybean	Full season sorghum
B (5.7)	36.94380	-77.57403	2012	-	Full season soybean	Full season soybean	Full season sorghum
C (10.8)	36.93160	-77.57868	2007	Double cropped rye-soybean	Full season soybean	Full season soybean	Full season sorghum
D (13.9)	36.92901	-77.57774	2007	Double cropped rye-soybean	Full season soybean	Full season soybean	Full season sorghum
E (17.6)	36.93736	-77.56942	2012	Double cropped rye-soybean	-	Full season soybean	Full season sorghum
UM1 (1.1)	36.94674	-77.57080	NA	-	Full season corn	Full season soybean	Full season sorghum
UM2 (2.5)	36.94494	-77.55685	NA	-	-	-	Full season sorghum
UM3 (3.7)	36.91762	-77.58294	NA	-	-	Full season soybean	-

†Year of final reclamation protocols by Iluka (e.g., tillage, fertilization, pasture mix seeding).
*UM; unmined reference fields.

5.3.3.2. Data Collection and Processing

Orthorectified aerial imagery was sourced from Iluka (via a contractor), or Planet Labs PBC satellite imagery corrected for surface reflectance (Planet 2022; Wilson et al. 2017). Both Iluka and Planet images had approximately 3 x 3 m resolution. High resolution drone images (~0.16 m^2 per pixel) were also acquired by Iluka on select dates in the winter of 2019. Planet satellite images were used to calculate vegetation indices (VI) and aerial or drone images were used to calculate bare soil color indices (Table 5.3). Bare soil indices were derived from drone

images collected in 2019 for all fields in all years expect for Field E, where instead a Planet bare soil image was used due to limited data availability for this site. Additionally, all VI's were calculated using Planet images in 2018, 2019, 2020, and 2021 for all fields. Specific image dates for VI's were selected based on the planting date of soybean (Parvej et al. 2020), corn (Thomason et al. 2007), or sorghum (*Sorghum bicolor* L.) (Yang et al. 2000) for a given year. Planting date determines the physiological growth stage for a given crop, which can then be correlated to the best timing for VI calculations. Aerial images acquired by Iluka during active mining were used to locate the underlying mine pit and berm landform positions for each field for direct comparisons to vegetation productivity and other important variables (see Appendix D for aerial images).

Table 5.3. Remotely sensed data variables, indices, and supporting information.

Index Name	Equation	Citation	Data Source
Bare Soil Indices			
Individual Spectral Bands	Near-infrared (NIR)*, Red (R), Green (G), Blue (B)	(Guo et al. 2012)	Winter bare soil - Drone image
Brightness Index (BI)	$\frac{(R^2 + G^2 + B^2)}{(3.0)^{0.5}}$	(Raya et al. 2004)	Winter bare soil - Drone image
Coloration Index (CI)	$\frac{(\text{Red} - \text{Green})}{(\text{Red} + \text{Green})}$	(Khanal et al. 2018; Raya et al. 2004)	Winter bare soil - Drone image
Iron Oxide Index (IO)	$\frac{(\text{Red})}{(\text{Blue})}$	(Segal 1982)	Winter bare soil - Drone image
Vegetation Indices			
Normalized Difference Vegetation Index (NDVI)	$\frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})}$	(Candiago et al. 2015)	Growing season - Planet image
Green Normalized Difference Vegetation Index (GNDVI)	$\frac{(\text{NIR} - \text{Green})}{(\text{NIR} + \text{Green})}$	(Gitelson et al. 1996)	Growing season - Planet image
Topographic Indices			
Elevation, slope, profile (PR), planar (PL)	Calculated in ArcGIS GRID commands	(Guo et al. 2012; Si and Farrell 2004)	DEM†

†DEM, digital elevation model created from 2015 Iluka contour interval data.

*Drone images did not include NIR, so these bands were derived from Planet satellite images.

Grain yield for a given crop was collected by the grower using a 20/20 GPS yield monitor (Precision Planting, LLC, 23207 Townline Rd, Tremont, IL 61568) attached to the combine harvester. Yield data was filtered in the USDA Yield Editor open-source software to remove erroneous data points based on grain flow delay, start/end pass delays, minimum and maximum values for velocity, and standard deviation from the field mean (Sudduth and Drummond 2007). All remotely sensed data, including maps and summary statistics for yield data, were processed and analyzed in ArcGIS Pro software (Version 2.9.0, ESRI, Redlands, CA). Yield variability maps were created using the kriging interpolation method in ArcGIS Pro Spatial Analyst to create a prediction yield surface for each individual field (Betzek et al. 2019). Topographic variables (i.e., elevation and surface curvature) were derived from a kriged digital elevation model (DEM) (Erdede and Bektaş 2020) with a 24 x 24 m resolution. That DEM was created using contour interval data generated by Iluka in 2015 from orthorectified aerial imagery collected by an external vendor who utilized quality ground control points and conformed to the National Map Accuracy Standards (personal communication). Remotely sensed indices were calculated in ArcGIS Pro Raster Functions. The Extract Multi Values to Point tool was used to interpolate values from each raster layer (e.g., VI, DEM layers) at the exact spatial locations of yield data point features, thus creating a common spatial cell value for all datasets being compared. Spatial datasets that showed significant correlations with grain yield were investigated according to anthropogenic landform position (pit vs. berm). For this simple comparison analysis, cell values from each raster layer (e.g., vegetation index) were extracted from digitized point features located along berm and pit centers within each reclaimed field (n=30 points total per anthropogenic landform position).

5.3.3.3. Statistical Analyses

After all data processing and analyses were conducted in ArcGIS as outlined above, the associated spatial attribute tables were exported to Excel files and then statistically analyzed in JMP Pro software (JMP®, Version *15.1* SAS Institute Inc., Cary, NC, 1989-2019). Significant differences were interpreted at an $\alpha = 0.05$ for all analyses. To compare grain yield (response variable) among the various remotely sensed variables (predictor variables), Spearman's Rho nonparametric test was computed, and rank-based correlation coefficient ("r") results were

reported for each variable-by-variable relationship. We interpreted the strength of each relationship as negligible, weak, moderate, or strong, according to the r interpretations outlined in Akoglu (2018). A two-sample t-test was used to assess differences between pits and berms for important properties as indicated by moderate to strong significant Spearman's correlations. Boxplots were created in SigmaPlot to visualize differences (SigmaPlot®, Version 12.5, Systat Software, Inc.).

5.4. Results and Discussion

5.4.1 Land Reconstruction Study

5.4.1.1. Mine Landform Positions and Associated Soil Properties

A general overview of the morphological characteristics observed within LRS soil pedons (n=10) is given below in Table 5.4. Figure 5.5 presents GPS locations of these soil pedons overlying an active mine image. Examples of typical soil pedons and descriptions for pit, berm, and pit-berm transitional areas are also presented below in Figures 5.6-5.8. The full set of images for each soil profile and their associated landform reconstruction procedures over time (2015 to 2021) are presented in Appendix C1 and full profile descriptions are given in Appendix C2. Also, the associated soil chemical data for these horizons are given in Appendix C3.

Generally, soil profiles at the LRS were characteristic of their associated mine landform position and reconstruction materials handling, which included: 1) Berms showing thick, uniform profiles of sandy substratum/saprolite materials; 2) pit centers having a surficial capping of mixed tailings/slimes followed by various strongly contrasting layers of slimes and/or tailings; and 3) transition areas showing variable combinations of the above (Figures 5.6-5.8). Some soil profiles reflected a berm-pit transitional area given a surficial capping of mixed slimes and tailings materials, as indicated by a "2" prefix for horizons separating different materials and depositional events (e.g., Berm 2-1 and Berm 2-5 in Appendix C1-C2). Also, the Pit 2-5S soil was likely in such a transitional zone given the visual record of the photo monitoring and a thick capping (~120 cm) of well-mixed slimes-tailings (Figure 5.7; Appendix C1). Several soil profiles over both former pits and berms commonly had inclusions of saprolite, slimes, and mixed or "dissimilar"

materials within one or more horizons and to a much lesser extent, strongly contrasting particle size classes with depth (Table 5.4).

Table 5.4. General soil characteristics based on the LRS profile descriptions (see Appendix C2 for full profile descriptions). An "x" represents that a given characteristic is present.

ID	Landform Position	^Ap Texture	Depth to Densic Contact	No. of ^Cd	Banded Materials	Dissimilar Materials*	Contrasting Particle-size Class†
Berm 2-1	Berm-Pit Transition	fine-loamy	35 cm	2		x	
Pit 2-1E	Pit	coarse-loamy	43 cm	1			
Pit 2-1W	Pit	coarse-loamy	-	0		x	
Pit 2-2N	Pit	coarse-loamy	22 cm	1	x	x	
Berm 2-2	Berm	coarse-loamy	35 cm	3		x	
Pit 2-3	Pit	coarse-loamy	-	0			
Berm 2-3	Berm-Pit Transition	coarse-loamy	27 cm	2		x	x
Berm 2-5	Berm	coarse-loamy	-	0		x	
Pit 2-5S	Berm-Pit Transition	sandy	42 cm	1		x	x
Pit 2-5N	Pit	coarse-loamy	30 cm	2			

*Horizons comprised of differing materials such as slimes, tailings, and/or saprolite.
†Based on series differentiae for contrasting particle-size class (Soil Survey Staff 2014).

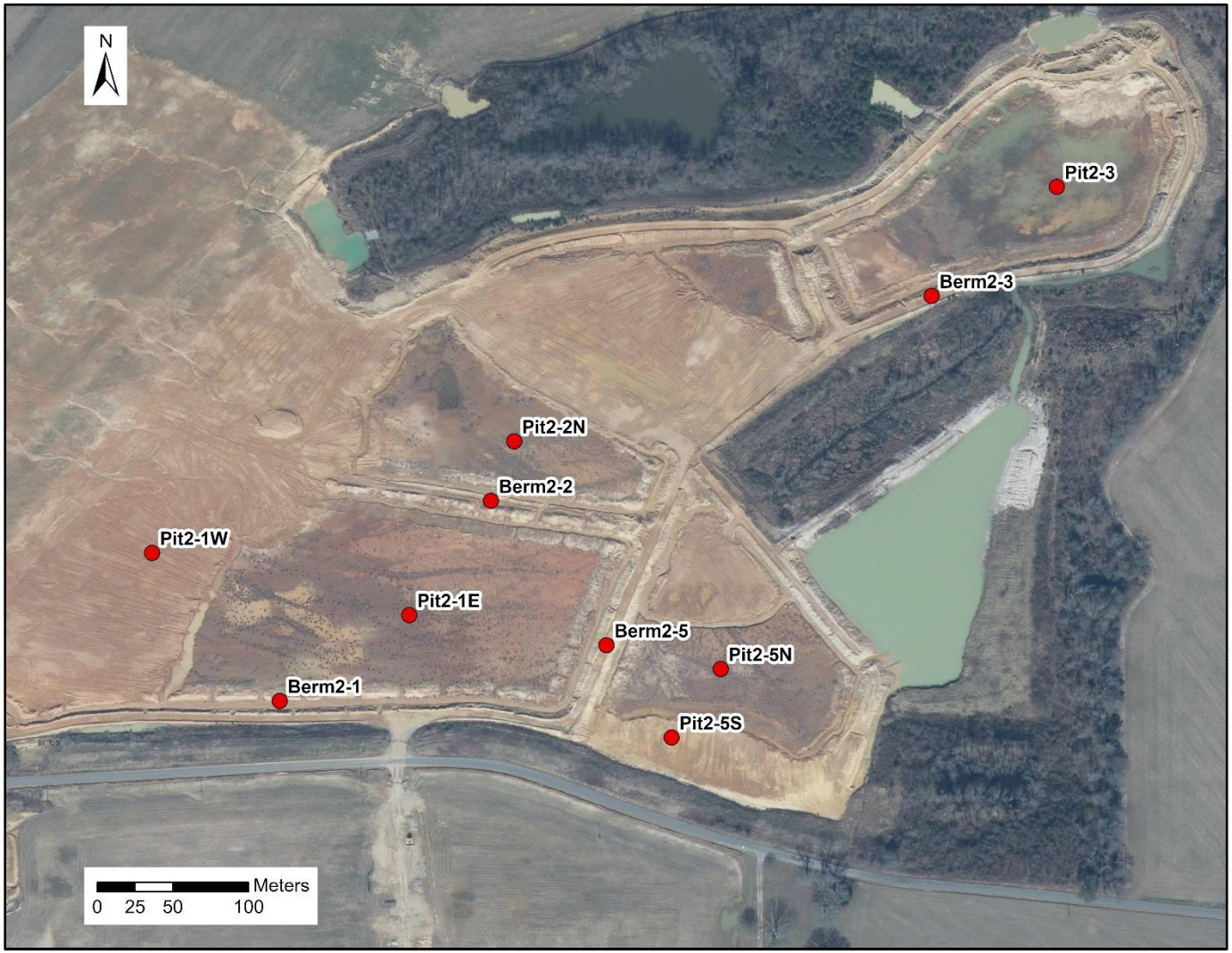


Figure 5.5. GPS locations for ten mine soil profiles described in October 2021 at the LRS site.

Overall, the uppermost part of these soil profiles was well-mixed (e.g., dipped, spread, and re-graded), as indicated by the common sandy clay loam surfaces below the ^Ap. Based on visual observations (no data collected), relatively better areas of vegetative growth were consistently observed for the 2-5 and 2-3 photo monitoring areas. For example, the southern portion of the 2-5 area had much more vigorous vegetative growth than the northern portion. One key difference that likely played a role in better vegetation performance was the depth to densic (^Cd) materials between Pits 2-5S and 2-5N (Table 5.4; Appendix C1-C2). Similarly, Pit 2-1E had relatively better rooting and a deeper depth to densic contact. Furthermore, the Pit 2-3 soil profile was relatively well-mixed throughout without the presence of densic materials, and based on photos and general site observations, this area was lower in local elevation and had better vegetative growth relative to the entire 2-3 mine cell. However, the corresponding berm within the mine cell (Berm 2-3) contained densic materials around 30 cm. Thus, not surprisingly based on our previous studies, depth to a root-limiting densic contact appears to be important for aboveground vegetation performance based on visual site observations. This observed relationship between the mine soil and vegetation assumes the fact that standard reclamation protocols were similarly followed across the entire site (e.g., comparable soil tillage techniques), as is typically the case, and that field soil moisture conditions were similar during soil ripping and other equipment use.

BERM LANDFORM

^**Ap** 0-19 cm; dark grayish brown (2.5Y 4/2), fine sandy loam, fine to medium sbk-shaped cloddy, very friable, common very fine to fine roots, 5% redox concentrations (5YR 5/8) and 10% depletions (2.5Y 4/1) as soft masses/root linings, bulk density: 1.55 g cm^{-3}.

^**C** 19-35 cm; brownish yellow (10YR 6/8), coarse sandy loam, 50:50 very thick platy and sls massive, very friable to friable, few very fine roots, smooth abrupt, 4% red (2.5YR 5/8) and gray (10YR 6/1) saprolite masses, smooth abrupt boundary, bulk density: 1.49 g cm^{-3}.

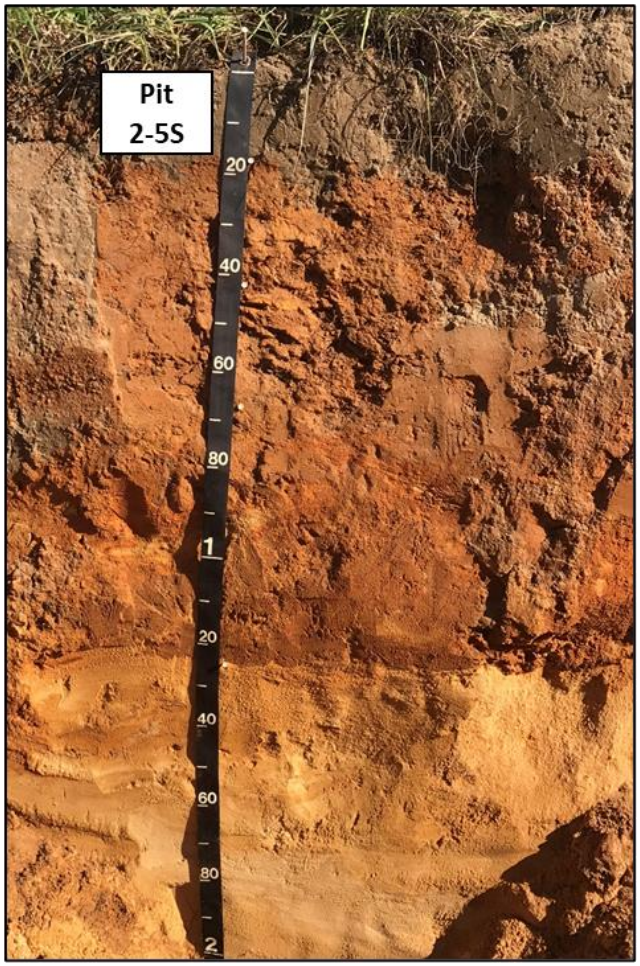
^**Cd1** 35-64 cm; brownish yellow (10YR 6/8), coarse sandy loam, very thick platy (20-30 mm diam.), firm, very few very fine roots, 3% red (2.5YR 5/8) and gray (10YR 6/1) saprolite masses, smooth abrupt boundary, bulk density: 1.69 g cm^{-3}.

^**Cd2** 64-100 cm; brownish yellow (10YR 6/8), coarse sandy loam, sls massive, firm, no roots, 3% red (2.5YR 5/8) and gray (10YR 6/1) saprolite masses, smooth abrupt boundary.

^**Cd3** 100-180 cm; light yellowish brown (10YR 6/4), fine sandy loam, sls massive, firm, no roots, 6% red (2.5YR 5/8) and gray (10YR 6/1) saprolite masses, smooth abrupt boundary.

Figure 5.6. Typical pedon for mine soils located on a mineral sands mining berm landform position. Full set of profile images (n=10) is given in Appendix C1, descriptions in C2, and chemical data in C3.

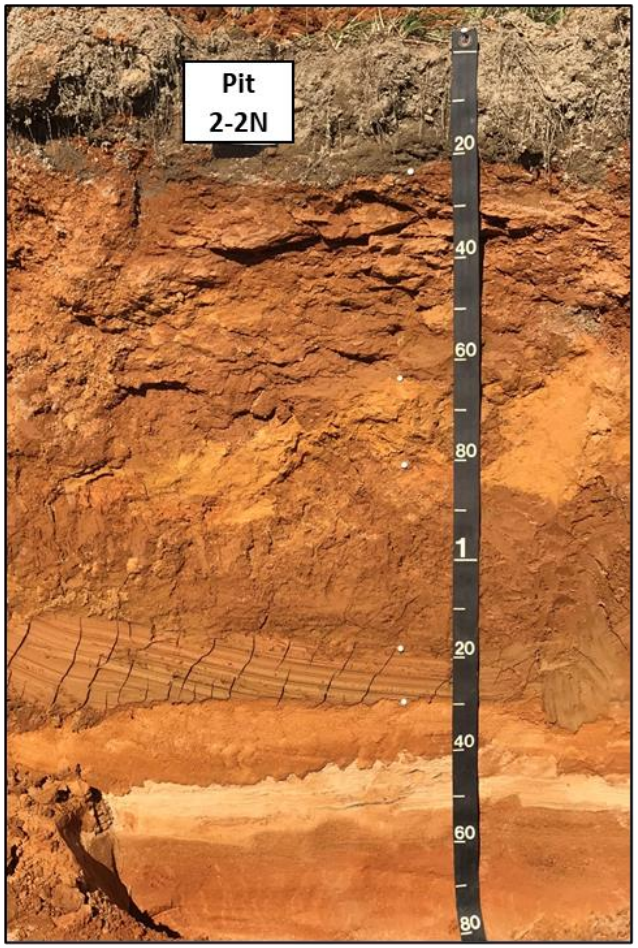
PIT-BERM TRANSITION



^**Ap** 0-18 cm; dark grayish brown (10YR 4/2), loamy fine sand, fine to medium sbk-shaped cloddy, very friable, common very fine to fine roots, 1% redox concentrations (7.5YR 5/6) and 1% depletions (10YR 5/2) as soft masses/root linings, wavy abrupt boundary, bulk density: 1.57 g cm^{-3}.
^**C** 18-42 cm; strong brown (7.5YR 5/6), sandy clay loam, medium to very coarse cloddy, friable to firm, few very fine to fine roots, pebbles (1%), wavy abrupt boundary, bulk density: 1.50 g cm^{-3}.
^**Cd** 42-67 cm; strong brown (7.5YR 5/6), sandy clay loam, very thick platy (10-40 mm diam.), firm to extra firm, very few very fine roots, pebbles (1%), wavy abrupt boundary, bulk density: 1.58 g cm^{-3}.
^**C'1** 67-125 cm; strong brown (7.5YR 5/8), loamy fine sand, sls massive, loose to friable, no roots, wavy abrupt boundary.
^**C'2** 125-200 cm; 40% yellow (10YR 7/6) and 60% brownish yellow (10YR 6/8), coarse sand over fine sand, sls massive, loose, no roots, wavy abrupt boundary.

Figure 5.7. Typical pedon for mine soils located on a mineral sands mining pit-berm transitional position. Full set of profile images (n=10) is given in Appendix C1, descriptions in C2, and chemical data in C3.

PIT LANDFORM



^**Ap** 0-22 cm; dark grayish brown (10YR 4/2), fine sandy loam, fine sbk-shaped cloddy (stronger within upper 10 cm), friable, common very fine to fine roots, 5% redox concentrations (5YR 5/8) as soft masses/root linings and 5% soft mass depletions (10YR 5/2), smooth abrupt boundary, bulk density: 1.57 g cm^{-3}.

^**Cd** 22-63 cm; yellowish red (5YR 5/6), sandy clay loam, medium to coarse clods/plates, firm to very firm, few very fine roots concentrated in upper 10 cm, smooth abrupt boundary, bulk density: 1.57 g cm^{-3}.

^**C1** 63-81 cm; brownish yellow (10YR 6/6), loamy fine sand, sls massive, very friable, no roots, wavy abrupt boundary, bulk density: 1.41 g cm^{-3}.

^**C2** 81-119 cm; strong brown (7.5YR 5/6), sandy clay loam, sls massive, friable, no roots, smooth abrupt boundary.

^**C3** 119-130 cm; yellowish brown (10YR 5/6), silty clay, sls massive, friable, no roots, smooth abrupt boundary.

^**C4** 130-200 cm; reddish yellow 7.5YR 6/8 (~142 cm), pink 7.5YR 7/4 (~153 cm), strong brown 7.5YR 5/6 (~166 cm), strong brown 7.5YR 5/8 (~190 cm), stratified fine (~25%) and coarse (~25%) sand, single grain, loose, no roots, smooth abrupt boundary.

Figure 5.8. Typical pedon for mine soils located on a mineral sands mining pit landform position. Full set of profile images (n=10) is given in Appendix C1, descriptions in C2, and chemical data in C3.

Surface ^Ap horizons generally had common very fine to fine roots that were much denser and more concentrated within the upper 0-5 cm. Textures in the ^Ap horizons were primarily fine sandy loam with several loamy sand and sandy clay loam textures. Redoximorphic features (gray and red mottles) were commonly observed in ^Ap horizons and their occurrence was variable within horizons indicating that the redox formed elsewhere, most likely during topsoil storage. Surface horizons (^Ap and horizon directly below ^Ap) had higher pH, extractable nutrients, and CEC (approximated) compared to subsurface horizons (Appendix C3). Seven out of ten soil profiles contained densic (^Cd) materials. However, the presence of densic materials was not related to presumed pit vs. berm positions since soils located on both former pits and berms generally contained densic materials, but one berm soil (Berm 2-5) did not. These root-limiting (^Cd) horizons usually had thick to very thick platy structure and elevated bulk density levels ($\geq$1.60 g cm^{-3}) compared to overlying or underlying horizons (see Appendix C2 for bulk density data plus full descriptions). Roots were present in very low abundance below the ^Ap, generally along horizontal cracks between plates and occurring in dense mats of very fine (< 1.0 mm diameter) roots.

Lack of rooting was also observed due to limitations posed by the loose structureless and acidic nature of sandier textured tailings common among berm soils. An example of this was the Berm 2-5 soil profile which did not contain any densic horizons. However, rooting notably dropped off below the ^Ap horizon, likely due to much lower water and nutrient holding capacities in the loamy fine sand textures. Also, rooting was not evident in this soil and the pH (7.4 vs. 4.9) and CEC (2.2 vs. 0.8 $cmol_c$ kg^{-1}) were both much higher in the ^Ap horizon (0-17 cm) than in the ^C2 horizon (31-59 cm) (Appendix C2 and C3). Some visual evidence of ripper traces was noted in most profiles, particularly at the contact between the ^Ap and subsoil, but not commonly lower (see Special Features in Appendix C1). Visual effects of deep ripping on rooting and soil morphology were rarely evident below the ^Ap contact with the subsoil, which indicates that ripping was either not effective due to inadequate soil moisture conditions (too dry or wet) and/or re-compaction occurred at some point during the final reclamation protocols. Overall, the major growth limiting factors at the LRS site included the following, which were common among both pit and berm soils: 1) High soil bulk density as indicated by presence of densic (^Cd) materials

and depth to first densic contact; 2) lack of subsoil structure; and 3) low pH (< 5.5) and low plant-available nutrient contents (particularly P) in the upper subsoil layers.

5.4.1.2. Taxonomic and Land Use Implications

Most of these mine soils classify as Anthroportic Udorthents according to current *Soil Taxonomy* due to lack of pedogenic development (e.g., no cambic horizon, ^Bw) and were formed in at least 50 cm of human transported material (Soil Survey Staff 2014). The Anthrodensic subgroup contains soils having "…a densic contact due to mechanical compaction in more than 90 percent of the pedon (measured laterally) within 100 cm of the soil surface" (Soil Survey Staff 2014), which qualify most of the mine soils described in this current chapter. Also, previously described mineral sands mine soils contained multiple densic contacts below the ^Ap horizon characterized by massive or thick platy structures that inhibit rooting except in 10-cm spaced cracks and would classify as Anthrodensic (Orndorff et al. 2015). Previous classification efforts using the 2006 version of *Soil Taxonomy* classified similar pedons ranging from Typic Udorthents and Typic Udifluvents to Typic Dystrudepts (Meredith et al. 2008). At the family level, mineral sands mine soils in this region usually have an "acid" reaction class with a mixed mineralogy, and sometimes contain more than one strongly contrasting particle-size classes or an "aniso" class (e.g., clayey over sandy) (Meredith et al. 2008). The particle-size control section for these soils includes the lower boundary of the ^Ap or at 25 cm (whichever is deeper) to a depth of 100 cm or a root-limiting layer (whichever is shallower). The ten mine soils in this current chapter did not qualify for one or more pairs of strongly contrasting particle-size classes within 100 cm due to limitations posed by the particle-size class control section since most of these soils contained densic materials (^Cd). However, two soils (Berm 2-3 and Pit 2-5S) had strongly contrasted textures at depths greater than the particle-size control section. Overall, the land use limitations posed by these soils are due to severe mechanical compaction, lack of structural development, and low pH and CEC, all of which could in part be alleviated through proper subsurface tillage and liming and fertilization regimes. Also, strongly contrasting textures, indicated by prominent color changes, may cause internal drainage and other management issues. Refer to Chapter 6 for additional details on the taxonomic placement and interpretations of mineral sands mine soils.

5.4.2. Rowcrop Variability Study

5.4.2.1. Spatial Variability of Rowcrop Yield

The full set of yield monitor interpolation maps for the mined and unmined rowcrop fields in this study are presented in Appendix D, along with their associated active mine (pits + berms) and bare soil imagery. Figure 5.9 below illustrates active mine and bare soil images for Fields A and B, and Figure 5.10 provides an example of yield variability maps for these same fields. Crop yields on reclaimed mined lands were highly variable across growing seasons and the maps showed clear spatial patterns that appeared consistent from year-to-year despite different crops. An example of this was Field A, which showed similar areas of higher yield production in 2018 (soybean) vs. 2019 (corn) (Figure 5.10). Also, relative crop yields in several fields appeared to visually align with the pit and berm soil locations. The most obvious example of this was Field A, or the uppermost field in Figure 5.10, which had higher relative yields along the linear and somewhat cross-shaped berm feature compared to polygon-shaped pit features (see Figure 5.9 for reference). The spatial association of vegetation and other properties on pit vs. berm landform positions is evaluated and discussed below in Section 5.4.2.3. Higher crop yield variation was observed in 2019 for Fields A, B, C and D, and this was likely due to the lower annual rainfall for Dinwiddie County relative to other years (Table 5.5).

Table 5.5. Rainfall for Dinwiddie County (10-month period). Data source: NOAA (2022).

Rainfall (mm)					
Month	**Year**				**30-Year Average**
	2018	**2019**	**2020**	**2021**	
Jan.	94	90	81	80	87
Feb.	58	116	129	158	74
March	75	93	61	101	102
April	111	102	118	58	88
May	194	89	85	56	102
June	162	166	142	90	109
July	144	146	97	189	124
Aug.	116	77	260	174	116
Sept.	99	34	209	87	118
Oct.	159	114	139	80	90
Average	121	103	132	107	101

Yield statistics, including mean, range, and coefficient of variation (CV) of the yield for each field per growing season, are given in Table 5.6. Fields C and D showed a much higher CV (CV = 47 and 50%, respectively) in the driest year (2019) compared to other years. Further, the long-term (previous ten years) county average for soybean growing on local unmined lands was 2.21 Mg ha^{-1} (National Agricultural Statistics Service 2021). Based on the county average yield for all soils in production for a given crop, reclaimed fields had a relatively similar or higher soybean yield average except in 2019, when yields in most fields were lower than the county average, likely due to drier than normal conditions. However, it is important to note that county yield averages as mentioned here include all local county fields in each crop, which vary widely in terms of soil quality and land management (e.g., irrigation, soil fertility). Based on the 1972-1984 long-term county average for sorghum (limited data for recent years), which is 2.73 Mg ha^{-1}, reclaimed lands generally had a higher relative yield compared to the county average (National Agricultural Statistics Service 2021). The nearby unmined fields used in this study, which are classified as prime farmlands, generally produced slightly higher mean crop yields relative to the reclaimed fields, which is similar to findings in previous research on mined vs. unmined yields in this area (Orndorff et al. 2011). Based on our data for soybean fields in 2020 (when a direct comparison was possible), we estimated a yield reduction of 6.8% on reclaimed mined lands. However, for sorghum fields in 2021, the average yield on unmined lands was slightly lower compared to mined lands (6.38 vs. 6.67 Mg ha^{-1}), indicating that sorghum is also a promising potential crop. Also, in 2021, the CV of sorghum yields on reclaimed mined lands was much lower compared to the soybean yield CV on mined lands in previous years, despite the relatively lower rainfall in 2021.

Table 5.6. Yield summary statistics for reclaimed mined and unmined (UM) lands.

Field	Crop	Mean	Minimum	Maximum	CV†
		Yield (Mg ha^{-1})			
2018					
A	Soybean	2.55	0.40	4.92	36%
C	Soybean	3.72	1.15	6.30	26%
D	Soybean	3.69	0.40	8.78	35%
E	Soybean	2.35	0.36	5.11	35%
2019					
A	Soybean	1.98	0.13	4.97	44%
B	Soybean	2.30	0.17	5.74	39%
C	Soybean	1.98	0.23	5.31	47%
D	Soybean	1.60	0.20	4.76	50%
Corn Plotł	Corn	6.87	1.01	11.37	29%
UM #1	Corn	6.58	0.30	13.20	34%
2020					
A	Soybean	2.99	0.74	4.96	28%
B	Soybean	2.81	0.54	5.22	31%
C	Soybean	2.42	0.16	5.23	38%
D	Soybean	2.62	0.10	6.25	39%
E	Soybean	2.02	0.30	4.80	45%
UM #1	Soybean	3.01	0.37	6.94	28%
UM #3	Soybean	2.50	0.74	4.32	33%
2021					
A	Sorghum	6.76	2.86	11.83	17%
B	Sorghum	6.36	3.64	10.34	14%
C	Sorghum	6.82	2.82	11.00	19%
D	Sorghum	6.67	2.07	10.75	21%
E	Sorghum	6.73	2.13	12.98	27%
UM #1	Sorghum	5.51	0.83	9.95	30%
UM #2	Sorghum	7.25	3.08	13.49	24%

†CV = Coefficient of variation calculated as the standard deviation divided by the mean x 100, expressed as a percentage.
łCorn experimental research plot in the NE corner of Field A (in 2019 only); thus, these data are not included in statistical analyses.

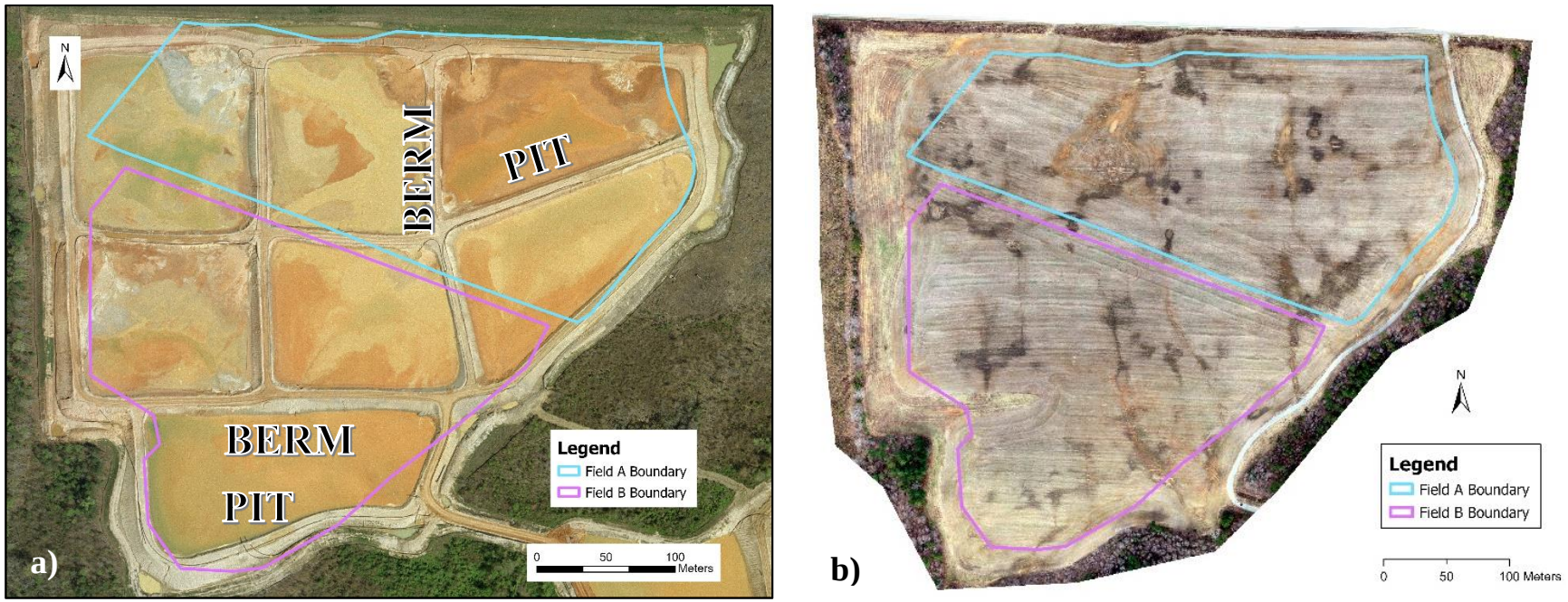


Figure 5.9. Active mining (left) depicting pit and berm locations, and bare soil imagery (right) on Fields A and B. For the full set of images on all reclaimed and unmined fields, refer to Appendix D.

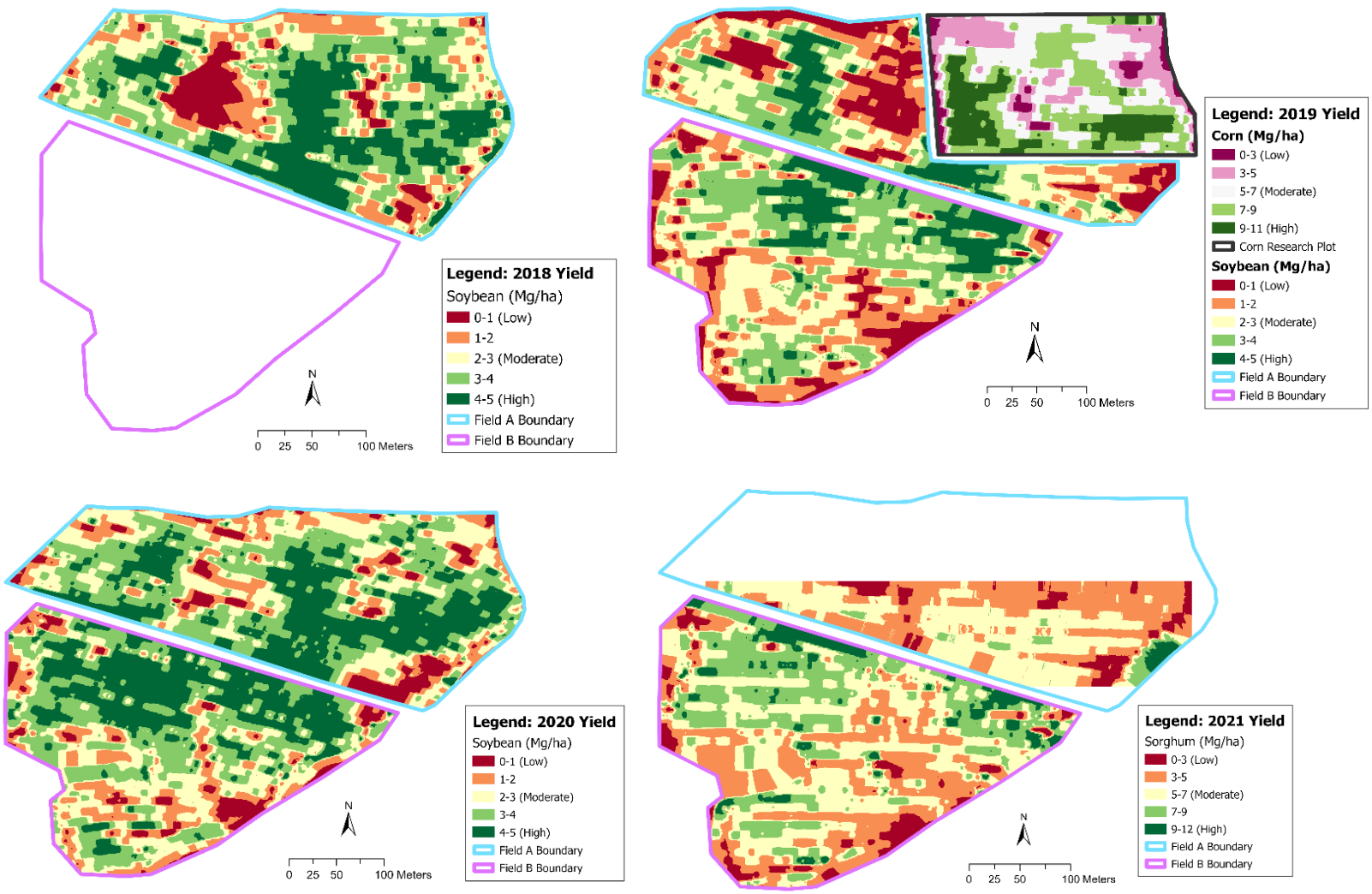


Figure 5.10. Yield monitor interpolation maps for reclaimed rowcrops on Fields A and B in the 2018-2021 growing seasons. For the full set of yield variability maps on all reclaimed and unmined fields, refer to Appendix D. Note: White areas represent an absence of data.

5.4.2.2. Relationships Between Yield and Remotely Sensed Variables

Across fields and growing seasons, crop yield generally had strong and positive correlations with both vegetation indices (VI) – normalized difference vegetation index (NDVI) and green NDVI (GNDVI) (Table 5.7). Variability maps of NDVI for each rowcrop field per growing season are given in Appendix D following the yield interpolation maps. Generally, crop variation was spatially similar between the two visual maps (yield monitor vs. VI data). Both VI's are widely used in precision agriculture research, but GNDVI is more sensitive to chlorophyll concentrations (Candiago et al. 2015; Rogovska and Blackmer 2009). Our results indicate that NDVI and GNDVI are similarly good predictors of yield and could be used to monitor crop health throughout the growing season. Yield had weak to moderate correlations with topographic variables (elevation, slope, curvature), but results were not consistent across fields and growing seasons (Table 5.7). Elevation usually had positive correlations with yield, which were most consistent from year-to-year for Field B. Yield had weaker correlations with slope, which was inconsistent among the different fields. For example, as slope increased on Field A in 2018 and 2020, yield decreased, but slope was positively correlated with yield on most other fields (Table 5.7). Bao-Liang et al. (2009) found that topographic indices (e.g., upslope length) strongly correlated with grain yield in drier years, but in wetter years, topography had no correlation with yield. For our data, the positive influence of elevation on yield was likely weakened or negatively correlated with yield in drier years (2019 and 2021), and this is evident in Fields C through E. Guo et al. (2012) similarly found that cotton yield was negatively correlated with elevation and slope, but their results were consistent across growing seasons. Regarding surface curvatures (PR and PL), significant correlations were much weaker overall compared to elevation and slope, like findings in Guo et al. (2012) and, in many cases, correlations were negligible ($< \pm 0.10$). We found that yield generally had weak and negative correlations with profile (PR) curvatures, indicating that as convexity increased, yield decreased. For planar (PL) curvatures, yield generally had weak positive correlations, indicating that as concave surfaces increased, yield increased. Kaspar et al. (2003) found that both PR and PL were negatively correlated with corn yield and these influences were more apparent in dry years. However, Guo et al. (2012) found that cotton yield was positively correlated with PR (i.e., higher yield at convex surfaces).

Table 5.7. Spearman's correlations (r) between yield and remotely sensed variables. Bold font indicates no significance ($p < 0.05$).

Predictor Variable*	Field A		Field B			Fields C and D				Field E		
	Annual Rowcrop Yield†											
	2018	2020	2019	2020	2021	2018	2019	2020	2021	2018	2020	2021
NDVI	0.77	0.75	0.58	0.76	0.57	0.53	0.48	0.72	0.46	0.74	0.38	0.36
GNDVI	0.77	0.76	0.58	0.77	0.59	0.57	0.49	0.73	0.44	0.73	0.41	0.39
Elevation	0.16	0.16	0.44	0.45	0.24	0.19	-0.03	0.13	0.04	0.34	0.17	0.09
Slope	-0.21	-0.15	-0.03	0.03	0.11	0.24	0.13	0.24	0.16	0.18	0.25	0.15
Profile	**-0.00**	**-0.00**	0.03	-0.06	-0.05	-0.12	-0.04	-0.14	-0.10	-0.04	-0.02	-0.03
Planar	0.12	0.14	0.26	0.34	0.24	0.01	-0.05	-0.01	0.02	0.08	0.05	0.03
Blue	0.45	0.34	0.16	0.12	0.14	0.08	-0.03	**0.00**	**-0.00**	0.27	0.12	0.01
Green	0.37	0.26	0.03	-0.03	**0.00**	0.05	-0.04	-0.02	-0.05	0.24	0.08	-0.02
Red	0.25	0.16	-0.07	-0.12	-0.06	-0.06	-0.11	-0.13	-0.15	0.17	**0.01**	-0.08
NIR	0.43	0.39	0.32	0.44	0.27	0.14	0.27	0.15	0.26	0.02	-0.11	-0.16
BI	0.25	0.16	-0.07	-0.12	-0.06	-0.06	-0.11	-0.12	-0.15	0.15	-0.02	-0.08
CI	-0.50	-0.39	-0.25	-0.29	-0.24	-0.25	-0.15	-0.20	-0.22	-0.21	-0.20	-0.13
IO	-0.56	-0.43	-0.37	-0.44	-0.40	-0.23	-0.14	-0.19	-0.27	-0.28	-0.23	-0.14

*NDVI=normalized difference vegetation index; GNDVI=green normalized difference vegetation index; NIR=near-infrared band; BI=brightness index; CI=coloration index; IO=iron oxide index. Individual bands (blue, green, red, NIR) and spectral indices (BI, CI, IO) were derived from bare soil images, while vegetation and topographic parameters were derived from Planet satellite images.
†For these field areas, soybeans were grown in 2018-2020 and sorghum was grown in 2021 (per Tables 5.2 and 5.5).

Further, correlation results between yield and the individual visible (red, green, blue) and near-infrared (NIR) bands were inconsistent among fields and growing seasons (Table 5.7). Field A for some reason had the strongest (positive) correlations with all individual bands. Out of all individual bands, the NIR band generally provided the most consistent and positive correlations with yield. Across most fields, the blue and green bands were unreliable predictors of yield. Yield usually had a negative correlation with the brightness index (BI) for most fields in most years, but the relationship was negligible (i.e., weak; < 0.1). The BI indicates relative magnitude of soil reflectance, like the NIR band (Mandal 2016). While we did not find BI to be a useful index per se, other studies have successfully correlated BI to soil organic matter (Leone et al. 1995) and CEC (Khanal et al. 2018) levels. Much more consistently, yield had weak to moderate negative correlations with the coloration index (CI) and iron oxide index (IO) for all fields in all years. The CI is a ratio of the red and green bands that indicates areas of heightened soil color, which could be due to various soil colorants such as minerals and/or areas of higher soil organic matter and moisture, and these attributes are strongly absorbed by all wavebands (Sánchez-Marañón 2011). The IO would clearly indicate zones of redness influenced by hematite and other iron minerals, whereas the CI band could be due to a combination of factors, including wet areas due to depressions or low rainfall infiltration rates.

Soil reflectance is largely influenced by soil texture, hence the NIR band derived from bare soil imagery (Barnes and Baker 2000). Raya et al. (2004) found that the NIR band was positively correlated with sand contents and negatively correlated with organic matter in soils, while CI had a moderately strong positive correlation with clay contents. Similarly, Khadse (2012) found that lighter and sandier soils with lower organic matter had higher spectral reflectance. Additionally, Khanal et al. (2018) successfully utilized bare soil imagery to capture field-scale variability of crop yield and soil properties. They found that the NIR band was one of the most important explanatory variables for soil organic matter prediction, and that CI was an important predictor of yield and magnesium and potassium soil levels. Others have successfully correlated lower soil reflectance (darker soil) with higher soil organic matter (Dalal and Henry 1986; Krishnan et al. 1981; Pitts et al. 1986). Lower reflectance could also indicate zones of soil wetness since water-filled pores increases the absorption of light (Sánchez-Marañón 2011).

5.4.2.3. Effect of Anthropogenic Landform Position on Site and Vegetative Properties

Significant moderate to strong correlations ($0.30 < r < 0.77$) between yield and remotely sensed variables were investigated further in relation to the underlying mine landform positions (pit vs. berm) for each field. Differences between pit and berm landform positions on Fields A and/or B were found for GNDVI, CI, elevation, and the NIR band (Figure 5.11). The CI (soil color) in Field A was higher on pit positions, but there was no difference for Field B. Alternatively, GNDVI in Field A was higher on berm positions, but Field B also had no differences. In Field B, actual elevation was higher on berm positions vs. pits. Berm positions in both Fields A and B had greater soil reflectance (NIR) than pit positions. Further, GNDVI was higher on berm positions in Field D, while the NIR band was higher on pit positions in Field C (Figure 5.12). For Field E, GNDVI was also higher on berm positions, while IO was higher on pit positions (Figure 5.13). It appears that across some fields, berm positions supported better soybean productivity, given the strong relationship between GNDVI and grain yield. There is a lack of evidence that berms are higher in elevation since only one field (B) had a higher local elevation compared to pits, and this may be due to the relatively low resolution of the DEM (Figure 5.14). Two fields (A and E) contained former pits with greater values for soil color indices (CI and IO) compared to berm positions, which could be due to depressional areas (zones of wetness), higher soil organic matter, and/or exposed slimes (reddish, highly pigmented soils) common in pit positions. As discussed in the last section, soil reflectance has been shown to positively correlate with coarsening soil texture, with increasing sand contents having higher reflectance in visible and NIR spectral ranges (Barnes and Baker 2000; Guo et al. 2012; Raya et al. 2004). Finer textured soil particles would likely be influenced more by various soil colorants (e.g., iron oxides, soil organic matter) due to their smaller surface areas which are more easily pigmented and altered by light (Sánchez-Marañón 2011).

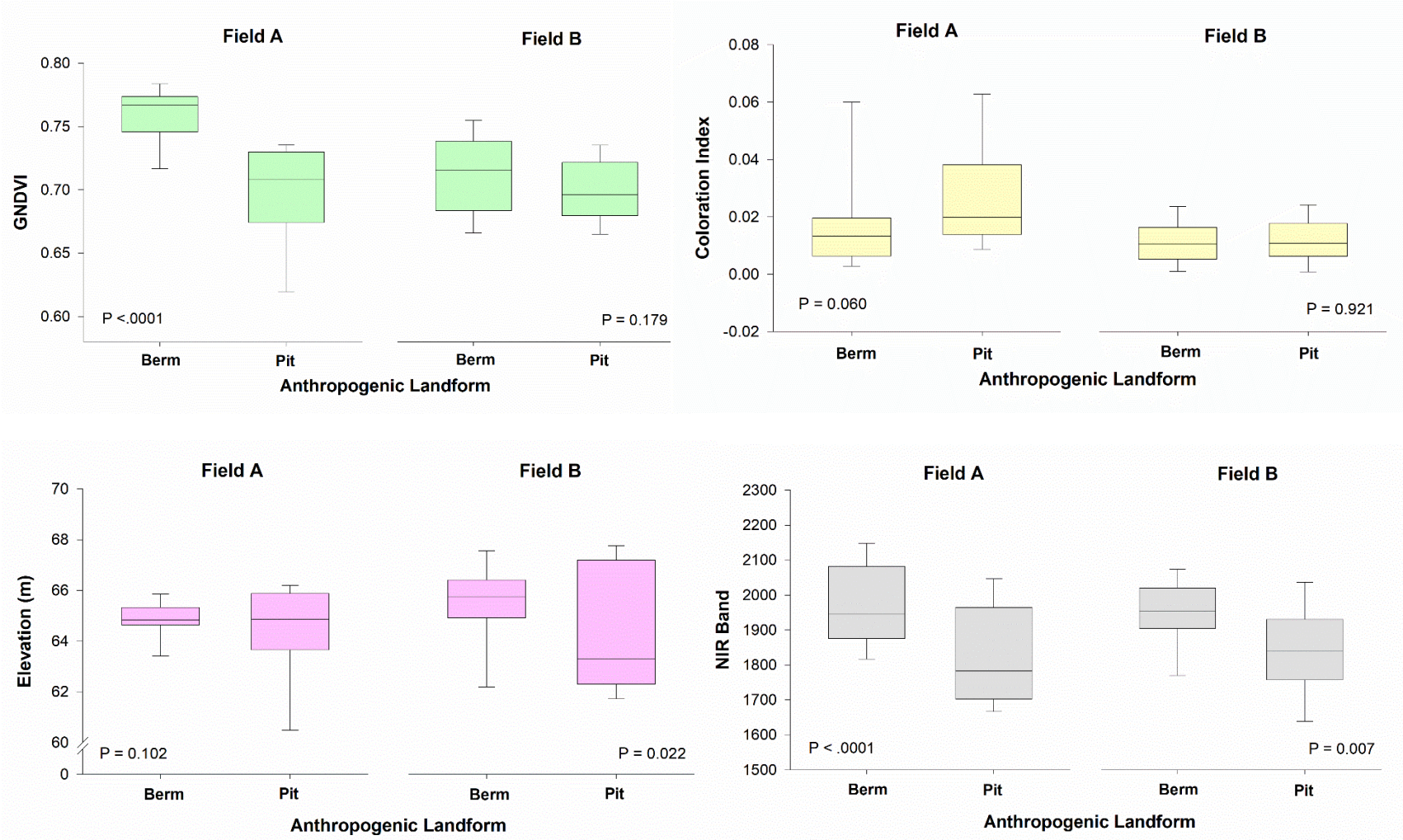


Figure 5.11. Boxplots for GNDVI (2020 data), CI, elevation, and NIR to show differences between pit and berm anthropogenic landform position (pit vs. berm) on Fields A and B.

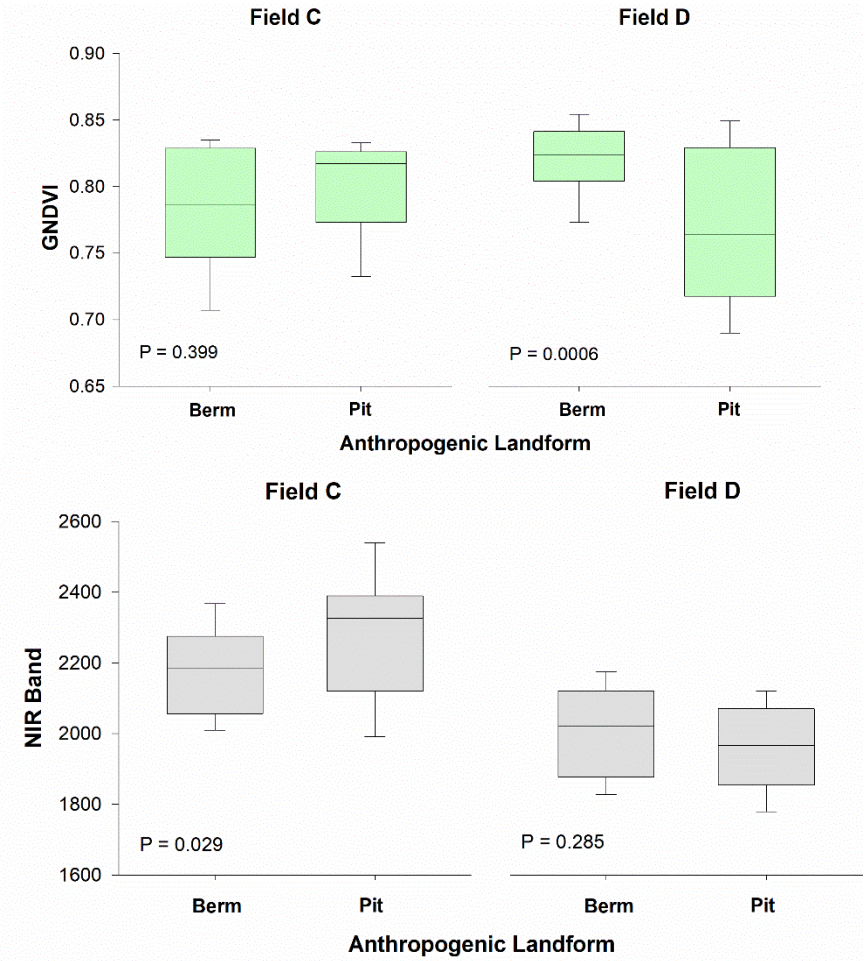


Figure 5.12. Boxplots for GNDVI (2020 data) and NIR to show differences between pit and berm anthropogenic landform position (pit vs. berm) on Fields C and D.

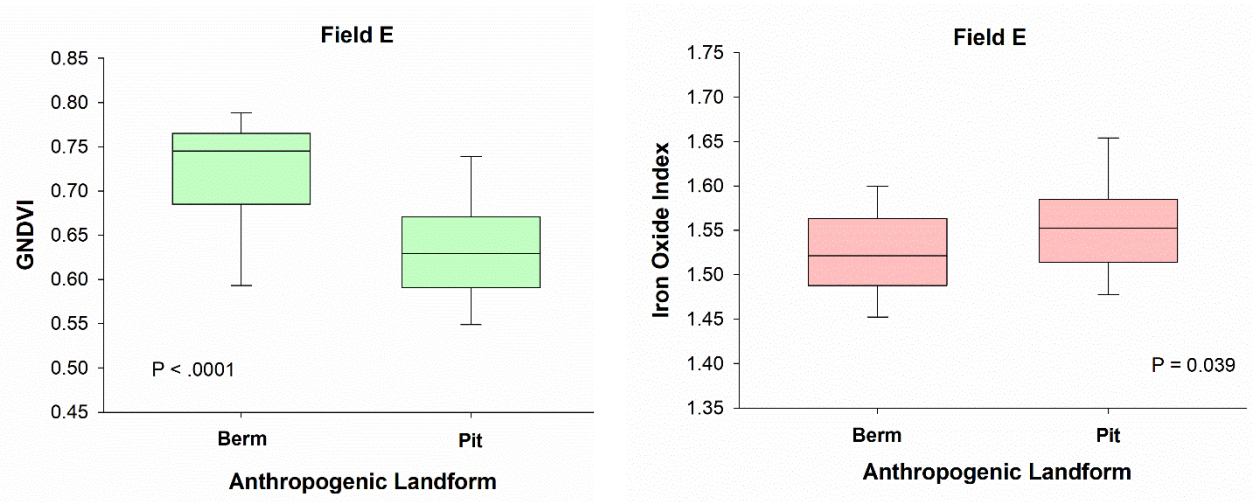


Figure 5.13. Boxplots for GNDVI (2018 data) and IO to show differences between pit and berm anthropogenic landform position (pit vs. berm) on Field E.

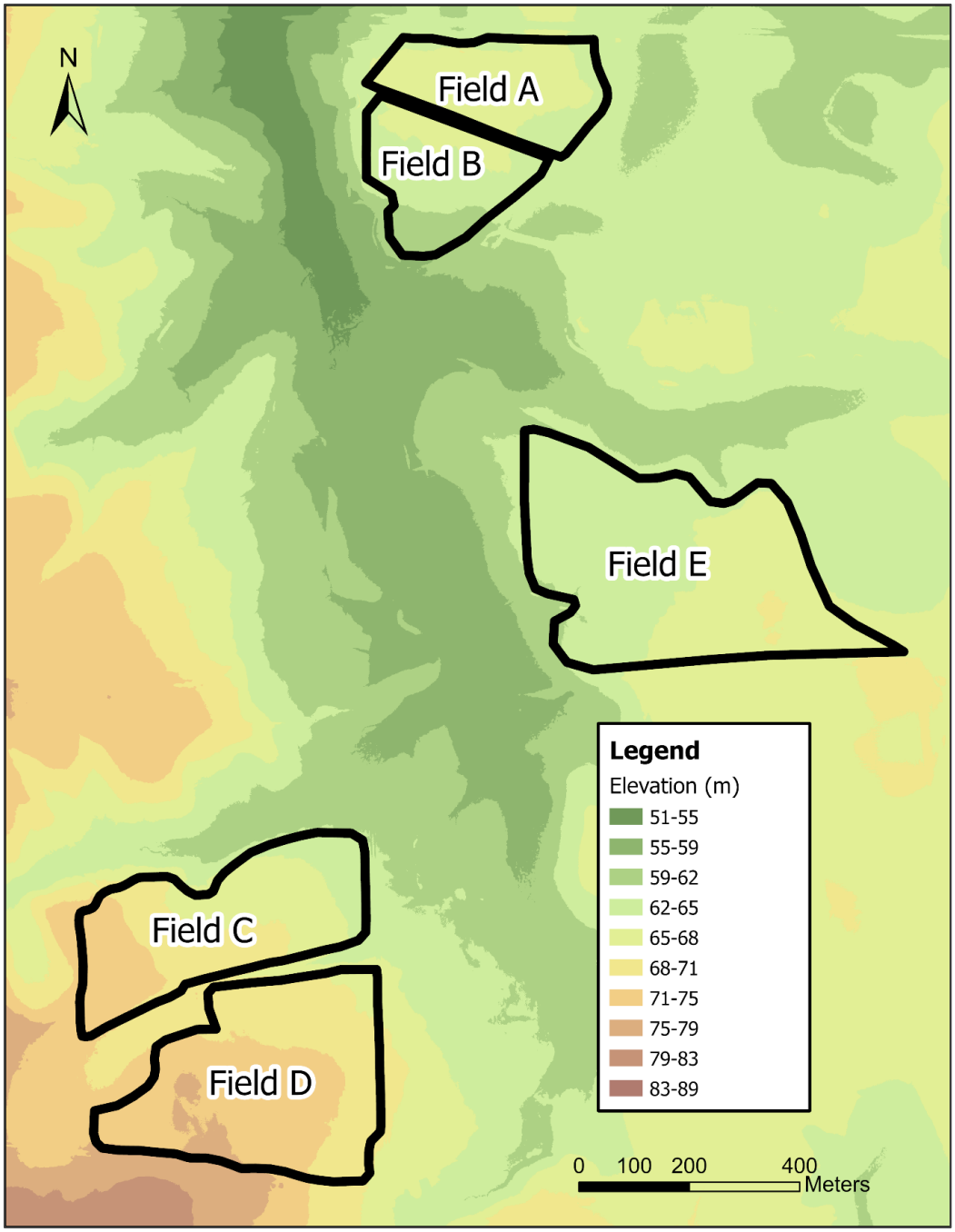


Figure 5.14. Reclaimed rowcrop field locations A through E overlying a 24 x 24 m digital elevation model based on aerial survey data in 2015 (via an Iluka contractor).

Our datasets and analyses contained some apparently conflicting information since two fields (A and B) had higher NIR reflectance on berms, while another field showed higher reflectance on pit positions. Generally, berm positions are likely to be sandier textured and lighter colored because they are derived from tailings and/or barren substratum (fewer weathered materials) and due to their lack of contact and mixing with higher slimes (Fe+clay) within dewatering pits. However, pits may exhibit a mixture of different final surface textures and colors due to the variable nature of the dewatering and final landform reconstruction process (e.g., re-mixing, dipping/spreading, grading), which often includes reworked slimes and tailings materials. Given the higher variability of remotely sensed properties on pit positions (Figures 5.11-5.13 above), a larger number of ground observations would likely be required to accurately assess the variability of mine soil texture and color along with minor changes in local elevations. However, there was some evidence of pit positions being lower on the overall mined landscape and having a redder and/or darker soil color, which would be expected due to the higher slimes (Fe+clay) contents and increased settling over time. Locally concave pit areas would be more likely to hold water and accumulate soil organic matter vs. the more stable and built-up berm landform positions. These results, however, were inconsistent across the study fields, so it is difficult to make broad generalizations.

Further, Moravec et al. (2017) found that both fine and coarse resolution DEM's were good predictors of yield on undulating sites (average slope of ~6%). Our study fields were flatter (average slope of ~1-3% depending on the field) and subtle differences in microtopography may not have been captured by the DEM data employed here unless finer scale data were collected at the field scale. Also, we cannot discount the fact that reclamation procedures may have differed slightly across different sites over the relatively long time periods involved (10 to 20+ years since reclamation). Regardless, local post-reclamation topographic variables did not have a strong influence on crop yield and there is little effect of the resulting original mine landform position on final reconstructed site topography. However, as noted above, the underlying relict mine pit/berm positions probably have a stronger influence. Further ground-based data and studies are needed to better understand the main drivers of high vs. low yielding areas in relation to the overall mine land reconstruction process.

5.5. Summary and Conclusions

The short-, mid-, and long-range lateral and vertical variability of mineral sands mine soils observed in this study and others (e.g., Orndorff et al. 2005; 2011) is an issue that potentially confounds our ability to predict post-mining crop productivity. This variability results from segregation of coarse (tailings) and fine (slimes) particles in pits during dewatering of the processed mineral sands host materials coupled with variable grading and local mixing of contrasting materials during final landform reconstruction. Following photo-monitoring of a reconstructed mine site (LRS), the overall morphology and properties of different soil profiles generally represented their associated underlying mining influences (berms vs. pits). In some cases, berm profiles were not aligned directly on top of the original narrow berm (~10 m wide) landform position and contained approximately 60-100 cm of mixed slimes-tailings materials, indicating a transitional pit-berm area. Regardless of the presumed underlying landform position, root-limiting densic (^Cd) materials were common across profiles. Depth to densic contact was important for better plant rooting and appeared to affect aboveground productivity at the time of sampling. Other factors that likely limited plant rooting and growth were higher acidity and lower water and nutrient holding capacities observed in soil profiles dominated by loose sandy tailings and substratum materials.

Spatial variability of soil properties and vegetation was addressed through analysis of yield monitor data and remotely sensed variables such as NDVI, elevation, and soil color (i.e., individual visible and NIR bands and different indices). Local variability of yield within and between fields appeared more distinct in drier growing seasons. Interestingly, yields of several different crops over two years were numerically comparable to yields on nearby unmined prime farmlands. This finding may indicate that over extended periods of time (e.g., > 10-20 years) frequent tillage and fertilization/liming practices may elevate yield potentials significantly higher than we have observed in our earlier controlled plot studies. Sorghum appears to be a promising crop for mined lands given their relatively low CV and high yields vs. unmined reference yields. Generally, VI's, elevation, NIR band, and soil color indices (CI and IO) were the best predictors of yield. Berm positions had an advantage in vegetation productivity vs. pits and in some cases appeared to have higher reflectance, which may indicate a lighter, sandier soil texture. Pit surface positions, on the

other hand, appeared to have more complex bare soil colors (e.g., reds, darks) and, at least in one field, were lower in local relative elevation vs. berm positions.

Given our findings at the LRS, we cannot always make broad generalizations about mechanical compaction, since root-limiting layers were observed on both pit and berm positions. However, berms were generally comprised of sandier, lighter colored tailings materials compared to the pits, as expected. While we cannot directly compare the observational LRS study to the rowcrop spatial variability study, we can speculate that berm positions may in some cases support better rooting and rainfall infiltration simply due to their much sandier textures, and over time as organic matter accumulates, these areas may be better for crop growth vs. pit positions, especially in years of ample rainfall. Pits are likely more easily compacted given their generally finer textured soils due to the inclusions and mixing of slimes materials upward with sandy tailings during final reclamation protocols. Dipping and spreading, as discussed in the literature review, is a process that uses a long-arm bucket excavator to redistribute slimes over onto the final surface to homogenize areas dominated by tailings. In summary, we can speculate that the above soil physical properties give berm positions a slight advantage over pits. Additionally, differences in mine soil vs. landform position are likely site-specific given the inconsistencies of our results across field sites.

Future research should focus on systematic ground truth data collection of soil properties to correlate with crop yield data. We recommend this sampling approach on multiple reclaimed mine sites to verify if there is a consistent relationship between the underlying mining influences and soil properties or if the correlation among local soil properties vs. yield is site-specific. Further, with the use of high resolution (< 3 x 3 m) bare soil imagery, spectral bands and indices such as those used in this study may serve as important predictors for mine soil properties, aiding in soil fertility management plans. A common example is the development of yield management zones which characterizes areas of low, moderate, and high producing yield with important soil properties (Jaynes et al. 2005; Raya et al. 2004; Rodrigues and Corá 2015; Vrindts et al. 2005). Also, depth to a limiting soil property, such as a densic contact, may be helpful for the development of unique soil mapping criteria for mined lands given their highly variable nature (Bell et al. 1994).

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5.7. References

Akoglu, H. 2018. User's guide to correlation coefficients. Turkish journal of emergency medicine 18: 91-93. doi:10.1016/j.tjem.2018.08.001.

Ballester, C., J. Hornbuckle, J. Brinkhoff, J. Smith and W. Quayle. 2017. Assessment of in-season cotton nitrogen status and lint yield prediction from unmanned aerial system imagery. Remote Sensing 9: 1149. doi:10.3390/rs9111149.

Bao-Liang, C., B. Cheng-Si, F. Walley and T. Yates. 2009. Topographic indices and yield variability in a rolling landscape of western Canada. Pedosphere 19: 362-370. doi:10.1016/S1002-0160(09)60127-2.

Barnes, E. and M. Baker. 2000. Multispectral data for mapping soil texture: possibilities and limitations. Applied Engineering in Agriculture 16: 731. doi:10.13031/2013.5370.

Barnhisel, R. and R. Gray. 1990. Managing restored prime farmland for corn production. In: Conference Proceedings of the 7th Annual Meeting, American Society for Surface Mining and Reclamation. J Skousen, J Sencindiver and D Samuel (eds). pp. 143-149. Lexington, KY.: 143-149.

Bearden, E.D. 1984. A comparison of variability of undisturbed and surface mined soils in Freestone County, Texas. M.S. Thesis, Texas A&M University.

Bell, J.C., R.L. Cunningham and C.T. Anthony. 1994. Morphological characteristics of reconstructed prime farmland soils in western Pennsylvania. Journal of environmental quality 23. doi:10.2134/jeq1994.00472425002300030016x.

Berquist Jr, C. and C. Bailey. 1998. Late cenozoic reverse faulting in the fall zone, southeastern Virginia. p.1-126. In: Geological Society of America, 1998 Annual Meeting, Abstracts with Programs.

Betzek, N.M., E.G. de Souza, C.L. Bazzi, K. Schenatto, A. Gavioli and P.S.G. Magalhães. 2019. Computational routines for the automatic selection of the best parameters used by interpolation methods to create thematic maps. Computers and Electronics in Agriculture 157: 49-62. doi:10.1016/j.compag.2018.12.004.

Blake, G.R. and K.H. Hartge. 1986. Bulk density. p. 363-375. In: A. Klute (ed.) Methods of Soil Analysis, Part 1. 2nd ed. Madison, Wisconsin. doi:10.1002/gea.3340050110

Boerner, R.E.J., A.J. Scherzer and J.A. Brinkman. 1998. Spatial patterns of inorganic N, P availability, and organic C in relation to soil disturbance: A chronosequence analysis. Applied Soil Ecology 7: 159-177. doi:10.1016/S0929-1393(97)00037-1.

Brooks, D.R. 1989. Reclamation in Australia's heavy mineral sands industry. p 11-26. In: D.G. Walker et al. (eds). Proceedings of the America Society of Mining and Reclamation. doi:10.21000/JASMR89010010.

Candiago, S., F. Remondino, M.D. Giglio, M. Dubbini and M. Gattelli. 2015. Evaluating multispectral images and vegetation indices for precision farming applications from UAV images. Remote Sensing 7: 4026-4047. doi:10.3390/rs70404026.

Carpenter, R.H. and S.F. Carpenter. 1991. Heavy mineral-deposits in the upper coastal-plain of North-Carolina and Virginia. Econ Geol Bull Soc 86: 1657-1671. doi:10.2113/gsecongeo.86.8.1657.

Cox, T. and S. Witter. 1978. Applications of remote sensing technology to disturbed lands In: Reclamation of Drastically Disturbed Lands p. 705-727.

Cunningham, C.G., M.L. Zientek, W.J. Bawiec and G.J. Orris. 2005. Geology and nonfuel mineral deposits of Latin America and Canada. Report 1294B, U.S. Geological Survey.

Dalal, R. and R. Henry. 1986. Simultaneous determination of moisture, organic carbon, and total nitrogen by near infrared reflectance spectrophotometry. Soil Science Society of America Journal 50: 120-123. doi:10.2136/sssaj1986.03615995005000010023x.

Daniels, W.L., L.W. Zelazny, M.M. Alley and K.C. Haering. 1991. The development of restoration strategies for prime agricultural soils following mineral sands mining in the coastal plain of the eastern USA. p. 26-37. In: Proc. 1991 Aust. Mining. Ind. Council Environ. Workshop. AMIC, Dickson, ACT, Australia.

Daniels, W.L., M.H. Genthner and R.L. Hodges. 1992. Soil development in sandy tailings derived from mineral sands mining in Florida. p. 37-47. In: Proceedings of the 9th National Meeting of the American Society for Surface Mining and Reclamation, Duluth, 14–18 June. ASSMR, Lexington, KY. doi:10.21000/JASMR92010037.

Daniels, W., M. Alley, L. Zelazny, Y. Lei, V. Groover and P. Schroeder. 1996. Strategies for rehabilitating prime farmlands following mineral sands mining in Virginia, USA. p. 412-427. In: Proceedings of 3rd International and the 21st Annual Minerals Council of Australia. Environ. Workshop. Vol. 2. 14-18 Oct.

Daniels, W., P. Schroeder, S. Nagle, L. Zelazny and M. Alley. 2003a. Reclamation of prime farmland following mineral sands mining in Virginia. Mining Engineering 55: 42-48. doi:10.21000/JASMR99010146.

Daniels, W.L. 2003b. Strategies for the return of heavy mineral sands mines to productive agricultural uses. p. 373. In: Proceedings of the International Conference on Sustainable Development Indicators in the Mineral Industries.

Daniels, W.L., Z.W. Orndorff and P.D. Schroeder. 2003c. Chemical and physical properties of mineral sands mine soils in southeastern Virginia. p. 209-227. In: Proc., 2003 National Meeting of the Am. Soc. of Mining and Reclamation, Lexington, KY. doi:10.21000/JASMR03010209.

Daniels, W.L., Z. Orndorff, M. Alley, L. Zelazny and C. Teutsch. 2007. Sustainability indicators for mineral sands mining in Virginia, USA. p. 1-8. In: Proc. 3rd International Conference on Sustainable Development Indicators in the Minerals Industry, June 2007, Milos island, Greece.

Daniels, W., C. Stilson and C. Zimmerman. 2012. Development of effective rehabilitation protocols for mineral sands mining in Virginia, USA. 97-103. In: Life-Of-Mine Conference, Brisbane, Qld, 10 - 12 July.

Daniels, W.L. and Z.W. Orndorff. 2013. Indicators of reclamation success for mineral sands mining in the USA. p. 226-231. In: 6th International Conference on Sustainable Development in the Minerals Industry. Milos Island, Greece.

Daniels, W.L., Z. Orndorff, C. Stilson, C. Zimmerman, and A. Haywood. 2018. Development of effective rehabilitation protocols for mineral sands mining in Virginia, USA. p. 127 – 133 In: From start to finish: A life-of-mine perspective. Spectrum Series 24. The Australasian Institute of Mining and Metallurgy, Carlton, Victoria, Australia.

Darmody, R., R. Dunker and R. Barnhisel. 2002. Reclamation of prime agricultural lands after coal surface mining: the Midwestern experience. In: Conference Proceedings for the National Meeting of the American Society of Mining and Reclamation, Lexington KY. : 900-915.

Dollhopf, D.J. 2000. Sampling strategies for drastically disturbed lands. Barnhisel, R.I., Darmody, R.G., Daniels, W.L. (eds). p. 21-40. In: Reclamation of Drastically Disturbed Lands. ASA, CSSA, SSSA, Madison, WI. doi:10.2134/agronmonogr41.c2.

Dunker, R. and R. Barnhisel. 2000. Cropland reclamation. p. 323-369. In: Reclamation of Drastically Disturbed Lands. American Society of Agronomy.

Dunker, R. and R. Darmody. 2005. Rowcrop response to topsoil replacement on high traffic vs low traffic soil reconstruction systems. p. 302-327. In: Proceedings of the National Meeting of the American Society of Mining and Reclamation, Breckenridge CO, June, 19-23. doi:10.21000/JASMR05010302.

Erdede, S.B. and S. Bektaş. 2020. Examining the interpolation methods used in forming the digital elevation models. Celal Bayar University Journal of Science 16: 207-214. doi:10.18466/cbayarfbe.678176.

Finke, P.A., J. Bouma and A. Stein. 1992. Measuring field variability of disturbed soils for simulation purposes. Soil Science Society of America Journal 56: 187-192. doi:10.2136/sssaj1992.03615995005600010029x.

Gao, F., M. Anderson, C. Daughtry and D. Johnson. 2018. Assessing the variability of corn and soybean yields in central iowa using high spatiotemporal resolution multi-satellite imagery. Remote Sensing 10: 1489. doi:10.3390/rs10091489.

Gitelson, A.A., Y.J. Kaufman and M.N. Merzlyak. 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sensing of Environment 58: 289-298. doi:10.1016/S0034-4257(96)00072-7.

Grandt, A.F. and L. Hossner. 1988. Productivity of reclaimed lands-cropland. p. 1321-135. In: L.R. Hossner (ed.) Reclamation of Surface Mined Lands. CRC Press, Boca Raton, FL.

Guo, W., S.J. Maas and K.F. Bronson. 2012. Relationship between cotton yield and soil electrical conductivity, topography, and Landsat imagery. Precision Agriculture 13: 678-692. doi:10.1007/s11119-012-9277-2.

Hatfield, J.L., A.A. Gitelson, J.S. Schepers and C.L. Walthall. 2008. Application of spectral remote sensing for agronomic decisions. Agronomy Journal 100: S-117. doi:10.2134/agronj2006.0370c.

Hodges, R., W. Daniels, P. Thomas and M. Genthner. 1997. Soil survey of Old Hickory Project area. Crop and Soil Env. Sci. Dept., Virginia Tech, Blacksburg, VA.

Hooks, C., R. Dunker, S. Vance and R. Darmody. 1992. Rowcrop response to truck and scraper hauled root media systems in soil reconstruction. p. 19-23. In: Proc. of the 1992 Natl. Symp. on Prime Farmland Reclamation. Dept. of Agron., Univ. of IL, Urbana, IL. doi:10.21000/JASMR05010302.

Hornung, A., R. Khosla, R. Reich, D. Inman and D. Westfall. 2006. Comparison of site-specific management zones: soil-color-based and yield-based. Agronomy Journal 98: 407-415. doi:10.2134/agronj2005.0240.

Hossner, L.R., H. Shahandeh and J.A. Birkhead. 1997. The impact of acid forming materials on plant growth on reclaimed minesoil. Journal of Soil and Water Conservation 52: 118-125.

Inman, D., R. Khosla, R. Reich and D. Westfall. 2008. Normalized difference vegetation index and soil color-based management zones in irrigated maize. Agronomy journal 100: 60-66. doi:10.2134/agronj2007.0020.

Jansen, I. and W. Dancer. 1981. Rowcrop yield response to soil horizon replacement after mining. p. 357-362. In: Proc. of the Symposium on Surface Mining Hydrology, Sedimentation and Reclamation. Louisville, KY. .

Jaynes, D.B., T.S. Colvin and T.C. Kaspar. 2005. Identifying potential soybean management zones from multi-year yield data. Computers and electronics in agriculture 46: 309-327. doi:10.1016/j.compag.2004.11.011.

Karan, S.K., S.R. Samadder and S.K. Maiti. 2016. Assessment Of The Capability Of Remote Sensing And Gis Techniques For Monitoring Reclamation Success In Coal Mine Degraded Lands. Journal Of Environmental Management 182: 272-283.

Kaspar, T.C., T.S. Colvin, D.B. Jaynes, D.L. Karlen, D.E. James, D.W. Meek et al. 2003. Relationship between six years of corn yields and terrain attributes. Precision agriculture 4: 87-101.

Keck, T.J., W.F. Quimby and G.A. Nielsen. 1993. Spatial distribution of soil attributes on reconstructed minesoils. Soil Science Society of America Journal 57: 782. doi:10.2136/sssaj1993.03615995005700030026x.

Khadse, G. 2012. Spectral reflectance characteristics of the soils on basaltic terrain of central Indian plateau. Journal of the Indian Society of Remote Sensing 40: 717-724. doi:10.1007/s12524-011-0187-y.

Khanal, S., J. Fulton, A. Klopfenstein, N. Douridas and S. Shearer. 2018. Integration of high resolution remotely sensed data and machine learning techniques for spatial prediction of soil properties and corn yield. Computers and electronics in agriculture 153: 213-225. doi:10.1016/j.compag.2018.07.016.

Krishnan, P., B. Butler and J. Hummel. 1981. Close-range sensing of soil organic matter. Transactions of the ASAE 24: 306-0311. doi:10.13031/2013.34246.

Leone, A., G. Wright and C. Corves. 1995. The application of satellite remote sensing for soil studies in upland areas of Southern Italy. Remote Sensing 16: 1087-1105. doi:10.1080/01431169508954465.

Lin, H.S., D. Wheeler, J. Bell and L. Wilding. 2005. Assessment of soil spatial variability at multiple scales. Ecological Modelling 182: 271-290. doi:10.1016/j.ecolmodel.2004.04.006.

Ma, B.L., L.M. Dwyer, C. Costa, E.R. Cober and M.J. Morrison. 2001. Early prediction of soybean yield from canopy reflectance measurements. Agronomy Journal 93: 1227-1234. doi:10.2134/agronj2001.1227.

Maguire, R. and S. Heckendorn. 2019. Laboratory procedures: Virginia Tech soil testing and plant analysis laboratory. Publication 452-881. Virginia Cooperative Extension. p. 16.

Mandal, U.K. 2016. Spectral color indices based geospatial modeling of soil organic matter in chitwan district, Nepal. International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences 41. doi:10.5194/isprsarchives-XLI-B2-43-2016.

Maresma, A., M. Ariza, E. Martínez, J. Lloveras and J.A. Martínez-Casasnovas. 2016. Analysis of vegetation indices to determine nitrogen application and yield prediction in maize (zea mays l.) from a standard uav service. Remote Sensing 8: 973. doi:10.3390/rs8120973.

McSweeney, K., I. Jansen, C. Boast and R. Dunker. 1987. Row crop productivity of eight constructed minesoils. Reclamation and Revegetation Research 6: 137-144.

Meredith, K.R. 2007. The influence of soil reconstruction methods on mineral sands mine soil properties. M.S. Thesis. Virginia Tech.

Meredith, K., W. Daniels, Z. Orndorff, M. Alley and C. Teutsch. 2008. The influence of soil reconstruction techniques on mineral sands mine soils in Virginia. p. 700-719. In: R.I. Barnhisel (Ed.), Proc., 2008 Nat. Meeting Amer. Soc. Mining and Reclamation, Richmond, VA, June 14-19. Published by ASMR, 3134 Montavesta Rd., Lexington, KY. doi:10.21000/JASMR08010700.

Moravec, D., J. Komárek, J. Kumhálová, M. Kroulík, J. Prošek and P. Klápště. 2017. Digital elevation models as predictors of yield: comparison of an UAV and other elevation data sources. Agronomy Research 15: 249-255.

Mummey, D.L., P.D. Stahl and J.S. Buyer. 2002. Soil microbiological properties 20 years after surface mine reclamation: Spatial analysis of reclaimed and undisturbed sites. Soil Biology and Biochemistry 34: 1717-1725. doi:10.1016/S0038-0717(02)00158-X.

National Agricultural Statistics Service. 2021. United States Department of Agriculture, National Agricultural Statistics Service (NASS). Quick Stats. Available online at: http://www.nass.usda.gov/Quick_Stats/ (accessed 23 Jan. 2022).

Newton, M.C. and A.J. Romeo. 2006. Geology of the old hickory heavy mineral sand deposit, Dinwiddie and Sussex counties, Virginia. p. 464-480. In: Proceedings of the 42nd Forum on the Geology of Industrial Minerals. North Carolina Geological Survey, Information Circular. Citeseer.

NOAA. 2022. Climate at a glance: County time series. National Oceanic Atmospheric Administration (NOAA). National Centers for Environmental Information. Available online at: https://www.ncdc.noaa.gov/cag/.

Nyamadzawo, G., M.K. Shukla and R. Lal. 2008. Spatial variability of total soil carbon and nitrogen stocks for some reclaimed minesoils of southeastern Ohio. Land Degradation & Development 19: 275-288. doi:10.1002/ldr.841.

Orndorff, Z.W., W.L. Daniels and J.M. Galbraith. 2005. Properties and classification of mineral sands mine soils in southeastern Virginia. In: R.I. Barnhisel (Ed.), Proc., 2005 Nat. Meeting Amer. Soc. Mining and Reclamation, Breckenridge, CO, June 19-23. Published by ASMR, 3134 Montavesta Rd., Lexington, KY, 40502. doi: 10.21000/JASMR05010842.

Orndorff, Z.W., W.L. Daniels, K.R. Meredith, M.M. Alley and A.F. Wick. 2011. Effects of prime farmland soil reconstruction methods on post-mining productivity of mineral sands mine soils in Virginia. p. 504-518. In: R.I. Barnhisel (Ed.), Proc. Nat. Meeting Amer. Soc. Mining and Reclamation, Bismarck, ND, June 11-16. Published by ASMR, 3134 Montavesta Rd., Lexington, KY, 40502. doi:10.21000/JASMR11010504.

Orndorff, Z., W. Lee Daniels, S. Koropchak, P. Donovan and M. Reiter. 2015. Reclamation of mineral sands mining: Annual research report. Submitted to Iluka Mineral Resources. p. 112.

Parvej, M.R., D.L. Holshouser, R.J. Kratochvil, C.M. Whaley, E.J. Dunphy, G.W. Roth et al. 2020. Early high-moisture wheat harvest improves double-crop system: II. Soybean growth and yield. Crop Science 60: 2650-2666. doi:10.1002/csc2.20174.

Pitts, M.J., J.W. Hummel and B.J. Butler. 1986. Sensors utilizing light reflection to measure soil organic matter. Transactions of the ASAE 29: 422-0428. doi:10.13031/2013.30166.

Planet. 2022. Planet explorer. PlanetScope & RapidEye daily satellite imagery. Available online at: https://www.planet.com/explorer/.

Raya, S., J. Singhb, G. Dasa and S. Panigrahyb. 2004. Use of high resolution remote sensing data for generating site-specific soil mangement plan. Red 550: 727.

Rodrigues, M.S. and J.E. Corá. 2015. Management zones using fuzzy clustering based on spatial-temporal variability of soil and corn yield. Engenharia Agrícola 35: 470-483. doi:10.1590/1809-4430-Eng.Agric.v35n3p470-483/2015

Rogovska, N. and A.M. Blackmer. 2009. Remote sensing of soybean canopy as a tool to map high pH, calcareous soils at field scale. Precision Agriculture 10: 175-187. doi:10.1007/s11119-008-9087-8.

Sánchez-Marañón, M. 2011. Color indices, relationship with soil characteristics. Encyclopedia of Agrophysics: 141-145. doi:10.1007/978-90-481-3585-1_237.

Schafer, W.M. 1979a. Variability of minesoils and natural soils in southeastern Montana. Soil Science Society of America Journal 43: 1207-1212. doi:10.2136/sssaj1979.03615995004300060031x.

Schafer, W.M. 1979b. Minesoil resources in the northern Great Plains: Characterization, evaluation and potential. PhD Diss. Montana State University-Bozeman, College of Agriculture.

Schoeneberger, P.J., D.A. Wysocki and E.C. Benham. 2012. Field book for describing and sampling soils, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Schroeder, P.D., W.L. Daniels and M.M. Alley. 2010. Chemical and physical properties of reconstructed mineral sand mine soils in southeastern Virginia. Soil Science 175: 2-9. doi:10.1097/SS.0b013e3181c78c53.

Segal, D. 1982. Theoretical basis for differentiation of ferric-iron bearing minerals, using landsat MSS data. Proceedings of Symposium for Remote Sensing of Environment, 2nd

Thematic Conference on Remote Sensing for Exploratory Geology, Fort Worth, TX: 949-951.

Shukla, M.K., R. Lal and D. VanLeeuwen. 2007. Spatial variability of aggregate-associated carbon and nitrogen contents in the reclaimed minesoils of eastern Ohio. Soil Science Society of America Journal 71: 1748. doi:10.2136/sssaj2006.0007.

Si, B.C. and R.E. Farrell. 2004. Scale-dependent relationship between wheat yield and topographic indices: A wavelet approach. Soil Science Society of America Journal 68: 577-587. doi:10.2136/sssaj2004.5770.

Simbahan, G., A. Dobermann and J. Ping. 2004. Screening yield monitor data improves grain yield maps. Agronomy Journal 96: 1091-1102. doi:10.2134/agronj2004.1091.

Soil Survey Staff. Natural Resources Conservation Service, United States Department of Agriculture. Official Soil Series Descriptions. Available online at: https://soilseries.sc.egov.usda.gov/OSD_Docs/O/ORANGEBURG.html (accessed 02 Jan. 2022).

Soil Survey Staff. 2014. Keys to soil taxonomy, 12th Ed. USDA-NRCS. US Gov. Print. Office, Washington, DC.

Stolt, M.H., J.C. Baker, T.W. Simpson, D.C. Martens, J.R. McKenna and J.R. Fulcher. 2001. Physical reconstruction of mine tailings after surface mining mineral sands from prime agricultural land. Soil Science 166: 29-37. doi:10.1097/00010694-200101000-00006.

Sudduth, K.A. and S.T. Drummond. 2007. Yield editor: Software for removing errors from crop yield maps. Agronomy Journal 99: 1471-1482. doi:10.2134/agronj2006.0326.

Thomason, W.E., S.B. Phillips and F.D. Raymond. 2007. Defining useful limits for spectral reflectance measures in corn. Journal of plant nutrition 30: 1263-1277. doi:10.1080/01904160701555176.

VanWormhoudt, A. 1993. Soil mineralogy of an upper coastal plain landscape in Virginia. M.S. Thesis. Virginia Tech. .

Vrindts, E., A.M. Mouazen, M. Reyniers, K. Maertens, M. Maleki, H. Ramon et al. 2005. Management zones based on correlation between soil compaction, yield and crop data. Biosystems Engineering 92: 419-428. doi:10.1016/j.biosystemseng.2005.08.010.

Wang, J., R. Yang and Y. Feng. 2017. Spatial variability of reconstructed soil properties and the optimization of sampling number for reclaimed land monitoring in an opencast coal mine. Arabian Journal of Geosciences 10: 1-13. doi:10.1007/s12517-017-2836-0.

Wick, A., W. Daniels, Z. Orndorff and M. Alley. 2013. Organic matter accumulation post-mineral sands mining. Soil Use and Management 29: 354-364. doi:10.1111/sum.12058.

Wilson, N., J. Greenberg, A. Jumpasut, A. Collison and H. Weichelt. 2017. Absolute radiometric calibration of planet dove satellites, flocks 2p & 2e. Planet: San Francisco, CA, USA.

Yang, C., J. Everitt, J. Bradford and D. Escobar. 2000. Mapping grain sorghum growth and yield variations using airborne multispectral digital imagery. Transactions of the ASAE 43: 1927. doi:10.13031/2013.3098.

Zhang, M., P. Hendley, D. Drost, M. O'Neill and S. Ustin. 1999. Corn and soybean yield indicators using remotely sensed vegetation index. Precision Agriculture: 1475-1481. doi:10.2134/1999.precisionagproc4.c49b.

Zhou, W., K. Yang, Z. Bai, H. Cheng and F. Liu. 2017. The development of topsoil properties under different reclaimed land uses in the pingshuo opencast coalmine of loess plateau of China. Ecological Engineering 100: 237-245. doi:10.1016/j.ecoleng.2016.12.028.

Zimmerman, C., C. Stilson and W.L. Daniels. 2008. Reclamation of mineral sands mine and topsoil replacement study. p. 1429-1446. In: Proceedings America Society of Mining and Reclamation. doi:10.21000/JASMR08011429.

6. Taxonomic Classification of Two Different Mine Soil Types in Virginia Using Current and Proposed *Soil Taxonomy* Criteria

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Abbreviations: HAHT, human-altered and human-transported materials; ICOMANTH, International Committee for Anthropogenic Soils; VA, Virginia; CEC, cation exchange capacity; HMS, heavy mineral sands; COPE, Controlled Overburden Placement Experiment; SiS, siltstone; SS, sandstone; sbk, subangular; gr, granular; sls, structureless.

6.1. Abstract

Anthropogenic soils are growing in number and extent across the world and there is a need to recognize and classify human-altered and human-transported (HAHT) materials for improved soil land use and management. The 12th Ed. Keys to Soil Taxonomy (2014) defined HAHT materials in one diagnostic epipedon, seven subgroups, and many family classes, including differentiating criteria within these categories. Artesols, a new proposed soil order, recognizes HAHT materials at the highest level in *Soil Taxonomy*. Here, I classified and interpreted two different types of mine soils on reclaimed coal and mineral sands mines in Virginia. My objective was to assess the strengths and weaknesses of existing taxons (2014 keys) vs. the proposed Artseols soil order criteria and to review changes over time. In 34+ year old coal mine soils, cambic (^Bw) horizons were widespread across pedons and they classified as Typic Eutrudepts based on existing taxa. Appropriate HAHT subgroups (e.g., Anthroportic) have not yet been developed for mine soils with cambic horizons in the 12th Ed. Keys to Soil Taxonomy even though they occur in both coal and mineral sands mine soils. Mineral sands mine soils without diagnostic ^Bw horizons classified as Anthroportic or Anthrodensic Udorthents according to existing taxa, both of which acknowledged HAHT materials. Current "spolic" and "dredgic" family classes characterized each mine soil based on disturbance type but have a broad interpretation. Within Artesols, most of these mine soils classified as Portortharts at the great group level followed by one of the following subgroups: Typic (no major limitation or feature), Inceptic (weak pedogenic development), or Anthrodensic (limiting soil property; densic materials). The "art" formative element offers room for the addition of important taxa related to HAHT materials at subsequent lower levels, and this order offers a much wider selection of subgroups based on soil limitations and pedogenic pathways (e.g., Sulfic, Inceptic). Overall, the Artesols criteria are more relevant and helpful in interpreting the use and management of reclaimed mine soils given the wider selection of subgroups. However, I recommend more specific family or subgroup level criteria regarding landform position, disturbance type, and depth class to limiting properties.

6.2. Introduction

Globally, anthropogenic soils are becoming increasingly recognized in different soil classification systems (Dazzi and Papa 2015). Some of the first national attempts at characterizing anthropogenic soils occurred on coal mine soils in Appalachia, with over 30 soil series created and several series proposed, along with the proposal of the "Spolic" subgroup representing human-made deposits following mining (Haering et al. 2005; Sencindiver 1977). Further, the World Reference Base, or WRB as discussed earlier, established the Anthrosol and Technosol soil orders, which differ based on various factors such as disturbance type and origin of materials, but both recognize soils significantly impacted by human activity (Food and Agriculture Organization of the United Nations 2014). In 2014, US *Soil Taxonomy* defined human-altered and human-transported (HAHT) materials and recognized them in one diagnostic epipedon, seven subgroups (see Table 2.1), and new family class options (Soil Survey Staff 2014). Additional terminology related to HAHT materials was added in 2014 and included constructional anthropogenic landforms (e.g., landfills, mounds, dumps), destructional anthropogenic landforms (e.g., cutbanks, dredged channels), constructional anthropogenic microfeatures (e.g., dikes, spoil piles), destructional anthropogenic microfeatures (e.g., scalped areas, ditches), artifacts (e.g., stone flakes, bricks, litter), manufactured layers and contacts. Proper classification, interpretation, and mapping of HAHT soils is crucial given the fact that these soils can profoundly affect land use and management, including potential impacts to human health and the environment (Howard 2017). Since the Keys to Soil Taxonomy (Soil Survey Staff 2014) were updated in 2014, the International Committee for Anthropogenic Soils (ICOMANTH) has recognized the need to include higher taxa for distinguishing HAHT materials. Thus, the Artesols soil order was proposed by ICOMANTH to improve the classification and interpretation of HAHT soils. Anthropogenic landforms include lands reclaimed following surface mining disturbances along with a range of urbanization, road building, and other significant and intentional impacts by humans (Howard 2017).

The primary purpose of a soil survey is to characterize and group soils based on diagnostic criteria (e.g., *Soil Taxonomy*) so that survey end users can properly map, interpret, and manage soil resources (Soil Survey Staff 1975). In regard to surface mined lands, soil classification and mapping require knowledge and understanding of the mining methods and reclamation processes,

which in part depends on various regional and site factors (Indorante and Jansen 1984; Wood and Pettry 1989). Previous efforts have been made to map coal mine soils in southwestern Virginia (VA) using the Sewell, Fiveblock, Kaymine, and Cedarcreek series concepts (all Typic Udorthents) for both pre- and post SMCRA mined lands (Haering et al. 2005). These were some of the earliest (1970s) series criteria developed on mined lands in the USA, and by 2000, there were 30 series approved nationally for coal mine soils (Sencindiver and Ammons 2000). The differentiating criteria between the above four soil series include reaction class, particle-size class, rock type, and color. Haering et al. (2005) mapped and classified ~450 ha of mined lands within the Powell River Project (https://powellriverproject.org/) area using earlier *Soil Taxonomy* criteria for the above established mine soil series to assess their effectiveness for mapping mine soils. A secondary objective was to reclassify pre-SMCRA mine soils mapped using a much older classification system. They found that mine soil pedon descriptions adequately fit within particle-size class, texture, and pH criteria for the existing series concepts, but drainage class, rock type, and color did not meet previously established series criteria. The authors discussed the importance of addressing common mine soil properties including mixed rock types, poorly to very poorly drained, densic materials and depth to densic contact, and subsurface tillage (ripping effects) as either new series or phases for mapping purposes. These mine soils were classified much prior to the newest edition of *Soil Taxonomy*; thus, it is important to reclassify soils as new changes or updates are made to diagnostic criteria. Currently, there are 12 soil series available that are directly applicable to Appalachian coal mined lands (Skousen et al. 2021).

Large areas of mine soils are also associated with heavy mineral sands (HMS), such as ilmenite, rutile, and zircon, which are surface mined from placer deposits in coastal regions across the world including Africa, Australia, and North America (Brooks 2000). Orndorff et al. (2005) classified thirteen profiles ranging from two to six years old, as Fluventic Dystrudepts, Typic Udifluvents, Typic Quartzipsamments, and Typic Udorthents with common contrasting texture classes at the family level. These profiles and other more recent detailed and sampled profiles ($n > 20$) had not been re-classified to date by the newer 2014 *Soil Taxonomy* criteria before this study. Native soils within and around HMS mines in VA consist of highly weathered sandy surface Coastal Plain soils overlying Piedmont saprolite and substrata materials. Common native pre-

mining soils in and around HMS mined lands in VA and NC have been previously classified according to *Soil Taxonomy* as Typic Kandiudults (Meredith et al. 2008) and Typic Hapludults and Typic or Plinthic Paleudults (Edmonds et al. 1989). Hodges et al. (1997) conducted a detailed soil survey in 1990 of pre-mining native soils in Dinwiddie County/Old Hickory deposit using aerial photobase maps flown at 1:12,000 scale. Dominant upland soil series for that mapping project included the Orangeburg series (fine-loamy, kaolinitic, thermic Typic Kandiudults), Varina series (fine, kaolinitic, thermic Plinthic Paleudults), and Dothan series (fine-loamy, kaolinitic, thermic Plinthic Kandiudults). While numerous mine soil morphological properties within soil pedons/auger borings have been described on HMS mined lands, there have only been two significant attempts at their classification (Meredith et al. 2008; Orndorff et al. 2005) and these results have not been published in journal form to date. These studies classified mineral sands mine soils using the 2003 (9^{th} edition) criteria into a mix of the following subgroups: Typic Udorthents, Typic Udifluvents, Typic Quartzipsamments, Typic Dystrudepts, and Fluventic Dystrudepts with strongly contrasting particle size classes at the family level.

Additionally, soil classification efforts and associated soil/crop management interpretations are particularly important for intensively managed land uses such as prime agricultural farmlands (Wood and Pettry 1989). Dunker and Barnhisel (2000) discussed the inadequacy of mine soil classification, especially on reclaimed prime farmlands or croplands in general which are highly valuable land resources. Thus, these post-mining agricultural landscapes must be described, classified, mapped, and interpreted in ways that are useful to future landowners and interests, and such management efforts should be based on the unique morphological properties resulting in part from the local mining and reclamation processes. Barnhisel and Gray (2000) assessed coal mine soil morphology after five years since reclamation on a prime farmland site in Kentucky and found improved structure in the ^Ap horizon, but little change in subsoil morphology. After 10 and 20 years, cambic (^Bw) horizons were described in the upper subsoil, moving these soil profiles into the Inceptisols order. The authors proposed a more suitable soil series and concluded that proper soil horizon replacement practices contributed to successful pathways of pedogenesis for these mine soils.

Mine soils on surface mined lands in VA have not been classified or reclassified using the newest version of Keys to Soil Taxonomy (12th edition; 2014). As such, there is a need to update their taxonomic placement to support more recent soil morphological and genesis-oriented studies so that appropriate changes and additions can be made to existing taxa. Further, soil series criteria have not been proposed for the mineral sands mining areas to date, even though mined or reclaimed lands comprise over 1,500 ha in VA alone. While there have been several series established on reclaimed coal mined lands in this study region (Appalachia), there has not been an update on the classification of coal mine soils in the literature since 2005. Also, there is an opportunity to evaluate new developments in *Soil Taxonomy*, such as the Artesols order, using recent morphological descriptions of mine soils to evaluate the effectiveness of existing vs. proposed taxa in characterizing and interpreting different mine soils. Hence, the main objective of this study was to classify/re-classify and interpret a range of reclaimed mine soil pedons in two very different surface mine environments (coal and mineral sands) in VA according to the following: 1) The original Keys to Soil Taxonomy (1st edition; 1983); 2) current criteria (12th edition keys), and 3) the new proposed Artesols soil order criteria.

6.3. Materials and Methods

6.3.1. Study Locations

Mine soil profile descriptions were selected from a range of pre-existing pedon studies on a coal mine site in southwestern VA (Chapters 3 and 4) and mineral sands mine sites in southeastern VA (Chapter 5). The general background for these mine study areas is thoroughly described in the previous chapters. Details regarding the specific sites and soil pedons used in this study are given below in Table 6.1. Coal mine soils (CMS) were described at the Controlled Overburden Placement Experiment (COPE) in Wise County, while the mineral sands mine (MSM) soils were described at the Iluka (company) Old Hickory and Concord HMS deposits in Dinwiddie/Sussex counties (Figure 6.1).

Table 6.1. Site history and details of the soil pedons selected for this study.

Soil ID	General Location	Site Lat. (y)	Site Long. (x)	No. of Pedons	Date of Description	Soil Age (yrs.)
CMS #1-8	COPE	37.0113	-82.6856	8	2016	~ 34
MSM #1-4	Old Hickory	36.9156	-77.5603	4	2014	~ 11
MSM #5-8	Concord	36.8986	-77.5696	4	2015	~ 5
MSM #9-12	Concord	36.8994	-77.5569	4	2021	~ 2

6.3.2. Previous Pedon Datasets

Coal mine soil pedons (CMS #1-8) were selected from the COPE, which was built in 1982 as a lithosequence involving different ratios of siltstone (SiS) and sandstone (SS) rocks (Daniels et al. 1983). For mineral sands mine soil pedons, we selected four profiles (MSM #1-4) described at the Carraway-Winn Research Farm (CWRF) in 2014 at the Old Hickory deposit (Meredith et al. 2008), which was an experiment installed to assess soil and crop differences between (i.e., 78 Mg ha^{-1} biosolids with and without tillage, control, and topsoil). We also selected four soil profiles (MSM #5-8) described in 2015 (Orndorff et al. 2015) and four profiles (MSM #9-12) recently described in 2021 at the Concord deposit. Previous data and descriptions for MSM #9-12 were also reported and discussed in detail in Chapter 5. MSM soils were selected for a greater number of pedons to capture the high variability that is commonly observed within and among mine sites.

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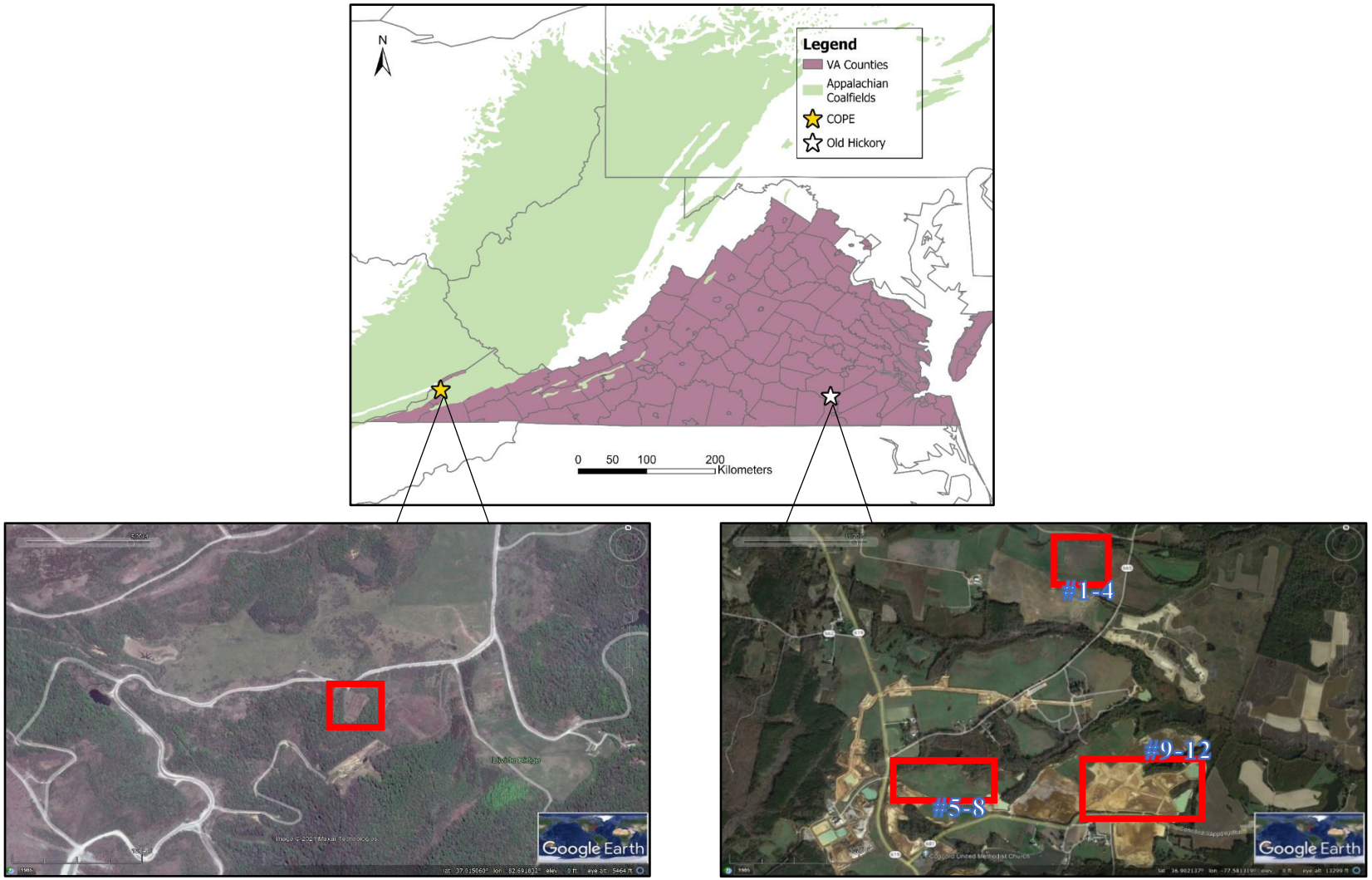


Figure 6.1. Geographic location of the main study areas (top). Satellite images (bottom) of the specific sites, including the COPE (2014 image; left side) and Old Hickory/Concord deposit (2015 image; right side). Note: MSM #1-8 were post final reclamation at that time.

6.3.3. Field and Laboratory Analyses

All selected mine soil pedons were classified or re-classified using the following taxonomic criteria: 1) The original 1st edition of the keys (Soil Management Support Services 1983); 2) current criteria of the keys (12th Ed.) (Soil Survey Staff 2014), and 3) the proposed Artesols soil order (received as a draft version from ICOMANTH). As a note, the caret (^) symbol was not used in *Soil Taxonomy* to denote horizons formed in HAHT materials prior to 2014. The particle-size control section for all pedons was defined via the current keys (12th Ed.) as 25 cm from the soil surface to either a depth of 100 cm or a root-limiting restrictive layer, if shallower. Soils were described using conventional Soil Survey Manual methods (Schoeneberger et al. 2012). Particle size distribution, where reported, was analyzed by the pipette method (Gee and Bauder 1986). The following soil properties were analyzed to meet the required reaction (pH) class, exchange capacity (CEC), and base saturation for certain taxonomic splits (Eutrudepts vs. Dystrudepts; 12th Ed. keys, see p. 187), and they represent our best available data for these taxonomic placements. All soil samples were analyzed for pH using a 1:1 soil:water slurry (McLean 1982). Soils were analyzed for effective CEC as the summation of bases (Ca, Mg, K, and Na) extracted by 1 *M* NH_4OAc (Thomas 1982), plus KCl-extractable Al (Barnhisel and Bertsch 1982). For the MSM #9-12 soils, CEC was determined by Mehlich I extractable bases (Ca, Mg, and K), plus soil-buffer acidity (H^+ and Al^{+3}) (Maguire and Heckendorn 2019) and was used as a general reference to the many other chemical datasets previously analyzed for MSM soils.

6.4. Results and Discussion

6.4.1. Coal Mine Soil Classification and Interpretation

Taxonomic placement according to the three versions of *Soil Taxonomy* criteria that we evaluated are given in Table 6.2 below and the associated descriptions and horizon data for classified CMS pedons are presented in Table 6.3. Much more detailed soil profile descriptions and images are given in Appendix A. Overall, these soils are typical of rock-derived mine soils in this region (Appalachia), with gravelly to very gravelly texture modifiers (i.e., > 15 or 35% rock fragments or skeletal) and low clay contents (< 18%) (Haering et al. 2005). On mined lands in this region, site specific factors (e.g., stratigraphy, topography, mining and reclamation method)

determine overall rock type and dominance within soil profiles, as well as other factors such as soil pH, drainage class, and slope classes. For these CMS, rock type was either dominantly one type (100% SS or SiS) or mixed but did not influence family level particle-size and reaction class (pH) across pedons. Despite the differences in rock type (parent material), taxonomic placement did not vary among the eight different pedons (Table 6.2) except for one pedon (MSM #4) due to the soil's lower base saturation (< 60%), which placed it into the "Dystrudepts" subgroup. However, most of these pedons are in the Eutrudepts subgroup due to their higher base saturation in these relatively unweathered soils. In the earliest edition of the Keys to Soil Taxonomy, these soils would be considered "Eutropepts", similar to Eutrudepts except that it does not include the "ud" formative element, indicating their udic soil moisture regime.

Currently, the mine soil map unit composition in the general area of the COPE predominantly includes the Kaymine-Fiveblock-Cedarcreek complex, 0 to 15% slopes, extremely stony, with a well-drained drainage class and mixture of rock types (Soil Survey Staff 2022). However, previous mine soil series mapping criteria does not capture the pedogenic development (^Bw; cambic) of these mine soils (Haering et al. 2005). Further, the densic materials noted in field descriptions and as detailed in Chapter 3 would clearly influence the taxonomy of these CMS (e.g., shallow depth, Anthrodensic; 12th edition), but ^Cd horizons were not designated at the time of their descriptions. We recognize the need for soil series mapping criteria that recognizes densic contacts common in HAHT soils, as well as relevant phases (e.g., ripped phases), as were proposed in previous mapping studies (e.g., Haering et al. 2005). While the current 12th Ed. Keys to Soil Taxonomy improved the recognition of HAHT soils as discussed earlier, these criteria only apply to the Entisols order. However, the next edition of the Keys to Soil Taxonomy will allow subgroup extragrades such as Anthroportic and Anthrodensic to be applied for all soil orders. The "spolic" family class was added for these CMS pedons via the 12th edition keys, indicating that these soils formed from human-transported materials, but do not indicate coal mining as the specific disturbance. Further, the Artesols proposed soil order clearly improves the interpretation of these CMS pedons at the subgroup level. Also, note that the soil moisture regime and soil temperature regime key out at the family level for Artesols. The great group is modified by "Inceptic", which recognizes that this mine soil is developing weak to moderate subsoil structure and indicating

pedogenic pathways, and "Anthroportic" signifies that at least 50 cm of human transported material was deposited.

Table 6.2. Coal mine soils (CMS) classified at the family level according to three *Soil Taxonomy* criteria (i.e., first edition Keys to Soil Taxonomy, current keys, and proposed order).

Original Plot	Pedon ID	1st Edition Keys	12th Edition Keys	Artesols Order
1 (SS†)	CMS 1	Loamy-skeletal, mixed, nonacid, mesic, Typic Eutropept	Loamy-skeletal, spolic, mixed, nonacid, mesic, Typic Eutrudept	Loamy-skeletal, spolic, mixed, nonacid, mesic, udic, Inceptic Portorthart
4 (SS)	CMS 2	Loamy-skeletal, mixed, nonacid, mesic, Typic Eutropept	Loamy-skeletal, spolic, mixed, nonacid, mesic, Typic Eutrudept	Loamy-skeletal, spolic, mixed, nonacid, mesic, udic, Inceptic Portorthart
26 (2:1 SS:SiS)	CMS 3	Loamy-skeletal, mixed, nonacid, mesic, Typic Eutropept	Loamy-skeletal, spolic, mixed, nonacid, mesic, Typic Eutrudept	Loamy-skeletal, spolic, mixed, nonacid, mesic, udic, Inceptic Portorthart
36 (2:1 SS:SiS)	CMS 4	Loamy-skeletal, mixed, nonacid, mesic, Typic Dystropept	Loamy-skeletal, spolic, mixed, nonacid, mesic, Typic Dystrudept	Loamy-skeletal, spolic, mixed, nonacid, mesic, udic, Inceptic Portorthart
2 (1:1 SS:SiS)	CMS 5	Loamy-skeletal, mixed, nonacid, mesic, Typic Eutropept	Loamy-skeletal, spolic, mixed, nonacid, mesic, Typic Eutrudept	Loamy-skeletal, spolic, mixed, nonacid, mesic, udic, Inceptic Portorthart
5 (1:1 SS:SiS)	CMS 6	Loamy-skeletal, mixed, nonacid, mesic, Typic Eutropept	Loamy-skeletal, spolic, mixed, nonacid, mesic, Typic Eutrudept	Loamy-skeletal, spolic, mixed, nonacid, mesic, udic, Inceptic Portorthart
9 (SiS)	CMS 7	Loamy-skeletal, mixed, nonacid, mesic, Typic Eutropept	Loamy-skeletal, spolic, mixed, nonacid, mesic, Typic Eutrudept	Loamy-skeletal, spolic, mixed, nonacid, mesic, udic, Inceptic Portorthart
15 (SiS)	CMS 8	Loamy-skeletal, mixed, nonacid, mesic, Typic Eutropept	Loamy-skeletal, spolic, mixed, nonacid, mesic, Typic Eutrudept	Loamy-skeletal, spolic, mixed, nonacid, mesic, udic, Inceptic Portorthart

† Plot number followed by treatment; SS=sandstone and SiS=siltstone.

Table 6.3. Eight coal mine soil (CMS) pedons from the Controlled Overburden Placement Experiment.

Original Plot	ID	Horizon	Depth	Color	Structure[‡]	RF[†]	Sand	Silt	Clay	Texture Class*		pH	CEC	BS[+]
			cm				%			Lab	Field		$cmol_c\ kg^{-1}$	%
1 (SS[#])	CMS 1	^A	0-9	10YR 3/2	2 gr	15	67.4	20.0	12.6	sl	l	5.5	6.5	100
		^Bw	9-29	10YR 4/4	1 sbk	36	69.8	17.9	12.3	sl	l	5.6	3.1	100
		^C1	29-65	10YR 3/4	0 sls	55	69.6	17.0	13.3	sl	l	6.8	3.5	100
		^C2	65-125+	10YR 4/2	0 sls	55	66.9	23.5	9.7	sl	l	7.4	3.9	100
4 (SS)	CMS 2	^A	0-7	10YR 3/2	2 gr	6	67.9	22.4	9.6	sl	l	5.7	5.0	100
		^BA	7-15	10YR 4/4	2 sbk	20	70.9	17.3	11.7	sl	sl	5.4	3.0	100
		^Bw	15-60	10YR 4/4	2 sbk	50	74.7	15.3	10.0	sl	sl	5.7	2.9	100
		^BC	60-97	10YR 4/4	1 sbk	40	71.5	16.8	11.7	sl	sl	6.3	2.7	100
		^C	97-125+	10YR 4/1	0 sls	35	37.6	39.4	23.1	l	cl	6.6	4.9	100
26 (2:1 SS:SiS)	CMS 3	^A	0-7	10YR 3/2	2 gr	30	56.7	31.0	12.3	sl	sil	5.3	5.1	100
		^Bw	19-39	10YR 3/3	1 sbk	55	58.3	29.1	12.6	sl	sl	7.0	3.4	100
		^C	39-125+	10YR 3/3	0 sls	65	62.2	25.7	12.1	sl	sl	7.8	14.2	37

Table 6.3. Continued.

36 (2:1 SS:SiS)	CMS 4	^A	0-10	10YR 3/2	2 gr	30	59.1	29.1	11.8	sl	l	5.3	12.0	36
		^BA	10-27	10YR 3/2	1 sbk	40	59.7	28.0	12.3	sl	sl	5.8	7.6	54
		^Bw	27-52	10YR 4/3	1 sbk	55	62.4	26.4	11.2	sl	sl	6.8	5.4	55
		^C	52-125+	10YR 4/4	0 sls	50	70.7	19.5	9.7	sl	sl	7.0	4.6	63
2 (1:1 SS:SiS)	CMS 5	^A	0-9	10YR 3/2	2 gr	15	57.8	28.3	13.9	sl	1	5.5	7.1	100
		^Bw	9-30	10YR 3/6	1 sbk	20	55.3	32.4	12.4	sl	1	6.4	4.2	100
		^C1	30-84	10YR 4/4	0 sls	65	69.9	19.3	10.8	sl	1	7.5	3.4	100
		^C2	84-125+	10YR 4/1	0 sls	50	65.2	22.9	12.0	sl	cl	7.5	4.0	100
5 (1:1 SS:SiS)	CMS 6	^A	0-9	10YR 3/2	2 gr	15	67.0	23.4	9.6	sl	sil	5.8	9.2	100
		^AB	9-19	10YR 3/4	1 sbk	23	63.2	24.6	12.2	sl	l	6.1	4.9	100
		^Bw	19-39	10YR 4/3	1 sbk	30	59.2	26.3	14.6	sl	l	7.4	4.1	100
		^BC	39-105	10YR 4/2	1 sbk	53	57.5	29.6	12.9	sl	cl	7.8	5.2	100
		^C	105-125+	10YR 4/4	0 sls	40	-	-	-	-	ls	-	-	-

Table 6.3. Continued.

9 (SiS)	CMS 7	^A	0-13	10YR 3/1	2 gr	10	36.9	48.7	14.5	sil/l	l	6.3	15.2	100
		^Bw	13-41	10YR 3/2	1 sbk	56	36.5	50.2	13.3	sil	cl	8.4	6.4	99
		^BC	41-75	10YR 3/2	1 sbk	68	29.3	55.7	15.0	sil	l	8.6	9.4	99
		^C	75-125+	10YR 3/2	0 sls	53	40.1	45.8	14.1	l	l	8.5	9.6	99
15 (SiS)	CMS 8	^A	0-12	10YR 3/2	2 gr	22	56.9	31.2	11.8	sl	sil	6.1	6.8	100
		^Bw	12-32	10YR 3/2	1 sbk	32	38.8	47.8	13.4	l	l	7.8	4.7	100
		^BC	32-58	10YR 4/2	1 sbk	45	35.8	50.6	13.6	sil	l	8.1	4.8	100
		^CB	58-86	10YR 4/1	1 sbk	75	28.8	55.2	16.0	sil	l	8.3	8.9	100
		^C	86-125+	10YR 4/2	0 sls	75	37.2	49.0	13.8	sil/l	cl	8.3	9.4	100

#Rock types for each plot in parenthesis; SS=sandstone and SiS=siltstone

łStructure type/grade abbreviations via Schoeneberger (2012)

†Rock Fragments

*Texture class for both laboratory particle size analysis and field textures; abbreviations via Schoeneberger (2012)

[+]BS=Base saturation

6.4.2. Mineral Sands Mine Soil Classification and Interpretation

Taxonomic placement for MSM soil pedons and associated descriptions and data are found in Tables 6.4 and 6.5, respectively. Images of MSM #1-8 are given in Figures 6.2 and 6.3, while MSM #9-12 images are in Appendix C1. Native soils (Hapludults and Paleudults) in the surrounding landscape commonly have sandy loam, loamy sand, and sandy clay loam surface textures and well-developed Bt and Btv horizons with moderate to strong subangular blocky structure. On the other hand, MSM soils often exhibit a variety of differing surface and subsurface morphological properties and contain densic materials with platy/massive structures (Orndorff et al. 2015). Cloddy structures shaped like subangular blocks with firm to very firm consistence have also been described, highlighting the impact of machinery on structure formation rather than in-situ subsoil aggregate formation (i.e., MSM #9-12 pedons). The MSM soil pedons had a wider array of classifications vs. CMS, particularly related to particle-size and reaction class at the family level due to diagnostic criteria. For example, several soils had pedogenic pathways indicated by one or more ^Bw (cambic) diagnostic horizons, while other pedons lacked significant subsoil pedogenesis, likely due to the presence of densic materials via grading impacts. Further, the "dredgic" family class was used for MSM soils via the current 2014 keys to indicate the presence of water-transported layers or horizons at least 50 cm thick, which comprised the entire pedon of these mine soils.

Similar to the CMS, subsoil development was only reflected in the Artesols classification at the subgroup level, while still identifying human-transported materials (e.g., Inceptic Portortharts). In previous work at these sites, MSM soil pedons at specific underlying mine landform positions related to the mining and reclamation process (pits and berms) exhibited different source materials–predominately slimes (fine textured), predominately tailings (coarse-textured), or a combination of both (mixed or layered), but results were not consistent (Orndorff et al. 2015). The "sandy" particle-size class indicated a berm located soil (see MSM #10) in one case, but not another (see MSM #9). Overall, straight tailings are not as common as soils with a mix or layering of materials, but in these cases, the "psamm" great group formative element would be used for a profile dominated by loamy fine sand or coarser textures (not observed in our study pedons). The "aniso" particle-size class would also indicate limitations caused by a pair of strongly

contrasting textures with a clear to abrupt boundary within the control section (see MSM #1). Overall, densic materials were the most common and limiting soil property in these soils, which would place them in a "shallow" depth class (i.e., root-limiting contact within 100 cm) at the family level for the 12th edition keys and for proposed Artesols.

Table 6.4. Mineral sands mine (MSM) soils classified at the family level according to three *Soil Taxonomy* criteria (i.e., first edition Keys to Soil Taxonomy, current keys, and proposed order).

Original Plot	Pedon ID	1st Edition Keys	12th Edition Keys	Artesols Order
101-4-Biosolids-No Till	MSM 1	Clayey over sandy, mixed, acid, thermic, Typic Dystropept	Clayey over sandy, aniso, dredgic, mixed, acid, thermic, Typic Dystrudept	Clayey over sandy, aniso, dredgic, mixed, acid, thermic, udic, Inceptic Portorthart
103-2-Control	MSM 2	Coarse-loamy, mixed, nonacid, thermic, Typic Udorthent	Coarse-loamy, dredgic, mixed, nonacid, thermic, Anthroportic Udorthent	Coarse-loamy, dredgic, mixed, nonacid, thermic, udic Typic Portorthart
203-3-Control	MSM 3	Coarse-loamy, mixed, acid, thermic, Typic Dystropept	Coarse-loamy, dredgic, mixed, acid, thermic, Typic Dystrudept	Coarse-loamy, dredgic, mixed, acid, thermic, udic, Inceptic Portorthart
303-2-Topsoil	MSM 4	Fine-loamy over sandy, mixed, nonacid, thermic, Typic Eutropept	Fine-loamy over sandy, dredgic mixed, nonacid, thermic, Typic Dystrudept	Fine-loamy over sandy, mixed, nonacid, thermic, udic, Inceptic Portorthart
ILR C1	MSM 5	Coarse-loamy, mixed, nonacid, thermic, Typic Udorthent	Coarse-loamy, dredgic, mixed, nonacid, thermic, shallow, Anthrodensic Udorthent	Coarse-loamy, dredgic, mixed, nonacid, thermic, shallow, udic, Anthrodensic Portorthart
ILR C3	MSM 6	Coarse-loamy, mixed, nonacid, thermic Typic Udorthent	Coarse-loamy, dredgic, mixed, nonacid, thermic Anthroportic Udorthent	Coarse-loamy, dredgic, mixed, nonacid, thermic, udic Typic Portorthart

Table 6.4. Continued.

ILR C4	MSM 7	Fine-loamy, mixed, nonacid, thermic, Typic Udorthent	Fine-loamy, dredgic, mixed, nonacid, thermic, shallow, Anthrodensic Udorthent	Fine-loamy, dredgic, mixed, nonacid, thermic, shallow, udic, Anthrodensic Portorthart
ILR C6	MSM 8	Fine-loamy, mixed, acid, thermic, Typic Udorthent	Fine-loamy, dredgic, mixed, acid, thermic, Anthroportic Udorthent	Fine-loamy, dredgic, mixed, acid, thermic, udic, Typic Portorthart
Berm 2-1	MSM 9	Fine-loamy, mixed, acid, thermic, Typic Udorthent	Fine-loamy, dredgic, mixed, acid, thermic, shallow, Anthrodensic Udorthent	Fine-loamy, dredgic, mixed, acid, thermic, shallow, udic, Anthrodensic Portorthart
Berm 2-5	MSM 10	Sandy, mixed, nonacid, thermic, Typic Udorthent	Sandy, dredgic, mixed, nonacid, thermic, shallow, Anthroportic Udorthent	Sandy, dredgic, mixed, nonacid, thermic, shallow, udic, Typic Portorthart
Pit 2-2N	MSM 11	Coarse-loamy, mixed, acid, thermic, Typic Udorthent	Coarse-loamy, dredgic, mixed, acid, thermic, shallow, Anthrodensic Udorthent	Coarse-loamy, dredgic, mixed, acid, thermic, shallow, udic, Anthrodensic Portorthart
Pit 2-5S	MSM 12	Fine-loamy, mixed, acid, thermic, Typic Udorthent	Fine-loamy, dredgic, mixed, acid, thermic, shallow, Anthrodensic Udorthent	Fine-loamy, dredgic, mixed, acid, thermic, shallow, udic, Anthrodensic Portorthart

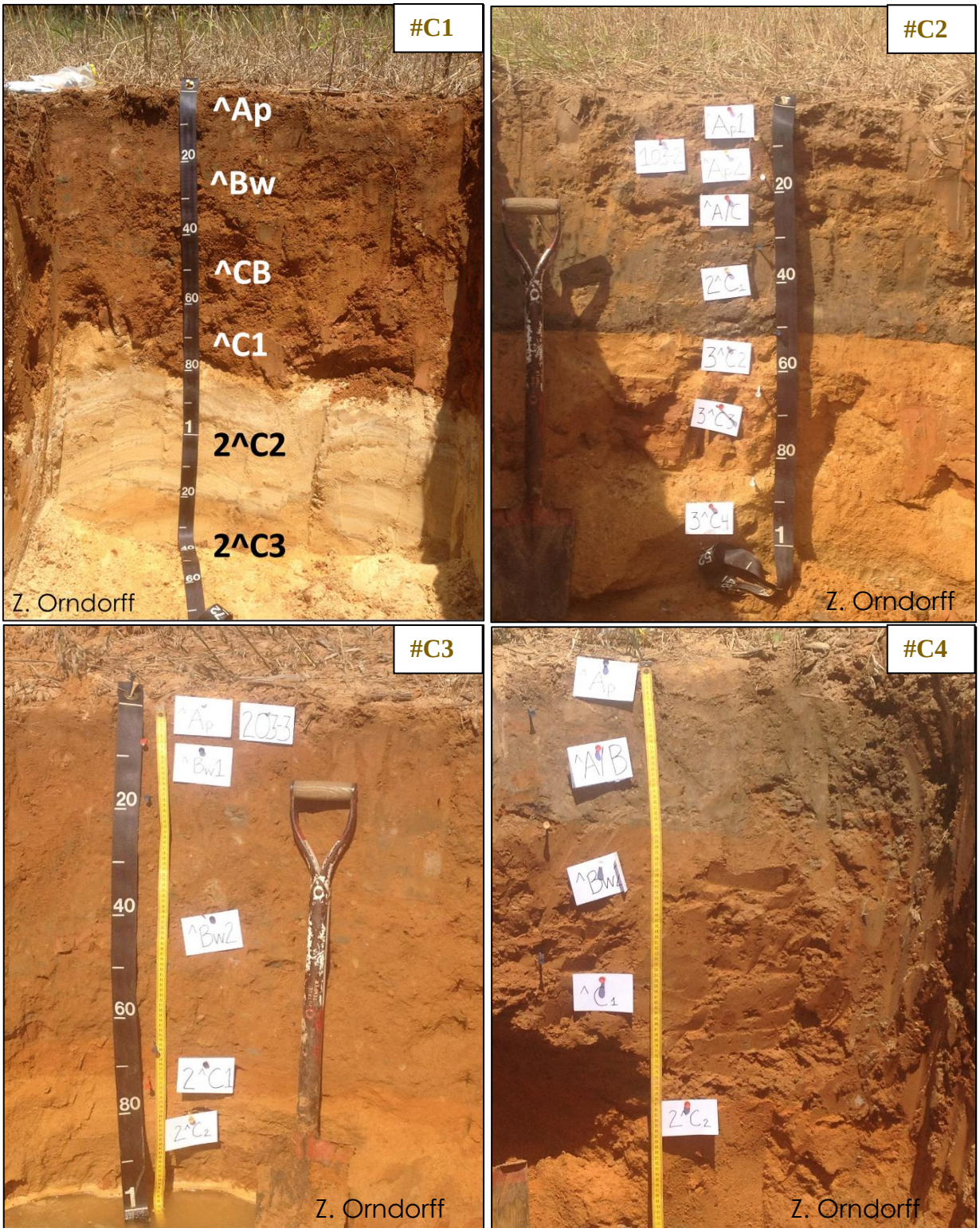


Figure 6.2. MSM #1-4 pedons at the Carraway-Winn Research Farm site in July 2014. Images by Zenah Orndorff used with permission.

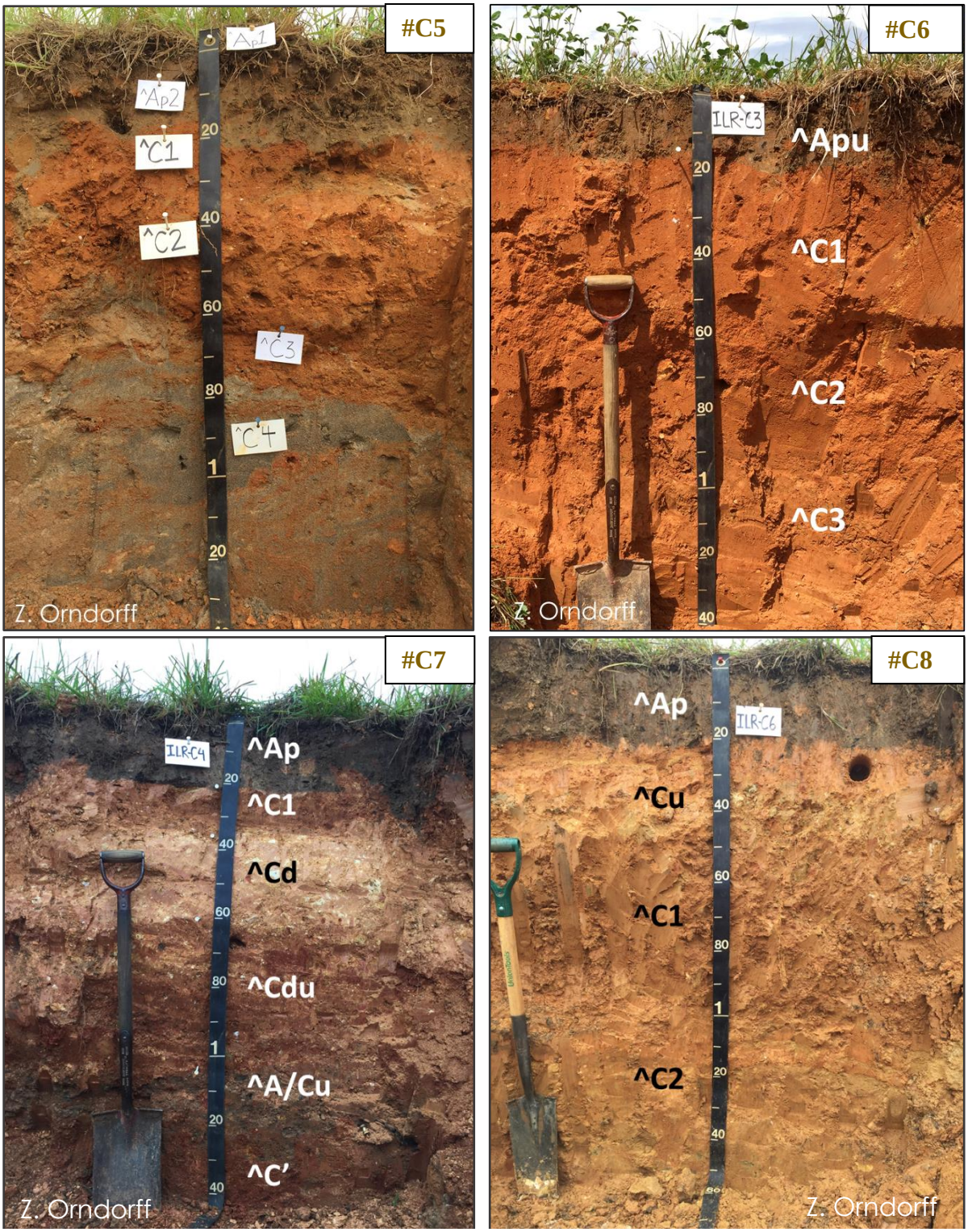


Figure 6.3. MSM #5-8 pedons at the Concord deposit in 2015. Images by Zenah Orndorff used with permission.

Table 6.5. Twelve mineral sands mine (MSM) soil pedons selected from three different sites at the Concord deposit.

Original Plot/ID	ID	Horizon	Depth	Color	Structure[ǂ]	Sand	Silt	Clay	Texture Class	Bulk Density	pH	CEC[†]	BS[+]
			cm				%			g cm^{-3}		cmol$_c$ kg^{-1}	%
101-4-Biosolids-No Till	MSM 1	^Ap	0-10	10YR 4/6	2 gr	64	12	24	scl	-	6.9	-	-
		^Bw	10-43	7.5YR 4/6	1 sbk	71	11	18	sl	-	6.5	3.2	62
		^CB	43-66	7.5YR 4/6	1 sbk	62	11	28	scl	-	4.9	3.6	39
		^C1	66-78	5YR 4/6	0 sls	16	24	60	c	-	5.0	7.5	40
		2^C2	78-120	2.5Y 7/4	0 sls	96	4	0	s	-	5.3	-	-
		2^C3	120+	10YR 5/8	0 sls	-	-	-	s	-	-	-	-
103-2-Control	MSM 2	^Ap1	0-8	10YR 4/4	2 gr	79	9	12	sl	-	6.1	-	-
		^Ap2	8-16	7.5YR 4/4	2 gr	80	8	12	sl	-	6.8	-	-
		^A/C	16-32	2.5Y 5/3	0 sls	79	10	12	sl	-	6.7	-	-
		2^C1	32-51	2.5Y 4/2	0 sls	79	6	15	sl	-	6.0	-	-
		3^C2	51-63	10YR 5/8	0 sls	89	3	8	ls/s	-	6.2	-	-
		3^C3	63-84	5YR 4/6	0 sls	10	20	70	c	-	5.0	-	-
		3^C4	84+	10YR 5/8	0 sls	97	2	1	s	-	5.9	-	-

Table 6.5. Continued.

203-3-Control	MSM 3	^Ap1	0-7	10YR 4/6	2 gr	71	10	19	sl	-	6.4	-	-
		^Bw1	7-17	7.5YR 4/6	1 sbk	72	9	19	sl	-	6.9	-	-
		^Bw2	17-66	7.5YR 4/6	1 sbk	70	13	17	sl	-	5.2	2.8	47
		2^C1	66-73	7.5YR 5/6	0 sls	81	6	13	sl	-	4.8	1.7	41
		2^C2	73-97	10YR 5/6	0 sls	96	2	2	s	-	4.9	-	-
		2^C3	97+	5YR 4/6	0 sls	16	16	68	c	-	4.9	-	-
303-2-Topsoil	MSM 4	^Ap	0-7	10YR 4/3	2 gr	70	16	14	sl	-	6.6	-	-
		^A/B	7-30	10YR 4/2	1 sbk	60	22	18	sl	-	7.1	5.5	85
		^Bw	30-53	7.5YR 4/6	1 sbk	68	8	24	scl	-	5.7	3.3	53
		^C1	53-83	7.5YR 4/6	0 sls	67	9	25	scl	-	4.9	3.1	45
		2^C2	83+	5YR 5/8	0 sls	91	4	5	s	-	5.0	-	-

Table 6.5. Continued.

ILR C1	MSM 5	^Ap1	0-3	7.5YR 4/3	1-2 gr	67	20	13	sl	-	6.8	-	-
		^Ap2	3-23	7.5YR 5/3	gr/sbk	64	23	13	sl	-	6.8	-	-
		^C	23-39	5YR 5/6	0 sls	72	13	15	sl	1.52	7.4	2.7	71
		^Cd	39-61	5YR 5/8	0 sls	60	21	19	sl	1.67	5.4	-	-
		^Cd/2C	61-75	5YR 5/8	0 sls	85	4	11	ls	-	5.2	-	-
		^2C	75-120+	N5-N7	0 sls	98	1	1	s	-	5.6	-	-
ILR C3	MSM 6	^Apu	0-16	10YR 4/3	gr/sbk	60	25	16	sl	-	6.6	-	-
		^C1	16-54	5YR 5/8	0 sls	77	11	12	sl	1.41	6.7	1.5	79
		^C2	54-87	5YR 5/8	0 sls	85	6	9	ls	-	5.1	1.1	41
		^C3	87+	5YR 6/6	0 sls	43	30	27	cl	-	5.2	4.2	33
ILR C4	MSM 7	^Ap	0-21	7.5YR 4/3	1-2 gr	68	19	13	sl	-	6.1	3.1	40
		^C1	21-33	5YR 6/8	0 sls	34	44	22	l	1.24	7.9	5.7	70
		^Cd	33-60	5YR 7/6	0 sls	23	53	24	sil	1.21	4.9	-	-
		^Cdu	60-104	2.5YR 4/8	0 sls	45	18	37	cl	-	5.2	-	-
		^A/Cu	104-124	10YR 5/4	0 sls	51	22	27	scl	-	5.6	-	-
		^C'	124-140+	10R 4/8	0 sls	34	21	45	c	-	5.1	-	-

Table 6.5. Continued.

ILR C6	MSM 8	^Ap	0-20	10YR 4/3	1-2 gr	64	23	13	sl	-	6.4	-	-
		^Cu	20-47	5YR 4/6	0 sls	33	42	25	l	1.42	5.5	3.1	44
		^C1	47-100	7.5YR 4/6	0 sls	30	25	45	c	1.38	5.1	6.4	27
		^C2	100+	7.5YR 4/6	0 sls	61	21	18	sl	-	5.1	-	-
Berm 2-1	MSM 9	^Ap	0-19	10YR 3/1	sbk*	-	-	-	scl	1.53	4.9	4.6	46
		^C	19-35	7.5YR 5/8	sbk	-	-	-	scl	1.54	7.2	9.0	100
		^Cd1	35-60	7.5YR 5/8	pl	-	-	-	scl	1.76	4.9	5.1	45
		2^Cd2	60-127	10YR 6/6	sls	-	-	-	sl	-	4.6	2.5	23
		2^C'	127-180+	10YR 6/6	sls	-	-	-	sl	-	4.4	2.5	19
Berm 2-5	MSM 10	^Ap	0-17	10YR 4/2	sbk	-	-	-	sl	1.62	5.9	4.2	79
		^C1	17-31	10YR 7/8	sls	-	-	-	ls	1.47	7.4	2.2	100
		^C2	31-59	10YR 7/6	sls	-	-	-	ls	-	4.9	0.8	50
		^C3	59-108	10YR 6/8	sls	-	-	-	sl/ls	1.54	4.6	0.5	74
		^C4	108-170+	10YR 7/4	sls	-	-	-	ls	-	4.5	0.3	83

Table 6.5. Continued.

Pit 2-2N	MSM 11	^Ap	0-22	10YR 4/2	sbk	-	-	-	sl	1.57	6.4	3.3	99
		^Cd	22-63	5YR 5/6	pl	-	-	-	scl	1.57	5.2	3.5	69
		^C1	63-81	10YR 6/6	sls	-	-	-	ls	1.41	5.4	1.3	97
		^C2	81-119	7.5YR 5/6	sls	-	-	-	scl	-	5.0	3.4	55
		^C3	119-130	10YR 5/6	sls	-	-	-	sic	-	5.1	6.5	55
		^C4	130-200+	7.5YR 6/8	sls	-	-	-	s	-	5.5	0.7	98
Pit 2-5S	MSM 12	^Ap	0-18	10YR 4/2	sbk	-	-	-	ls	1.57	5.8	2.3	84
		^C	18-42	7.5YR 5/6	sbk	-	-	-	scl	1.50	7.5	4.7	100
		^Cd	42-67	7.5YR 5/6	pl	-	-	-	scl	1.58	4.9	3.6	47
		^C'1	67-125	7.5YR 5/8	sls	-	-	-	ls	-	5.2	2.1	63
		^C'2	125-200+	10YR 7/6	sls	-	-	-	s	-	5.2	0.3	95

ŧStructure type/grade abbreviations via Schoeneberger (2012)
†CEC=cation exchange capacity
⁺BS=Base saturation
*Structure grades not recorded for MSM #9-12

6.5. Summary and Conclusions

Both coal and mineral sands mine soils are a product of drastic disturbance and anthropogenic material transport (either wet or dry) and contain many of the diagnostic characteristics described above. For example, as previously discussed in Chapter 5, mineral sands mine soils are reclaimed in rectangular mine cells where separated non-economic soil waste materials (e.g., slimes + tailings) are dewatered in pits surrounded by constructed walls or berms. Following reclamation of the final surface, unique features have been observed that are evidently created by the dewatering and reclamation processes (Meredith et al. 2008; Orndorff et al. 2005). These features include but are not limited to contrasting textural materials, very thick cloddy and platy structures, and one or more densic contacts. Appalachian coal mine soils are hard rock-derived from local sandstone and/or siltstone rock strata, and are fundamentally different than MSM sediment derived mine soils. However, at the family level, CMS and MSM pedons had similar classifications and interpretations up until the current edition (12^{th}) of Soil Taxonomy, which added diagnostic criteria for HAHT soils (e.g., Anthroportic and Anthrodensic subgroups). These HAHT related taxa improved the potential for overall soil interpretations compared to the original *Soil Taxonomy* keys edition (1^{st}), which did not recognize anthropogenic soils at any level, but still retained many family-level criteria such as particle-size classes, etc. The original taxa also did not recognize "densic" materials and link them with the "shallow" depth class restrictions until much later.

The proposed Artesols order further improves mine soil classification at the subgroup level in several ways. First, the "art" order formative element immediately conveys to survey users that the soil was formed in HAHT materials, allowing more specific information to be added at subsequent lower levels. The suborder formative element conveys information regarding the soil's physical condition and the great group categories reflect important HAHT materials. For our mine soils, the "orth" suborder formative element groups all other soils with 50 cm or more of HAHT materials, and the "port" great group formative elements refers specifically to human-transported materials. Additionally, there is a much greater range of selection for subgroups within this new order (e.g., Anthrodensic, Inceptic, Typic, Aquic, Sulfic). While both the 12^{th} edition keys and Artesols order criteria improved the interpretation of mine soils at the family level since the

inception of *Soil Taxonomy* (e.g., spolic and dredgic family classes), there should be more specific mapping criteria to help soil survey users determine limiting or unique properties related to the previous mining activity. On coal mined lands, taxonomic placement does not capture differences in rock types at the family level. While rock type affects soil properties such as texture and certain chemical properties, both in the short and long-term (see Chapter 3), the family level classification does not capture these differences because they largely do not affect land use interpretations. Since we do not know how rock type will influence long-term use and management as pedogenesis proceeds, series or higher-level criteria should be developed to include these specific CMS based on their dominant or mixed rock type. Previous mine soil series have included dominant rock types (Skousen et al. 2021), but only at that level (series) and additional updates are needed following our most recent COPE work. Further, given the complexity and short-range variability of reclaimed mine soils, mapping efforts should utilize larger and more detailed map scales (e.g., ≤ 1:12,000) when possible. Active mine aerial imagery would also be valuable for delineating map phases related to the HMS mining and reclamation process, such as pit vs. berm areas, or simply as a tool for soil survey ground mapping work. As discussed earlier and in Chapter 5, soils on pit vs. berm positions varied in terms of control section pH, presence of densic materials, and particle-size classes. Soil differences may in part be due to differences in soil reconstruction protocols and management (e.g., liming, ripping, machinery use/timing). Thus, mapping efforts and taxonomic unit development would likely need to be site-specific for these reclaimed lands.

For both coal and mineral sands mine soils, pedogenic pathways (e.g., cambic ^Bw horizons) were recognized in the 12th edition keys and Artesols order, but the current 2014 keys do not include HAHT subgroups within the Inceptisols order at this time. Thus, Artesols is more effective at acknowledging the genesis of these mine soils. However, since the next keys (13th edition) will supposedly include the HAHT subgroup extragrades for all soil orders including Inceptisols, the interpretation of a given soil's taxonomic placement at the family level will essentially be the same between the current system and Artesols. The main difference, however, is that Artseols conveys HAHT materials at the highest level (order), making space for other relevant taxa at lower levels of the keys. Given this foundation, there is an opportunity to build upon taxa related to the specific disturbance type and its associated limitations (e.g., poor internal

drainage, mechanical compaction) over time. To modify the Portorthart subgroups, Anthrodensic is appropriate for many of these MSM soils, which commonly had one or more densic contacts within 100 cm of the soil surface. Other limiting factors included strongly contrasting particle-size classes for the MSM soils and high percentage of rock fragments in CMS, both of which were addressed at the family level well before the current keys HAHT criteria. For both types of mine soils, densic contacts are either present or absent altogether and are the most extreme land use limitation posed by reclaimed mine soils. Since the depth to first densic contact varies widely among pedons, particularly for MSM soils, it is crucial to recognize and properly categorize a range of different depth classes to an "Anthrodensic" contact, ideally at the family level.

6.6. Acknowledgements

We thank Dr. John Galbraith for sharing the draft of the proposed Artesols order, which has been approved for inclusion in *Soil Taxonomy* after further refinement. Thank you to Athena Tilley, Sara Klopf, and Kelly Meredith, who assisted in the soil profile descriptions, data collection and processing, and laboratory analyses. Also, thanks to the COPE funders and previous researchers, especially Dan Johnson and Kathryn Haering.

6.7. References

Barnhisel, R. and P.M. Bertsch. 1982. Aluminum. p. 275-300. In: Methods of Soil Analysis. Part 2. 2nd ed. Chemical and Microbiological Properties. ASA and SSSA, Madison, WI.

Barnhisel, R. and R. Gray. 2000. Changes in morphological properties of a prime land soil reclaimed in 1979. p. 511-519. In: Proceedings of the 2000 Annual Meeting of the American Society for Surface Mining and Reclamation, Tampa, Fl. Amer. Soc. Surf. Mining Rec. doi:10.21000/JASMR00010511.

Brooks, D.R. 2000. Reclamation of lands disturbed by mining of heavy minerals. p 725-754. In: R.I Barnhisel, R.G. Darmody, W.L. Daniels (eds). Reclamation of Drastically Disturbed Lands. Agron. Monogr. 41. ASA and SSSA, Madison, WI.

Daniels, W.L., J.C. Bell, D.F. Amos and G.D. McCart. 1983. First year effects of rock type and surface treatments on mine soil properties and plant growth. p. 275-282. In: Proc

Symposium on Surface Mining, Hydrology, Sedimentology and Reclamation, November, College of Engineering, University of Kentucky, Lexington KY.

Dazzi, C. and G.L. Papa. 2015. Anthropogenic soils: general aspects and features. Ecocycles 1: 3-8. doi:10.19040/ecocycles.v1i1.23.

Dunker, R. and R. Barnhisel. 2000. Cropland reclamation. p. 323-369. In: Reclamation of Drastically Disturbed Lands. American Society of Agronomy.

Edmonds, W., R. J. Straw, C.D. Peacock, A.C. Blackburn, W.F. Kitchel, V.M.Owen et al. 1989. Soil survey of Greensville County, Virginia. Virginia Polytechnic Institute and State University, USDA-SCS. U.S. Govt. Print. Office,Washington, DC.

Food and Agriculture Organization of the United Nations. 2014. World reference base for soil resources. 2nd Ed. World Soil Resources Reports 106. FAO Rome, Italy. p 193.

Gee, G.W. and J.W. Bauder. 1986. Particle-size analysis. p. 383-411. In: A. Klute (ed.) Methods of Soil Analysis. Part I. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI. doi:10.1002/gea.3340050110

Haering, K.C., W.L. Daniels and J.M. Galbraith. 2005. Mapping and classification of southwest Virginia mine soils. Soil Science Society of America Journal 69: 463-472. doi:10.2136/sssaj2005.0463.

Hodges, R., W. Daniels, P. Thomas and M. Genthner. 1997. Soil survey of Old Hickory Project area. Crop and Soil Env. Sci. Dept., Virginia Tech, Blacksburg, VA.

Howard, J. 2017. Anthropogenic soils. Progress in Soil Science. Springer International Publishing 231. doi:10.1007/978-3-319-54331-4.

Indorante, S.J. and I.J. Jansen. 1984. Perceiving and defining soils on disturbed land. Soil Science Society of America Journal 48: 1334-1337. doi:10.2136/sssaj1984.03615995004800060027x.

Maguire, R. and S. Heckendorn. 2019. Laboratory procedures: Virginia Tech soil testing and plant analysis laboratory. Publication 452-881. Virginia Cooperative Extension. p. 16.

McLean, E.O. 1982. Soil pH and lime requirement. p. 199-223. In: A. Klute (ed.) Methods of Soil Analysis, Part 2. 2nd ed. Madison, WI.

Meredith, K., W. Daniels, Z. Orndorff, M. Alley and C. Teutsch. 2008. The influence of soil reconstruction techniques on mineral sands mine soils in Virginia. p. 700-719. In: R.I. Barnhisel (Ed.), Proc., 2008 Nat. Meeting Amer. Soc. Mining and Reclamation, Richmond, VA, June 14-19. Published by ASMR, 3134 Montavesta Rd., Lexington, KY. doi:10.21000/JASMR08010700.

Orndorff, Z., W. Lee Daniels, S. Koropchak, P. Donovan and M. Reiter. 2015. Reclamation of mineral sands mining: Annual research report. Submitted to Iluka Mineral Resources. p. 112.

Orndorff, Z.W., W.L. Daniels and J.M. Galbraith. 2005. Properties and classification of mineral sands mine soils in southeastern Virginia. In: R.I. Barnhisel (Ed.), Proc., 2005 Nat. Meeting Amer. Soc. Mining and Reclamation, Breckenridge, CO, June 19-23. Published by ASMR, 3134 Montavesta Rd., Lexington, KY, 40502. doi: 10.21000/JASMR05010842.

Orndorff, Z.W., W.L. Daniels, K. Sara, D. Patricia and K. Haering. 2015. Reclamation of Mineral Sands Mining: Annual Research Report. Submitted to Iluka Mineral Resources.

Schoeneberger, P.J., D.A. Wysocki and E.C. Benham. 2012. Field book for describing and sampling soils, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Sencindiver, J.C. 1977. Classification and genesis of minesoils. Ph.D. Diss. West Virginia Univ., Morgantown (Univ. Micro. 77-22 746).

Sencindiver, J.C. and J.T. Ammons. 2000. Minesoil genesis and classification. In: R. I. Barnhisel, R. G. Darmody and W. L. Daniels, (eds.), p. 595-613. Reclamation of Drastically Disturbed Lands. ASA, CSSA, SSSA, Madison, WI.

Skousen, J.G., W.L. Daniels and C.E. Zipper. Soils on Appalachian coal-mined lands. 2021. In: C.E. Zipper and J.G. Skousen (eds.), p. 85-110. Appalachia's Coal-Mined Landscapes, Resources and Communities in a New Energy Era. Springer Nature. 351 p. doi:10.1007/978-3-030-57780-3.

Soil Management Support Services. 1983. Keys to soil taxonomy. Technical Monograph No. 6. US Dept of Agriculture.

Soil Survey Staff. Natural Resources Conservation Service, United States Department of Agriculture. Web soil survey. Available online at: https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed 05 Apr. 2022).

Soil Survey Staff. 1975. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. Soil Conservation Service USDA. Agricultural Handbook No. 436.US Government Printing Office.

Soil Survey Staff. 2014. Keys to soil taxonomy, 12th Ed. USDA-NRCS. US Gov. Print. Office, Washington, DC.

Thomas, G. 1982. Exchangeable cations. p. 159-165. In: Method of Soil Analysis. Part 2. 2nd ed. Agronomy Monograph 9. ASA and SSSA, Madison, WI. doi:10.1002/gea.3340050110

Wood, C. and D. Pettry. 1989. Initial pedogenic progression in a drastically disturbed prime farmland soil. Soil Science 147: 196-207. doi:10.1097/00010694-198903000-00006.

7. Overall Discussion and Conclusions

This research program involved two very different post-mining landscapes in VA, but both mining environments – Appalachian coal mines and mineral sands mines in the Upper Coastal Plain – require a complete analysis of the resulting mine soils to accurately predict reclamation success and fully understand land management implications. In each setting, documenting soil genesis is an important assessment since it gauges the rate of ecosystem recovery through structural development and other pedogenic processes but is particularly important for the relatively unweathered rock-derived coal mine soils (SW VA) that I studied in the long-standing Controlled Overburden Placement Experiment (COPE). For the mineral sands mine soil studies (SE VA), the high degree of short-range spatial variation is one of the primary concerns and must be considered when mapping, interpreting, and managing these reclaimed lands, which are often converted back into rowcrop production given their historical land use (i.e., prime farmlands). In both instances, taxonomic classifications should hopefully characterize, define, and interpret their relative suitability and limitations so that differing post-mining land uses (e.g., forestry, rowcrop agriculture, wetlands, hayland/pasture, urban development) can be managed appropriately over the long-term.

The first two studies in the combined COPE assessed long-term (0 to 34 years) soil properties in three different sandstone (SS) and siltstone (SiS) coal mine rock spoil mixtures (RM experiment), as well as a range of surface amendments (topsoil, biosolids, sawdust) applied to a uniform 2:1 SS:SiS mix (SA experiment). Various hard rock spoil mixes are commonly used as the mine soil growth medium, but there is a lack of knowledge on how they weather and equilibrate over more extended periods of time (e.g., > 5 years). In both experiments, significant morphological transformations were obvious after 34 years of weathering across spoil types, including the development of transitional (e.g., ^BA, ^BC) horizons, diagnostic cambic (^Bw) horizons indicating pedogenic pathways, and root-limiting densic contacts in lower ^B/^C horizons. Both amended and non-amended mine soils dropped in subsurface EC over time but maintained levels in their ^A horizons likely due to plant cycling of cations and other elements. Across rock types (RM experiment), overall temporal changes for surface soil properties were

observed for pH (decreased), CEC (increased), Fe-oxides (increased), extractable P (decreased), sand (decreased), and silt + clay (increased). Rock type had a greater impact on surface soil texture than on soil chemical properties, which converged among rock types over time due to physical weathering, leaching, and organic matter accumulation (e.g., litter and rooting additions). However, chemical properties were more stable over time in the subsoil, particularly for pH, which remained much higher in the SiS vs. SS soils. In the SA experiment, the organic amendments (sawdust and biosolids) imparted a somewhat thicker and darker ^A horizon vs. the control and topsoil treatments. Overall, addition of surface amendments did not contribute to major soil-related benefits over the long-term when compared to the control, but our data indicates that biosolids were more effective at supplying soil nutrients (i.e., extractable P and total-N) over this period. Soil carbon (C) sequestration rates were lower than expected, not influenced by rock types or surface amendments, and ranged from 0.16 to 0.28 Mg ha yr^{-1} across both experiments. Land use interpretations for these mine soils are not necessarily impacted by different original spoil rock types or surface amendments. However, densic contacts were commonly observed across both experiments and may pose land use concerns (e.g., rooting restrictions, poor internal drainage) over additional periods of time. While our study did not directly assess aboveground productivity, future work should focus on how long-term changes in soil properties translate to productivity potentials since many important chemical properties were comparable, at least in the surface soil, after this 34-year time frame.

In contrast, the mineral sands mine soils study did not have a longer-term pedogenesis component like the COPE, but I focused my work on mine soil morphological properties across the underlying mining derived landforms (i.e., pit vs. berm positions) to relate observed short-range variability to the land reconstruction process. Generally, soil profiles exhibited somewhat contrasting characteristics at different surficial positions with former mine pit centers containing more mixed and/or layered materials, i.e., slimes (fine-textured) and tailings (coarse-textured), while former enclosing berms were composed of sandier materials, but some included a mixed slimes/tailings capping. Other properties such as depth to densic contact (^Cd) were common in soils among both pit and berm positions. Regardless of differences related to former pit vs. berm locations during active mining, these reconstructed mine soils are highly variable over very short

distances both vertically and laterally which needs to be accounted for in the development of land use interpretations.

Since intensive rowcrop production on post-mining mineral sands areas is desired by many landowners, we also correlated remotely sensed variables with crop yields at five older (9 to 14 years) reclaimed rowcrop sites to better understand drivers of yield variation. The best correlations with GPS-monitored yields were for vegetation indices (generally positive strong for NDVI) and the coloration and iron oxide spectral indices (generally negative moderate for both) derived from bare soil imagery. Relative elevation was correlated with yield to a lesser extent and that correlation was inconsistent among fields, likely due to the lower resolution data used coupled with the generally flat to slightly sloping landscapes. Also, vegetation and bare soil features were directly related to underlying mining influences. Berm soil positions supported better productivity on three out of five fields assessed. Pit soil positions appeared redder (slimes) and darker (wet) in color, and possibly a combination of both in certain areas (exposed slimes with wet conditions). Since our yield prediction results were not highly consistent across fields, future efforts to understand soil related drivers of yield variation should be addressed on a site-by-site basis via gridded soil sampling. Additionally, we found that soybeans in 2020 only had a 6.8% yield reduction when compared to nearby unmined yields, and reclaimed land crop yields were numerically similar to long-term county yield averages for most soils. This was surprising given the estimated yield reductions (~25%) in previous work on similar regional reclaimed mined lands (Daniels et al. 2018) and speaks to the improvements made in land reconstruction protocols over time coupled with proper agricultural post-mining practices such as deep tillage. Understanding how a given site's mine soils and inherent variability may affect crop productivity potentials will ultimately help landowners optimize land use decisions and management practices.

To better interconnect major conclusions from the above two studies, we applied previous, existing, and proposed *Soil Taxonomy* criteria to both sites since these studies increase the amount of useful information available regarding mine soils. Currently, the growing rate and occurrence of anthropogenic disturbances and resulting soils greatly exceeds efforts for their full characterization and taxonomic classification. Fortunately, the existing taxa in Keys to Soil Taxonomy (12^{th} edition) were updated in 2014 to include human-altered and human-transported

(HAHT) materials, including seven subgroups (e.g., Anthroportic, Anthrodensic) and new family class options (e.g., spolic, dredgic). The 34-year-old coal mine soils, when classified to the 2014 criteria (current taxa), were essentially all Typic Eutrudepts. However, the much more variable mineral sands pedons ranged from Anthrodensic and Anthroportic Udorthents to Typic Dystrudepts based on current taxa. Additionally, the absence of HAHT subgroups in the Inceptisols order (2014 criteria) was a problem since many of these reclaimed soils contained diagnostic cambic (^Bw) horizons. However, future editions of the Keys to Soil Taxonomy will include the Artesols soil order and HAHT criteria.

The proposed Artesols order provides a much higher level of information regarding anthropogenic soils with an opportunity to add specific soil and landform features at lower levels. While the Artesols order criteria utilize the existing HAHT subgroups, they also include a much wider selection, most importantly the "Inceptic" subgroup to acknowledge mine soils with weak subsoil development (cambic; ^Bw). At the family level, family classes are added to convey the nature of disturbance – for coal mines this is "spolic" or human-transported and for mineral sands this is "dredgic" or water-transported. The major land-use limitation for these two mine soils is related to densic contacts. As noted in the mineral sands studies, depth to densic contact ranged across soilscapes, but most of these soils would be classified as Anthrodensic at the subgroup level. Additionally, in the case of the coal mine soils, densic contacts were often noted within 100 cm of the soil surface, but most also contained diagnostic cambic horizons. Thus, options for Anthrodensic depth classes should be considered at the family-level, especially since some applicable subgroups (e.g., Inceptic) may also include densic contacts. Updated criteria on drainage classes due to perched layers resulting from soil compaction or abrupt textural changes would be necessary for some particularly troublesome Anthrodensic soils. As fundamental changes in *Soil Taxonomy* occur over time, such as the incorporation of the proposed Artesols order, information on how mine soils vary spatially and develop over time would hopefully be updated and added to lower taxonomic categories to improve land-use interpretations and applications.

Overall, coal and mineral sands mine soils are both clearly limited by their physical attributes (e.g., rock content and/or high soil bulk density), and in the case of mineral sands mine

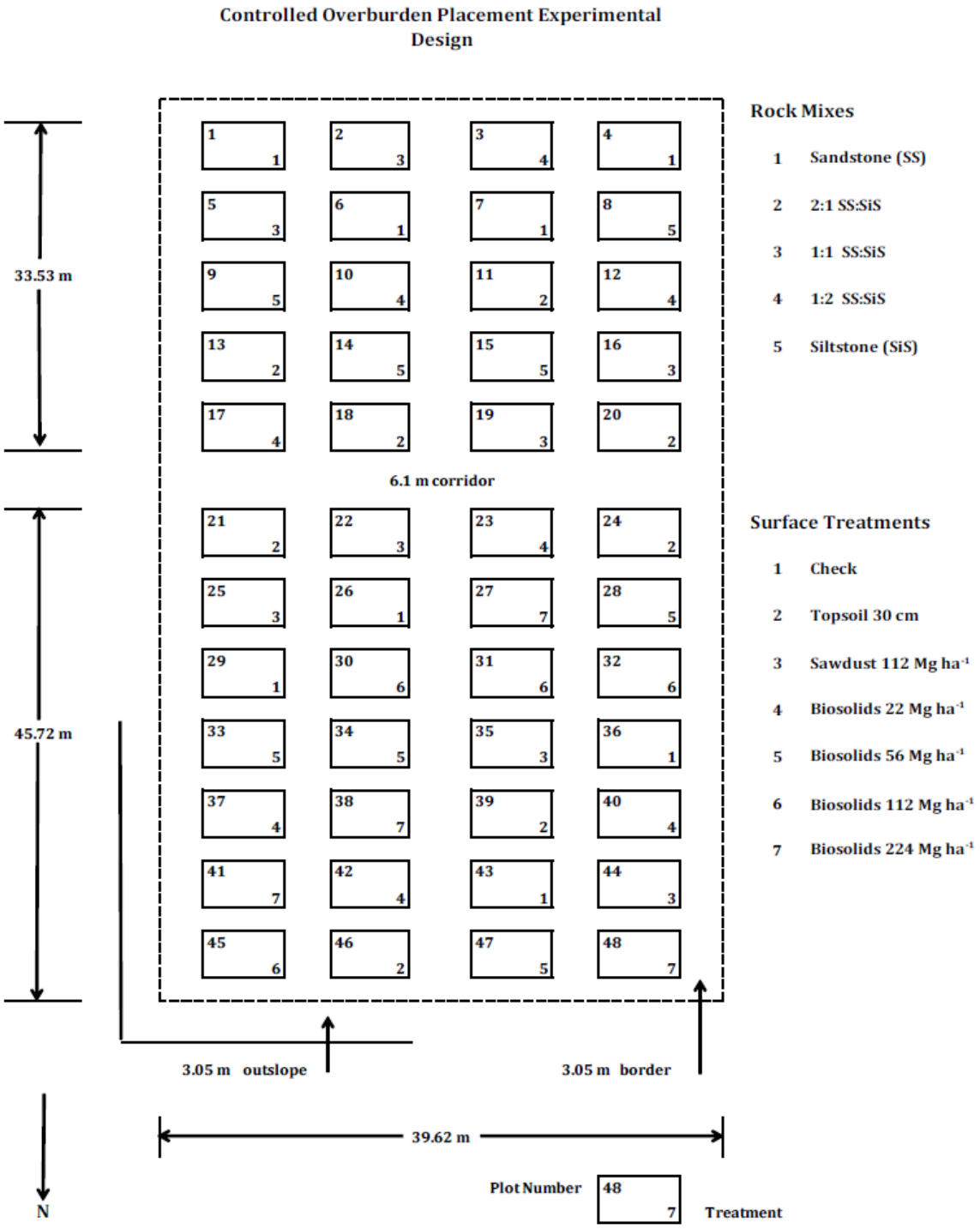
soils, are further complicated by their short-range variability which would complicate standard resolution (1:24,000) soil mapping and interpretation efforts. Much longer time periods are needed in terms of rock-derived coal mine soils to determine how limiting soil properties (e.g., pedogenic compacted layers) persist or change over time, and if SS/SiS rock type is a contributing factor to the suitability of certain land uses (e.g., forestry). These combined studies also point out how different these two different types of mine soils are although they are somewhat similar taxonomically.

7.1. References

Daniels, W.L., Z. Orndorff, C. Stilson, C. Zimmerman, and A. Haywood. 2018. Development of effective rehabilitation protocols for mineral sands mining in Virginia, USA. p. 127 – 133 In: From start to finish: A life-of-mine perspective. Spectrum Series 24. The Australasian Institute of Mining and Metallurgy, Carlton, Victoria, Australia. https://www.ausimm.com/publications/spectrum-series/from-start-to-finish-life-of-mine-perspective/

APPENDICES

Appendix A1: Plot Layout for the Controlled Overburden Placement Experiment (COPE) (RCBD; n=4) in Wise County, Virginia.



Appendix A2: Historical Profile Descriptions at the COPE. Note: The caret (^) symbol was not added until 2014.

1983 Profile Descriptions

Treatment: Pure Sandstone
Plot number: CP4
Date: 5/25/83

A 0-8 cm; dark brown (10YR 4/3 moist) loam; weak, fine to medium subangular blocky structure; very friable; many very fine and common fine roots; clear smooth boundary.

C 8-40+ cm; dark brown (10YR 4/3 moist) loam; structureless, massive; friable; common very fine and few fine roots to 40 cm with some to 60 cm.

Comments: Surface horizon delineated primarily on loosening and aggregation. Weak peds were distinct in fescue root mat area. Significant rooting to 40 cm with some roots extending to 60 cm. Pit face is 50-60% coarse fragments with many up to 10 cm in diameter. Spoil in bottom of pit was saturated. C horizon material broke to weak subangular blocky when crumbled. Upper C horizon slightly more compact than lower portion.

Treatment: Pure Siltstone
Plot number: CP8
Date: 5/26/83

A 0-9 cm; dark gray (10YR 4/1) to dark grayish brown (10 YR 4/2) loam/silt loam when moist; weak very fine to fine subangular blocky structure; very friable; many very fine and common fine roots; clear smooth boundary.

C 9-75+ cm; dark gray (10YR 4/1 moist) loam/silt loam; structureless, massive; friable to very friable; common very fine and few fine roots to 45 cm.

Comments: Surface horizon delineated on basis of loosening and aggregation. Roots occur in mats along the faces of rock fragments. Prominent rooting to 45 cm and few roots to 75 cm. Several large (3-5 cm) voids throughout profile. Soil between coarse fragments ranges from compact to very loose. Coarse fragments occupy 70-80% of the pit face; many greater than 10 cm in diameter. C horizon material crumbles to subangular blocky clods. Color change noted between the A and C horizon.

Treatment: Pure Siltstone
Plot number: CP9
Date: 5/26/83

A 0-10 cm; dark gray (10YR 4/1 moist) loam to silt loam; weak fine to medium subangular blocky structure; very friable; many very fine and few fine roots; clear smooth boundary.

C 10-75+ cm; dark gray (10YR 4/1 moist) loam to silt loam; structureless massive friable; common very fine and few fine roots to 47 cm.

Comments: Surface horizon delineated on basis of loosening and aggregation. Several voids present in pit face which contains 70-80% coarse fragments mostly from 3-10 cm in diameter. Prominent rooting to 45 cm with few roots at 75 cm. Roots occur in mats along rock fragment faces. Soil material between rock fragments is generally loose and single grain; however, localized pockets of compact, massive material are present.

Treatment: Topsoil over 2:1 Sandstone:Siltstone
Plot number: CP21
Date: 6/3/83

A 0-4 cm; yellowish brown (10YR 5/4 moist) loam; weak fine subangular blocky structure; very friable; many very fine and common fine roots; clear smooth boundary.

C 5-14 cm; yellowish brown (10YR 5/4 moist) loam; structureless, massive; very friable; common very fine and few fine roots; clear smooth boundary.

2C 14-70+ cm; dark brown (10YR 4/3 moist) loam/sandy loam; structureless, massive; friable; common very fine and few fine roots prominent to 30 cm.

Comments: Surface horizon delineated on basis of loosening and aggregation. Prominent rooting to 30 cm with few roots at 70 cm. C horizon material is topsoil whereas 2C material is mine soil. A and C horizons contain 10% coarse fragments up to 4 cm while 2C horizon is 35% coarse fragments up to 15 cm. Roots occur in mats along rock fragment faces. Several sandstone fragments weathered in place in the 2C horizon.

Treatment: Sawdust over 2:1 Sandstone:Siltstone
Plot number: CP 22
Date: 6/2/83

A 0-5 cm; dark grayish brown (10 YR 4/2) to very dark grayish brown (10 YR 3/2) loam when moist; structureless, single grain; loose; many very fine and common fine roots; abrupt smooth boundary.

C 5-70+ cm; dark brown (10 YR 4/3 moist) loam; structureless, massive friable; common very fine and few fine roots prominent to 70 cm.

Comments: Surface texture is difficult to discern due to sawdust particles.
C horizon is somewhat compact. Vertical roots to 70 cm. Pit face is 60-70% coarse fragments and 5-10% bridging voids.

Treatment: Sawdust over 2:1 Sandstone:Siltstone
Plot number: CP 25
Date: 6/2/83

A 0-5 cm; dark brown (10YR 3/3 moist) loam; weak fine subangular blocky structure; very friable; many very fine and common fine roots; abrupt smooth boundary.

C 5-65+ cm; dark brown (10YR 4/3 moist) loam; structureless, massive; friable; common very fine and few fine roots prominent to 30-40 cm.

Comments: Slight aggregation and loosening in A horizon. Localized zones of compaction in C horizon. Pit face contains 50% coarse fragments frequently greater than 10 cm in diameter and 5% bridging voids. Prominent rooting to 35 cm with a few roots extending to 65 cm. Large boulder (40 cm x 100 cm) on adjacent pit face. Several small oxidized sandstone fragments weathered in place. Lower portion of C horizon is less compact.

Treatment: Control, 2:1 Sandstone:Siltstone
Plot number: CP 26
Date: 6/2/83

A 0-4cm; dark brown (10YR 4/3 moist) loam, structureless, single grain, and weak fine subangular blocky; very friable; many very fine and common fine roots; clear wavy boundary.

C 4-66+ cm; dark brown (10YR 4/3 moist) loam; structureless, massive; friable; few very fine and few fine roots prominent to 10 cm.

Comments: Compaction evident throughout profile extending to the surface in places. Compaction less below 60 cm. Prominent rooting to 10 cm, deeper roots follow rock faces and fissures with little if any penetration into compacted soil. Pit face is 50% rock fragments. Large bridging voids in adjacent pit face.

Treatment: 224 Mg/ha Sludge over 2:1 Sandstone:Siltstone
Plot number: CP 27
Date: 6/2/83

A 0-7 cm very dark gray (10YR 3/1 moist) loam; weak fine to medium subangular blocky structure; friable; many very fine and common fine roots; abrupt smooth boundary.

C 7-66+cm; dark brown (10YR 3/3 moist) loam; structureless, massive; firm; few very fine and few fine roots prominent to 27 cm; moist.

Comments: Traffic pan evident below zone of sludge incorporation to 50 cm. Thick (3-5 cm) thatch layer on mineral surface. Roots concentrated in zone of sludge incorporation with little penetration into mine soil. Zone of sludge incorporation (0-7 cm) is very loose and held together by plant roots. Pit face contains 40% coarse fragments with one large (30 cm x 60 cm) boulder.

Treatment: 56 Mg/ha Sludge over 2:1 Sandstone:Siltstone
Plot number: CP 34
Date: 6/2/83

A 0-4 cm; dark yellowish brown (10YR 4/4 moist); (sludge pockets very dark gray (10 YR 3/1) loam; weak fine to medium subangular blocky structure; very friable; many very fine and common fine roots; clear smooth boundary.

C 5-65+ cm; dark yellowish brown (10YR 4/4 moist) loam; structureless, massive; friable; few very fine and few fine roots prominent to 15 cm.

Comments: Prominent rooting to 15 cm and no root penetration below 30 cm. Sludge is located in 6-8 cm pockets and is not continuous over the entire surface. Where sludge is not present the surface horizon is delineated due to loosening and aggregation. C horizon is somewhat compact in localized zones. Thick (3-5 cm) thatch layer is present. The pit face is 40% coarse fragments, with a large (30 cm x 60cm) boulder at a depth of 50 cm.

Treatment: 224 Mg/ha Sludge over 2:1 Sandstone:Siltstone
Plot number: CP38
Date: 6/3/83

A 0-11 cm; very dark grayish brown (10YR 3/2 moist) loam; weak medium subangular blocky structure; friable; many very fine and common fine roots; abrupt smooth boundary.

C 11-70+ cm; dark brown (10YR 4/3 moist) loam; structureless, massive; friable; few very fine and few fine roots prominent to 15 cm.

Comments: Surface horizon very loose and predominantly sludge material.
C horizon is compact from 15-50 cm. Depth of prominent rooting is 15 cm with no roots below 45 cm. Pit face contains 40-50% coarse fragments and few (<5%) bridging voids. Moderately thick (2-3 cm) thatch layer present.

Treatment: Topsoil over 2:1 Sandstone:Siltstone
Plot number: CP 39
Date: 6/3/83

A 0-4 cm; dark yellowish brown (10 YR 4/4 moist) loam; weak fine sub-angular blocky structure; very friable; many very fine and common fine roots; moist; clear smooth boundary.

C 4-12 cm; reddish brown (2.5 YR 4/4 moist) loam; structureless, massive; very friable; common very fine and few fine roots; abrupt smooth boundary.

2C 12-72 cm; dark yellowish brown (10 YR 4/4 moist) loam; structureless, massive; friable; common very fine and few fine roots prominent to 30 cm.

Comments: Surface horizon delineated on basis of loosening and aggregation. Prominent rooting to 30 cm with few roots at 70 cm. Pit face contains 50% coarse fragments, many greater than 15 cm. Only 10% of the A and C horizons are coarse fragments. 2C horizon somewhat compact in localized zones. Roots grow in mats along coarse fragments faces. Thin thatch layer present.

Treatment: Control, 2:1
Sandstone:Siltstone Plot number: CP 43
Date: 6/3/83

A 0-6 cm; brown (10 YR 5/3 moist) loam; weak fine subangular blocky structure; very friable; many very fine and common fine roots; clear smooth boundary.

C 6- 70+ cm; dark grayish brown (10 YR 4/2 moist) loamy sand; structureless, massive; very friable; common very fine and few fine roots prominent to 45 cm.

Comments: Surface horizon delineated on basis of loosening and aggregation. C horizon breaks to angular blocky and subangular blocky clods. Prominent rooting to 45 cm and very few roots at 70 cm. Many very fine roots in upper 10 cm of C horizon. Pit face contains 50% coarse fragments and 10% bridging voids. Soil material is somewhat compact between coarse fragments. Roots grow in mats along coarse fragment faces. Large (70 cm x 70 cm) boulder in pit face which extends to the surface.

1985 Profile Descriptions

Site: Plot 1
Date Sampled: 11/13/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: Sandstone.
Sampled by: J. Roberts and R.S. Li.

A 0-5 cm; Dark yellowish brown (10YR 4/4); gravelly sandy loam;weak, very fine to fine granular structure; very friable; many very fine and few fine roots; clear wavy boundary.

C1 5-36 cm; Dark yellowish brown (10YR 4/4)and dark greyish brown (10YR 4/2); gravelly sandy loam; massive and weak fineto medium subangular blocky; friable; common very fine roots and few fine roots; clear wavy boundary.

C2 36-110+ cm; Dark yellowish brown (10YR 4/4) and dark greyish brown (10YR 4/2); massive; friable; few very fine roots.

Remarks: Very dense fescue root mat composed of very fine roots. Common rock fragments generally less than 7.6 cm wide. The C1 horizon roots concentrated on rock fragment faces. Coarse fragments were as large as 40 cm, but generally 2 to 7.6 mm in size. Greyer areas contained noticeably more clay. Roots penetrate to a depth of 105 cm. The C2 contains more cobbles than the overlying C1 horizon. Compacted area noted about 10 cm wide that crossed the pit face diagonally from a depth of 20 to 70cm.

Site: Plot 4
Date Sampled: 11/13/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: Sandstone.
Sampled by: J. Roberts and R.S. Li.

A 0-6 cm; Dark greyish brown (10YR 4/2) and dark yellowish brown (10 YR 4/4); gravelly sandy loam; weak, very fine to fine granular structure; very friable; many very fine and common fine roots; clear wavy boundary.

C1 6-44 cm; Dark greyish brown (10YR 4/2) and dark yellowish brown (10YR 4/4): very gravelly sandy loam; massive and very weak fine subangular blocky; friable; common very fine roots; clear wavy boundary.

C2 44-105+ cm; Dark greyish brown (10YR 4/2) (7.5YR 5/8 few fine distinct sandstone fragments); massive; friable; few very fine roots.

Remarks: Very dense surficial root mat. Common pebbles throughout (2-7.6 mm). Evidence of compaction in a band 10 cm wide that began at a depth of about 55 cm. Roots penetrated about 100 cm. Black stains on exterior of oxidized sandstone fragments attributed to manganese.

Site: Plot 8
Date Sampled: 11/13/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: Siltstone.
Sampled by: J. Roberts and R.S. Li.

A 0-6 cm; Dark greyish brown (2.5YR 4/2); very gravelly silt loam; weak, very fine to fine granular structure; very friable; many very fine roots; clear wavy boundary.

C1 6-52 cm; Dark gray (10YR 4/1): gravelly silt loam; moderate fine to medium granular and subangular blocky; friable; many very fine roots; diffuse irregular boundary.

C2 52-83+ cm; Dark gray (10YR 4/1); gravelly silt loam; moderate fine subangular blocky and massive; friable; few very fine roots.

Remarks: Very dense root mat composed of very fine roots. Common rock fragments generally less than 7.6 cm wide. The C1 horizon roots distinctly concentrated on coarse fragment faces. Coarse fragments ranged from 2 to 50 mm in size and were elongated in one-dimension 2X greater than the width. Uniform distribution of coarse fragment sizes. Rock fragments were noticeably angular. There seemed to be an increase in clay in the lower C2 horizon.

Site: Plot 9
Date Sampled: 11/13/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: Siltstone.
Sampled by: J. Roberts and R.S. Li.

A 0-5 cm; Dark grayish brown (2.5Y 4/2); very gravelly silt loam; weak, very fine to fine granular structure; very friable; many very fine roots; clear wavy boundary.

C1 5-56 cm; Dark gray (10YR 4/1); very gravelly silt loam; moderate fine to medium granular and subangular blocky; friable; many very fine roots; diffuse irregular boundary.

C2 56-98+ cm; Dark gray (10YR 4/1); very gravelly silt loam; massive and moderate fine subangular blocky; friable; few very fine roots.

Remarks: Very dense root mat composed of very fine roots. Common rock fragments generally less than 7.6 cm wide. The C1 horizon roots concentrated on rock fragment faces. Coarse fragments were as large as 50 cm and elongated in one-dimension 2X the width. Very similar to morphology expressed in Plot 8.

Site: Plot 21
Date Sampled: 11/13/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: 2:1 Sandstone:Siltstone spoil mix amended to a depth of 30 cm with topsoil composed of A, E, B, and Cr horizons.
Sampled by: J. Roberts and R.S. Li.

A 0-6 cm; Dark brown (10YR 4/3); gravelly sandy loam; weak, very fine granular structure; very friable; many very fine roots; clear wavy boundary.

C 6-16 cm; Dark brown (10YR 4/3); gravelly sandy loam; weak, very fine granular to massive; very friable; common very fine roots and few fine roots; abrupt smooth boundary.

2C 16-96+ cm; Dark grayish brown (2.5Y 4/2); very gravelly sandy loam; massive; friable; few very fine roots.

Remarks: Very dense fescue root mat composed of very fine fescueroots. Patches of moss were commonly noticeable in this plot on the surface and were not seen as frequently in the rock mix plots. Roots were concentrated on rock fragment faces. Roots did not penetrate to a depth greater than 40 cm. A highly compacted area was noted at a depth of 35 cm that was about 10 cm wide.

Site: Plot 22
Date Sampled: 11/13/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: 2:1 Sandstone:Siltstone spoil mix amended with 112 Mg/ha Sawdust.
Sampled by: J. Roberts and R.S. Li.

Oe 2-0 cm; partially decomposed tall fescue litter.

A 0-7 cm; Very dark grayish brown (10YR 3/2): gravelly sandy loam; weak, very fine to fine granular structure: very friable; many very fine roots: clear wavy boundary.

AC 7-28 cm; Very dark grayish brown (2.5Y 3/2); very gravelly sandy loam; massive and weak fine to medium subangular blocky; friable; common very fine roots: clear wavy boundary.

C 38-106+ cm; Dark grayish brown (10YR 4/2); massive; friable; few very fine roots.

Remarks: Very dense fescue root mat composed of very fine roots. Very moist soil in the pit face. Visibly stripped sand grains under the Oe horizon and a "graying" of the upper A. Parent material mottles (reddish yellow 7.5YR 6/8) associated with sandstone fragments. Roots to a depth of 90 cm.

Site: Plot 25
Date Sampled: 11/13/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: 2:1 Sandstone:Siltstone spoil mix amended with 112 Mg/ha Sawdust.
Sampled by: J. Roberts and R.S. Li.

Oe 2-0 cm; partially decomposed tall fescue litter.

A 0-7 cm; Dark brown (10YR 3/3); gravelly loam; moderate fine granular and subangular blocky structure; very friable; many very fine roots; clear smooth boundary.

AC 7-16 cm; Dark grayish brown (10YR 4/2); very gravelly sandy loam; massive and weak fine to medium subangular blocky; friable; common very fine roots; clear wavy boundary.

C 16-59+ cm; Dark grayish brown (10YR 4/2); massive; firm; few fine roots.

Remarks: Very dense fescue root mat composed of very fine roots. Very moist soil in the pit face. Visibly stripped sand grains under the 0e horizon and a "graying" of the upper A. Parent material mottles (reddish yellow 7.5 YR 6/8) associated with sandstone fragments. Roots to a depth of 50 cm. Rock covered bottom of the pit at a depth of 59 cm.

Site: Plot 26
Date Sampled: 11/26/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: 2:1 Sandstone:Siltstone spoil mix (Control).
Sampled by: J. Roberts and W.L. Daniels.

A 0-4 cm; Dark brown (10YR 3/3); gravelly sandy loam; weak, very fine and fine granular structure; very friable; common fine roots; clear smooth boundary.

C1 4-18 cm; Dark brown (10YR 4/3); gravelly sandy loam; weak, fine and medium subangular blocky; friable; few very fine roots; clear wavy boundary.

C2 18-100+ cm; Dark brown (10YR 4/3); very gravelly sandy loam; massive and weak, moderate subangular blocky structure; firm; few very fine roots.

Remarks: No dense fescue root mat and sparsely vegetated. Roots were concentrated on rock fragment faces. Compaction in this plot was not as noticeable. Parent material mottles were few and orange, yellow, and gray in color.

Site: Plot 28
Date Sampled: 11/26/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: 2:1 Sandstone:Siltstone spoil mix amended with 56 Mg/ha Sewage Sludge.
Sampled by: J. Roberts and W.L. Daniels.

Oe 2-0 cm; partially decomposed tall fescue litter.

A 0-14 cm; Dark yellowish brown (10YR 3/2); gravelly loam; weak, fine and medium subangular blocky structure; very friable; many very fine and few fine roots; clear smooth boundary.

C1 14-25 cm; Dark yellowish brown (10YR 4/4); very gravelly sandy loam; weak fine to medium subangular blocky; friable; common very fine roots; clear wavy boundary.

C2 25-50+ cm; Dark yellowish brown (10YR 4/4); massive; firm; few fine roots.

Remarks: Very dense fescue root mat composed of very fine roots. Very moist soil in the pit face. Roots to a depth of 50 cm. Rock occupied a large volume of the pit face on the right side in the subsoil. A zone of compaction was noted at a depth of 25 cm.

Site: Plot 34
Date Sampled: 11/26/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: 2:1 Sandstone:Siltstone spoil mix amended with 56 Mg/ha Sewage Sludge.
Sampled by: J. Roberts and W.L. Daniels.

0e 2-0 cm; partially decomposed tall fescue litter.

A 0-11 cm; Dark yellowish brown (10YR 3/2); gravelly sandy loam; weak, very fine and fine granular structure; very friable; many very fine and few fine roots; clear wavy boundary.

C1 11-44 cm; Yellowish brown (10YR 5/4); gravelly sandy loam; massive and weak, medium subangular blocky; both firm and friable areas; few very fine roots; clear wavy boundary.

C2 44-92+ cm; Dark yellowish brown (10YR 5/4); very gravelly sandy loam; massive; firm; few very fine roots.

Remarks: Very dense fescue root mat composed of very fine roots. Very moist soil in the pit face. Fine roots to a depth of 80 cm. A large bridging void was found at a depth of 80 cm. W.L. Daniels indicated there were fewer bridging voids present in these 1985 pits than in 1983 when pits were excavated in these plots.

Site: Plot 38
Date Sampled: 11/26/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Power River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: 2:1 Sandstone:Siltstone spoil mix amended with 224 Mg/ha Sewage Sludge.
Sampled by: J. Roberts and W.L. Daniels.

Oe 2-0 cm; partially decomposed tall fescue litter.

A 0-12 cm; Dark yellowish brown (10YR 3/2); gravelly loam; weak, fine and moderate granular structure; very friable; many very fine and few fine roots; clear smooth boundary.

C 12-98+ cm; Dark brown (10YR 4/3); very gravelly sandy loam; massive; firm; few very fine roots.

Remarks: Very dense fescue root mat composed of very fine roots.Very moist soil in the pit face. A compacted zone beneath 29 cm and extended to a depth of 48 cm. Large rocky areas were noted at the bottom of the pit.

Site: Plot 39
Date Sampled: 11/26/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: 2:1 Sandstone:Siltstone spoil mix amended to a depth of 30 cm with topsoil composed of A, E, B,and Cr horizons.
Sampled by: J. Roberts and W.L. Daniels.

A 0-5 cm; Dark brown (10YR 3/3); gravelly sandy loam; weak, very fine and fine granular structure; very friable; common very fine roots; clear smooth boundary.

C 5-15 cm; Yellowish brown (10YR 5/4); gravelly sandy loam; weak, very fine to fine granular and moderate subangular blocky structure; very friable; common very fine roots; abrupt smooth boundary.

2C 15-100+ cm; Dark grayish brown (10YR 4/2); very gravelly sandy loam; weak, fine to moderate subangular blocky and massive structure; friable; few very fine and fine roots.

Remarks: Very dense fescue root mat composed of very fine fescue roots. Moss patches were again apparent as in the other topsoil plot. Roots were concentrated on rock fragment faces.

Site: Plot 43
Date Sampled: 11/26/85
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Wise Co., Virginia. Powell River Valley Project Area.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: KY-31 Tall Fescue.
Parent Material: 2:1 Sandstone:Siltstone spoil mix (Control).
Sampled by: J. Roberts and W.L. Daniels.

A 0-3 cm; Dark brown (10YR 3/3); gravelly sandy loam; weak, very fine granular structure; very friable; common very fine and few fine roots; clear smooth boundary.

C 3-93+ cm; Dark greyish brown (10YR 4/2); very gravelly sandy loam; massive; firm; few very fine roots.

Remarks: No dense fescue root mat and sparsely vegetated. A compacted zone began at 30 cm and extended to a depth of 55 cm. Parent material mottles were few and orange, yellow, and gray in color.

1989 Profile Descriptions

Site: Plot 1
Parent Material: Sandstone
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Powell River Project Area, Wise County, Virginia.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: Ky-31 tall fescue.
Described by: K.C. Haering and W.L. Daniels, 9/11/89.

A	0-7 cm	Dark yellowish brown (l0YR 4/4) gravelly sandy loam; weak fine subangular blocky structure; very friable; many fine and very fine roots; clear smooth boundary.
AC	7-17 cm	Dark yellowish brown (10YR 4/6) very gravelly sandy loam; weak medium subangular blocky structure; very friable; common fine and very fine roots; clear wavy boundary;
Cl	17-51 cm	Dark yellowish brown (10YR 4/6) very gravelly sandy loam; massive, with some areas of weak subangular blocky and platy structure; friable, common fine and very fine roots, especially along coarse fragment faces; very compacted; clear wavy boundary.
C2	51+ cm	Dark yellowish brown (10YR 4/6) very gravelly sandy loam; massive; friable; few very fine roots; much less compacted than Cl, with bridging voids apparent between rock fragments,

Notes: Most rooting ends in the Cl horizon, which was dense and compacted. There appeared to be less coarse fragments in this profile than any of the others.

Site: Plot 9
Parent Material: Siltstone
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Powell River Project Area, Wise County, Virginia.
Topography: Very gently sloping.
Drainage: Well drained.
VegetationKy-31 tall fescue
Described by: K.C. Haering and W.L. Daniels, 9/11/89.

A	0-9 cm	Very dark grayish brown (l0YR 3/2) very gravelly silt loam; weak fine granular and subangular blocky structure; very friable; many fine and very fine roots, clear wavy boundary.
AB	9-20 cm	Dark gray (l0YR 4/1) very gravelly silt loam; weak medium subangular blocky structure; friable; many very fine and fine roots; clear wavy boundary
Bw	20-36 cm	Dark gray (l0YR 4/1) and gray (l0YR 5/1) very gravelly silt loam; weak medium subangular blocky structure; friable; many very fine and common fine roots; dense andcompacted; clear wavy boundary.
Cl	36-49 cm	Grey (SY 5/1) and dark gray (l0YR 4/1) very gravelly loam; massive friable; common fine and very fine roots, especially on coarse fragment faces; dense and compacted; clear wavy boundary.
C2	49+ cm	Dark gray (l0YR 4/1) very gravelly loam; massive; friable; few fine and very fine roots; less compact than Cl, with bridging voids apparent between coarse fragments.

Notes: The quantity and depth of roots in this profile was greater than in the sandstone profile. There were also more coarse fragments. The AB horizon was somewhat dense, but the Bw and Cl horizons are the zone of compaction in this profile. The Bw horizon was described as such because of definite structure development, but is most likely not a true cambic horizon.

Site: Plot 16
Parent Material: 1:1 sandstone:siltstone mixture.
Classification: Typic Udorthent, loamy-skeletal, mixed mesic.
Location: Powell River Project Area, Wise County, Virginia.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: Ky-31 tall fescue.
Described by: K.C. Haering, 9/20/89.

A	0-6 cm	Dark brown (l0YR 3/3) grading to dark yellowish brown (10YR 3/4) very gravelly sandy loam; weak fine subangular block structure; very friable; many fine and very fine roots; clear wavy boundary.
AC	6-28 cm	Dark yellowish brown (l0YR 4/4) very gravelly sandy loam; weak medium subangular blocky structure; friable; many very fine and common fine roots; clear smooth boundary.
Cl	28-55 cm	Dark yellowish brown (10YR 4/4) very gravelly sandy loam; massive, with patches of weak subangular blocky structure; friable; common fine and very fine roots; dense and compacted; clear wavy boundary.
C2	55+ cm	Dark yellowish brown (10YR 4/4) very gravelly sandy loam; massive; friable; few fine and very fine roots; much less compacted than Cl, with bridging voids apparent.

Notes: Weathered, stripped sand grains were apparent inthe top 2 cm of the A horizon. Sand appears to have been concentrated there. Most roots were found in the Aand AC horizon, but roots extended down through the compacted Cl horizon on coarse fragment faces. The compacted zone ended higher in this profile than in the other profiles. Distinct zones of sandstone and siltstone weathering were observed in this profile. This was also apparent inthe mixed SS/SiSpits of thesurface amendment experiment.

Site: Plot 21
Parent Material: Topsoil (30 cm) over 2:1 sandstone:siltstone mix.
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Powell River Project Area, Wise County, Virginia.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: Ky-31 tall fescue.
Described by: K.C. Haering, 9/11/89.

A	0-5 cm	Dark brown (l0YR 4/3) gravelly sandy loam; weak fine granular structure; very friable; many fine and very fine roots; clear smooth boundary.
AC	5-18 cm	Dark yellowish brown (10YR 4/6) gravelly sandy loam; weak fine granular and subangular blocky structure; very friable; common fine and many very fine roots; abrupt smooth boundary.
IICl	18-55 cm	Dark yellowish brown (10YR 4/4) with patches of yellowish brown (l0YR 5/6) very gravelly sandy loam; massive, with areas of weak platy and subangular blocky structure; common fine and very fine roots; very compacted; clear wavy boundary.
IIC2	55+ cm	Dark yellowish brown (l0YR 4/4) very gravelly sandy loam; massive; friable; few fine and very fine roots; much less compact than IICl.

Notes: There is an abrupt boundary between the two types of parent material ("topsoil" and overburden) in this profile. The horizon below this boundary (IICl) was denseand very compacted.

Site: Plot 22
Parent Material: 2:1 sandstone:siltstone mix amended with sawdust.
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Powell River Project Area, Wise County, Virginia.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: Ky-31 tall fescue.
Described by: K.C. Haering, 9/11/89.

A	0-11 cm	Dark brown (10YR 3/3) gravelly sandy loam, weak fine granular structure; very friable; many fine and very fine roots, clear wavy boundary.
A/C	11-20 cm	Dark brown (10YR 3/3) and dark yellowish brown (10 YR 4/4) very gravelly sandy loam; weak fine granular and subangular blocky structure; friable; common fine and many very fine roots; clear wavy boundary.
C1	20-58 cm	Dark yellowish brown (10YR 4/4) very gravelly sandy loam; massive; friable; few very fine and fine roots; compacted; clear wavy boundary.
C2	58+cm	Dark yellowish brown (10YR 4/4) very gravelly sandy loam; massive; friable; few very fine roots; less compacted than C1, with bridging voids apparent.

Notes: Stripped sand grains apparent in upper part of A horizon. The A horizon in this profile was thicker and darker than those in the rock mix and topsoil-amended profiles, tonguing into the A/C along rock faces. A thick litter layer and root mat was observed. There was less structure apparent in the C1 horizon than in the other surface amendment profiles.

Site: Plot 26
Parent Material: Control - 2:1 sandstone:siltstone mix.
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Powell River Project Area, Wise County, Virginia.
Topography: Very gently sloping.
Drainage Well drained.
Vegetation: Ky-31 tall fescue.
Described by: K.C. Haering, 9/11/89.

A	0-9 cm	Dark brown (10YR 3/3) very gravelly sandy loam; weak fine subangular blocky structure; friable; common fine and very fine roots; clear smooth boundary.
AC	9-29 cm	Dark yellowish brown (l0YR 4/3) very gravelly sandy loam;weak medium subangular blocky; friable; common fine and few very fine roots; clear smooth boundary.
Cl	29-72 cm	Dark yellowish brown (l0YR 4/4) very gravelly sandy loam,with patches of brownish yellow (l0YR 5/6) and yellowish brown (l0YR 6/8) sandstone; massive; friable; few very fine roots; compacted; clear wavy boundary
C2	72+ cm	Dark yellowish brown (l0YR 4/4) very gravelly sandy loam; massive; friable; few very fine roots; not as compacted as Cl.

Notes: This profile appeared to have a larger proportion of siltstone than would be indicated by the rock mixture and thus had greater structure development in the AC horizon. The A horizon appeared to be sandier than the other horizons, perhaps as a result of the removal of finer material because of sparse vegetation. The root mat in this profile was not as thick as those observed inother profiles (RM and SA experiment). The C1 horizon was very compacted.

Site: Plot 34
Parent Material: 2:1 sandstone:siltstone mix amended with 56 Mg/ha sewage sludge.
Classification: Typic Udorthent, loamy-skeletal, mixed, mesic.
Location: Powell River Project Area, Wise County, Virginia.
Topography: Very gently sloping.
Drainage: Well drained.
Vegetation: Ky-31 tall fescue.
Described by: K.C. Haering, 9/20/89.

A	0-10 cm	Dark brown (10YR 3/3) gravelly sandy loam; weak fine granular and subangular blocky structure; very friable; many fine and very fine roots; clear wavy boundary.
AC	10-25 cm	Dark yellowish brown (10YR 4/4) very gravelly sandy loam; weak medium subangular blocky structure; friable; common fine and many very fine roots; clear smooth boundary
C1	25-68 cm	Dark yellowish brown (l0YR 4/6) very gravelly sandy loam,with patches of yellowish brown (l0YR 5/6) sandstone; massive; friable; common very fine and fine roots, especially along coarse fragment faces; compacted; gradual wavy boundary.
C2	68+cm	Dark yellowish brown (l0YR 4/6) very gravelly sandy loam; massive; friable; few fine and very fine roots; less compacted than C1 with large (20 cm) bridging voids.

Notes: A horizon has a thick, dense, root mat. Sand grains were apparent in the upper part of the A horizon. The C1 horizon was dense and compacted.

2016 Profile Descriptions

COP Plot 1
Date Sampled: 9-21-2016
Described and Sampled by: D. Johnson, J. Buckwalter, K. Haering
Parent Material: 100% Sandstone
Vegetation: Mostly Solidago altissima var. altissima. Also, Lespedeza cuneata, Erigeron sp, creeping charlie (Glecheroma hederacea), mix of native forbs, Clematis virginiana, tall fescue, broomsedge, and Allegheny blackberry. 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 (12) very fine and common (3) fine roots; 15% rock fragments by volume (15% gravel); low relative bulk density; no packing voids; clear wavy boundary.
^Bw	9-29	Dark yellowish brown (10YR 4/4) very cobbly loam; weak subangular blocky structure; friable; many (8) very fine and common (2) fine roots; 36% rock fragments by volume (36% cobbles); low relative bulk density; no packing voids; clear wavy boundary.
^C1	29-65	Dark yellowish brown (10YR 3/4) very cobbly loam; structureless massive with small pockets of weak subangular blocky structure; friable; common (3) fine roots; 55% rock fragments by volume (50% cobbles, 5% stones); medium relative bulk density; no packing voids; gradual irregular boundary.
^C2	65-125+	Dark grayish brown (10YR 4/2) very cobbly loam; structureless massive structure; friable; common (1) fine and few (0.2) very coarse roots; 55% rock fragments by volume (50% cobbles, 5% stones); medium relative bulk density; few packing voids.

COP Plot 2
Date Sampled: 9-22-2016
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) cobbly 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% cobbles); 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.

COP Plot 4
Date Sampled: 9-22-2016
Described and Sampled by: D. Johnson, J. Buckwalter, K. Haering
Parent Material: 100% Sandstone
Vegetation: Mostly Allegheny blackberry (Rubus allegheniensis) and goldenrod (Solidago altissima var. altissima). Some native ferns, Erigeron sp., broomsedge and 2 Tulip poplar (Liriodendron tulipifera) seedlings. No woody overstory.

Horizon	Depth	Description
	--cm--	
O	4-0	Partially decomposed mixed leaf litter.
^A	0-7	Very dark grayish brown (10YR 3/2) loam; moderate granular structure; friable; many (15) very fine, common (4) fine and (1) coarse roots; 6% rock fragments by volume (6% gravel); low relative bulk density; no packing voids; clear smooth boundary.
^BA	7-15	Dark yellowish brown (10YR 4/4) gravelly sandy loam, with many (25%) very dark grayish brown (10YR 3/2) lithochromic color variegations; moderate subangular blocky structure; friable; common (4) fine and (1) coarse roots; 20% rock fragments by volume (20% gravels); low relative bulk density; no packing voids; clear wavy boundary.
^Bw	15-60	Dark yellowish brown (10YR 4/4) very stony sandy loam, with common (10%) dark yellowish brown (10YR 4/6) and (5%) very dark grayish brown (10YR 3/2) lithochromic color variegations; moderate subangular blocky structure; friable; common (2) fine roots; 50% rock fragments by volume (25% stones, 25% cobbles); high relative bulk density; no packing voids; gradual irregular boundary.
^BC	60-97	Dark yellowish brown (10YR 4/4) very stony sandy loam, with common (10%) yellowish brown (10YR 5/8) and (5%) very dark grayish brown (10YR 3/2) lithochromic color variegations; weak subangular blocky structure; very friable; common (2) fine roots; 40% rock fragments by volume (20% stones, 20% cobbles); medium relative bulk density; few packing voids; clear wavy boundary.
^C	97-125+	Dark gray (10YR 4/1) very cobbly clay loam, with many (25%) yellowish brown (10YR 5/8) and (25%) black (10YR 2/1) lithochromic color variegations; structureless massive structure; firm; few (0.5) coarse roots; 35% rock fragments by volume (20% gravels, 15% cobbles); medium relative bulk density; few packing voids.

Remarks: Large boulder in upper 50cm of profile.

COP Plot 5
Date Sampled: 9-22-2016
Described and Sampled by: D. Johnson, J. Buckwalter, K. Haering
Parent Material: 1:1 Sandstone:Siltstone
Vegetation: Thick vegetation. Mostly Lespedeza cuneata, two species of Erigeron, Solidago altissima var. altissima, and Solidago sp. Also, Allegheny blackberry, Clematis virginiana, Carex sp., tall fescue. Few small Quercus rubra and Ulmus sp. around pit.

Horizon	Depth	Description
	--cm--	
O	3-0	Partially decomposed mixed leaf litter.
^A	0-9	Very dark grayish brown (10YR 3/2) gravelly silt loam; moderate granular structure; friable; many (12) very fine and (5) fine and common (3) coarse roots; 15% rock fragments by volume (15% gravel); low relative bulk density; no packing voids; clear smooth boundary.
^AB	9-19	Dark yellowish brown (10YR 3/4) gravelly loam; weak subangular blocky structure; friable; common (4) fine, (3) very fine, and (1) coarse roots; 23% rock fragments by volume (20% gravels, 3% stones); low relative bulk density; no packing voids; clear wavy boundary.
^Bw	19-39	Brown (10YR 4/3) gravelly loam, with common (3%) yellowish brown (10YR 5/8) and (3%) light yellowish brown (10YR 6/4) lithochromic color variegations; weak subangular blocky structure; friable; common (3) very fine roots; 30% rock fragments by volume (20% gravels, 10% stones); high relative bulk density; no packing voids; gradual wavy boundary.
^BC	39-105	Dark grayish brown (10YR 4/2) very cobbly clay loam, with common (3%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; firm; common (3) fine roots; 53% rock fragments by volume (30% cobbles, 20% gravels, 3% stones); medium relative bulk density; few packing voids; clear irregular boundary.
^C	105-125+	Dark yellowish brown (10YR 4/4) very cobbly loamy sand, with common (3%) yellowish brown (10YR 5/8) and (5%) light yellowish brown (10YR 6/4) lithochromic color variegations; structureless massive structure; very friable; few (0.5) coarse and (0.5) fine roots; 40% rock fragments by volume (25% cobbles, 15% gravels); low relative bulk density; few packing voids.
Remarks:		Large boulder between 20-60cm in profile. Bw, BC, and C horizons run on strong diagonal to surface.

COP Plot 7
Date Sampled: 9-22-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 100% Sandstone
Vegetation: Fairly sparse vegetation (<50% cover). Mostly Solidago altissima var. altissima. Also, Allegheny blackberry, native ferns, an unknown grass, Solidago sp. No woody overstory except for Autumn olive that looks like it was cleared from the plot.

Horizon	Depth	Description
	--cm--	
O	2-0	Partially decomposed mixed leaf litter.
^A	0-10	Very dark grayish brown (10YR 3/2) cobbly loam; moderate granular structure; friable; many (5) very fine and common (4) fine and (3) coarse roots; 20% rock fragments by volume (10% cobbles; 10% gravels); low relative bulk density; no packing voids; clear smooth boundary.
^Bw	10-34	Dark yellowish brown (10YR 4/6) cobbly sandy loam; moderate subangular blocky structure; friable; common (3) fine and few (0.2) coarse roots; 30% rock fragments by volume (15% cobbles, 15% gravels); medium relative bulk density; no packing voids; gradual smooth boundary.
^BC	34-101	Dark yellowish brown (10YR 4/6) extremely gravelly sandy loam, with common (5%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (1) fine roots; 66% rock fragments by volume (40% gravels, 25% cobbles, 1% stones); high relative bulk density; no packing voids; clear irregular boundary.
^C	101-125+	Dark grayish brown (10YR 4/2) very cobbly clay loam, with many (25%) yellowish brown (10YR 5/8) and (25%) black (10YR 2/1) lithochromic color variegations; structureless massive structure; firm; few (0.5) coarse roots; 35% rock fragments by volume (20% gravels, 15% cobbles); high relative bulk density; no packing voids.

Remarks: Huge 125 cm x 125 cm boulder was dug from pit.

COP Plot 9
Date Sampled: 9-22-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 100% Siltstone
Vegetation: Multiflora rose, blackberry, lespedeza cuneata, tall fescue, Solidago altissima var altissima (fairly even mix). Tulip poplar in overstory.

Horizon	Depth	Description
	--cm--	
O	3-0	Partially decomposed mixed leaf litter.
^A	0-13	Very dark gray (10YR 3/1) loam; moderate granular structure; very friable; many (10) very fine and (5) fine and common (1) very coarse roots; 10% rock fragments by volume (10% gravels); low relative bulk density; few packing voids; clear smooth boundary.
^Bw	13-41	Very dark grayish brown (10YR 3/2) very cobbly clay loam; weak subangular blocky structure; friable; common (4) very fine and (4) fine roots; 56% rock fragments by volume (30% gravels, 25% cobbles, 1% stones); low relative bulk density; common packing voids; gradual wavy boundary.
^BC	41-75	Very dark grayish brown (10YR 3/2) extremely cobbly loam; weak subangular blocky structure; very friable; common (3) fine and few (0.5) coarse roots; 68% rock fragments by volume (35% cobbles, 30% gravels, 3% stones); low relative bulk density; many packing voids; gradual wavy boundary.
^C	75-125+	Very dark grayish brown (10YR 3/2) very cobbly loam; structureless massive structure; friable; common (3) fine and few (0.2) coarse roots; 53% rock fragments by volume (30% cobbles, 20% gravels, 3% stones); low relative bulk density; common packing voids.

Remarks: Pit caved in around edges while digging with excavator. Old pit 100cm behind this pit. B horizons were less developed in Siltstone pits than pits in other rock mixes.

COP Plot 14
Date Sampled: 9-22-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 100% Siltstone
Vegetation: (~75% cover), lespedeza cuneata, Allegheny blackberry, tall fescue. Northern red oak (Quercus rubra) in overstory.

Horizon	Depth	Description
	--cm--	
O	5-0	Partially decomposed mixed leaf litter.
^A	0-10	Very dark gray (10YR 3/1) gravelly loam; moderate granular structure; friable; many (10) very fine and (5) fine and common (2) medium and (1) coarse roots; 25% rock fragments by volume (25% gravel); low relative bulk density; few packing voids; clear smooth boundary.
^Bw	10-35	Very dark grayish brown (10YR 3/2) very gravelly silt loam, with few (1%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (3) fine and (2) coarse roots and few (0.2) very coarse roots; 45% rock fragments by volume (25% gravels, 10% cobbles, 10% boulders); medium relative bulk density; many packing voids; gradual wavy boundary.
^BC	35-61	Very dark gray (10YR 3/1) extremely cobbly loam, with few (1%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (2) very fine and few (0.2) coarse roots; 75% rock fragments by volume (35% gravels, 30% cobbles, 10% boulders); low relative bulk density; many packing voids; gradual irregular boundary.
^C	61-125+	Very dark gray (10YR 3/1) extremely cobbly clay loam, with few (1%) yellowish brown (10YR 5/8) lithochromic color variegations; structureless massive structure; friable; common (1) very fine and very few (0.1) coarse roots; 75% rock fragments by volume (35% gravels, 30% cobbles, 10% boulders); medium relative bulk density; common packing voids.

Remarks: B horizons seem to be less developed in 100% siltstone than other rock mixes. Pit caved in several times while digging with excavator, very loose overall. Several boulders dug from pit.

COP Plot 15
Date Sampled: 9-22-2016
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 than plot 14 and plot 9 siltstone. B horizons in siltstone plots are less developed than other rock mixes overall.

COP Plot 19
Date Sampled: 9-22-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 1:1 Sandstone:Siltstone
Vegetation: Sparse herbaceous veg (~50%), mostly Allegheny blackberry and Lespedeza cuneata. Some Solidago altissima var altissima and Carex sp. Tulip poplars and Northern red oaks (Quercus rubra) in overstory.

Horizon	Depth	Description
	--cm--	
O	5-0	Partially decomposed mixed leaf litter.
^A	0-11	Very dark grayish brown (10YR 3/2) gravelly silt loam; moderate granular structure; friable; many (7) very fine and common (2) fine and (1) coarse roots; 30% rock fragments by volume (30% gravels); low relative bulk density; no packing voids; clear smooth boundary.
^Bw	11-46	Dark yellowish brown (10YR 3/6) extremely gravelly loam, with common (5%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (4) fine and (1) coarse roots; 61% rock fragments by volume (30% gravels, 15% cobbles, 15% stones, 1% boulders); medium relative bulk density; few packing voids; gradual wavy boundary.
^BC	46-101	Dark grayish brown (10YR 4/2) very cobbly sandy loam, with common (5%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (1) fine roots and few (0.5) coarse roots; 55% rock fragments by volume (30% gravels, 20% cobbles, 5% boulders); high relative bulk density; common packing voids; clear irregular boundary.
^C	101-125+	Very dark gray (10YR 3/1) extremely gravelly loamy sand, with many (35%) brown (10YR 4/3) lithochromic color variegations; structureless massive structure; friable; few (0.5) fine and (0.1) coarse roots; 70% rock fragments by volume (40% gravels, 20% stones, 10% boulders); medium relative bulk density; common packing voids.

Remarks: 2% of coarse fragments are carboliths in ^BC horizon (46-101cm).

COP Plot 24
Date Sampled: 9-22-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone amended with 30cm of topsoil.
Vegetation: Tall fescue, Carex sp., Erigeron sp, Solidago altissima var altissima, poison ivy. Northern red oak (Quercus rubra) in overstory. Also, some Autumn olive.

Horizon	Depth	Description
	--cm--	
O	5-0	Partially decomposed mixed leaf litter.
^A1	0-10	Very dark grayish brown (10YR 3/2) gravelly loam with common (8%) yellowish brown (10YR 5/8) lithochromic color variegations; moderate granular structure; friable; many (6) very fine and common (2) fine and (1) coarse roots; 15% rock fragments by volume (15% gravels); low relative bulk density; no packing voids; clear smooth boundary.
^A2	10-19	Dark yellowish brown (10YR 4/6) gravelly sandy loam; moderate subangular blocky structure; friable; common (3) fine and (1) coarse roots; 15% rock fragments by volume (15% gravels); low relative bulk density; no packing voids; abrupt smooth boundary.
^Bw	19-61	Very dark grayish brown (10YR 3/2) extremely gravelly sandy loam, with common (10%) yellowish brown (10YR 5/8) and (3%) black (10YR 2/1) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; weak subangular blocky structure; friable; few (0.5) fine and (0.1) coarse roots; 65% rock fragments by volume (40% gravels, 20% cobbles, 5% stones); high relative bulk density; no packing voids; gradual smooth boundary.
^C	61-125+	Dark grayish brown (10YR 4/2) extremely gravelly sandy loam, with common (3%) yellowish brown (10YR 5/8) and few (1%) black (10YR 2/1) lithochromic color variegations; structureless massive structure; friable; few (0.2) coarse roots; 75% rock fragments by volume (40% gravels, 20% boulders, 15% stones); high relative bulk density; few packing voids.

Remarks: Large boulder lower half of profile. Bw, BC, and C horizons run on strong diagonal to surface. 8% of coarse fragments in ^Bw horizon (19-61 cm) are carboliths.

COP Plot 25
Date Sampled: 9-21-2016
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 ¾) 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 ¾) 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.

COP Plot 26
Date Sampled: 9-22-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone with no amendment – control
Vegetation: Lespedeza cuneata and Solidago altissima var altissima, Clematis virginiana, Erigeron sp. Northern red oak (Quercus rubra) and small Acer rubrum in overstory.

Horizon	Depth	Description
	--cm--	
O	5-0	Partially decomposed mixed leaf litter.
^A	0-7	Very dark grayish brown (10YR 3/2) gravelly silt loam; moderate granular structure; friable; common (4) fine and (3) very fine roots; 30% rock fragments by volume (30% gravel); low relative bulk density; no packing voids; clear smooth boundary.
^Bw	19-39	Dark brown (10YR 3/3) very cobbly sandy loam, with common (5%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (1) very fine and few fine (0.5) and (0.1) coarse roots; 55% rock fragments by volume (30% gravels, 20% cobbles, 5% stones); high relative bulk density; no packing voids; gradual wavy boundary.
^C	105-125+	Dark brown (10YR 3/3) extremely stony sandy loam, with common (5%) yellowish brown (10YR 5/8) lithochromic color variegations; structureless massive structure; very friable; very few (0.1) very fine roots; 65% rock fragments by volume (35% gravels, 30% stones); high relative bulk density; no packing voids.

Remarks: 1% of coarse fragments in ^Bw and ^C horizons (7-125+cm) are carboliths.

COP Plot 30
Date Sampled: 9-23-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone amended with 112 Mg/ha sewage sludge
Vegetation: Solidago altissima var altissima, tall fescue, Allegheny blackberry, some Lespedeza cuneata. Northern red oak (Quercus rubra) in overstory.

Horizon	Depth	Description
	--cm--	
O	3-0	Partially decomposed mixed leaf litter.
^A	0-10	Very dark gray (10YR 3/1) gravelly silt loam; moderate granular structure; friable; many (6) fine and common (3) very fine and (3) coarse roots; 16% rock fragments by volume (15% gravel, 1% cobbles); low relative bulk density; no packing voids; clear wavy boundary.
^BA	10-25	Dark grayish brown (10YR 4/2) very cobbly loam, with common (3%) yellowish brown (10YR 5/8) lithochromic color variegations; moderate subangular blocky structure; friable; common (3) very fine and (2) fine roots; 40% rock fragments by volume (20% cobbles, 20% gravels); medium relative bulk density; few packing voids; clear wavy boundary.
^Bw	25-50	Brown (10YR 4/3) extremely gravelly sandy loam, with common (3%) yellowish brown (10YR 5/8) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; weak subangular blocky structure; friable; few (0.2) very fine and (0.2) coarse roots; 65% rock fragments by volume (40% gravels, 25% cobbles); high relative bulk density; no packing voids; gradual wavy boundary.
^C	50-125+	Dark grayish brown (10YR 4/2) extremely gravelly sandy loam, with common (3%) yellowish brown (10YR 5/8) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; structureless massive; friable; few (0.2) very fine and (0.2) coarse roots; 60% rock fragments by volume (45% gravels, 10% stones, 5% cobbles); high relative bulk density; few packing voids.

COP Plot 31
Date Sampled: 9-23-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone amended with 112 Mg/ha sewage sludge
Vegetation: Very little herbacous 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 cobbles across top of pit face.

COP Plot 32
Date Sampled: 9-23-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone amended with 112 Mg/ha sewage sludge
Vegetation: Lots of poison ivy. Solidago altissima var altissima, aster sp., tall fescue, Lespedeza cuneata, Allegheny blackberry, Abies sp. Northern red oak (Quercus rubra) in overstory.

Horizon	Depth	Description
	--cm--	
O	5-0	Partially decomposed mixed leaf litter.
^A	0-10	Very dark grayish brown (10YR 3/2) gravelly loam; moderate granular structure; friable; many (8) very fine and (3) fine and few (0.2) coarse roots; 25% rock fragments by volume (25% gravels); low relative bulk density; no packing voids; clear smooth boundary.
^AB	10-23	Dark brown (10YR 3/3) very gravelly loam, with common (5%) yellowish brown (10YR 5/8) lithochromic color variegations; moderate subangular blocky structure; friable; many (6) very fine, common (3) fine, and few (0.5) very coarse roots; 35% rock fragments by volume (25% gravels, 10% cobbles); low relative bulk density; no packing voids; abrupt wavy boundary.
^Bw	23-57	Brown (10YR 4/3) very gravelly loam, with many (40%) dark yellowish brown (10YR 4/6) lithochromic color variegations; moderate subangular blocky structure; friable; common (2) fine and few (0.2) coarse roots; 52% rock fragments by volume (40% gravels, 10% cobbles, 2% stones); high relative bulk density; no packing voids; clear irregular boundary.
^BC	57-87	Brown (10YR 4/3) very gravelly sandy loam, with many (35%) dark yellowish brown (10YR 4/6) lithochromic color variegations; weak subangular blocky structure; friable; few (0.5) coarse and (0.2) fine roots; 52% rock fragments by volume (40% gravels, 10% cobbles, 2% stones); high relative bulk density; no packing voids; clear irregular boundary.
^C	87-125+	Very dark grayish brown (10YR 3/2) very gravelly sandy loam, with common (15%) dark yellowish brown (10YR 4/6) lithochromic color variegations; structureless massive; friable; few (0.5) medium roots; 55% rock fragments by volume (35% gravels, 10% cobbles, 10% stones); medium relative bulk density; no packing voids.

COP Plot 33
Date Sampled: 9-27-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone amended with 56 Mg/ha sewage sludge
Vegetation: Little veg (<10% cover), some Allegeny blackberry and Lespedeza cuneata. Mostly autumn olive in overstory, plus Quercus rubra nearby.

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 and common (2) fine and (2) coarse roots; 45% rock fragments by volume (40% gravels, 5% cobbles); low relative bulk density; no packing voids; clear smooth boundary.
^BA	10-20	Dark grayish brown (10YR 4/2) extremely gravelly silt loam; moderate subangular blocky structure; friable; common (3) very fine, (2) medium, and (1) very coarse roots; 60% rock fragments by volume (40% gravels, 10% stones, 10% cobbles); medium relative bulk density; no packing voids; gradual irregular boundary.
^Bw	20-40	Dark grayish brown (10YR 4/2) extremely gravelly loam, with common (8%) yellowish brown (10YR 5/8) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; moderate subangular blocky structure; friable; common (2) very fine and few (0.2) coarse roots; 75% rock fragments by volume (50% gravels, 20% cobbles, 5% stones); high relative bulk density; no packing voids; gradual irregular boundary.
^BC	40-60	Brown (10YR 4/3) extremely gravelly sandy loam, with common (5%) yellowish brown (10YR 5/8) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; weak subangular blocky structure; friable; few (0.5) very fine and (0.1) coarse roots; 75% rock fragments by volume (45% gravels, 20% cobbles, 10% stones); high relative bulk density; few packing voids; gradual wavy boundary.
^C	60-125+	Dark brown (10YR 3/3) extremely gravelly sandy loam, with common (5%) yellowish brown (10YR 5/8) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; structureless massive; friable; few (0.2) very fine and (0.1) very coarse roots; 60% rock fragments by volume (40% gravels, 10% stones, 10% cobbles); medium relative bulk density; few packing voids.

Remarks: 3% of coarse fragments in ^BC and ^C horizons (40-125 cm) are carboliths.

COP Plot 34
Date Sampled: 9-27-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone with 56 Mg/ha sewage sludge
Vegetation: Viola sp., autumn olive, Quercus rubra.

Horizon	Depth	Description
	--cm--	
O	5-0	Partially decomposed mixed leaf litter.
^A	0-10	Very dark gray (10YR 3/1) very gravelly loam; moderate granular; friable; many (5) very fine and common (3) fine and (1) very coarse roots; 45% rock fragments by volume (40% gravels, 5% cobbles); low relative bulk density; no packing voids; clear wavy boundary.
^BA	10-22	Dark yellowish brown (10YR 3/4) very cobbly loam, with many (30%) very dark grayish brown (10YR 3/2) lithochromic color variegations; moderate subangular blocky structure; friable; common (3) very fine and (1) coarse roots; 50% rock fragments by volume (25% gravels, 20% cobbles, 5% boulders); medium relative bulk density; no packing voids; clear irregular boundary.
^Bw	22-40	Brown (10YR 4/4) extremely gravelly loam, with common (3%) light yellowish brown (10YR 6/4) and few (1%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (1) fine and few (0.2) coarse roots; 70% rock fragments by volume (40% gravels, 10% boulders, 10% stones, 10% cobbles); medium relative bulk density; few packing voids; gradual wavy boundary.
^BC	40-69	Yellowish brown (10YR 5/4) extremely gravelly sandy loam, with common (5%) very dark grayish brown (10YR 3/2) and few (1%) yellowish brown (10YR 5/8) and (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; weak subangular blocky structure; friable; common (2) very fine and few (0.2) coarse roots; 80% rock fragments by volume (40% gravels, 20% boulders, 10% stones, 10% cobbles); medium relative bulk density; common packing voids; gradual irregular boundary.
^C	69-125+	Brown (10YR 4/3) extremely gravelly sandy loam, with many (25%) very dark grayish brown (10YR 3/2) lithochromic color variegations; structureless massive; very friable; common (1) very fine and few (0.2) coarse and (0.2) very coarse roots; 80% rock fragments by volume (45% gravels, 20% boulders, 10% stones, 5% cobbles); medium relative bulk density; many packing voids.
Remarks:		Large boulders on left and right sides of pit face.

COP Plot 35
Date Sampled: 9-23-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone amended with 112 Mg/ha sawdust
Vegetation: Sparse herbaceous veg (~10%), Allegheny blackberry, some Lespedeza cuneata, unknown aster, white pine seedling. Mostly autumn olive in overstory, plus Quercus rubra.

Horizon	Depth	Description
	--cm--	
O	5-0	Partially decomposed mixed leaf litter.
^A	0-10	Dark grayish brown (10YR 4/2) very gravelly silt loam; moderate granular structure; friable; many (6) very fine, common (2) fine, and few (0.5) coarse roots; 35% rock fragments by volume (35% gravels); low relative bulk density; no packing voids; clear smooth boundary.
^Bw	10-37	Dark grayish brown (10YR 4/2) extremely stony loam, with few (1%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (3) fine and few (0.5) coarse roots; 80% rock fragments by volume (30% gravels, 25% stones, 20% cobbles, 5% boulders); high relative bulk density; no packing voids; clear wavy boundary.
^BC	37-77	Brown (10YR 4/3) extremely cobbly sandy loam, with common (3%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (1) fine and few (0.2) medium roots; 75% rock fragments by volume (35% gravels, 30% cobbles, 10% stones); high relative bulk density; few packing voids; gradual wavy boundary.
^C	77-125+	Dark yellowish brown (10YR 4/4) extremely gravelly sandy loam, with common (3%) yellowish brown (10YR 5/8) lithochromic color variegations; structureless massive; friable; few (0.2) fine and (0.2) coarse roots; 65% rock fragments by volume (40% gravels, 20% cobbles, 5% stones); medium relative bulk density; no packing voids.

Remarks: Several large stones near the surface of pit face and a large 100cm by 100cm boulder dug from pit. 1% of coarse fragments in ^C horizon (77-125+cm) are carboliths.

COP Plot 36
Date Sampled: 9-27-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone with no amendment - control
Vegetation: Allegheny blackberry, Lespedeza cuneata, tall fescue, native ferns, Erigeron sp., poison ivy, Solidago altissima var. altissima, Rudbeckia hirta, some Ulmus sp. Seedlings. Northern red oak (Quercus rubra) and Sassafras albidum in overstory.

Horizon	Depth	Description
	--cm--	
O	6-0	Partially decomposed mixed leaf litter.
^A	0-10	Very dark grayish brown (10YR 3/2) gravelly loam; moderate granular structure; friable; many (12) very fine and common (2) fine, (2) coarse, and (1) very coarse roots; 30% rock fragments by volume (30% gravels); low relative bulk density; no packing voids; clear smooth boundary.
^BA	10-27	Very dark grayish brown (10YR 3/2) very gravelly sandy loam; weak subangular blocky structure; friable; many (7) very fine, common (2) fine and (1) coarse, and few (0.5) very coarse roots; 40% rock fragments by volume (40% gravels); medium relative bulk density; no packing voids; clear wavy boundary.
^Bw	27-52	Brown (10YR 4/3) very gravelly sandy loam, with few (1%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (2) very fine and few (0.3) coarse roots; 55% rock fragments by volume (35% gravels, 20% cobbles); high relative bulk density; no packing voids; clear irregular boundary.
^C	52-125+	Dark yellowish brown (10YR 4/4) very gravelly sandy loam, with common (10%) brown (10YR 4/3) and (3%) yellowish brown (10YR 5/8) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; structureless massive; friable; common (1) fine and few (0.5) coarse and (0.1) very coarse roots; 50% rock fragments by volume (30% gravels, 15% cobbles, 5% stones); medium relative bulk density; no packing voids.

Remarks: Pit caved in around edges.

COP Plot 39
Date Sampled: 9-27-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone amended with 30 cm topsoil.
Vegetation: (<20% cover), some Allegeny blackberry, tall fescue and Acer rubrum seedlings. Northern red oak (Quercus rubra) in overstory.

Horizon	Depth	Description
	--cm--	
O	3-0	Partially decomposed mixed leaf litter.
^A	0-8	Very dark grayish brown (10YR 3/2) very gravelly loam; moderate granular structure; friable; many (6) very fine and common (2) fine and (1) coarse roots; 40% rock fragments by volume (40% gravels); low relative bulk density; no packing voids; clear smooth boundary.
^AB	8-17	Dark yellowish brown (10YR 4/4) very gravelly sandy loam, with many (20%) very dark grayish brown (10YR 3/2) and common (10%) light yellowish brown (10YR 6/4) lithochromic color variegations; moderate subangular blocky structure; friable; common (3) very fine, (3) fine, and (1) coarse and few (0.2) very coarse roots; 45% rock fragments by volume (40% gravels, 5% cobbles); low relative bulk density; no packing voids; abrupt wavy boundary.
^Bw	17-44	Brown (10YR 4/3) extremely gravelly sandy loam, with common (3%) yellowish brown (10YR 5/8) lithochromic color variegations; weak subangular blocky structure; friable; common (1) very fine and few (0.2) coarse roots; 75% rock fragments by volume (40% gravels, 20% cobbles, 10% boulders 5% stones); medium relative bulk density; no packing voids; clear irregular boundary.
^C	44-125+	Dark brown (10YR 3/3) extremely gravelly sandy loam, with common (3%) yellowish brown (10YR 5/8) and (5%) light yellowish brown (10YR 6/4) lithochromic color variegations; structureless massive; friable; few (0.5) very fine and (0.1) coarse roots; 80% rock fragments by volume (40% gravels, 20% boulders, 10% stones, 10% cobbles); medium relative bulk density; no packing voids.

COP Plot 43
Date Sampled: 9-28-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone with no amendment - control
Vegetation: (<40% cover). Unknown grass, broomsedge, Allegheny blackberry, Rudbeckia hirta, Solidago altissima var. altissima. Tulip poplars and Northern red oaks (Quercus rubra) in overstory.

Horizon	Depth	Description
	--cm--	
O	5-0	Partially decomposed mixed leaf litter.
^A	0-7	Very dark grayish brown (10YR 3/2) gravelly silt loam; moderate granular structure; friable; common (4) very fine and (2) fine and few (0.5) very coarse roots; 36% rock fragments by volume (36% gravels); low relative bulk density; no packing voids; clear wavy boundary.
^Bw	7-27	Dark brown (10YR 3/3) very gravelly loam; moderate subangular blocky structure; friable; many (5) very fine and common (2) fine and (1) very coarse roots; 55% rock fragments by volume (40% gravels, 10% stones, 5% cobbles); low relative bulk density; no packing voids; clear irregular boundary.
^BC	27-57	Brown (10YR 4/3) extremely gravelly sandy loam, with common (3%) yellowish brown (10YR 5/8) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; moderate subangular blocky structure; friable; common (1) very fine and few (0.2) medium roots; 75% rock fragments by volume (45% gravels, 20% stones, 10% cobbles); high relative bulk density; few packing voids; gradual irregular boundary.
^C1	57-87	Dark brown (10YR 3/3) extremely gravelly sandy loam, with common (3%) yellowish brown (10YR 5/8) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; structureless massive; friable; few (0.2) very fine and (0.1) coarse roots; 70% rock fragments by volume (45% gravels, 20% cobbles, 5% stones); medium relative bulk density; few packing voids; gradual wavy boundary.
^C2	87-125+	Very dark gray (10YR 3/1) extremely gravelly sandy loam, with common (10%) dark brown (10YR 3/3) and few (1%) yellowish brown (10YR 5/8) lithochromic color variegations; structureless massive; friable; few (0.5) medium and (0.5) coarse roots; 70% rock fragments by volume (50% gravels, 20% cobbles); medium relative bulk density; few packing voids.

Remarks: Profile was directly under a red oak tree.

COP Plot 44
Date Sampled: 9-28-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone amended with 112 Mg/ha sawdust
Vegetation: (<60% cover). Solidago altissima var. altissima, Clematis virginiana, tall fescue, Lespedeza cuneata, and Allegheny blackberry. Quercus rubra and Acer rubrum in overstory.

Horizon	Depth	Description
	--cm--	
O	5-0	Partially decomposed mixed leaf litter.
^A	0-14	Very dark brown (10YR 2/2) very gravelly loam; moderate granular; friable; many (6) very fine and common (2) medium, fine (1) and (1) coarse roots; 40% rock fragments by volume (40% gravels); low relative bulk density; no packing voids; abrupt wavy boundary.
^BA	14-27	Brown (10YR 4/3) extremely gravelly sandy loam, many (25%) very dark grayish brown (10YR 3/2) lithochromic color variegations; weak subangular blocky; friable; common (3) very fine and few (0.5) coarse roots; 65% rock frag. by vol. (40% gravels, 20% cobbles, 5% stones); med. relative bulk density; no packing voids; gradual wavy boundary.
^Bw	27-47	Dark yellowish brown (10YR 4/4) extremely gravelly sandy loam, with few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; weak subangular blocky structure; friable; common (1) very fine and few (0.5) coarse roots; 80% rock fragments by volume (40% gravels, 20% cobbles, 10% boulders, 10% stones); high relative bulk density; no packing voids; gradual irregular boundary.
^BC	47-77	Dark brown (10YR 3/3) extremely stony sandy loam, with common (10%) dark yellowish brown (10YR 4/4) and few (1%) yellowish brown (10YR 5/8) and light yellowish brown (10YR 6/4) lithochromic color variegations; weak subangular blocky structure; friable; common (1) fine and few (0.5) coarse roots; 80% rock fragments by volume (30% gravels, 20% stones, 20% cobbles, 10% boulders); high relative bulk density; few packing voids; clear irregular boundary.
^Cu	77-125+	Dark yellowish brown (10YR 4/4) extremely gravelly sandy loam, with common (10%) dark yellowish brown (10YR 4/4) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; structureless massive; very friable; common (3) very fine and few (0.2) coarse and (0.2) very coarse roots; 61% rock fragments by volume (40% gravels, 10% stones, 10% cobbles, 1% boulders); medium relative bulk density; few packing voids.
Remarks:		1% carboliths in ^A horizon (0-14cm). Foil bag buried at 100 cm.

COP Plot 46
Date Sampled: 9-28-2016
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 near 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.

COP Plot 47
Date Sampled: 9-22-2016
Described and Sampled by: D. Johnson, J. Buckwalter
Parent Material: 2:1 Sandstone:siltstone amended with 56 Mg/ha sewage sludge
Vegetation: (~75% cover). Allegheny blackberry, tall fescue, Solidago altissima var. altissima, Solidago sp., some Lespedeza cuneata and Dichanthelium sp. Northern red oak (Quercus rubra) in overstory. Carya sp near plot.

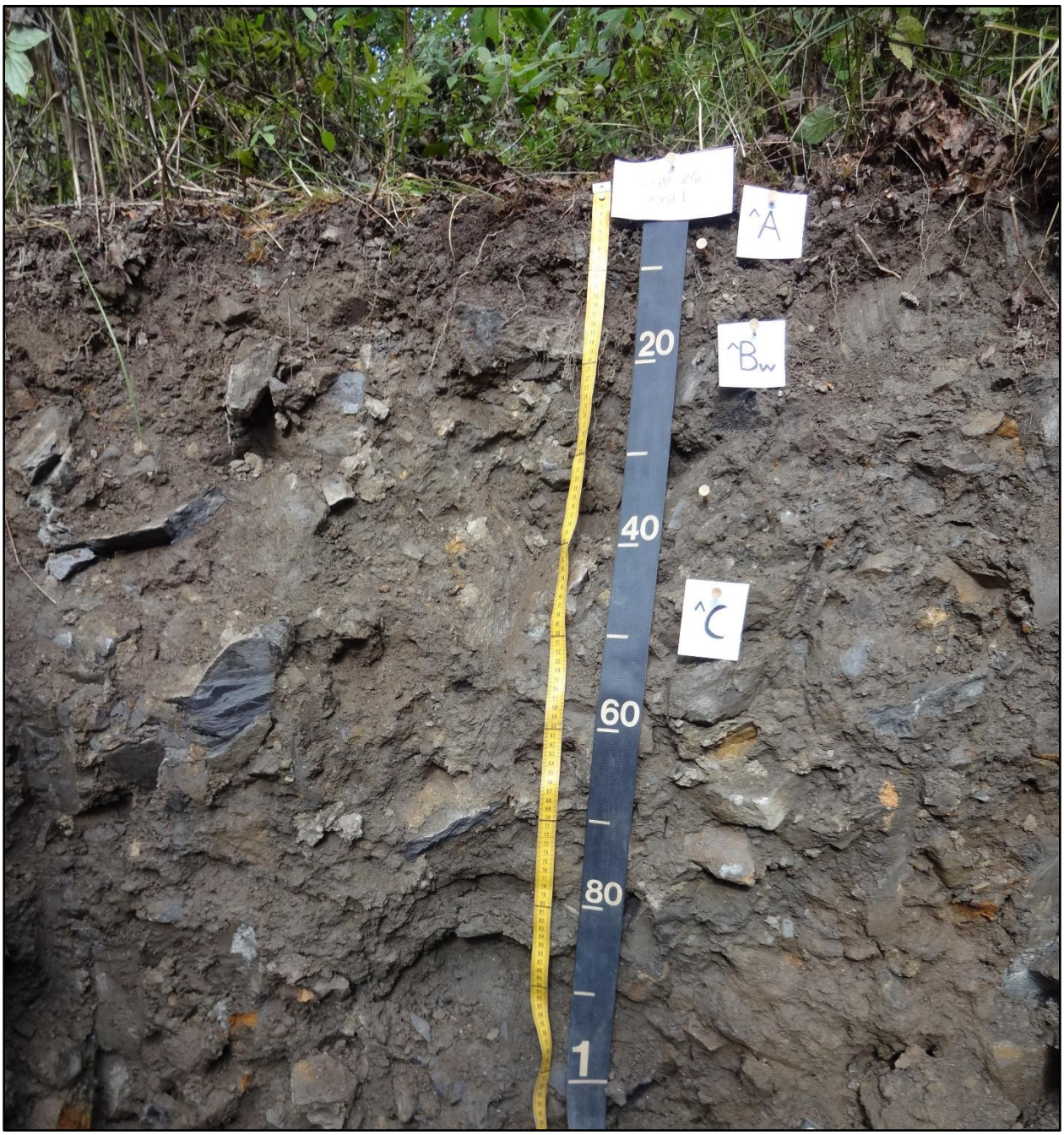
Horizon	Depth	Description
	--cm--	
O	6-0	Partially decomposed mixed leaf litter.
^A	0-10	Very dark grayish brown (10YR 3/2) very gravelly loam; moderate granular structure; friable; many (6) very fine, common (1) coarse, and few (0.5) very coarse roots; 40% rock fragments by volume (40% gravels); low relative bulk density; no packing voids; clear smooth boundary.
^BA	10-24	Dark grayish brown (10YR 4/2) extremely gravelly loam; moderate subangular blocky structure; friable; common (3) very fine and (1) coarse roots; 60% rock fragments by volume (40% gravels, 20% cobbles); medium relative bulk density; no packing voids; clear wavy boundary.
^Bw	24-50	Dark yellowish brown (10YR 4/6) extremely gravelly sandy loam, with many (30%) very dark grayish brown (10YR 3/2) lithochromic color variegations; moderate subangular blocky structure; friable; common (1) very fine roots; 65% rock fragments by volume (35% gravels, 20% cobbles, 10% stones); high relative bulk density; no packing voids; gradual wavy boundary.
^BC	50-69	Dark yellowish brown (10YR 4/6) extremely gravelly sandy loam, with common (3%) yellowish brown (10YR 5/8) and few (1%) light yellowish brown (10YR 6/4) lithochromic color variegations; weak subangular blocky structure; friable; few (0.5) very fine roots; 65% rock fragments by volume (35% gravels, 20% cobbles, 10% stones); medium relative bulk density; no packing voids; gradual wavy boundary.
^C	69-125+	Dark yellowish brown (10YR 4/4) extremely gravelly sandy loam, with many (30%) very dark grayish brown (10YR 3/2), common (5%) yellowish brown (10YR 5/8), and few (2%) light yellowish brown (10YR 6/4) lithochromic color variegations; structureless massive; very friable; few (0.3) fine roots; 75% rock fragments by volume (40% gravels, 20% cobbles, 15% stones); medium relative bulk density; few packing voids.

Appendix A3: Soil Profile Photos of Rock Mix and Surface Amendment Treatments in August and September 2016.

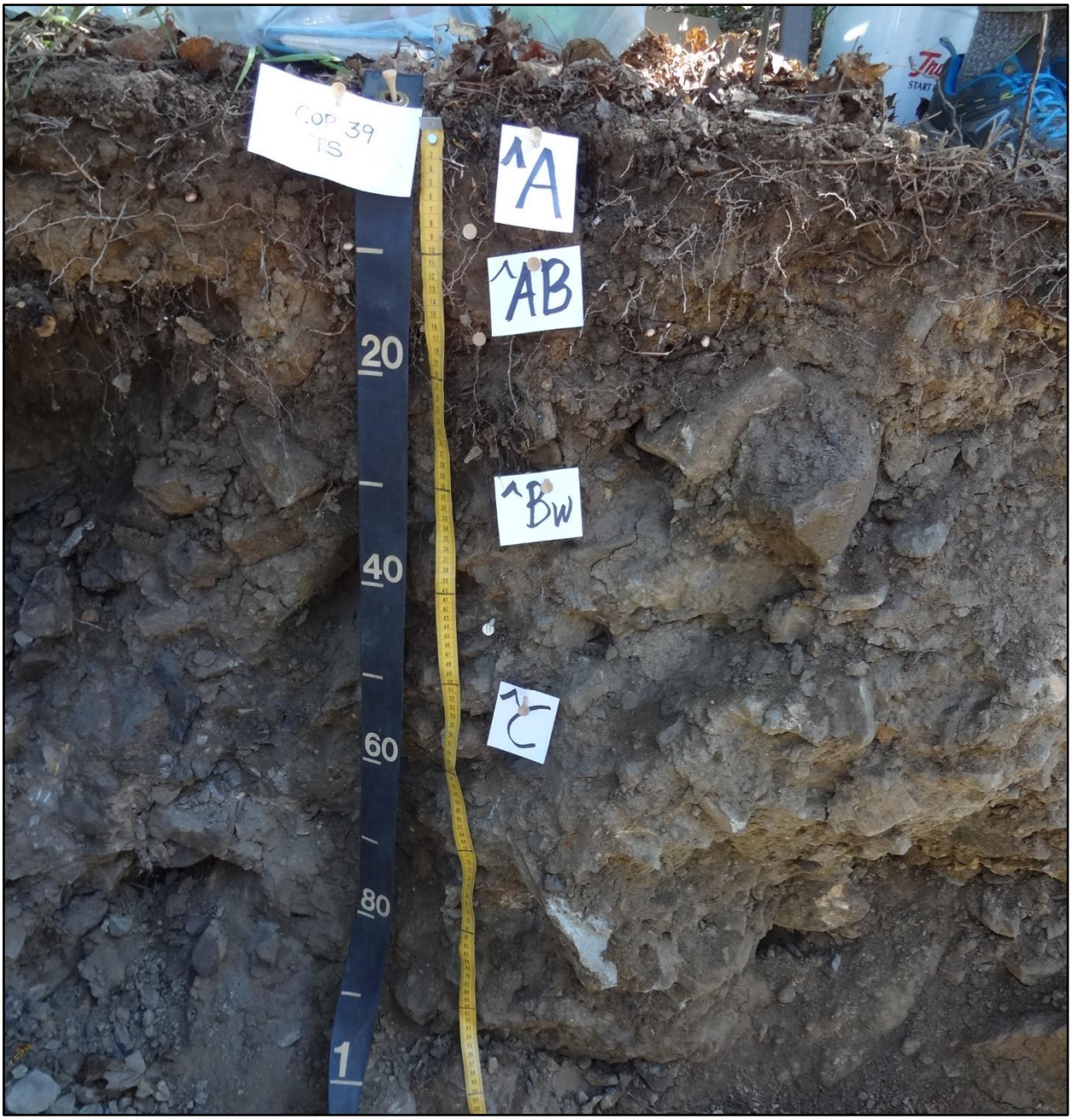
100% Sandstone, Plot No. 7

1:1 SS:SiS, Plot No. 2

100% SiS, Plot No. 14



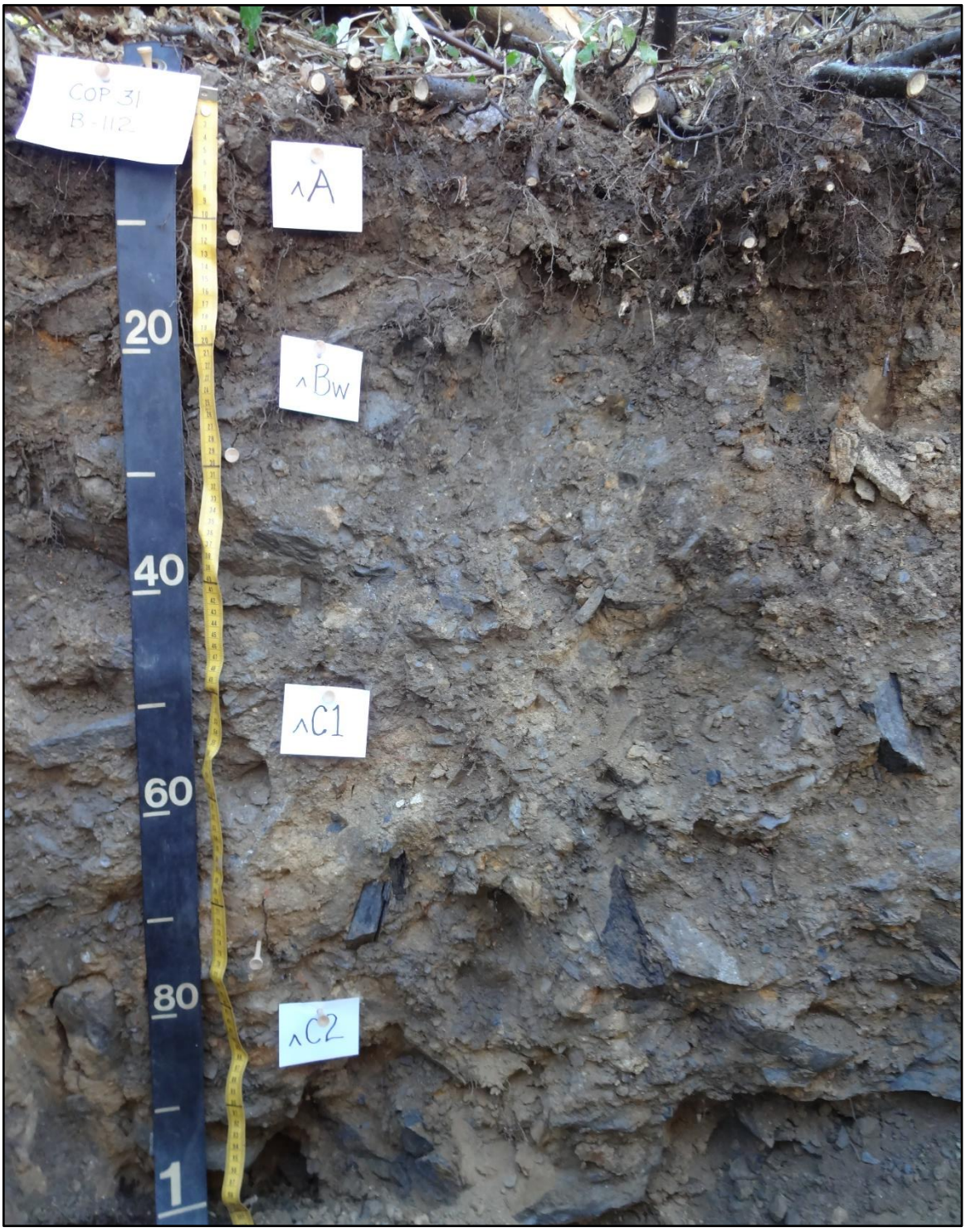
Control (2:1 SS:SiS only, no amendment), Plot No. 26



Topsoil (30 cm), Plot No. 39

Sawdust (112 Mg ha^{-1}), Plot No. 35

Biosolids (56 Mg ha^{-1}), Plot No. 47



Biosolids (112 Mg ha^{-1}), Plot No. 31

Appendix B: Mineral Sands Mine Land Reconstruction and Final Reclamation Protocols

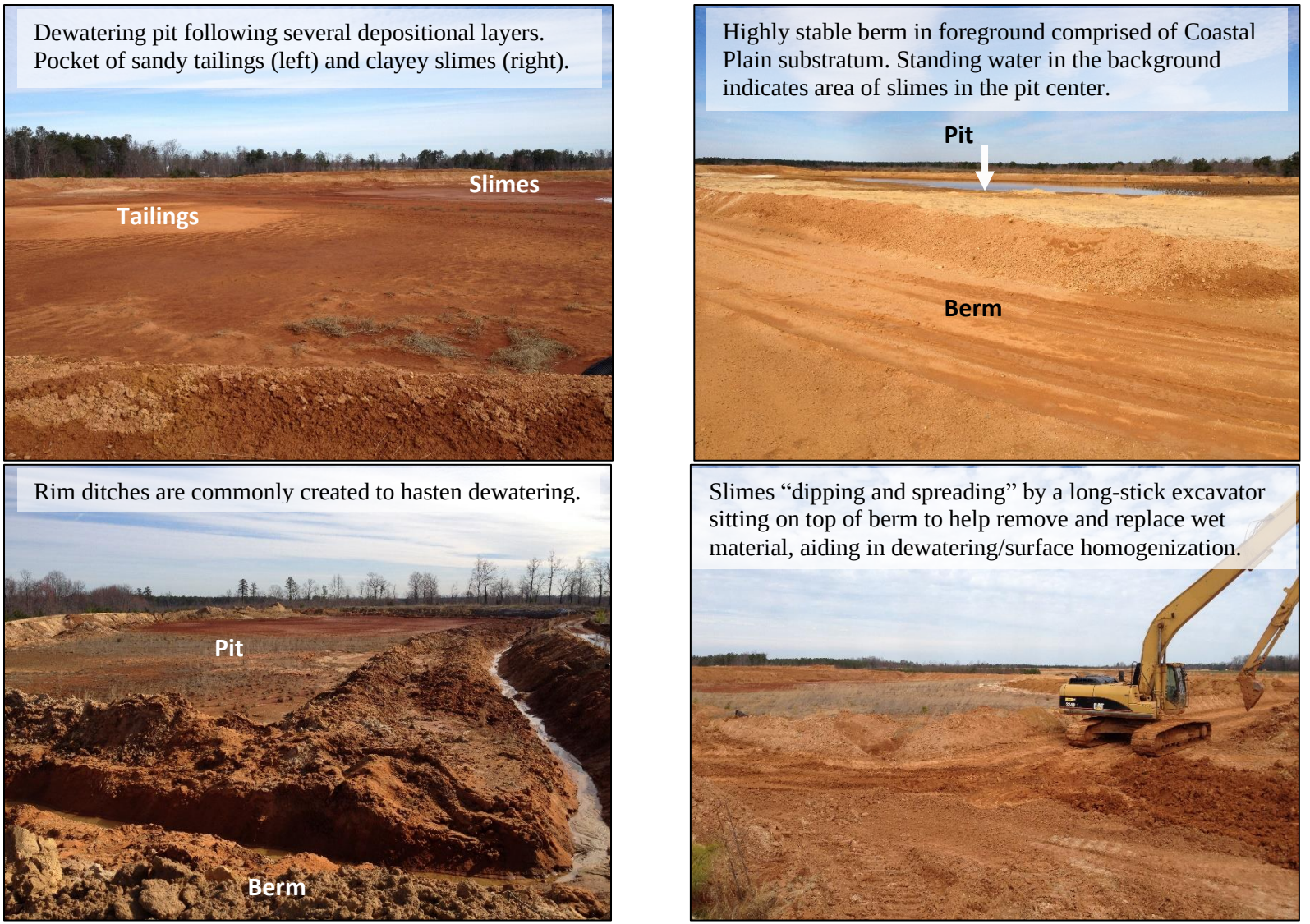


Figure B1. Images of the mine pit dewatering process (no specific order). Note that this process takes months to several years.

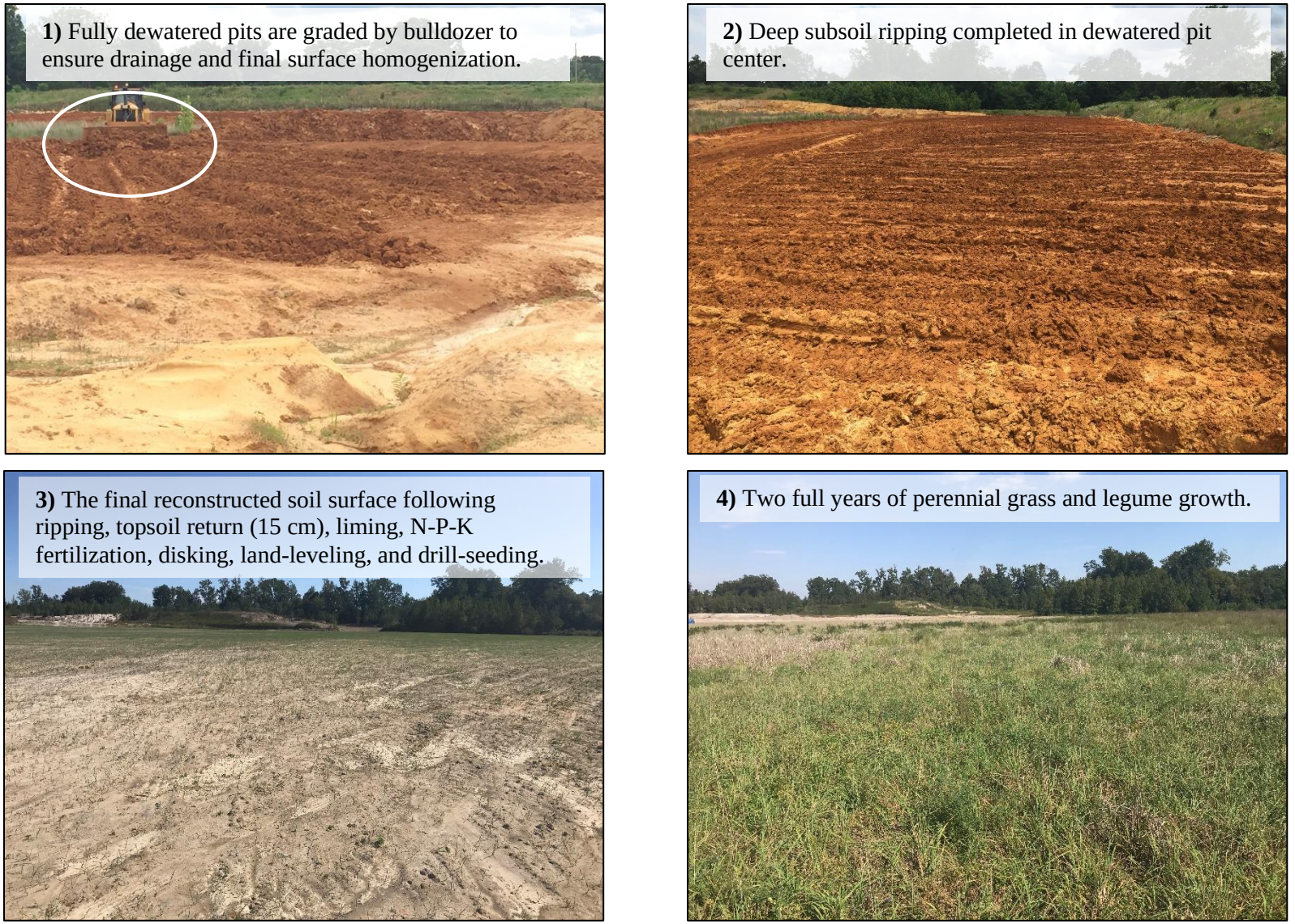


Figure B2. Sequential images of the final mined land reconstruction process, which occurs following complete pit dewatering.

Appendix C1: Land Reconstruction Study (LRS) Location and Associated Soil X Landform Images

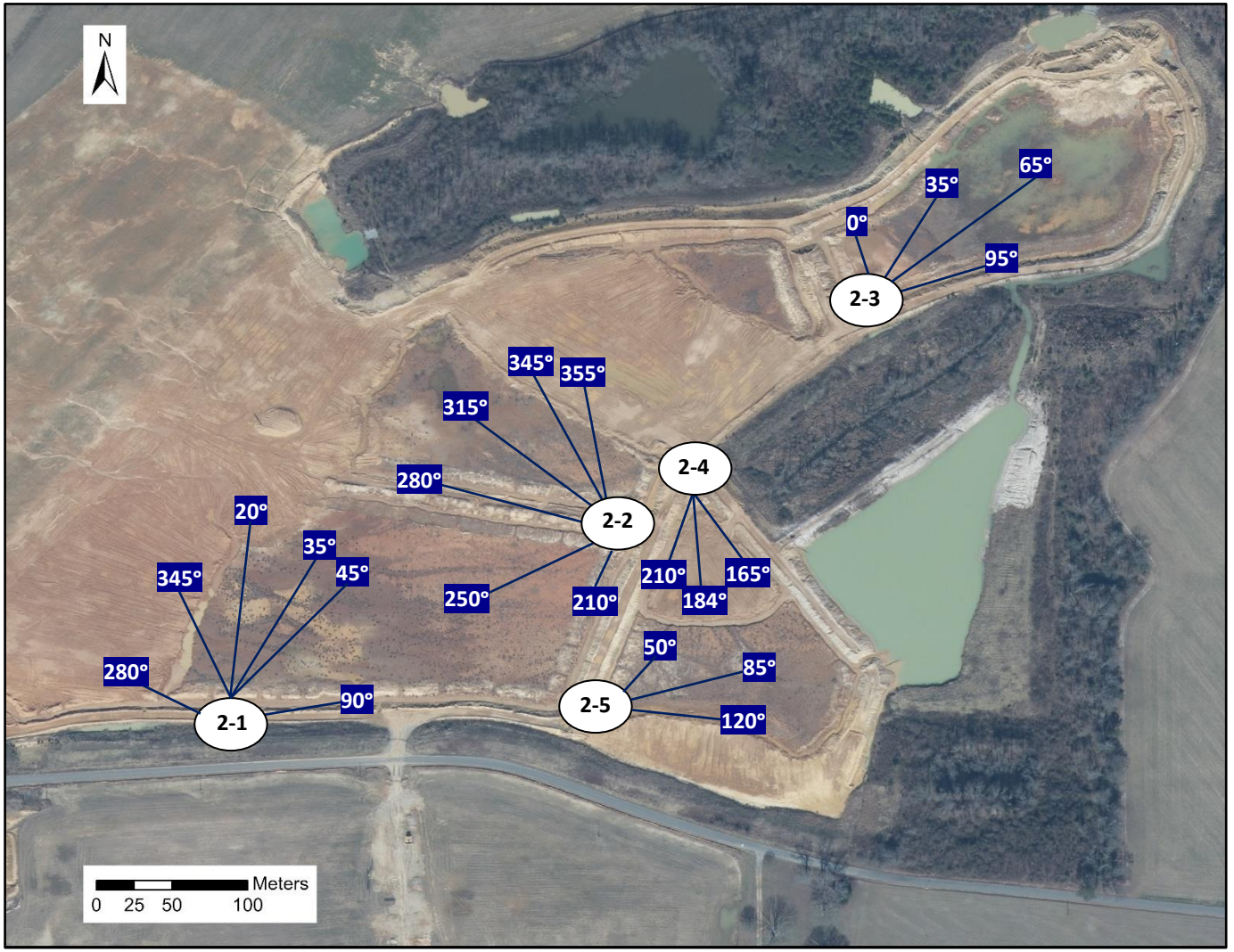


Figure C1.1. Five photo-monitoring GPS points and associated azimuths at the LRS site.

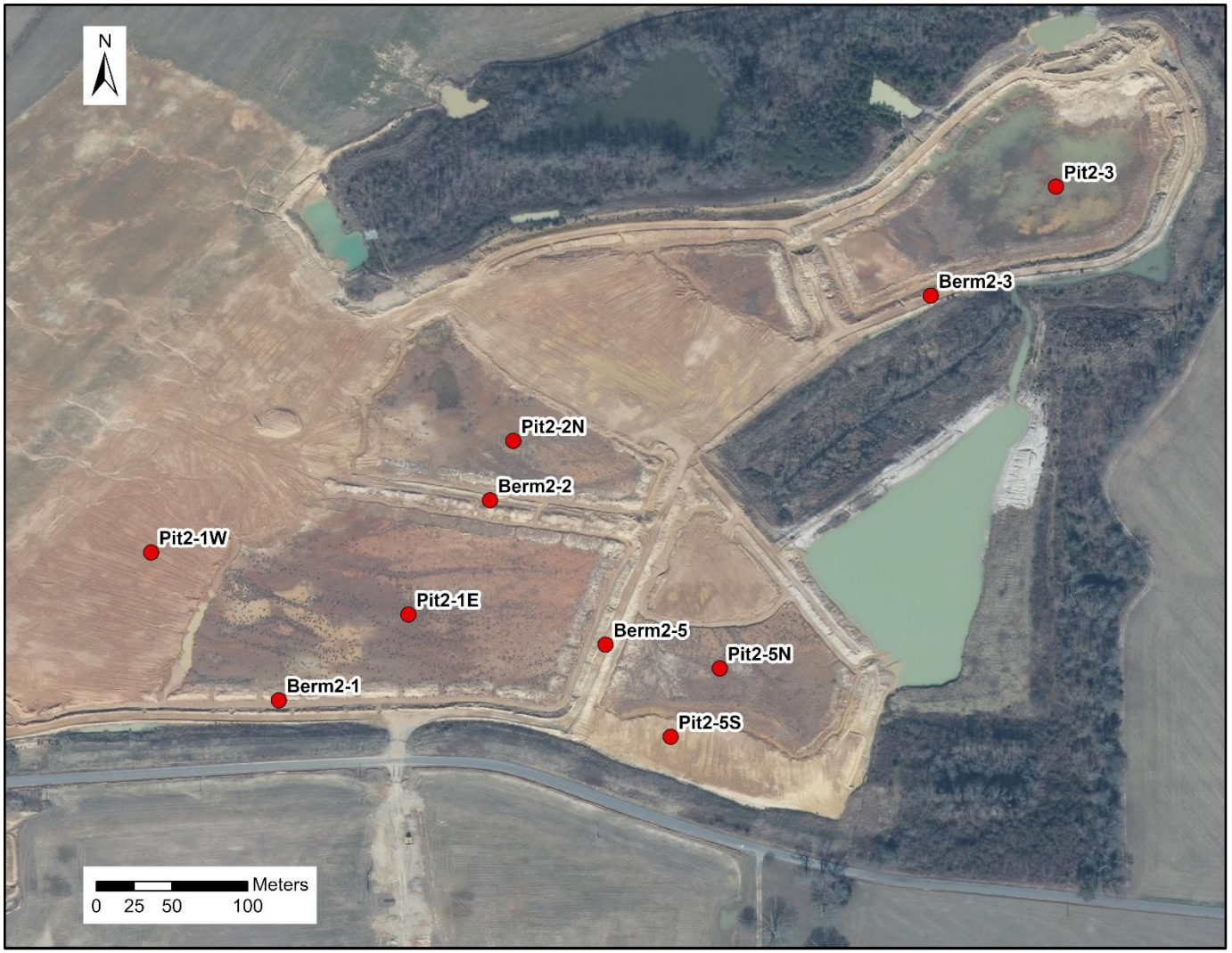
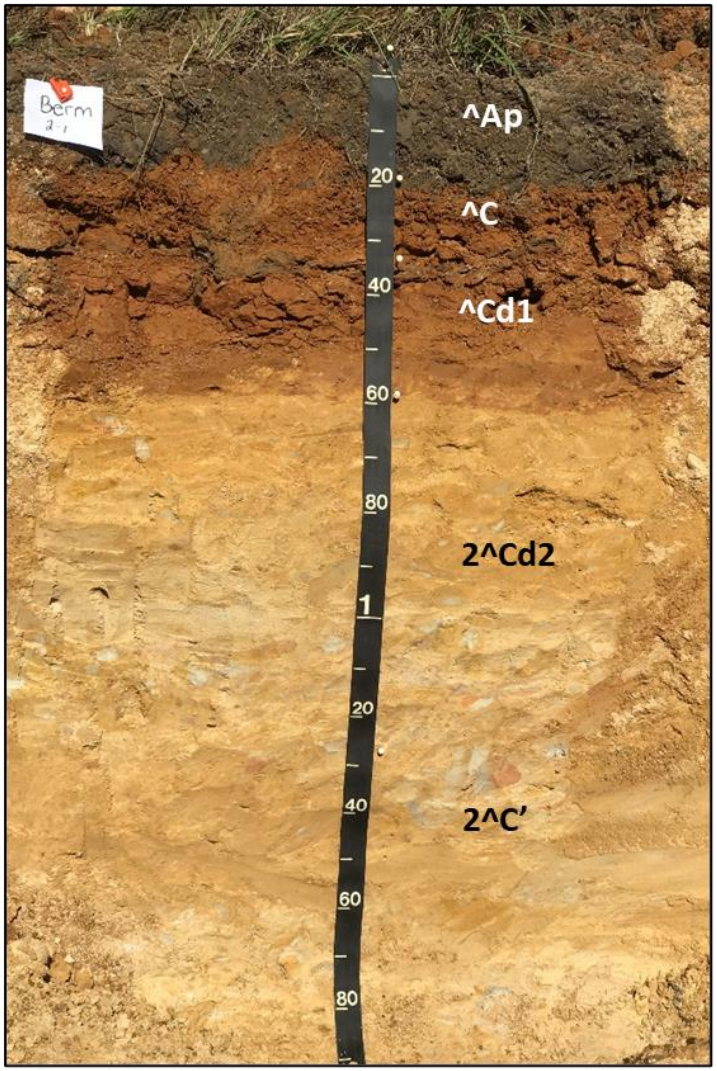
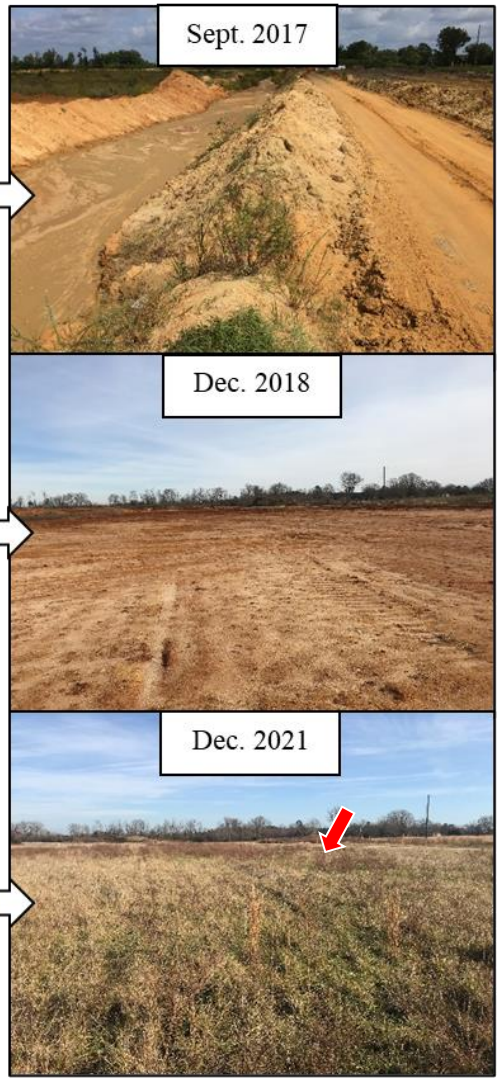


Figure C1.2. GPS locations for ten mine soil profiles described in October 2021.

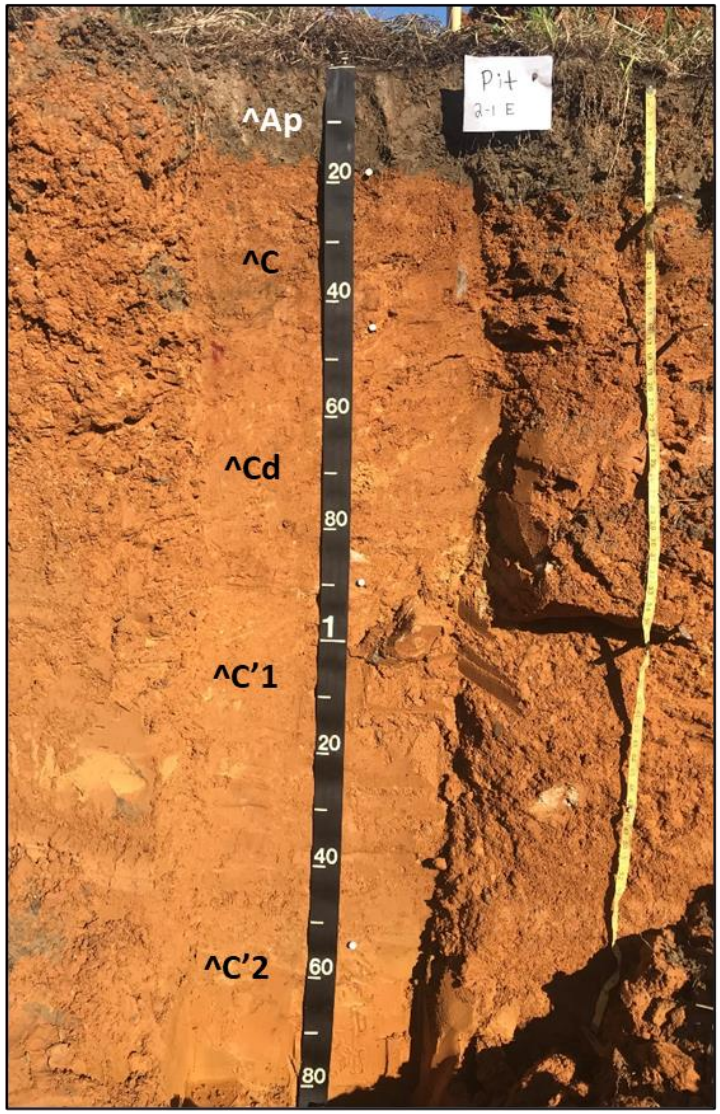
Location: Berm 2 - 1
Date: 10/19/2021
Described by H. Angel and J. Galbraith

LR2 - 1 90˚ photo-monitoring view. Arrow represents location of the soil profile described in October 2021.

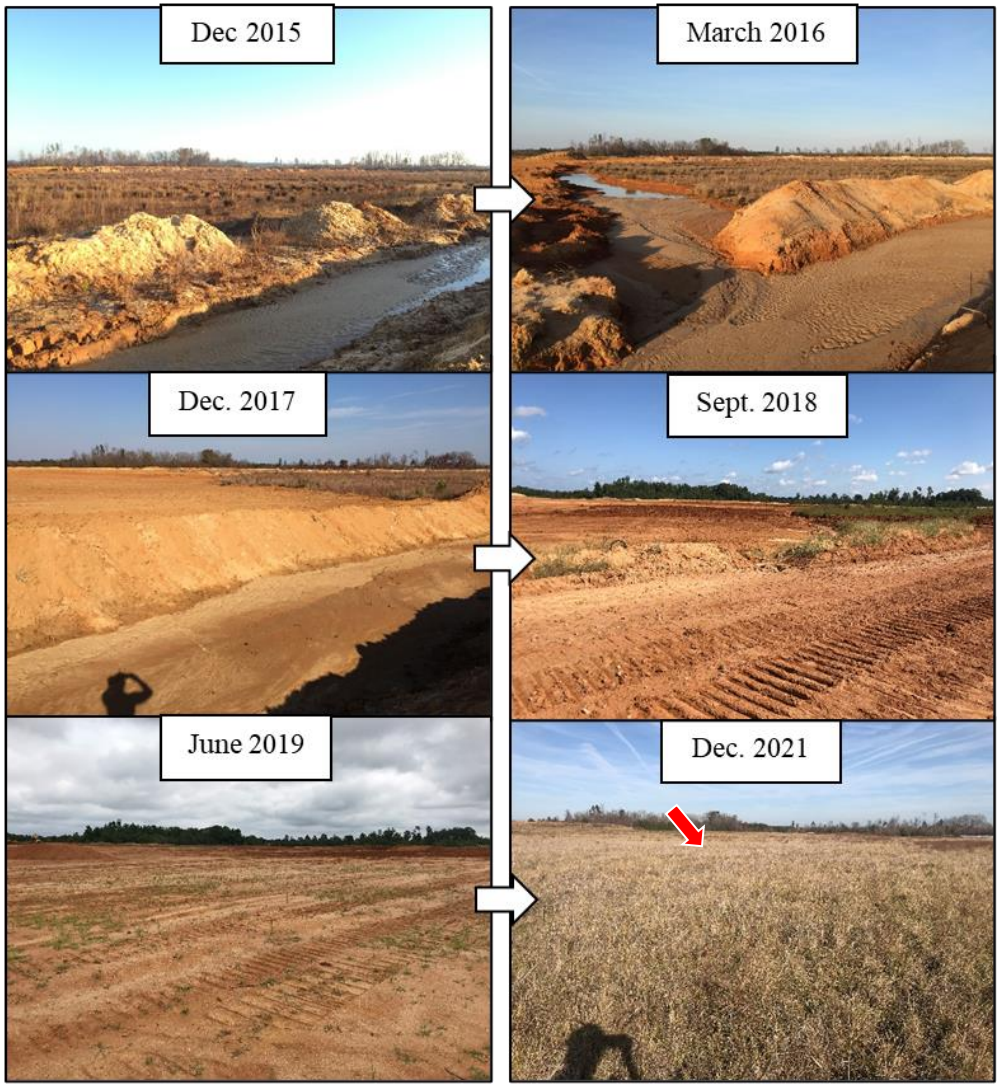




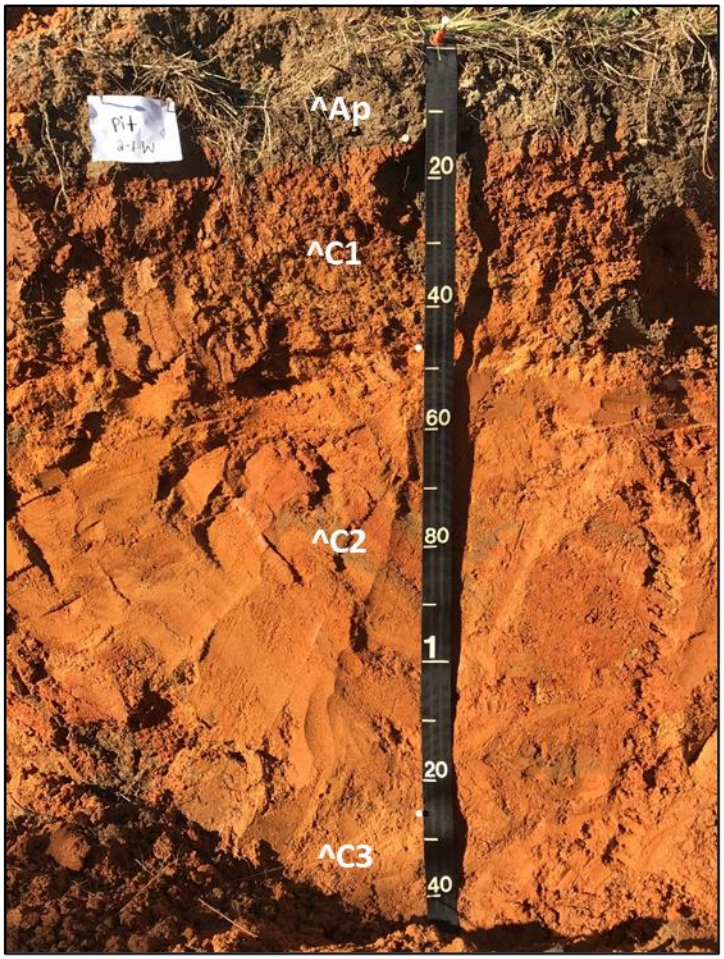
Location: Pit 2 - 1E
Date: 10/18/2021
Described by H. Angel and J. Galbraith



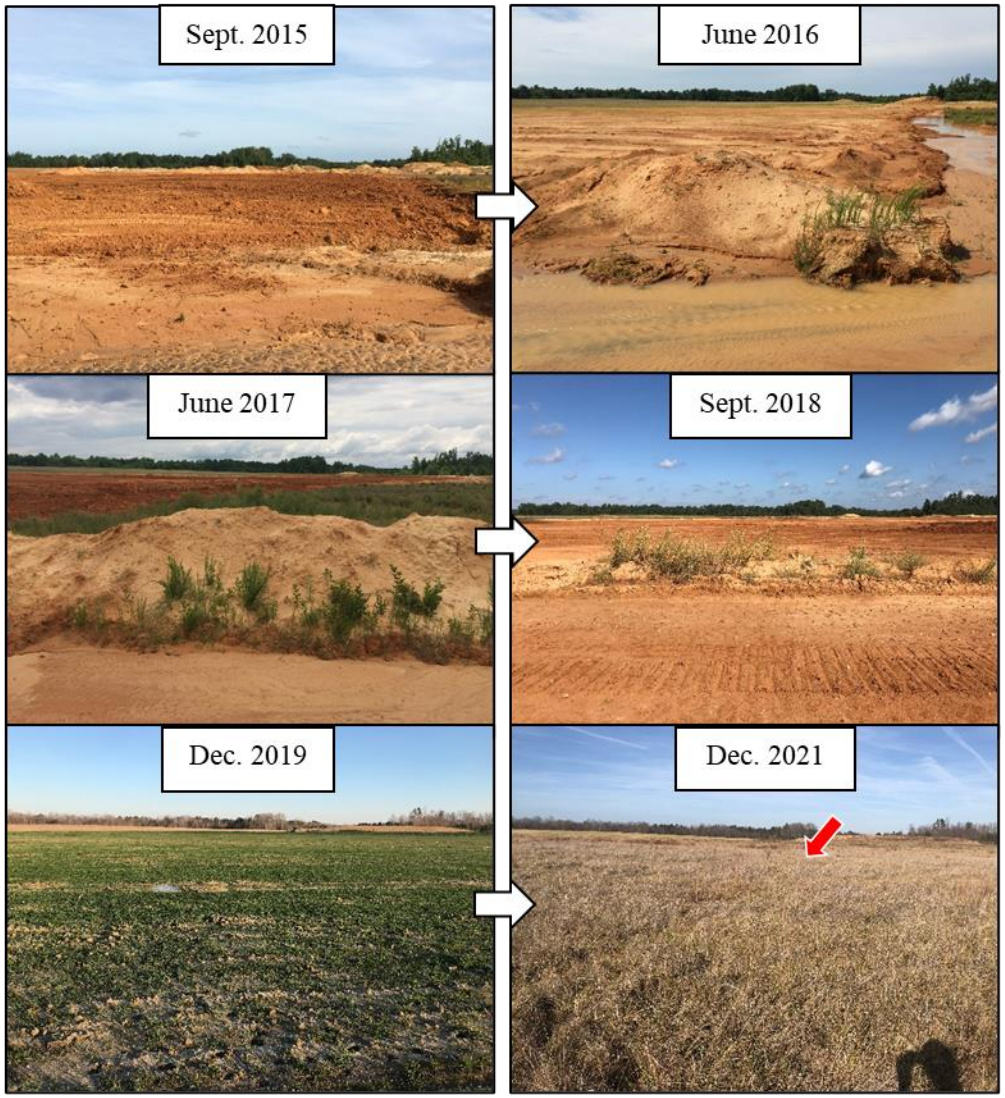
LR2 - 1 45° photo-monitoring view. Arrow represents location of the soil profile described in October 2021.



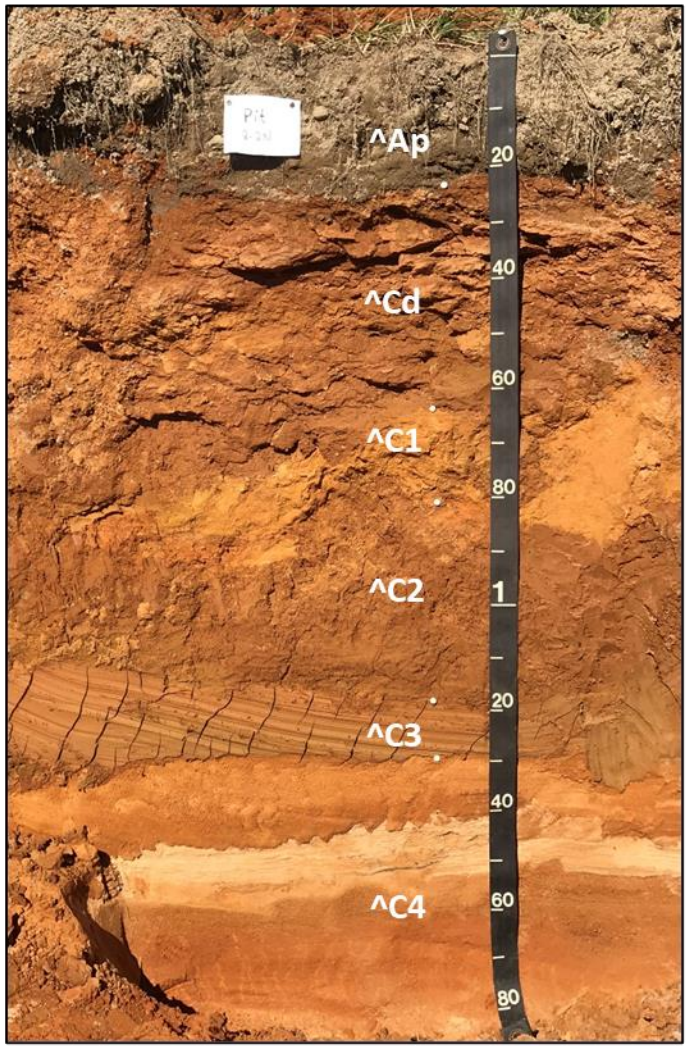
Location: Pit 2 - 1W
Date: 10/18/2021
Described by H. Angel and J. Galbraith



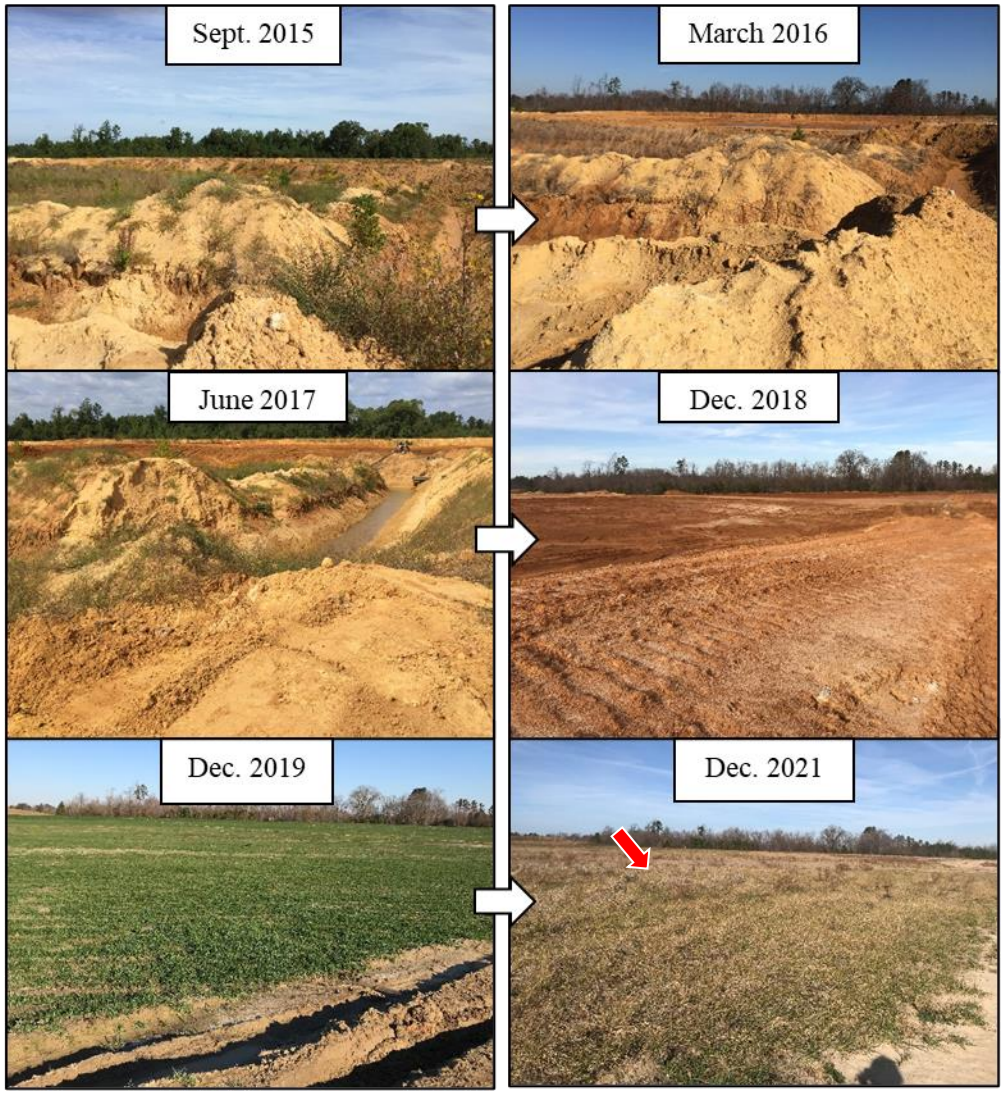
LR2 - 1 20˚ photo-monitoring view. Arrow represents location of the soil profile described in October 2021.



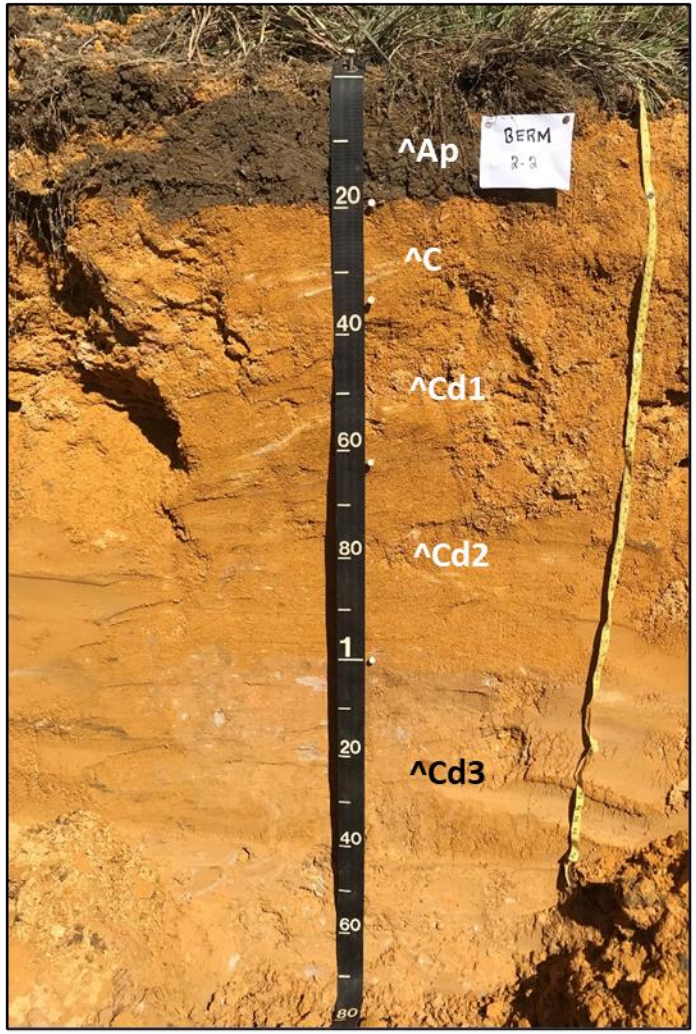
Soil Location/Landform: Pit 2 - 2N
Date: 10/18/2021
Described by H. Angel and J. Galbraith



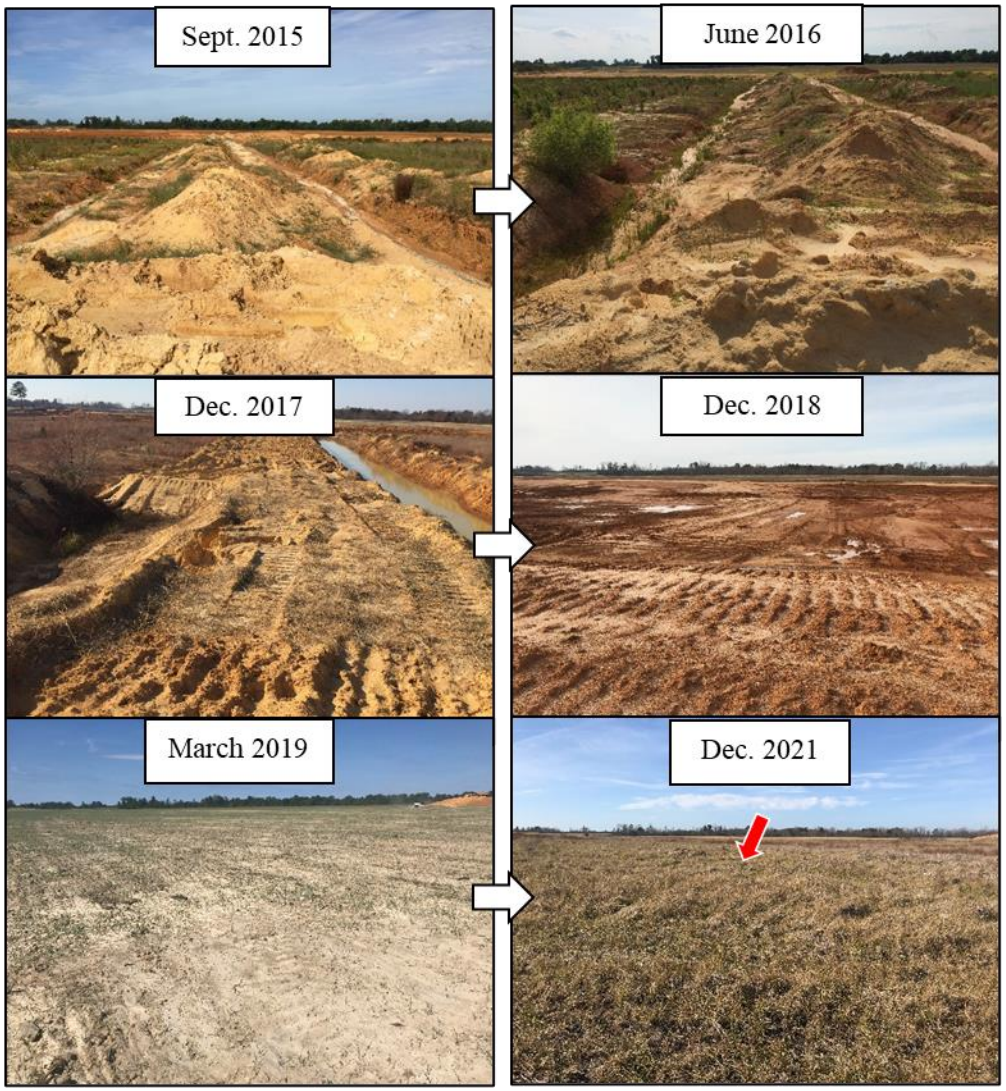
LR2 - 2 355° photo-monitoring view. Arrow represents location of the soil profile described in October 2021.



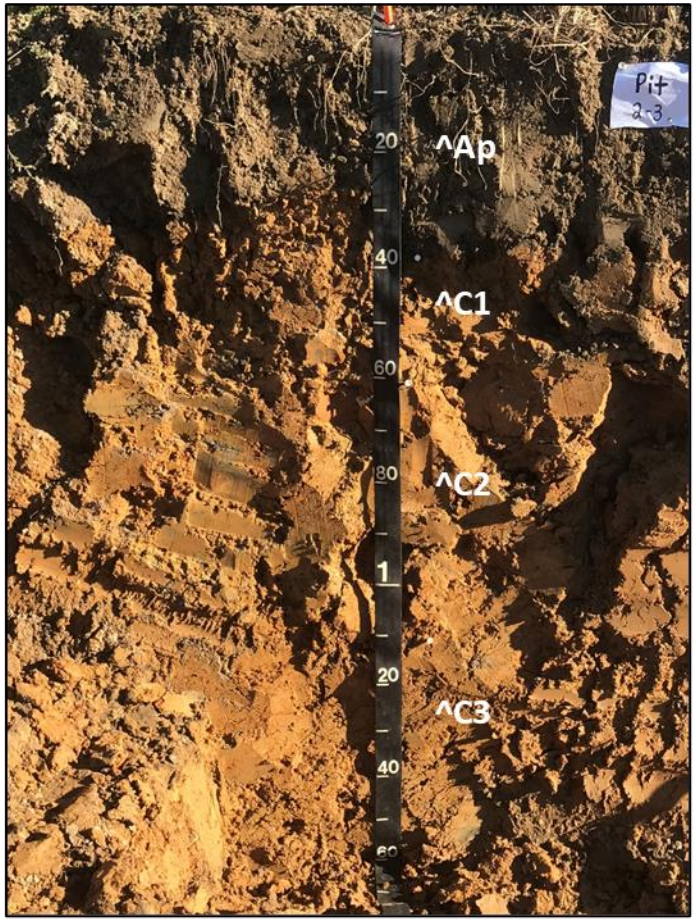
Soil Location/Landform: Berm 2 - 2
Date: 10/18/2021
Described by H. Angel and J. Galbraith



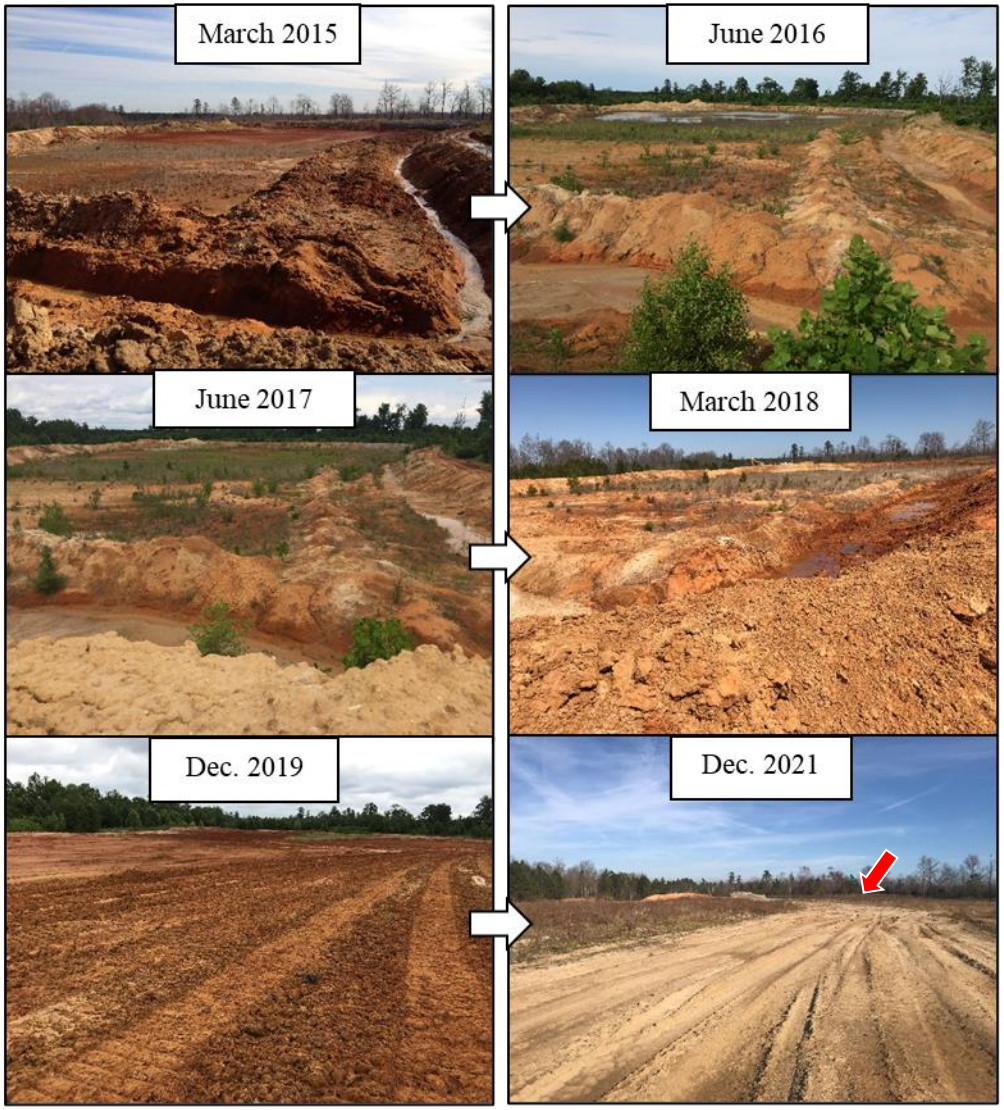
LR2 - 2 280° photo-monitoring view. Arrow represents location of the soil profile described in October 2021.



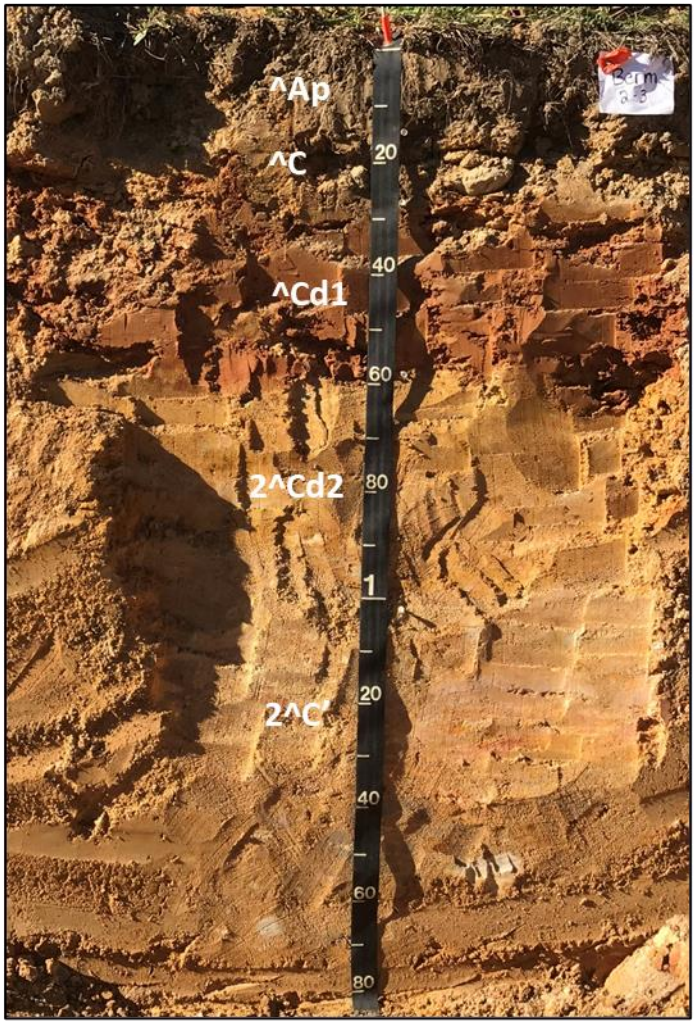
Soil Location/Landform: Pit 2 - 3
Date: 10/19/2021
Described by H. Angel and J. Galbraith



LR2 - 3 65° photo-monitoring view. Arrow represents location of the soil profile described in October 2021.

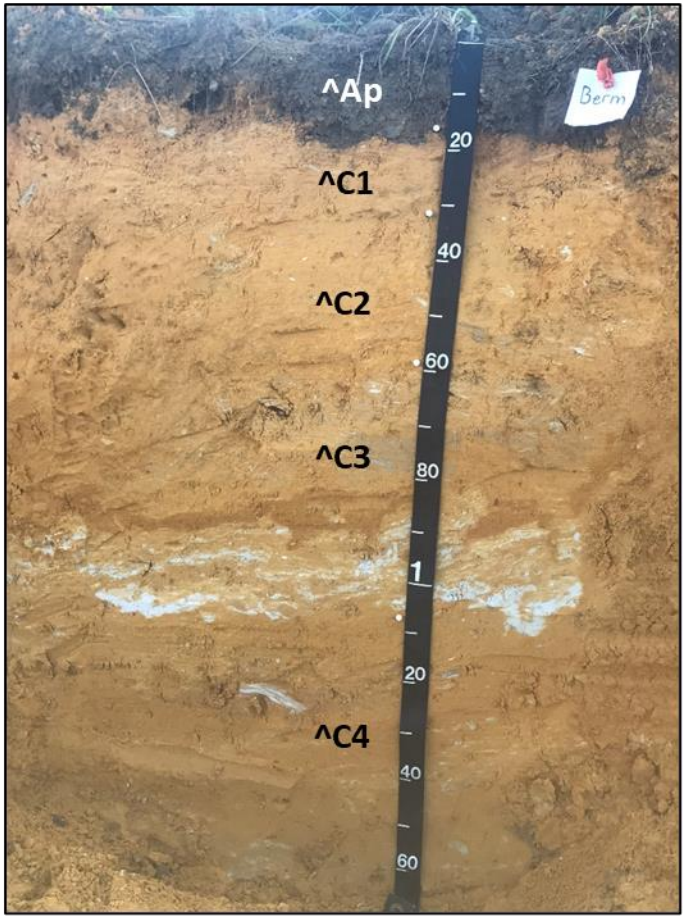


Soil Location/Landform: Berm 2 - 3
Date: 10/19/2021
Described by H. Angel and J. Galbraith



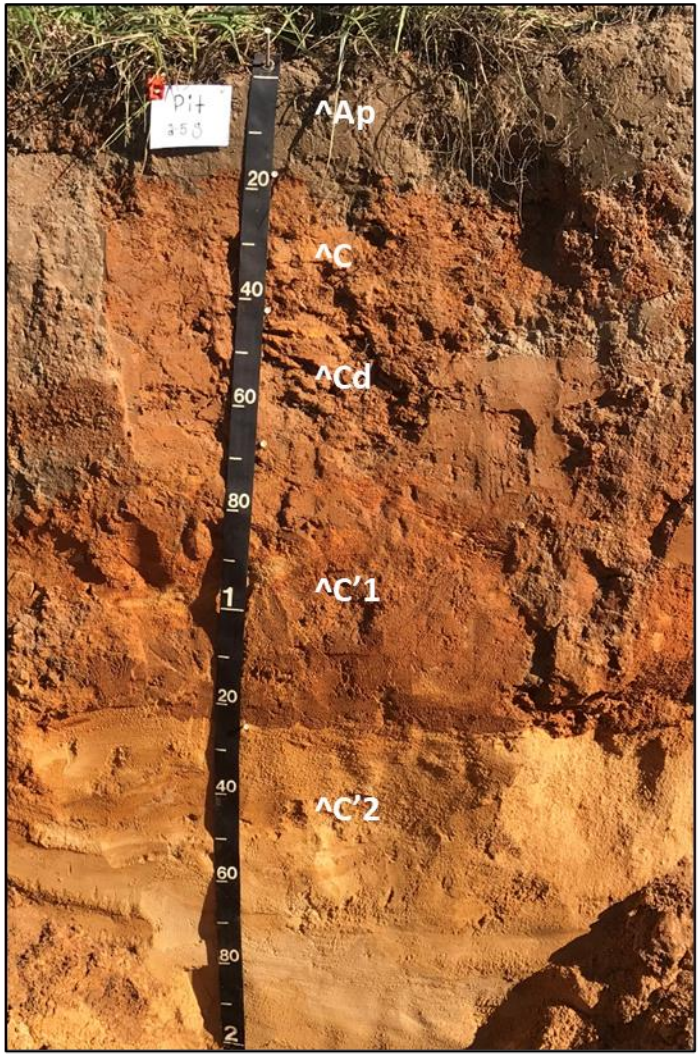
LR2 - 3 95° photo-monitoring view. Arrow represents location of the soil profile described in October 2021.

Soil Location/Landform: Berm 2 - 5
Date: 10/19/2021
Described by H. Angel and J. Galbraith

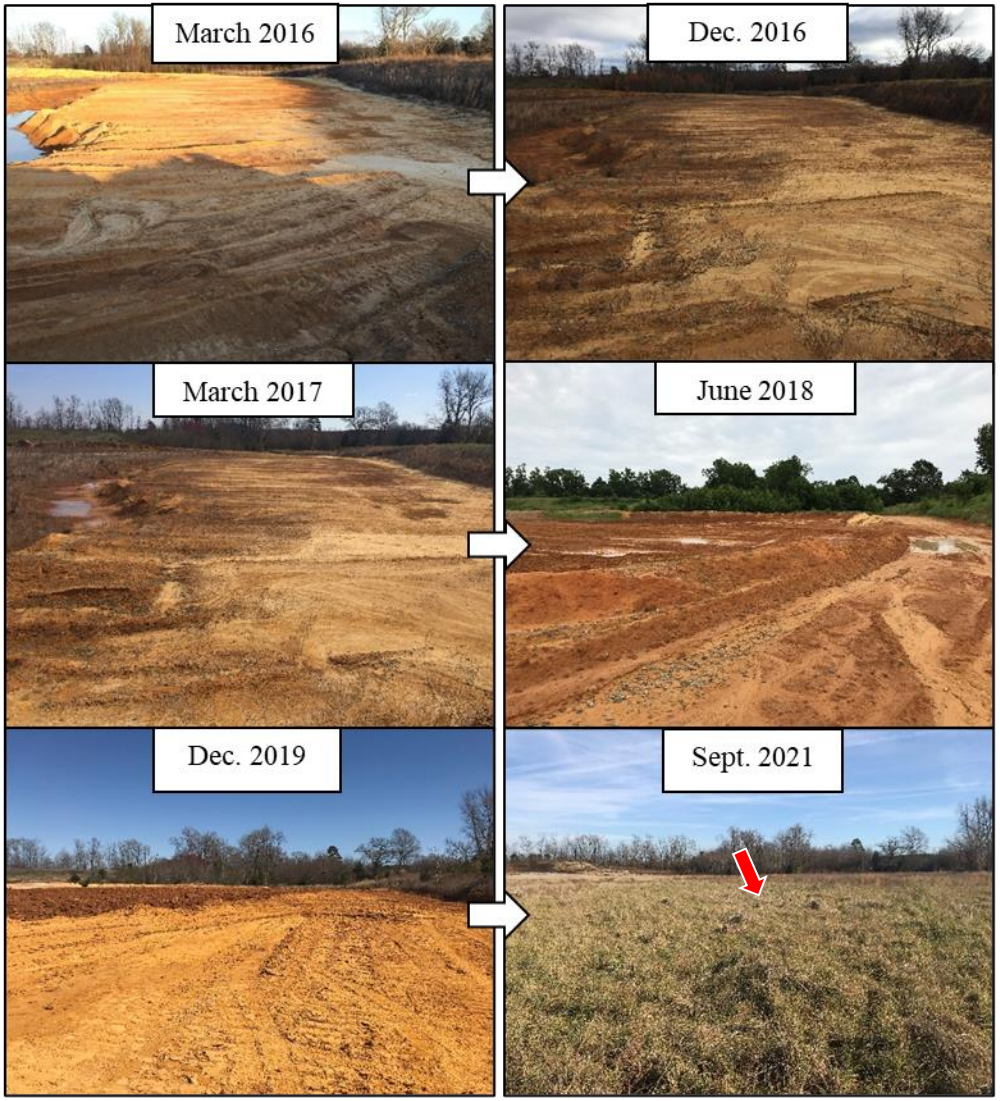


LR2 - 4 210° photo-monitoring view. Arrow represents location of the soil profile described in October 2021.

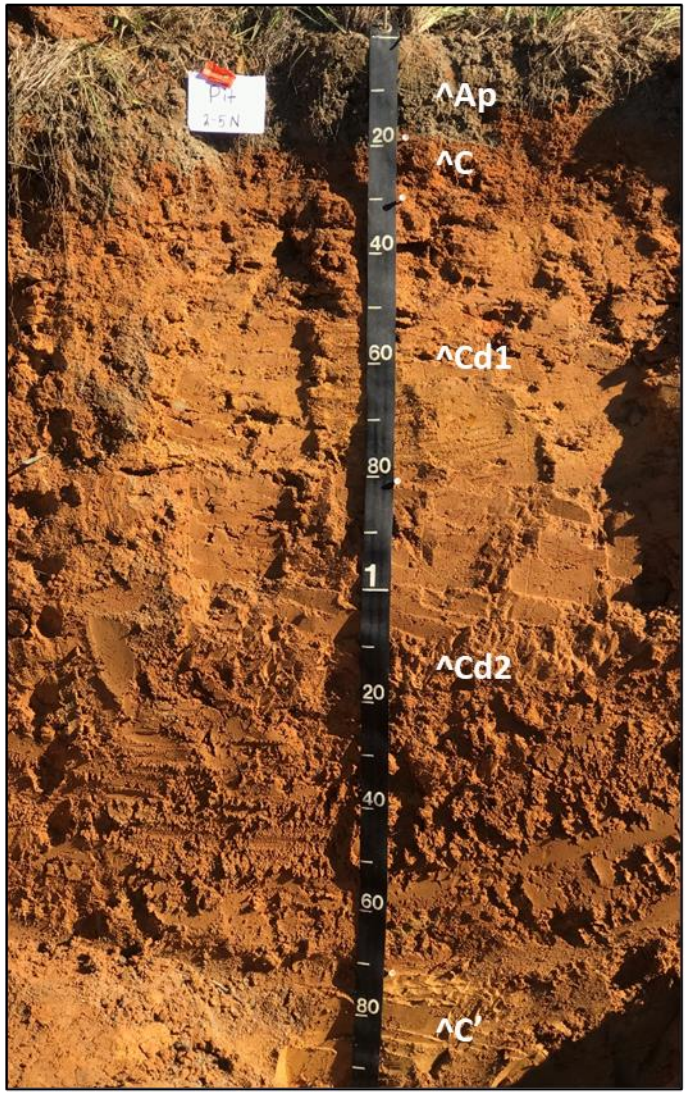
Soil Location/Landform: Pit 2 - 5S
Date: 10/19/2021
Described by H. Angel and J. Galbraith



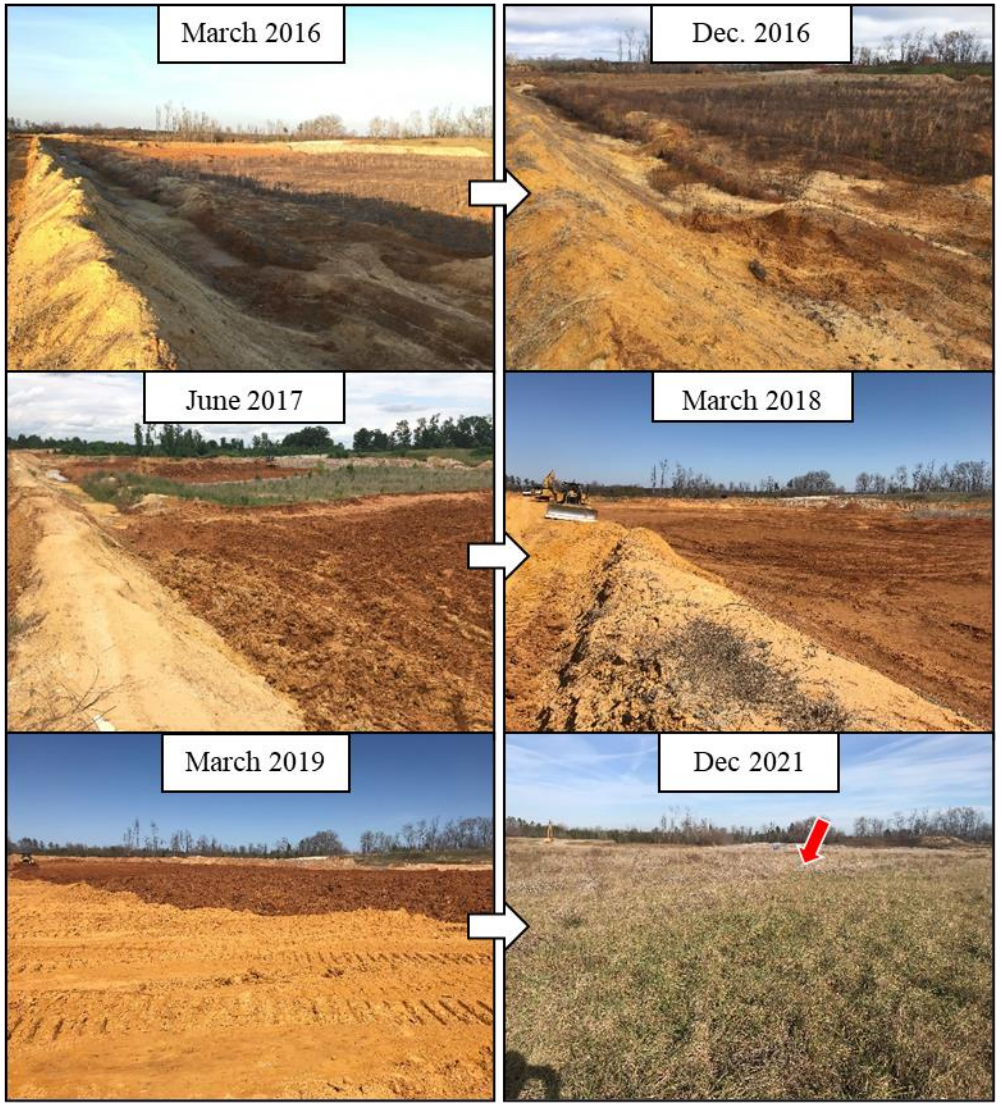
LR2 - 5 120° photo-monitoring view. Arrow represents location of the soil profile described in October 2021. (Note: No images collected in 2015).



Soil Location/Landform: Pit 2 - 5N
Date: 10/19/2021
Described by H. Angel and J. Galbraith

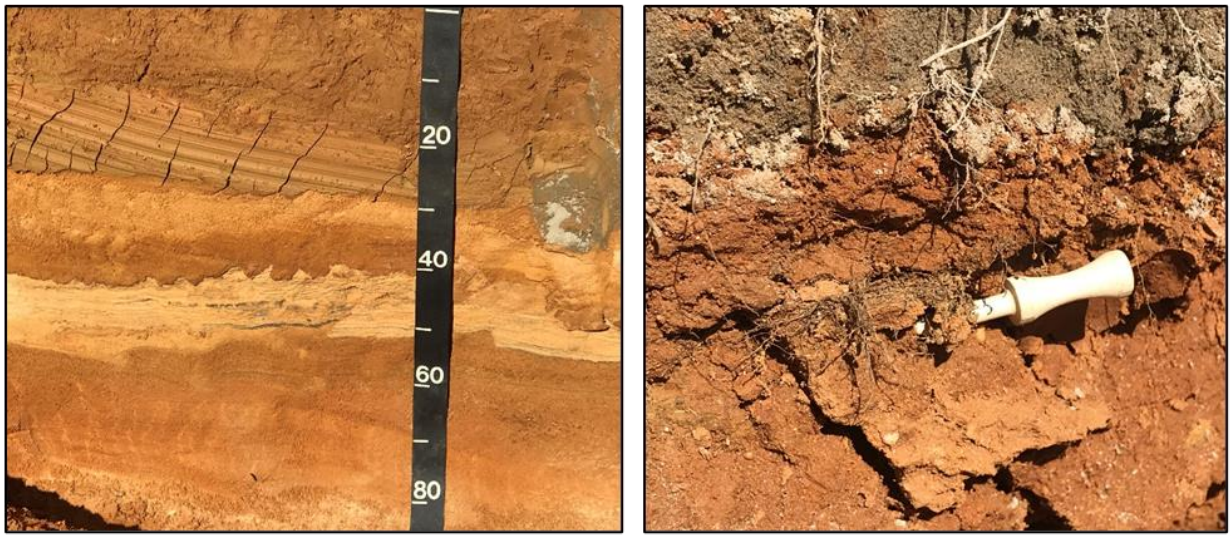


LR2 - 5 50˚ photo-monitoring view. Arrow represents location of the soil profile described in October 2021. (Note: No images collected in 2015).



Special Features Observed in Profiles

Cloddy structure breaking into horizontal plates (left). Ripper trace (right). See Pit 2-1E profile image above.



Mineral sands and tailings banding (left). Matted roots between plates; golf tee for scale (right). See Pit 2-2N profile image above.

Saprolite clod (left) and lens (right) in the lower profile (> 90 cm). See Berm 2-5 profile image above.

Matted roots concentrated along a prominent plate (left) and thin redox concentration (yellowish red, 5YR 5/8) layer directly underneath the ^Ap horizon (right). See Berm 2-2 profile image above.

Appendix C2: Full Soil Profile Descriptions at the LRS Site.

Horizon	Depth (cm)	Description†
		Berm 2-1
^Ap	0-19	Very dark gray (10YR 3/1); sandy clay loam; fine to medium sbk-shaped cloddy; friable; common very fine to medium roots concentrated in upper 5 cm; wavy abrupt boundary; bulk density of 1.53 g cm^{-3}.
^C	19-35	Strong brown (7.5YR 5/8); sandy clay loam; medium to coarse sbk-shaped cloddy; friable to firm; few very fine to fine roots; wavy abrupt boundary; bulk density of 1.54 g cm^{-3}.
^Cd1	35-60	Strong brown (7.5YR 5/8); sandy clay loam; very thick platy (10-40 mm diam.); extra firm; very few very fine roots; wavy abrupt boundary; bulk density of 1.76 g cm^{-3}.
2^Cd2	60-127	Brownish yellow 10YR 6/6 (60%), white 10YR 8/2 (35%), and white 10YR 8/1 (5%); sandy loam; structureless (sls) massive; firm to very firm; no roots; wavy abrupt boundary.
2^C'	127-180 +	Brownish yellow 10YR 6/6 (70%) and white 10YR 8/2 (30%); sandy loam; sls massive; friable; no roots; wavy abrupt boundary.
		Pit 2-1E
^Ap	0-18	Dark grayish brown (2.5Y 4/2); fine sandy loam; medium sbk-shaped cloddy; very friable; common very fine to fine roots concentrated in upper 5 cm; 5% redox concentrations (5YR 5/8) and 15% depletions (2.5Y 4/1) as soft masses/root linings; smooth abrupt boundary; bulk density of 1.57 g cm^{-3}.
^C	18-43	Dark grayish brown (10YR 4/6); sandy clay loam; very coarse sbk-shaped cloddy; friable; few very fine to fine roots; 1% redox concentrations (5YR 5/4) and 5% depletions (10YR 5/4) along root channels; smooth abrupt boundary; bulk density of 1.54 g cm^{-3}.
^Cd	43-89	Strong brown (7.5YR 5/6); sandy clay loam; very thick cloddy plates (20-30 mm diameter); firm to extra firm; very few very fine roots; smooth abrupt boundary; bulk density of 1.65 g cm^{-3}.
^C'1	89-155	Strong brown (7.5YR 5/6); sandy clay loam; sls massive; friable; no roots; smooth abrupt boundary.
^C'2	155-180 +	Brownish yellow (10YR 6/6); silty clay loam; sls massive; friable; no roots; smooth abrupt boundary.
		Pit 2-1W
^Ap	0-13	Dark grayish brown (10YR 4/2); fine sandy loam; fine to medium sbk-shaped cloddy; very friable; common very fine roots concentrated in upper 5 cm; 1% redox concentrations (7.5YR 5/4) and 1% depletions (10YR 5/2) as soft masses; smooth abrupt boundary; masses of slimes (5%); bulk density of 1.57 g cm^{-3}.

^C1	13-46	Yellowish red (5YR 5/6); sandy clay loam; very thick platy (10-30 mm diam.); friable; few very fine roots; wavy abrupt boundary; tailings/slimes inclusions (5%); bulk density of 1.46 g cm^{-3}.
^C2	46-125	Yellowish red (5YR 5/8); fine sandy loam; sls massive; friable; no roots; wavy abrupt boundary; uniformly mixed mineral sands, tailings, and slimes (40%); bulk density of 1.60 g cm^{-3}.
^C3	125-160 +	Reddish yellow (5YR 6/8); fine sand; single grain; loose; no roots; wavy abrupt boundary.
		Pit 2-2N
^Ap	0-22	Dark grayish brown (10YR 4/2); fine sandy loam; fine sbk-shaped cloddy (stronger within upper 10 cm); friable; common very fine to fine roots; 5% redox concentrations (5YR 5/8) as soft masses/root linings and 5% soft mass depletions (10YR 5/2); smooth abrupt boundary; bulk density of 1.57 g cm^{-3}.
^Cd	22-63	Yellowish red (5YR 5/6); sandy clay loam; medium to coarse cloddy plates; firm to very firm; few very fine roots concentrated in upper 10 cm; smooth abrupt boundary; bulk density of 1.57 g cm^{-3}.
^C1	63-81	Brownish yellow (10YR 6/6); loamy fine sand; sls massive; very friable; no roots; wavy abrupt boundary; bulk density of 1.41 g cm^{-3}.
^C2	81-119	Strong brown (7.5YR 5/6); sandy clay loam; sls massive; friable; no roots; smooth abrupt boundary.
^C3	119-130	Yellowish brown (10YR 5/6); silty clay; sls massive; friable; no roots; smooth abrupt boundary.
^C4	130-200 +	Reddish yellow 7.5YR 6/8 (~142 cm), pink 7.5YR 7/4 (~153 cm), strong brown 7.5YR 5/6 (~166 cm), and strong brown 7.5YR 5/8 (~190 cm); stratified fine (~25%) and coarse (~25%) sand; single grain; loose; no roots; smooth abrupt boundary.
		Berm 2-2
^Ap	0-19	Dark grayish brown (2.5Y 4/2); fine sandy loam; fine to medium sbk-shaped cloddy; very friable; common very fine to fine roots growing in mats; 5% redox concentrations (5YR 5/8) and 10% depletions (2.5Y 4/1) as soft masses/root linings; smooth abrupt boundary; bulk density of 1.55 g cm^{-3}.
^C	19-35	Brownish yellow (10YR 6/8); coarse sandy loam; 50:50 very thick platy and sls massive; very friable to friable; few very fine roots; smooth abrupt boundary; 4% red (2.5YR 5/8) and gray (10YR 6/1) saprolite masses; bulk density of 1.49 g cm^{-3}.
^Cd1	35-64	Brownish yellow (10YR 6/8); coarse sandy loam; very thick platy (20-30 mm diam.); firm, very few very fine roots growing in clusters; smooth abrupt boundary; 3% red (2.5YR 5/8) and gray (10YR 6/1) saprolite masses; bulk density of 1.69 g cm^{-3}.
^Cd2	64-100	Brownish yellow (10YR 6/8); coarse sandy loam; sls massive; firm; no roots; smooth abrupt boundary; 3% red (2.5YR 5/8) and gray (10YR 6/1) saprolite masses.

^Cd3	100-180 +	Light yellowish brown (10YR 6/4); fine sandy loam; sls massive; firm; no roots; smooth abrupt boundary; 6% red (2.5YR 5/8) and gray (10YR 6/1) saprolite masses.
		Pit 2-3
^Ap	0-39	Dark grayish brown (2.5Y 4/2); fine sandy loam; fine to very coarse sbk-shaped cloddy; very friable; common very fine to medium roots; 10% redox concentrations (5YR 5/8) and 15% depletions (10YR 5/2) as soft masses/root linings; wavy abrupt boundary; bulk density of 1.53 g cm^{-3}.
^C1	39-60	Yellowish brown (10YR 5/6); sandy clay loam; coarse to very coarse sbk-shaped cloddy (30-70 mm diam.) and very thick platy (10-20 mm diam.); friable (plates) to firm (clods); few very fine to fine roots; wavy abrupt boundary; 5% pebbles; bulk density of 1.59 g cm^{-3}.
^C2	60-110	Yellowish brown (10YR 5/6); sandy clay loam; sls massive; friable to very friable and ~25% firm clods; no roots; wavy abrupt boundary; bulk density of 1.63 g cm^{-3}.
^C3	110-160 +	Strong brown (7.5YR 5/6); sandy clay loam; sls massive; friable; no roots; wavy abrupt boundary.
		Berm 2-3
^Ap	0-15	Dark grayish brown (2.5Y 4/2); fine sandy loam; fine to medium sbk-shaped cloddy; friable; common very fine to fine roots; wavy abrupt boundary; bulk density of 1.53 g cm^{-3}.
^C	15-27	Yellowish brown (10YR 5/4); coarse sandy loam; very thick platy (10-20 mm diam.); friable to firm; few very fine to fine roots; wavy abrupt boundary; bulk density of 1.61 g cm^{-3}.
^Cd1	27-58	Strong brown (7.5YR 4/6); clay; very thick platy (10-40 mm diam.); extra firm; very few very fine roots; saprolite pink/white lense (2%); wavy abrupt boundary.
2^Cd2	58-102	Brownish yellow (10YR 6/8); coarse sandy loam; sls massive; firm to extra firm; no roots; wavy abrupt boundary; bulk density of 1.64 g cm^{-3}.
2^C'	102-200 +	Brownish yellow (10YR 6/6); coarse sandy loam; sls massive; friable to firm; no roots; soft masses of pink/white saprolite (5%); smooth abrupt boundary.
		Berm 2-5
^Ap	0-17	Dark grayish brown (10YR 4/2); fine sandy loam; fine sbk-shaped cloddy; friable; common very fine to fine roots; 3% redox concentrations (5YR 5/8) and 10% depletions (10YR 5/2) along ped surfaces; smooth abrupt boundary; bulk density of 1.62 g cm^{-3}.
^C1	17-31	Yellow (10YR 7/8); loamy fine sand; sls massive; loose; few very fine to fine roots; wavy abrupt boundary; bulk density of 1.47 g cm^{-3}.
^C2	31-59	Yellow (10YR 7/6); loamy fine sand; sls massive; loose; no roots; wavy abrupt boundary.

^C3	59-108	30% white (10YR 8/1), 30% very pale brown (10YR 7/4), and 40% brownish yellow (10YR 6/8); fine sandy loam (40%) and loamy fine sand (60%); sls massive; very friable; no roots; wavy abrupt boundary; bulk density of 1.54 g cm^{-3}.
^C4	108-170 +	50:50 very pale brown (10YR 7/4) and pale brown (10YR 6/3); loamy fine sand; sls massive; loose; no roots; wavy abrupt boundary; saprolite mass (5%).
		Pit 2-5S
^Ap	0-18	Dark grayish brown (10YR 4/2); loamy fine sand; fine to medium sbk-shaped cloddy; very friable; common very fine to fine roots; 1% redox concentrations (7.5YR 5/6) and 1% depletions (10YR 5/2) as soft masses/root linings; wavy abrupt boundary; bulk density of 1.57 g cm^{-3}.
^C	18-42	Strong brown (7.5YR 5/6); sandy clay loam; medium to very coarse cloddy; friable to firm; few very fine to fine roots; wavy abrupt boundary; pebbles (1%); bulk density of 1.50 g cm^{-3}.
^Cd	42-67	Strong brown (7.5YR 5/6); sandy clay loam; very thick platy (10-40 mm diam.); firm to extra firm; very few very fine roots; wavy abrupt boundary; pebbles (1%); bulk density of 1.58 g cm^{-3}.
^C'1	67-125	Strong brown (7.5YR 5/8); loamy fine sand; sls massive; loose to friable; no roots; wavy abrupt boundary.
^C'2	125-200 +	40% yellow (10YR 7/6) and 60% brownish yellow (10YR 6/8); coarse sand over fine sand; sls massive; loose; no roots; wavy abrupt boundary; variable pockets of sandy clay loam.
		Pit 2-5N
^Ap	0-19	Dark grayish brown (10YR 4/2); fine sandy loam; fine to medium sbk-shaped cloddy; friable; common very fine to fine roots; 2% redox concentrations (5YR 5/6 & 5/4) and 2% depletions (5YR 5/2) as soft masses; 3% slimes pockets; smooth abrupt boundary; bulk density of 1.62 g cm^{-3}.
^C	19-30	Yellowish red (5YR 5/6); sandy clay loam; medium to very coarse sbk-shaped cloddy; friable to firm; few very fine to fine roots; wavy abrupt boundary; bulk density of 1.50 g cm^{-3}.
^Cd1	30-82	Reddish yellow (7.5YR 6/6); sandy clay loam; very thick platy; very firm to extra firm; very few very fine to fine roots; smooth abrupt boundary; bulk density of 1.59 g cm^{-3}.
^Cd2	82-171	Strong brown (7.5YR 5/6); clay loam; sls massive; very firm; no roots; smooth abrupt boundary.
^C'	171-200 +	Brownish yellow (10YR 6/8); silty clay; sls massive; firm; no roots; smooth abrupt boundary.

†Refer to Schoeneberger (2012) in Chapter 5 references for texture and structure abbreviations and other description details.

Appendix C3: Routine Chemical Data for Soil Horizons at the LRS site.

Soil ID	Horizon	pH	Mehlich I Extractable Nutrients (mg kg^{-1})									CEC†	Base Sat.
			P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	$cmol_c\ kg^{-1}$	%
Berm2-1	^Ap	4.9	9	33	305	62	0.6	4.8	0.4	106	0.1	4.6	46
	^C	7.2	5	27	1589	121	0.2	22.4	0.3	25	0.1	9.0	100
	^Cd1	4.9	1	36	321	72	0.2	13.1	0.2	13	0.1	5.1	45
	2^Cd2	4.6	1	16	67	24	0.1	1.0	0.2	3	0.1	2.5	23
	2^C'	4.4	1	15	55	21	0.1	0.4	0.1	2	0.1	2.5	19
Pit2-1E	^Ap	5.0	3	27	302	58	0.9	7.5	0.7	126	0.1	4.6	45
	^C	7.2	4	22	743	94	0.3	10.1	0.4	22	0.1	4.5	100
	^Cd	6.3	3	26	494	76	0.2	7.3	0.3	11	0.1	3.2	100
	^C'1	4.8	1	25	185	47	0.2	7.5	0.2	8	0.1	2.7	51
	^C'2	5.1	1	45	382	88	0.2	5.2	0.3	11	0.1	5.8	48
Pit2-1W	^Ap	5.1	5	52	346	60	1.4	6.7	0.4	88	0.1	4.4	54
	^C1	7.2	7	26	748	132	0.3	8.4	0.3	17	0.1	4.9	100
	^C2	4.9	1	16	108	26	0.2	9.0	0.2	7	0.1	0.8	94
	^C3	5.3	3	10	57	15	0.2	1.8	0.1	5	0.1	0.5	93
Berm2-2	^Ap	6.3	32	45	554	75	1.1	11.8	0.5	79	0.1	3.7	95
	^C	5.6	3	20	226	44	0.2	1.4	0.2	7	0.1	1.6	99
	^Cd1	4.8	1	16	80	30	0.2	0.4	0.2	2	0.1	1.2	56
	^Cd2	4.7	1	16	66	27	0.1	0.6	0.1	2	0.1	1.6	37
	^Cd3	4.4	1	33	59	20	0.2	0.4	0.2	3	0.1	3.6	15
Pit2-2N	^Ap	6.4	34	34	558	50	1.0	8.1	0.5	35	0.1	3.3	99
	^Cd	5.2	2	32	366	64	0.3	7.9	0.2	11	0.1	3.5	69
	^C1	5.4	2	17	182	36	0.3	2.8	0.1	6	0.1	1.3	97
	^C2	5.0	1	37	267	58	0.4	10.2	0.2	13	0.1	3.4	55
	^C3	5.1	1	57	527	102	0.7	12.6	0.3	10	0.2	6.5	55
	^C4a*	5.5	1	7	64	13	0.2	0.7	0.1	6	0.1	0.5	98
	^C4b*	5.5	1	13	117	21	0.2	0.7	0.1	3	0.1	0.8	98

Berm2-3	^Ap	6.1	6	31	487	79	0.3	7.1	0.3	24	0.1	3.5	91
	^C	4.8	5	30	250	56	0.2	3.8	0.2	26	0.1	4.0	44
	^Cd1	4.9	1	30	231	55	0.2	5.7	0.2	14	0.1	4.0	42
	2^Cd2	4.5	1	14	66	37	0.2	0.4	0.2	3	0.1	2.9	23
	2^C'	4.5	1	14	56	34	0.1	0.2	0.1	2	0.1	3.4	18
Pit2-3	^Ap	5.2	18	28	276	32	0.5	9.3	0.4	57	0.1	3.8	45
	^C1	5.3	4	23	478	60	0.2	5.5	0.2	15	0.1	4.0	73
	^C2	4.6	1	21	209	40	0.2	3.1	0.2	10	0.1	4.9	29
	^C3	4.9	2	23	338	48	0.2	3.9	0.2	13	0.1	5.0	43
Berm2-5	^Ap	5.9	7	41	523	75	0.9	6.9	0.3	82	0.1	4.2	79
	^C1	7.4	19	12	365	45	0.3	4.9	0.2	10	0.1	2.2	100
	^C2	4.9	4	13	49	17	0.2	0.9	0.2	3	0.1	0.8	50
	^C3	4.6	1	10	39	15	0.2	0.3	0.1	3	0.1	0.5	74
	^C4	4.5	1	8	28	11	0.1	0.2	0.1	4	0.1	0.3	83
Pit2-5S	^Ap	5.8	12	35	299	42	0.8	5.8	0.5	72	0.1	2.3	84
	^C	7.5	6	15	827	69	0.2	11.6	0.2	14	0.1	4.7	100
	^Cd	4.9	1	26	240	53	0.2	3.7	0.1	7	0.1	3.6	47
	^C'1	5.2	1	29	182	40	0.2	5.0	0.1	7	0.1	2.1	63
	^C'2a*	5.1	1	5	40	9	0.1	0.6	0.1	3	0.1	0.3	93
	^C'2b*	5.2	1	6	39	9	0.1	0.6	0.1	3	0.1	0.3	97
Pit2-5N	^Ap	5.3	5	45	325	54	1.0	6.5	0.4	109	0.1	3.6	60
	^C	5.1	1	21	285	56	0.2	2.7	0.2	11	0.1	3.0	64
	^Cd1	5.0	1	30	227	54	0.2	7.5	0.2	11	0.1	3.3	50
	^Cd2	5.0	1	41	271	67	0.2	16.7	0.3	22	0.1	4.8	41
	^C'	4.9	1	48	382	93	0.2	22.3	0.2	11	0.2	7.5	37

†Cation exchange capacity as the summation of Mehlich I extractable bases (Ca, Mg, and K), plus soil-buffer acidity (H^+ and Al^{+3}).
*^C4 a and b = pink and brown colored sand, respectively; ^C’2 a and b = fine sand and coarse sand, respectively.

Appendix D: Yield Monitor Interpolation Maps and Remotely Sensed Imagery

Fields A and B

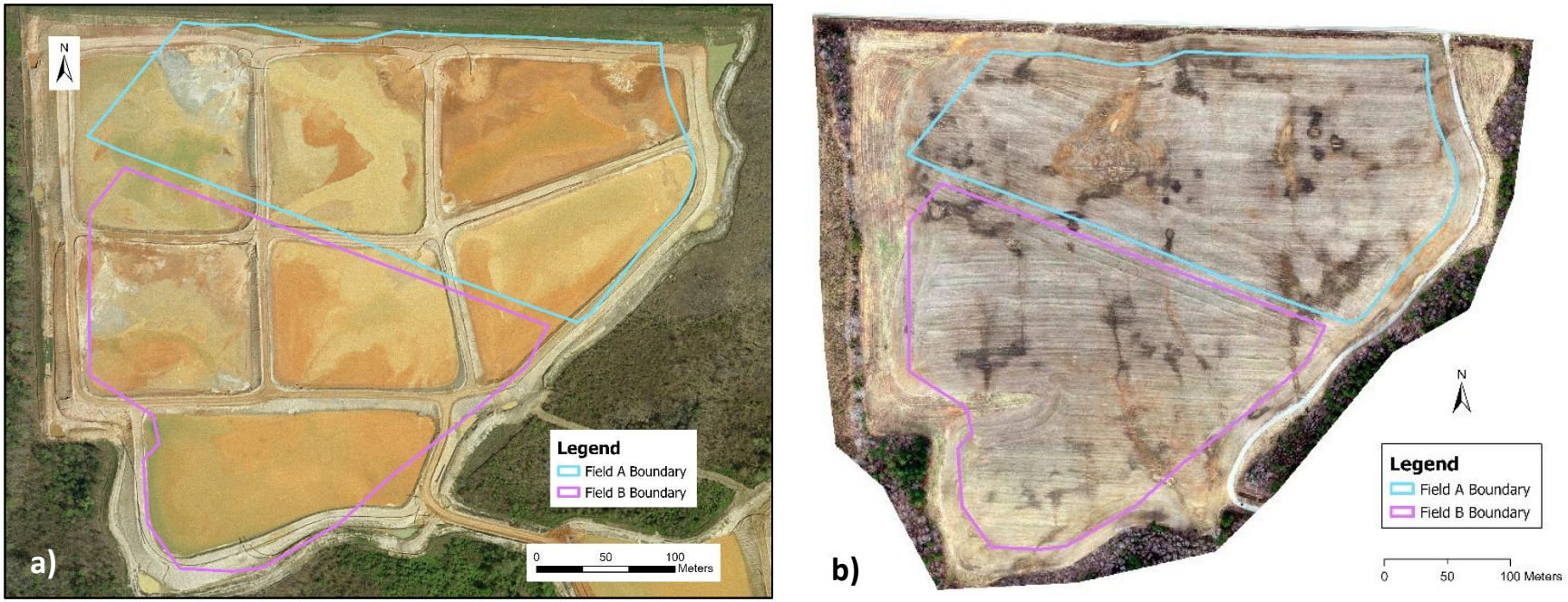


Figure D1. Fields A and B: a) Active mine satellite image (2008); and b) bare soil image collected by drone (2019).

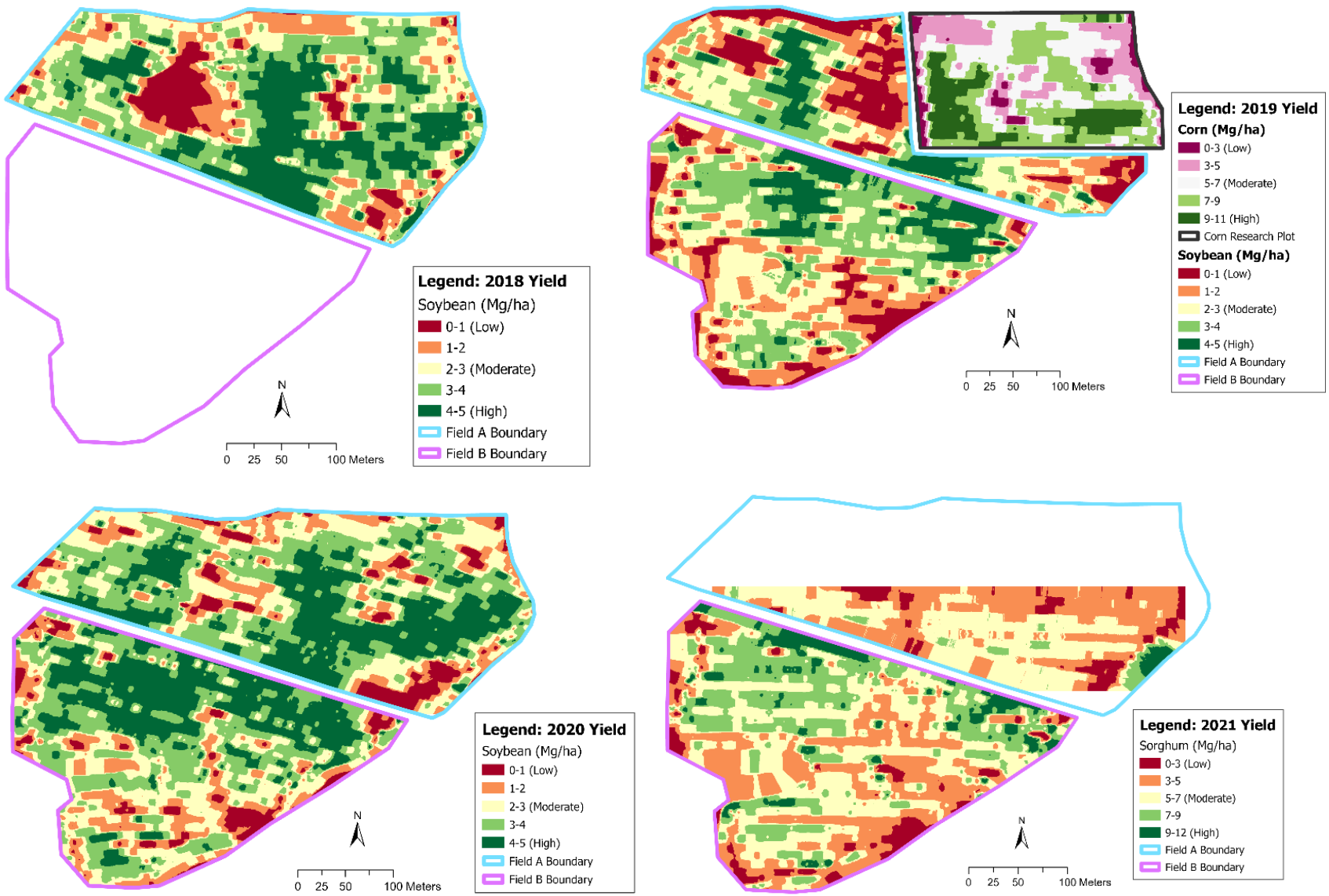


Figure D2. Yield interpolations for Fields A and B from 2018 to 2020 (soybean/corn) and in 2021 (sorghum).

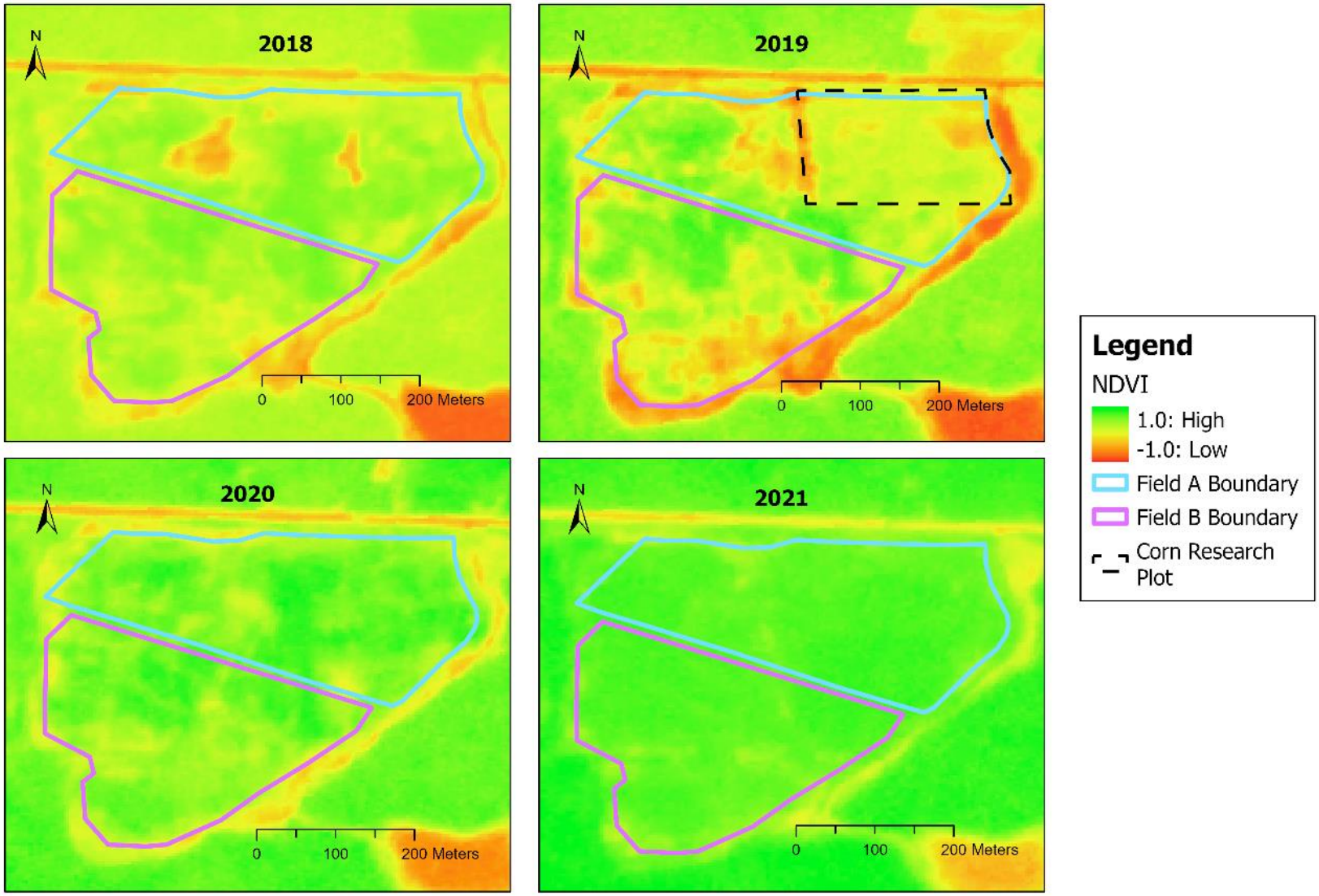


Figure D3. NDVI derived via Planet satellite images in 2018 through 2021 on Fields A and B.

Fields C and D

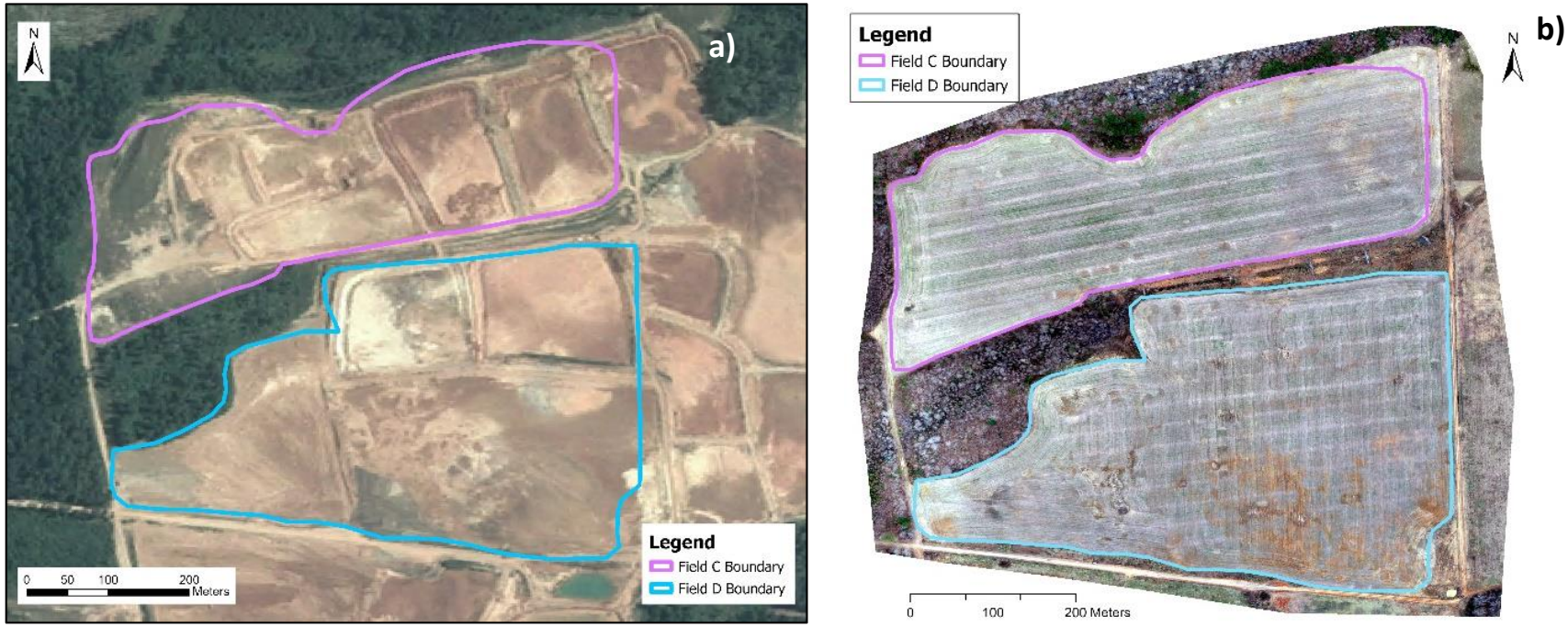


Figure D4. Fields C and D: a) Active mine satellite image (2004); and b) bare soil image collected by drone (2019).

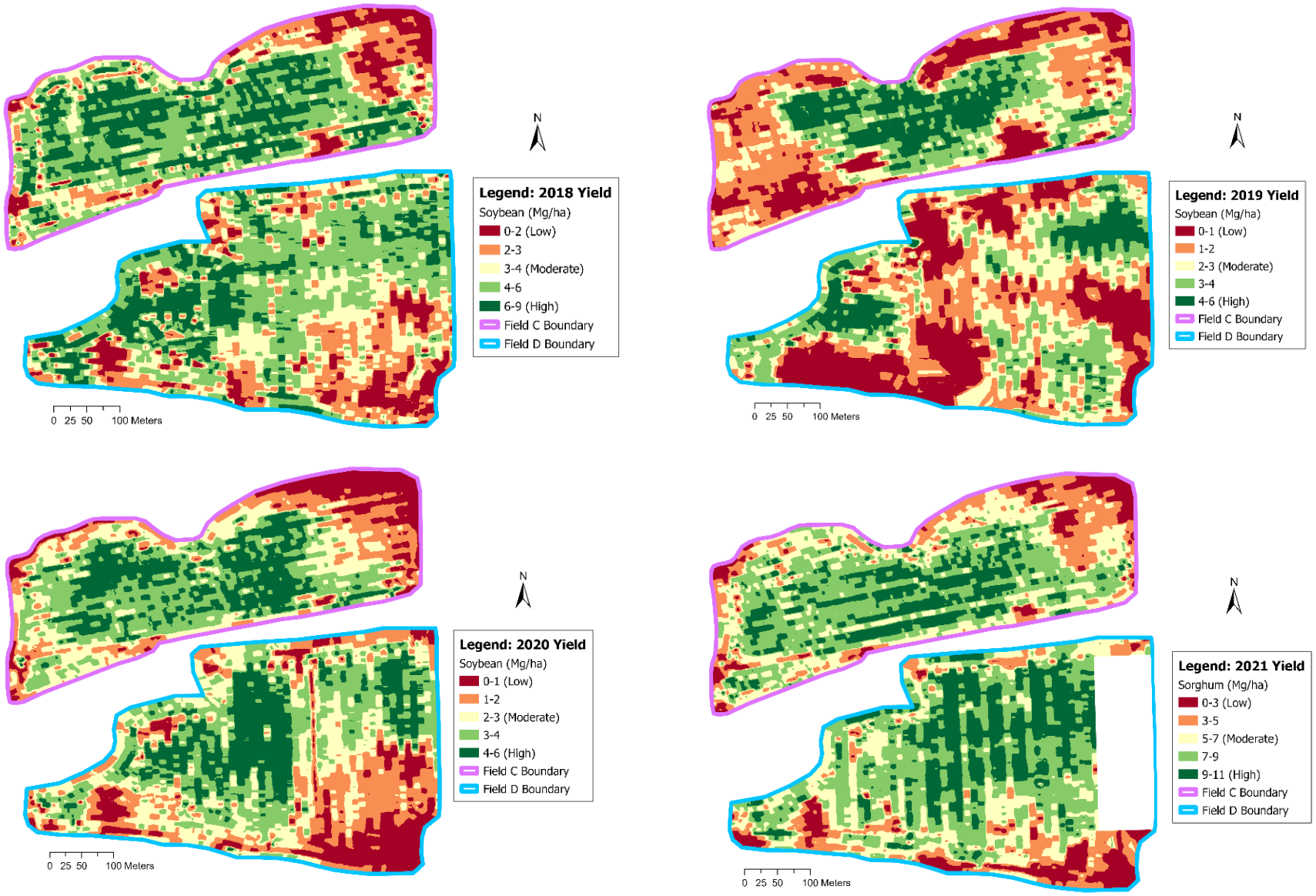


Figure D5. Yield interpolations for Fields C and D from 2018 to 2020 (soybean) and in 2021 (sorghum).

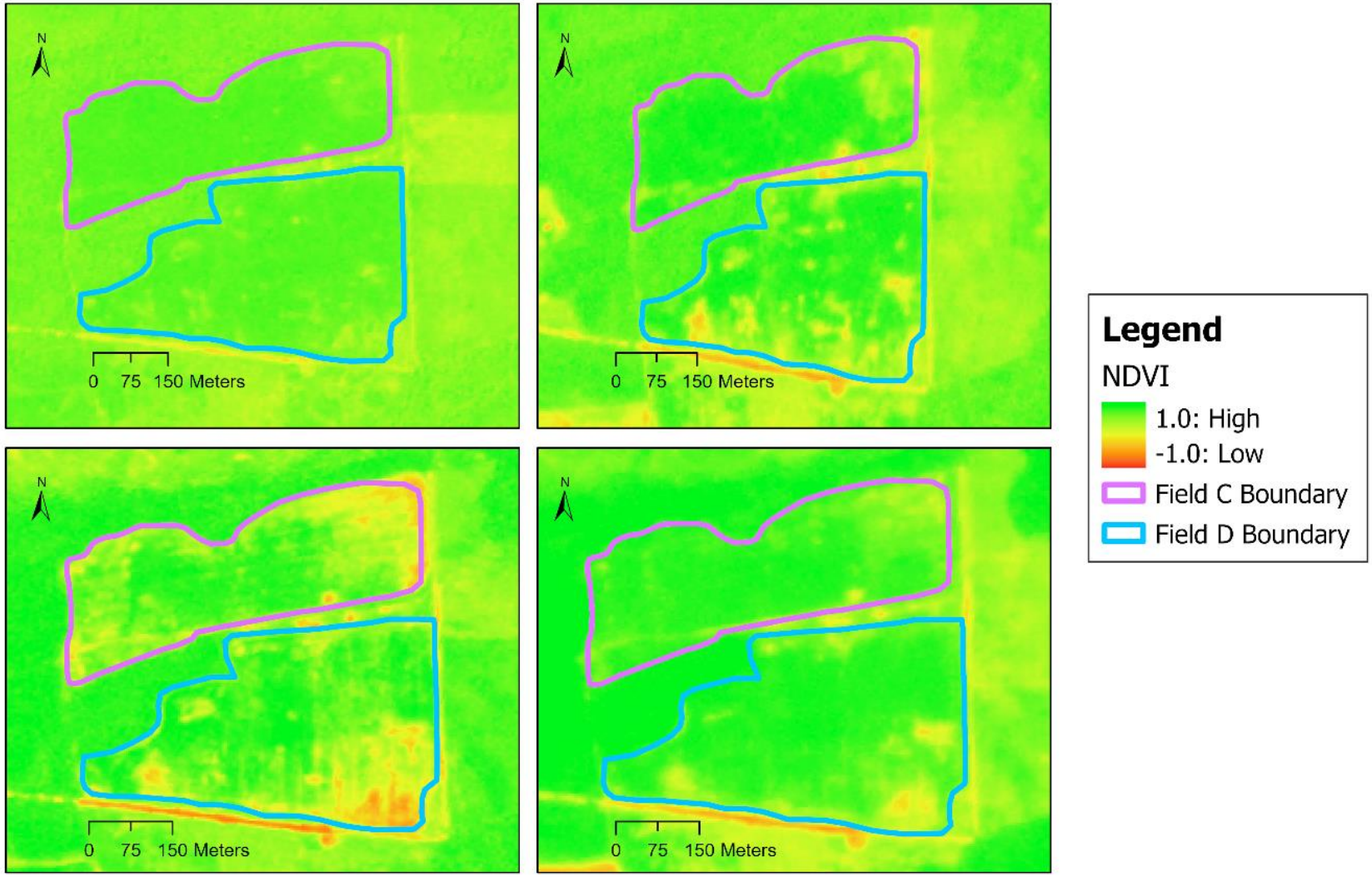


Figure D6. NDVI derived via Planet satellite images in 2018 through 2021 on Fields C and D.

Field E

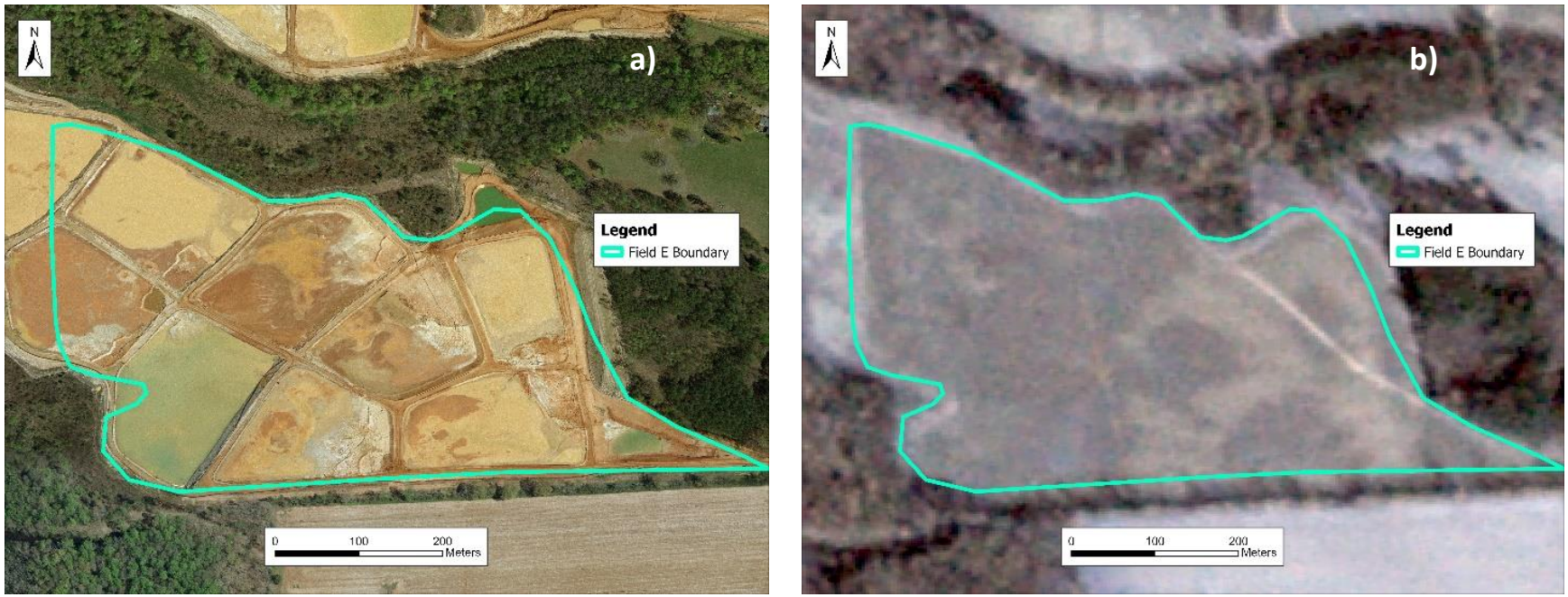


Figure D7. Field E: a) Active mine satellite image (2008); and b) bare soil image via Planet Satellite image (2019).

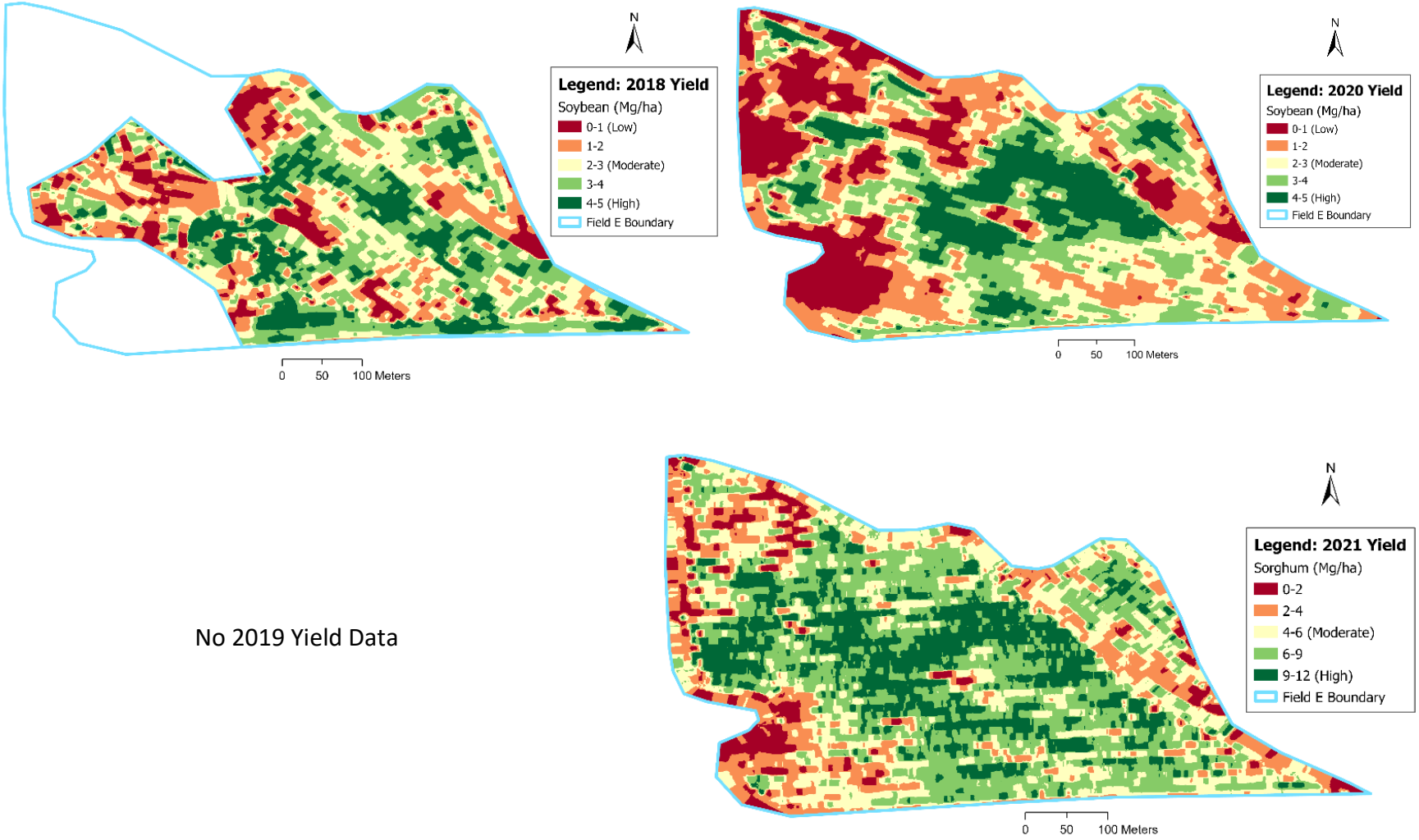


Figure D8. Yield interpolations for Field E from 2018 to 2020 (soybean) and in 2021 (sorghum).

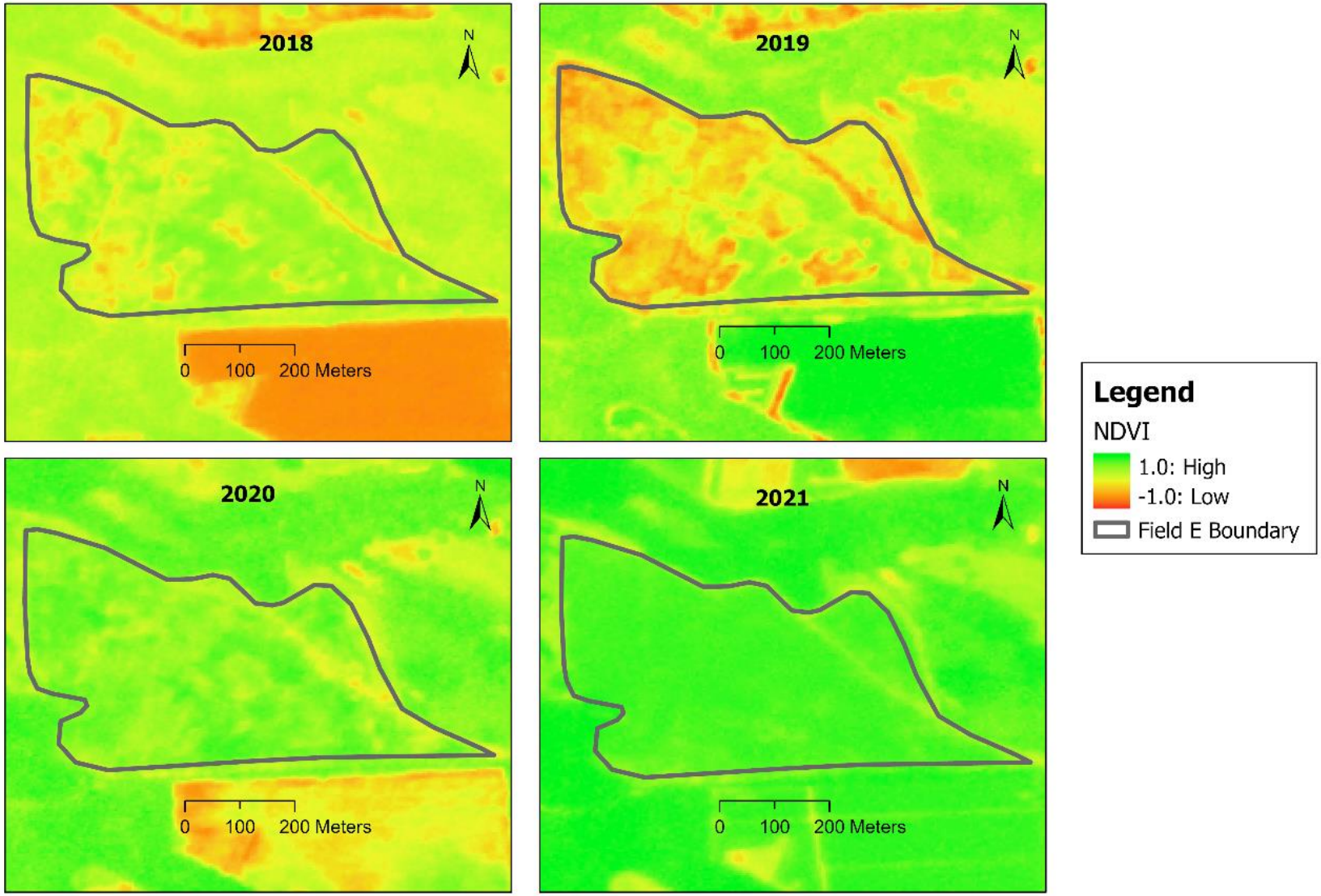


Figure D9. NDVI derived via Planet satellite images in 2018 through 2021 on Field E.

Unmined (UM) Field Yield Interpolations

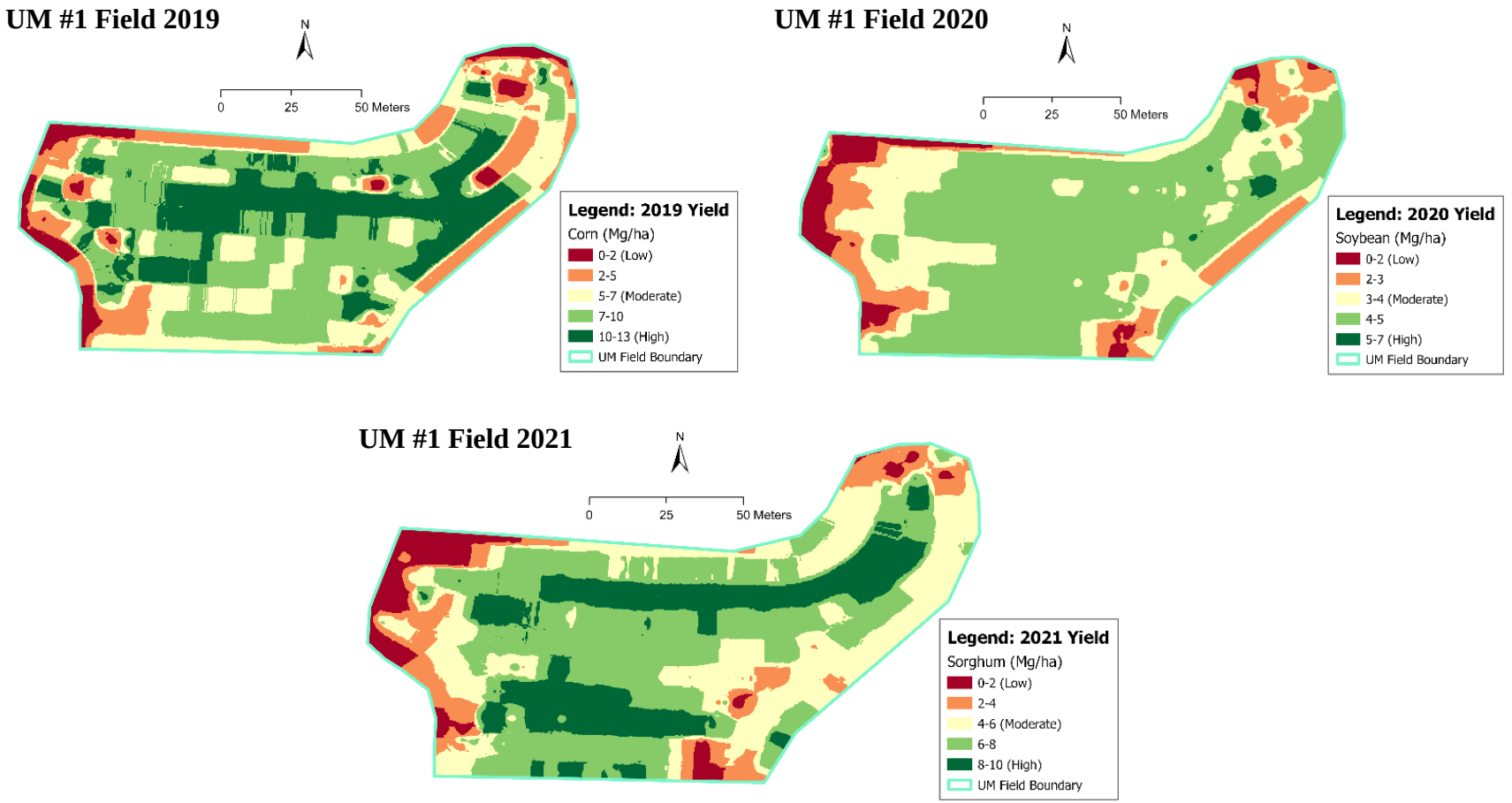


Figure D10. Yield interpolations for unmined (UM) Field #1 in 2019 (corn), 2020 (soybean) and 2021 (sorghum).

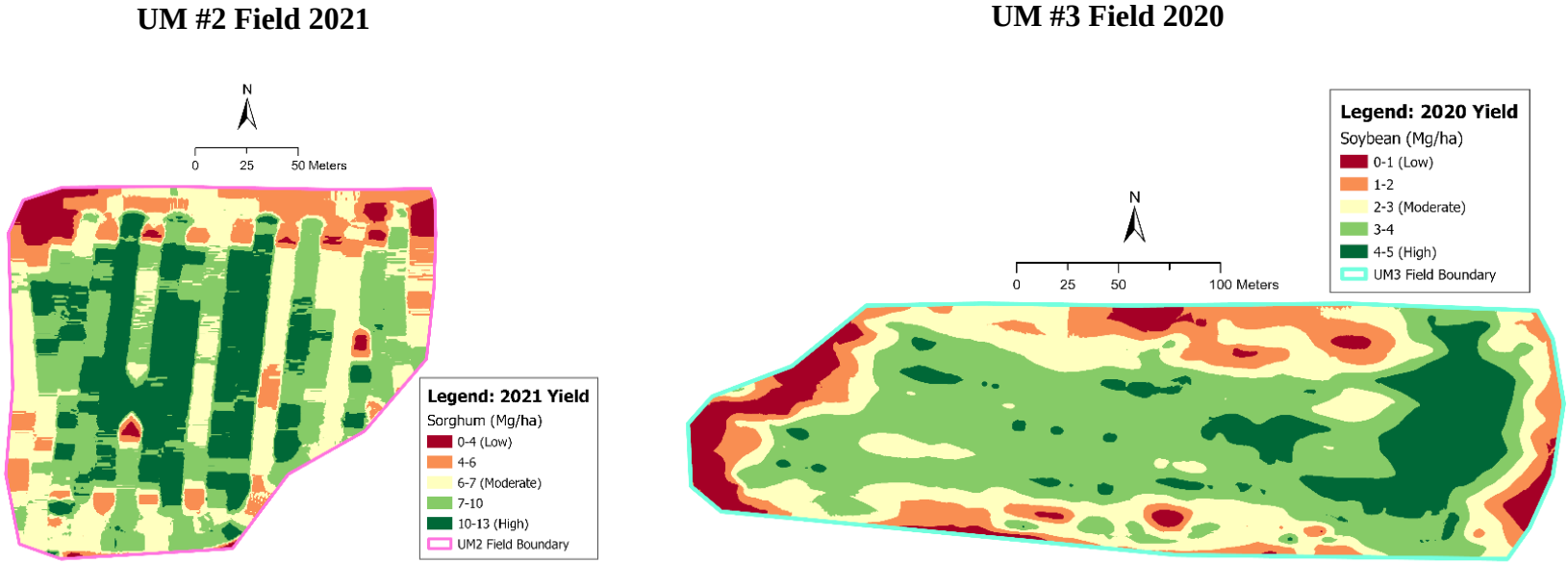


Figure D11. Yield interpolations for unmined (UM) Field #2 in 2021 (sorghum) and UM Field #3 in 2020 (soybean).