ABSTRACT

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THE EFFECTS OF TWO TYPES OF RECLAMATION ON ABANDONED NON-COAL SURFACE MINES IN CUYAHOGA VALLEY NATIONAL PARK, OHIO

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Thesis Advisor: Anne J. Jefferson

The Cuyahoga Valley National Park (CUVA) was established in 1974 as a National Recreation Area. At that time, park staff aimed to reclaim 40 degraded sites within CUVA following guidelines outlined in the Surface Mining Control and Reclamation Act of 1977 (SMCRA). This included restoring abandoned slopes to more natural grades and seeding them with a mix of native and non-native grasses, legumes, and woody plants. Plants were chosen to prevent erosion, improve water quality, and be visually appealing. It was projected that most non-native species would give way to native woody species and allow for natural succession to occur within 20 years. While decreased erosion and increased plant life were documented by the 1990s, non-woody and invasive plants continue to dominate. In 2016, the park secured funding for deep-ripping reclamation with the goal of improving conditions for reforestation. The objectives of this thesis were to research the history of mine reclamation in this area and determine the effects of both SMCRA reclamation and deep-ripping reclamation on soil

texture, soil bulk density, and saturated hydraulic conductivity on previously glaciated non-coal surface mines.

Five abandoned mine sites and four forested reference areas of similar location, slope, and aspect were chosen for this study. At these sites, I have collected 205 bulk density soil samples and 289 soil probe samples for grain size distribution analysis and have performed 66 infiltration rate measurements to determine saturated hydraulic conductivity. Soil texture encompasses silt loams, loams, and sandy loams. Bulk density of the top 5 cm of soil is significantly higher in the mined sites in comparison to forest locations, though values are not high enough at the mine sites to restrict root penetration. However, bulk density samples at depth exceed root restriction values. Mine sites also have significantly slower values for saturated hydraulic conductivity than reference locations.

Deep-ripping reclamation was conducted at one site in September 2017 to improve drainage and root penetration. Near-surface bulk density samples and saturated hydraulic conductivity measurements were collected approximately nine months later. Deep-ripping did not appear to significantly alter bulk density or saturated hydraulic conductivity. These results suggest that as the study continues, it would benefit from the collection of more samples over time and deeper in the soil profile.

The sites in CUVA continue to meet guidelines for SMCRA in terms of decreased erosion and increased plant life. However, the lack of native tree recruitment onto the sites is of great concern to the staff at CUVA. Quantifying the soil properties and determining how both SMCRA and deep-ripping alter these properties is a significant first step in reforesting these mine sites.

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Catherine Terese Ruhm

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Thesis written by

Catherine Terese Ruhm

B.S., Mercyhurst University, 2016

M.S., Kent State University, 2018

Approved by

________Anne J. Jefferson________, Advisor

________Daniel K. Holm________, Chair, Department of Geology

________James L. Blank________, Dean, College of Arts and Sciences

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INTRODUCTION

Reclamation of soils and forests disturbed by surface mining

The Appalachian Region of the United States (U.S.), regularly referred to as Appalachia, is a 205,000-square-mile region located along the Appalachian Mountains historically covered by temperate, deciduous forest (MacDonald et al., 2015; ARC, 2018). Historical use of this land for economic purposes has primarily consisted of mining, forestry, agriculture, and chemical and heavy industry (ARC, 2018). These economic activities result in extensive forest fragmentation, net loss of productive forestland, and deforestation (Zipper et al., 2011; MacDonald et al. 2015). With growing interest in restoration of surface mines and other deforested landscapes, it is critical to understand how the quality of soil, hydrological, and biological properties change with mining and post-mining reclamation activities.

While the industries of the Appalachian Region have diversified in the past few decades, mining, particularly surface mining, continues to be a booming industry in the region (Zipper et al., 2011; MacDonald et al., 2015; ARC, 2018). Surface mining refers to a broad category of mining in which the resource is removed from the surface of a mining site. Surface mining includes strip mining, open-pit mining, and mountaintop removal mining. Surface mining includes , and often refers to, the mining of a coal seam near the surface of the Earth. However, surface mining can also refer to the mining of other minerals, topsoil, and construction resources such as sand and gravel (EPA, 2016).

Up until the mid-1970s, efforts to reclaim lands disturbed by mining and associated activities were relatively nonexistent (Angel et al., 2005; Burger et al., 2005;

Zipper et al., 2011; MacDonald et al., 2015; Monteleone et al., 2018). At the time, little to no attention was focused on reestablishing antecedent topography (Burger et al., 2005; MacDonald et al., 2015). If revegetation efforts took place, it was unlikely that native plants or trees were used (MacDonald et al., 2015). Common problems at former surface mine sites included land instability and surface water contamination caused by unregulated deposition of spoils and other excavated materials (Zipper et al., 2011). Then, in August of 1977, the U.S. Congress passed the Surface Mining Control and Reclamation Act of 1977 (SMCRA), also referred to as Public Law 95-87 (SMCRA, 1977). Enforced by the Office of Surface Mining and Reclamation Enforcement (OSMRE), the primary goal of SMCRA is to return a post-mining landscape to conditions equal to or better than the conditions of the land prior to mining (SMCRA, 1977; MacDonald et al., 2015; Monteleone et al., 2018).

Reclamation attempts that follow SMCRA policy primarily focus on preventing erosion. This is achieved through three main steps. First, the land is regraded to near the original contour or, where that is not possible, lower than the angle of repose. The goal of grading the land in this manner is to reintroduce stable topography to the area, which is judged based on the length and degree of incline of a slope, soil texture, and degree of compaction (MacDonald et al., 2015). Second, the regraded land surface is compacted using heavy machinery to prevent the erosion of loose material (MacDonald et al., 2015; Davis, 2017). Third, the reclamation area is seeded with plants, primarily grasses, legumes, and other herbaceous plants. Woody shrubs may also be used. Plants are chosen for their resilience in extreme conditions such as highly acid and compacted soils.

Reclamation practices encouraged by SMCRA policies ultimately create landscapes that are not conducive to reforestation, especially not by native forest (Burger et al., 2005; Zipper et al., 2011; MacDonald et al., 2015; Monteleone et al., 2018). Due to the extreme conditions on the sites, native plants or trees are rarely selected for planting (Schenk, 1987; Zipper et al., 2011; MacDonald et al., 2015). Where mine surfaces are compacted to encourage landform stability, the density of the soil is generally too great to allow root elongation by tree seedlings (Zipper et al., 2011). High bulk density also limits soil oxygen, which can inhibit root growth and microbe activity and lead to decreased nutrient and water uptake by the plants (Zipper et al., 2011). Additionally, if saplings are planted on a site, the effects of bulk density are oftentimes compounded by competition from the plants seeded during reclamation (Burger et al., 2005; Zipper et al., 2011; Bockstette et al., 2017; Monteleone et al., 2018). Rapidly growing grasses and legumes, planted to establish soil stability, will outcompete young trees for water, nutrients, and sunlight (Burger et al., 2005; Zipper et al., 2011). These harsh conditions lead to high rates of seedling mortality and surviving saplings can be stressed beyond recovery by herbivorous animals and insect damage (Zipper et al., 2011; Monteleone et al., 2018). Even if a tree survives all these conditions for the first year following planting, it is extremely unlikely to survive subsequent years. Overall, the first year rate of survival is too low to allow proper reforestation and trees become a rare occurrence in previously forested landscape (Davis, 2017; Monteleone et al., 2018). It quickly became apparent by those involved with mine reclamation that trees were unlikely to survive on SMCRA sites. Therefore, in lieu of planting native trees, they often chose early successional woody species such as black locust (*Robinia pseudoacacia*) and autumn olive (*Elaeagnus umbellata*). These fast-growing, non-native and invasive woody plants prevent native woody plants' movement onto and subsequent succession in reclaimed mine sites (Zipper et al., 2011).

In 2004, in response to unsuccessful reforestation attempts on mine surfaces within Appalachia reclaimed under SMCRA, the Appalachian Regional Reforestation Initiative (ARRI) was formed (OSMRE, 2018a). A cooperative effort between the states with territory in Appalachia and OSMRE, ARRI consists of a variety of researchers, industry personnel, and regulatory personnel from a wide range of disciplines (Angel et al., 2005; OSMRE, 2018a). Together, they researched attempts to reforest abandoned mine surfaces. They determined that proper reclamation of coal mines within Appalacha can result in reforestation that supports watershed protection, diverse wildlife, and economic growth, among other environmental services (Angel et al., 2005; Burger et al., 2005; Zipper et al., 2011; MacDonald et al., 2015; Monteleone et al., 2018). Using this knowledge, they created the Forestry Reclamation Approach (FRA). Published as a series of advisories, newsletters, and brochures since 2005, the FRA provides a guide to restoration attempts at these mines that meets the requirements of SMCRA and offer additional guidelines to reestablish native tree cover (Angel et al., 2005; Burger et al., 2005; Zipper et al., 2011; MacDonald et al., 2015; Monteleone et al., 2018; OSMRE, 2018b).

The FRA consists of five main steps for increasing the likelihood of successful reforestation at mine sites (Angel et al., 2005; Burger et al., 2005). First, those involved in the reclamation must create a rooting medium, or topsoil, that is sufficient for healthy tree growth. This medium must be at least 1.22 m deep and consist of topsoil and weathered sandstone or the best available material (Burger et al., 2005; Skousen et al., 2011). Second, the topsoil must be graded in such a way that it is loose and does not lead to root-restricting compaction (Burger et al., 2005; Sweigard et al., 2007a; Sweigard et al., 2007b). Following grading, ground covers that are compatible to tree growth must be established. The FRA suggests using slow-growing grasses and legumes with sprawling growth patterns and a tolerance to a large variety of soil conditions. These ground cover plants should allow for a balance of erosion control and minimal competition for sunlight, water access, and growth space (Burger et al., 2005; Burger et al., 2009). Fourth, reclamation teams should plant a mix of tree species seedlings native to the area. These trees species should be readily found in mature forests in the area and have the potential to grow into mature, healthy trees. It is further recommended that approximately 20% of the seedlings are of species well-adapted to survival in conditions common to newly reclaimed mine sites and that would support soil growth and wildlife recruitment and diversity (Burger et al., 2005; Davis et al., 2012). Finally, the trees should be planted using the best planting methods, including storing dormant seedlings in moist, cool conditions until they can be planted in the appropriate season at the proper depth. The FRA also recommends using experienced tree-planting crews for tree-planting over large areas (Burger et al., 2005; Davis et al., 2010). Beyond the five steps described in the FRA, additional studies have also demonstrated that the soil should be moderately acidic, low in soluble salts, and well-drained (Zipper et al., 2011; Monteleone et al., 2018). The soil should also have low gravel content, such that most of the material passes through a 2 mm sieve (Monteleone et al., 2018).

Of the five FRA steps, perhaps the most commonly overlooked and problematic is the one that calls for topsoil to be replaced using loose grading methods following the cessation of mining operations (Burger et al., 2005; Sweigard et al., 2007a; Sweigard et al., 2007b; Zipper et al., 2011). Commonly, use of heavy machinery results in inadvertent soil compaction (Sweigard et al., 2007a; Sweigard et al., 2007b; Zipper et al., 2011). Additionally, mines that were reclaimed prior to the 2005 announcement of the FRA would have been regraded using methods resulting in high compaction to prevent erosion (Sweigard et al., 2007a; Sweigard et al., 2007b).

Where loose topsoil is not achieved during original reclamation, ARRI recommends loosening the compacted soil using deep-ripping reclamation methods (Sweigard et al., 2007b; Zipper et al., 2011; MacDonald et al., 2015). Also referred to as subsurface ripping and deep-tillage, deep-ripping was originally used to reclaim Midwestern farmlands impacted by mining activities (Sweigard et al., 2007b). Deep-ripping is achieved by a bulldozer with shank attachments that penetrate approximately 1 m into the soil making passes through the area in need of reclamation (Sweigard et al., 2007b; Bockstette et al., 2017). The type of shank attachment used and the pattern in which the bulldozer rips the soil is determined based on the soil at the location of interest. For example, for soils high in clay content and lacking large boulders, it recommends using a bulldozer with two plow-shaped attachments to rip the site in a cross-hatch pattern or perpendicular directions. Referred to as cross-ripping, this pattern of ripping prevents the formation of narrow trenches that do not properly break up the soil (Sweigard et al., 2007b) (Figures 1-2).

Beyond reducing soil compaction, deep-ripping promotes increased infiltration and rooting ability (Chong and Cowsert, 1997; Sweigard et al., 2007b). Trees can then be planted at the intersection of the cross-rips, allowing the roots to grow in four directions for stability and resistance to being blown over in strong winds (Sweigard et al., 2007b; Davis, 2017). A study by Chong and Cowsert (1997) demonstrated these benefits, focusing on the hydrologic regime and the effects of deep-ripping on infiltration rates, both immediately following ripping and over the course of three years. Their study took place on Horse Creek Mine, a reclaimed surface coal mine in Illinois. They quantified the immediate and sustained changes in infiltration rates following deep-ripping to depths of 20, 40, 60, and 80 cm. Specifically, they found that deep-ripping to 80 cm significantly accelerated the rate of infiltration relative to 20, 40, and 60 cm. Ripping to 20, 40, and 60 centimeters had comparatively little effect on increasing infiltration rates. Chong and Cowsert (1997) concluded that deep-ripping can increase infiltration. Based on their results, they recommend deep-ripping to a depth of 80 cm and immediately planting vegetative cover or mulching the soil to minimize surface runoff and erosion

Figure 1: The Dover site during deep-ripping treatment in 18-19 September 2017. Left: The bulldozer used for deep-ripping, not in use. Note the plow-shaped shanks. Right: The bulldozer during deep-ripping, ripping west to east along the gradual portion of the hillslope.

Figure 2: Snowville Quarry on 12 September 2018 after deep-ripping. Deep-ripping took place 10-11 September 2018. Left: Snowville Quarry facing southwest. Picture was taken on the flat portion of the site facing up toward the sloped portion of the site. Note the cross-rips. Right: Close-up view of an east to west rip on the flat portion of Snowville Quarry.

Soil properties that influence hydrology and rooting

Soil texture refers to a classification system soil scientists use to communicate the relative abundance of the fine earth fractions of a soil (sand, silt, and clay) when the gravel (>2 mm) portion is excluded (Schaetzl & Anderson, 2005; Osman, 2013). Loam, for example, has high proportions of silt and sand and low concentrations of clay and is considered a medium textured soil that is well-suited to support most tree species due to its ability to retain sufficient amounts of water, nutrients, and air while allowing adequate pore space for root growth (Schaetzl & Anderson, 2005; Osman, 2013). If gravel makes up >15% of the soil volume, the classification is modified to include "gravelly" before the texture name. Thus, a gravelly loam is a soil wherein the fine earth class can be considered a loam, but overall the soil consists of 15% gravel or more (Schaetzl & Anderson, 2005). Loams, especially silt loams, are commonly found in Appalachian forests (Ritchie & Steiger, 1974; NCSS, 1986; NCSS, 1998; NCSS, 2004; NCSS, 2005; NCSS, 2011a; NCSS, 2011b; NCSS, 2015; NCSS, 2016).

The texture of a soil may change with depth in a soil profile, and texture changes are often associated with horizon boundaries. Horizonation occurs with the weathering and transport of earth materials downward through a soil profile. The basic soil horizons in order down the profile of a soil are the O, A, E, B, C, and R horizons. The presence and diversity of these horizons in different soils is highly variable. Where it is present, the O horizon is the uppermost horizon. Also referred to as the "organic horizon," it is primarily dead and decomposing organic matter resting at the surface of the Earth. The A horizon is the top mineral-based soil horizon in the profile and it often includes moderately coarse soil particles and organic material. The E horizon, or zone of eluviation, consists primarily of weathering-resistant minerals, such as uncoated quartz grains. The E horizon is not often present in temperate climates and therefore it is unlikely for a soil in northeastern Ohio to have an E horizon. The B horizon, or zone of accumulation, contains clays and metals weathered out of upper horizons. B horizons tend to have the finest texture and to thicken as soils age and weathering progresses. C horizons are the minimally altered part of the soil profile and thus tend to have the coarsest soil texture, up to and including sands, cobbles, and boulders. Below the C horizon is the R horizon, which is simply the bedrock of that area upon which the soil is formed. In some instances, the R horizon may make up a portion of the parent material of the soil overlaying it. However, this is not always the case and therefore the distinction between the C and the R horizons is important (Schaetzl & Anderson, 2005).

The bulk density of a soil is largely determined by percent of pore space within a soil sample relative to the overall volume of that sample. Soil bulk density increases with depth, because soils are compacted by the weight of the material above them. Additionally, soils at depth tend to have more abundant dense parent material, less light organic material, and less bioturbation from plants and animals (NRCS, 2008). Soil bulk density for the average forest loam is typically approximately 1.30 g cm^{-3} within the rooting zone (Osman, 2013). Overall, in loams, bulk density in the rooting zone needs to be less than 1.75 g cm^{-3} to prevent root growth restriction (NRCS, nd.). The bulk density that restricts rooting is lower for finer textured soils. For example, in a silty loams and silty clay loams, soils should not exceed 1.40 g cm^{-3} for ideal plant growth, and bulk densities in exceedance of 1.55 g cm^{-3} begin to affect root growth. At densities of 1.65 g cm^{-3} or greater, the bulk density significantly restricts root growth (NRCS, nd.).

Soil texture and bulk density are two significant controls on a soil's hydraulic conductivity, which is a measure of a soil's ability to transmit water. Hydraulic conductivity increases as moisture content increases within an unsaturated soil, until it reaches a constant value, the saturated hydraulic conductivity (K_{sat}), when all pore spaces are filled with water (Dunne & Leopold, 1978). Grain size plays an important role in a soil's K_{sat}, namely in the size and connectedness of pore spaces. Larger grains, such as sand and gravel, in a well sorted soil lead to larger pore spaces that are well connected. This increases the number and size of the paths water can travel through in a soil, thus increasing its hydraulic conductivity. Conversely, finer grained soils will have smaller, less connected pore spaces and lower hydraulic conductivity (Manning, 1997). The shape of the relationship between soil moisture and hydraulic conductivity depends on pore size and number and the interconnectedness of said pores. Consequently, it is complicated to measure and often the hydraulic properties of the soil are simply expressed as a function of K_{sat} (Hillel, 2004). Increased bulk density as a result of soil compaction decreases pore spaces and pore connectedness, consequently decreasing K_{sat}. Due to the fact that bulk density increases with depth, K_{sat} tends to decrease with depth. (Manning, 1997; Hillel, 2004; Schaetzl & Anderson, 2005).

Objectives

This thesis is one component of the larger Forest Soils and Trees Ecosystem Restoration (FoSTER) Project, a collaboration between the National Park Service (NPS) staff at Cuyahoga Valley National Park (CUVA) and Kent State University (KSU) Departments of Geology and Biological Sciences. The long-term goal of FoSTER is to reforest the abandoned mine sites within CUVA and investigate the development and interactions of soil properties, hydrology, and native trees and tree mycorrhizae. Park staff have selected five mine sites on which to begin reforestation attempts and these sites are the focus of FoSTER.

FoSTER also offers a unique opportunity to expand on existing research on Appalachian mine reclamation and reforestation. This opportunity arises for two reasons. First, unlike most of the sites studied during development of the FRA, FoSTER sites are not coal surface mines. Rather they are sites where topsoil, sand and gravel, or other construction resources were mined. Second, northeastern Ohio, including the FoSTER sites, was glaciated during the Last Glacial Maximum (LGM) <15,000 years ago, whereas a large portion of Appalachia and therefore the sites studied by the ARRI were south of the LGM extent. The glacial and glacio-fluvial deposits serve as the parent material for soils formed within the LGM extent. For this reason, the soils of northeastern Ohio are young in comparison to most Appalachian soils, which have been derived from in situ weathering of bedrock.

Within the FoSTER framework, this thesis addresses two overarching questions. *How do physical and hydrological properties of soils within SMCRA-reclaimed mine sites of northeastern Ohio compare to those of soils underlying mature, forested landscapes? How do the soil properties within the reclaimed mine sites change following deep-ripping treatment?*

The objectives of this study are to:

1. Compile the history of mine reclamation activities within CUVA using personal interviews with park staff, park archives, and historical records of northeastern Ohio;
2. Compare soil texture, bulk density, and hydraulic conductivity of soils within the mine sites to soils in forested reference locations; and
3. Determine whether deep-ripping alters bulk density and hydraulic conductivity at a previously reclaimed mine site.

SETTING

Cuyahoga Valley National Park

The northward flowing portion of the Cuyahoga River sits at the bottom of a glacial trough between the northeastern Ohio cities of Akron and Cleveland. The bedrock of the Cuyahoga Valley consists of Devonian and Mississippian shales and Mississippian and Pennsylvanian sandstones, overlain by glacial till, lake deposits, ground and ridge moraines, and outwash mostly deposited during glacial recession (circa 15,000 BP). These surficial sediment deposits consist of a variety of coarse debris, sand, gravel, and clay (Cockrell, 1992; ODNR, 2005).

Ohio is in the humid continental zone, making its climate generally temperate (City-Data, 2018). The average temperature is 10.75°C (U.S. Climate Data, 2018). Near Cleveland, winters are cold with an average low temperature of -5.55°C in January and an average annual snowfall of 143 cm (City-Data, 2018; U.S. Climate Data, 2018). In June, the average high temperature is 28.33°C (U.S. Climate Data, 2018). The average annual precipitation is 983 mm (City-Data, 2018).

Historically, the Cuyahoga Valley has been home to various settlements since the Paleolithic Era (circa 12-14,000 BP). After the indigenous people were displaced by European settlement, agriculture was the main economic activity of the area (Cockrell, 1992). Opening of the Akron-Cleveland stretch of the Ohio and Erie Canal in 1827 and the construction of railways and road networks beginning in the late 1850s bolstered the economy of Cleveland and Akron (Cockrell, 1992; Rotman, 2010). Regional economic activity expanded to include extensive logging and the quarrying of sandstone and mineral resources (Cockrell, 1992).

By the beginning of the 1900s, recreational use of the Cuyahoga Valley and surrounding landscapes was bolstered by the formation of metropolitan parks around Cleveland and Akron, joined together by scenic highways. Land in the valley was bought up and developed by affluent Ohio citizens and organizations (Cockrell, 1992). By the 1920s, people began to build weekend and summer homes alongside Boy Scouts of America camps (NPS, 1975; Cockrell, 1992). In the 1940s through the 1960s, popular public attractions such as the Brandywine and Boston Mills Ski Areas, Blossom Music Center, Porthouse Theatre, and Hale Farm were established (Cockrell, 1992; Peak Resorts, 2018; Cleveland Orchestra, 2018; Kent State University, 2018; WRHS, 2018). With the development of these communities and attractions came the need for greater access to and through the valley. Interstates 80, 271, and 77 were built adjacent to and through the Cuyahoga Valley, connecting the scenic farmsteads and public attractions to the nearby metropolitan areas (Cockrell, 1992; Interstate-Guide, 2009; Interstate-Guide, 2016; Interstate-Guide, 2017).

With swelling residential and working populations in the region came an escalation in untreated wastewater entering the Cuyahoga River (Cockrell, 1992; Rotman, 2017). Sewage, industrial waste from the cities, and fertilizer runoff from agricultural areas led to unprecedented amounts of pollution in the Cuyahoga River and Lake Erie (Cockrell, 1992; McDiarmid, 2011; Grant, 2017; Rotman, 2017).

By the 1960s, Lake Erie was widely regarded as the most polluted of the Great Lakes and the Cuyahoga River had caught fire multiple times near where it meets Lake Erie. In 1969, the “Burning River” made national headlines. This incident helped ignite a national push for environmental regulation and pollution abatement (McDiarmid, 2011; Grant, 2017; Rotman, 2017). More locally, the Burning River also served as an impetus for conservation of the Cuyahoga Valley (Cockrell, 1992).

During the early 1970s the Lake Erie Watershed Conservation Foundation, along with several partner organizations, pushed to acquire lands in the valley on behalf of the state for the preservation of ecological, hydrological, and geomorphological resources and stability, the cleaning of waterways and reduction of pollution, and continued public enjoyment and recreation. To achieve these goals, these partner organizations began to push for the transformation of Cuyahoga Valley into a state park (Cockrell, 1992).

Early efforts to preserve Cuyahoga Valley as a state park were met with much opposition from current landowners and residents. In 1970, newly elected Congressman John F. Seiberling of Akron introduced a federal bill to establish a National Park in Cuyahoga Valley. The state supported this move and began to purchase land in the Cuyahoga Valley while the Governor of Ohio and the head of the Ohio Department of Natural Resources (ODNR) advocated for establishing a state park or a National Park in the valley. Seiberling’s bill received pushback from opposing members of Congress and his bill was soon suppressed (Cockrell, 1992).

In 1973, Seiberling proposed a modified bill to establish the valley as a National Recreation Area. On 27 December 1974, President Gerald R. Ford signed Seiberling’s bill and brought into effect Public Law 93-555, which established the Cuyahoga Valley National Recreation Area (CVNRA) (Public Law 93-555, 1974; Cockrell, 1992). Following the establishment of CVNRA, park staff and government officials continued to acquire new lands and develop them in accordance with their vision for the park (Cockrell, 1992). By 2000, CVNRA was a 13,354-hectare park encompassing 35 km of the Cuyahoga River and surrounding valley between Akron and Cleveland (Figure 3) (NPS, 2017a). In 2000, Congressman Regula, an advocate for the parks, spearheaded the successful movement to change Cuyahoga Valley's designation as a National Recreation Area to that of a National Park (NPS, 2017a; NPS, 2017b).

Following the introduction of SMCRA in 1977, when CVNRA acquired post-mining lands, park staff needed to reclaim them in accordance with SMCRA and with the park's goals for restoring ecological, hydrological, and geomorphological resources (Castlebury, 1987; Cockrell, 1992). By 1987, the Division of Resource Management at CVNRA had identified 40 disturbed areas within CVNRA (Figure 3) and determined that the park was responsible for the reclamation of 17 sites (Castlebury, 1987). Contractors were hired to remove any debris remaining from mining and construction activity and regrade the slopes to a 3:1 grade. No records exist as to how closely this reclamation attempted to mimic the original or surrounding topography. The sites were then seeded using a mix of grasses and legumes, both native and non-native. The species chosen were approved in an environmental impact report that stated they should not impede the natural succession of native forestland (Schenk, 1987). Though not all records of this reclamation process are complete or accessible, it can be estimated from records of individual sites that the entire process took approximately 16-18 months to complete (Schenk, 1987; Kopcak, 1991). Park staff and researchers who compiled the environmental impact report hypothesized that natural succession of native forestland would take place on the sites within twenty years (Schenk, 1987). Until then, restoration success was determined based on SMCRA guidelines of revegetation, topographic restoration, and erosion control (Schenk, 1987; Kopcak, 1991).

There is a wide variety of native plant life in the mature forests of Cuyahoga Valley. Among the plentiful native trees that could be expected to naturally move into the reclaimed areas are yellow birch (*Betula alleghaniensis*), tulip poplar (*Liriodendron tulipifera*), sycamore (*Platanus occidentalis*), white pine (*Pinus strobus*), red oak (*Quercus rubra*), pin oak (*Quercus palustris*), red maple (*Acer rubrum*), and hemlock (*Tsuga canadensis*) (Davis, 2017; Conservancy, 2016; Conservancy, 2017). Additionally, CUVA has over 90 species of grasses, including redtop (*Agrostis gigantea*), switchgrass (*Panicum virgatum*), bromegrass (*Bromus madritensis*), orchard grass (*Dactylis glomerata*), timothy (*Phleum pratense*), and Kentucky bluegrass (*Poa pratensis*). Among the >70 sedges in the park are horsetail (*Equisetum scirpoides*), wool grass (*Scirpus cyperinus*), and burr sedge (*Carex grayi*) (Davis, 2017; NPS, 2018a). Some notable common wildflowers in the park are spring beauty (*Claytonia virginica*), yellow trout lily (*Erythronium americanum*), Virginia bluebells (*Mertensia virginica*), violets (*Viola*), and birthroots (*Trillium*). Mid- to late-summer blossoms include goldenrods, such as Canada goldenrod (*Solidago canadensis*), and asters, such as calico aster (*Symphyotrichum lateriflorum*) (Davis 2017; NPS, 2018b).

Within the mine sites, any native plants, especially trees, are outcompeted by invasive and non-native plants. Primary among the plants that dominate the sites are common reed (*Phragmites australis*), autumn olive, and crownvetch (*Coronilla varia*) (Davis, 2017). Common reed crowds out native and desirable plant species (Tewksbury et al., 2002). While some *Phragmites* species are native to the U.S., more invasive strains were likely introduced by trade with Europe, where they are subject to higher rates of predation and competition (Saltonstall, 2002; Tewksbury et al., 2002). Autumn olive was seeded on the mine sites due to its ability to survive the harsh conditions of the sites (Schenk, 1987). It is an invasive plant from Asia that is difficult to control and shades out native plants. Its ability to fix nitrogen in the soil alters the ability of some native plant species that would otherwise thrive in the low-nutrient soil (Michigan, 2018). Finally, crownvetch is a perennial legume from the Mediterranean region of Europe, northern Africa, and southwest Asia chosen for reclamation projects for its ability to grow rapidly in a sprawling pattern in harsh conditions, covering bare soil and preventing erosion (Schenk, 1987; IPSAWG, 2006). It was assumed that crownvetch would die off at the mine sites within four years, allowing native trees to move into the areas (Schenk, 1987). Contrary to this, crownvetch continues to thrive on the sites, outcompeting native seedlings and grasses for sunlight and soil nutrients (IPSAWG, 2006; Davis, 2017). Despite the competition, some native grasses and wildflowers persist on the mine sites, including switchgrass, bromegrass, timothy, orchard grass, horsetail, Canada goldenrod, and some asters (Ruggles, 2018).

Sycamores have managed to grow on two of the mine sites being studied within CUVA. One site had a small stand of less than a dozen young trees growing near an intermittent stream running through the site. The second site had less than a dozen young trees in total scattered throughout the site. These trees are not near the desired levels of tree recruitment onto the sites, both in terms of numbers and species variety (Davis, 2017; Ruggles, 2018).

When it became evident in the early 2010s that the anticipated natural succession of native forest was not taking place at the mine sites, CUVA park staff began attempting reforestation via tree-planting. CUVA selected five mine sites as the focus of their renewed reforestation effort. The largest and most recent attempt to reforest one of the mine sites took place in 2012 when CUVA, with the help of volunteers, planted approximately 1,200 native trees on the Dover site. By 2016, despite park efforts to water trees and prevent deer grazing, approximately 95% of the trees had died. At the time, the cause of this unsuccessful planting effort was not well understood (Davis, 2017). Previous studies of reforestation failure at reclaimed surface coal mines pointed toward altered chemical properties as a cause (MacDonald et al., 2015), but since the CUVA sites lack coal, park staff sought alternative explanations (Davis, 2017).

Initial investigations into the high mortality of the saplings conducted by park ecologists and a consulting arborist revealed that the root systems were not as extensive as is typically seen in saplings of that size. A tree could easily be uprooted by hand, exposing a stunted tap root and diminished lateral roots. This suggested to park staff that the root system had been constrained by highly compacted soils, preventing the root elongation that is necessary for plant vitality (Davis, 2017). Consequently, park staff hypothesized that native tree mortality on CUVA’s reclaimed surface mine sites could be attributed, at least in part, to increased soil bulk density at depth and park staff began to look into approaches for decreasing bulk density to promote tree survival. In 2017, CUVA received funding from the NPS to mow, deep-rip, and plant two sites totaling 16.8 ha. Ultimately, the park’s goal is to rip and replant 5 sites, for a total of 27.48 ha (Davis, 2017). These sites are Dover, Snowville Quarry, Hines Hill Excavation, Cleveland Trust, and Rockside Road. Dover was the first site to be deep-ripped and ripping took place in September 2017. Details of site preparation, the deep-ripping process, and tree-planting efforts are described in the methods and results.

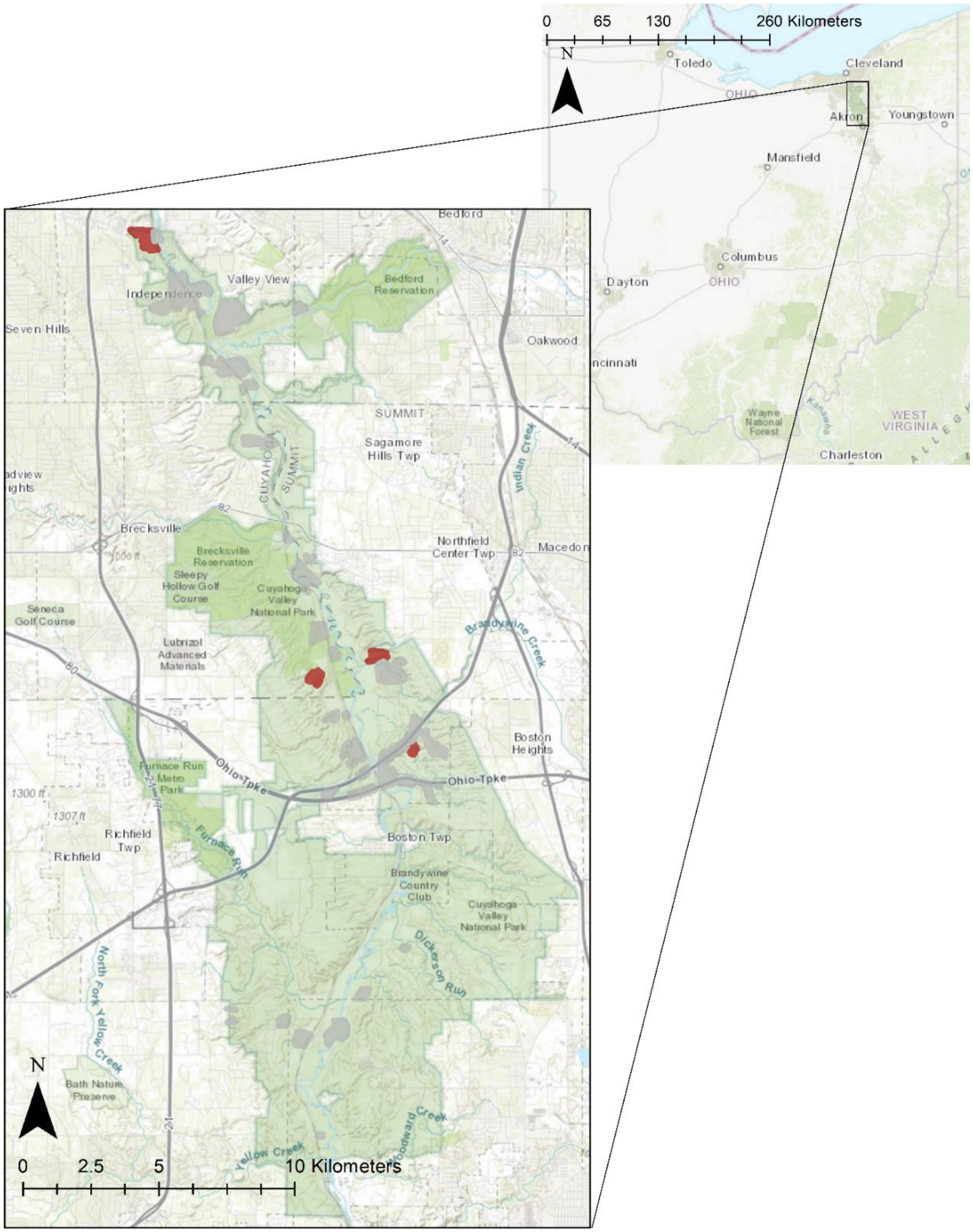

Figure 3: Cuyahoga Valley National Park boundaries (shaded green) as of 2016. Shaded gray areas indicate 50 disturbed mining locations in various states of reclamation. Red shaded areas are the five mine sites for this study. Note in the northwestern boundaries of CUVA two of the sites are adjacent and may appear as one large site. See Figures 10, B4, B5, and B6 for further details.

METHODS

Land Use History

During June-October 2018, interviews were conducted with three CUVA personnel who were involved with the reclamation and management of the FoSTER sites: Christopher Davis, Sonia Bingham, and William Hunter. These interviews focused on eliciting information on how and when the reclamations were conducted and any ongoing management and research taking place at the sites. CUVA personnel were also able to identify the existence and location of written and photographic documents in the Resource Management archives.

Davis is a plant ecologist in the Resource Management Division of CUVA. He has been involved with the reclamation of the FoSTER sites and the management of invasive plant species in CUVA since 2009. He identified where archived communication between park staff regarding the SMCRA reclamations, construction and reclamation logbooks, photographs, and environmental impact reports could be found in the Resource Management offices. He also provided FoSTER with ArcGIS datafiles and metadata. He was instrumental in hiring the Cuyahoga Soil and Water Conservation District in 2013 to perform a limited assessment of the soils on three of the mine sites in FoSTER and then making that data available to FoSTER.

Bingham is a wetland biologist with the Heartland Inventory & Monitoring Network, working with the Resource Management Division at CUVA. Bingham discussed the nature of a mitigated wetland located on one of the FoSTER sites. Additionally, she made groundwater data and wetland maps available to FoSTER.

Hunter is an outdoor recreation planner in the Resource Management Division of CUVA. Hunter discussed the land use history of one of the reference locations with FoSTER. He also provided Google Earth data to FoSTER.

Field and Instrumentation Methods

Selection of Sampling Points

To obtain a representative set of samples from each of the five FoSTER Project mine sites, I used ArcGIS to delineate the site and establish a grid such that points were evenly spaced in a grid. Grid sizes varied by size of the site in hectares such that each site had at least 5 sampling points per ha, for a total of 33 to 49 sampling points per site.

To determine how the soil, hydrological, and biological conditions of these sites compare to those of mature forests, four reference locations were established. Reference locations were selected such that they were of similar slope, aspect, and geologic conditions to the sites that would be compared against them. Reference locations were as close to the mine site as possible without encountering the effects of the mining disturbances and while remaining within CUVA boundaries. Reference locations were originally selected via ArcGIS and were refined using on-the-ground reconnaissance to determine if any indicators of disturbance were present. Indicators could include obvious motor vehicle trails, presence of invasive plant species, or lack of mature trees. The same sampling grid was employed within the reference locations, with 10 to 12 sampling points in each site. Dover, Snowville Quarry, and Hines Hill Excavation each have a reference location associated with them. Cleveland Trust and Rockside Road share a reference location.

Latitude and longitude coordinates of all sampling points from ArcGIS were transferred to handheld GPS units (Garmin GPSmap 62stc). The accuracy of the system used is less than 10 m during typical use. Prior to collecting any samples, I ground-truthed each point, ensuring that they were contained within their respective mine site or reference location boundaries based on visual cues of reclamation for sites and low disturbance for reference locations. This was most easily determined by encountering a tree line between the mining sites and the reference locations. Points outside of the site or reference location boundaries were replaced with new points as close to the original point as possible, but within the boundaries by at least 2 m. These new sampling points were noted so that original points were not confused with ground-truthed points during sampling. The latitude and longitude of each sampling point is provided in Appendix A. Maps showing mine sites, reference locations, and individual sampling points are provided in Appendix B.

Dover and Dover Reference

The Dover site is 8.41 ha. The sample grid size was 50 m by 50 m. This resulted in 43 sampling points on the site, with 5 per ha. Of these 43 points, 12 were moved from their original coordinates. Two were moved because they were very close to or over the site boundary. The other 10 were in stands of common reed, which pose a danger of encountering nests of stinging insects (i.e. wasps, bees, and hornets) when navigating through. Additionally, one point was added in the southwestern corner of the site, such that the original point sampled within the soil exposed from downslope mass movement and the additional point sampled a meter upslope of this bare soil. The Dover Reference location grid was also 50 m by 50 m, resulting in a sampling area of approximately 1.25 ha and 10 sampling points. None of the Dover Reference points had to be moved.

Snowville Quarry and Snowville Reference

Snowville Quarry is 8.40 ha. The sample grid size was 50 m by 50 m. This resulted in 42 sampling points on the site, with 5 per ha. Of these 42 points, two were moved from their original points because they were over the site boundary. The Snowville Reference grid was also 50 m by 50 m, resulting in a sampling area of approximately 1.63 ha and 11 sampling points. None of the Snowville Reference points had to be moved.

Hines Hill Excavation and Hines Hill Reference

The study area at Hines Hill Excavation is 3.62 ha. The sampling grid used was 31.25 m by 31.25 m, resulting in 49 sampling points on the site with 13 per ha. Of these 49 points, one point had to be moved because a tree at the mine boundary had fallen onto where the sampling point was originally located. The point was moved less than 1 m, placing it next to the fallen tree. The Hines Hill Reference grid was 41.25 m by 41.25 m, resulting in a sampling area of approximately 1.02 ha. Of the 12 points that were established, none had to be moved.

Cleveland Trust

The original study area of Cleveland Trust was 18.10 ha and a sampling grid of 45 m by 45 m was established. However, it was determined that only 3.50 ha would be reclaimed via deep-ripping and tree-planting. Sampling locations outside of this 3.50 ha area were disregarded and additional points were added within the original 45 m grid, resulting a 45 m by 23 m grid. This generated 40 sampling points in the final area of interest. After these points were established, one of them had to be moved because it was off the mine site. It was relocated to 2 m within the mine boundary,

Rockside Road

The Rockside Road site is 3.55 ha. The sampling grid was 32 m by 32 m. This resulted in 33 sampling points or 9 sampling locations per ha. None of the Rockside Road sampling points had to be moved.

Cleveland Trust and Rockside Road Reference

The sampling grid for the Cleveland Trust and Rockside Road Reference area was 88 m by 88 m. This resulted in 12 sampling points over an area of 5.48 ha. None of the Cleveland Trust and Rockside Road Reference sampling points had to be moved.

Grain Size Distribution

The first set of samples collected at all nine sampling areas (five mine sites and four reference locations) were general soil samples to a depth of 20 cm. At the Dover site, these samples were collected prior to deep-ripping. These samples were collected to facilitate analyses of a suite of chemical and physical characteristics of the soil including total organic carbon (TOC), total organic nitrogen (TON), soil acidity, metal concentrations, mineralogy, and grain size distribution. These analyses were carried out by various members of the FoSTER team. I took the lead role in the grain size distribution analyses, which will be described in this thesis.

I collected soil samples at each established sampling point using a classic footstep soil probe. The soil tube of the probe measures 12 inches (30.48 cm) long and 0.75 inches (1.90 cm) inner diameter. I marked the tube at 20 cm from the tip with the intent to collect soil samples to this depth or until rejection. At each new sampling point, the soil probe was cleaned with ethanol and disposable paper towels to prevent sample cross-contamination. Each bagged sample consisted of three soil probe samples collected in this method, with each collection being within 1 m of the original sampling point. If the probe was rejected prior to the 20 cm depth, I assumed the rejection was anomalous (e.g. one rock) and disposed of that part of the sample. If the probe was repeatedly rejected at <20 cm, I assumed the rejection was due to an impenetrable layer (e.g. gravel layer). I took the sample in the same triplicate fashion until rejection and noted the maximum depth. I stored all samples in an airtight, plastic, re-sealable, quart-sized baggies. I labeled each sample with the specific sampling point on site and the date the sample was collected. Samples were stored in a laboratory refrigerator at a temperature of 4°C until they could be prepared and analyzed.

To prepare the samples for all analyses, I sieved each sample prior to drying using a #10, 2 mm sieve. Soil aggregates were manually disaggregated during sieving and roots and shoots were discarded. Gravel (>2 mm) was weighed prior to drying and discarded. The sieved sample was then placed in a drying oven at 105°C for at least 24 hours to dry. Once a sample was dry, I returned it to the original sample bag, resealed, and stored it in laboratory drawers for future use.

The grain size distribution of sieved soil samples was analyzed using the Malvern Mastersizer 2000. In preparation for analysis, 2 g of each sieved and dried sample were organically digested with a 30% solution of hydrogen peroxide (H_2O_2). H_2O_2 was added to the sample in 1 mL increments until all organic material was burned off, as indicated by a lack of fizzing. After digestion, the sample was oven-dried at 115°C and stored in a microtube at room temperature.

Prior to analysis on the Malvern, each subsample was weighed and then sieved using a #18, 1 mm sieve. Fine earth fractions greater than 1 mm have the potential to damage the Malvern and therefore are not included in the portion run on the instrument. This very coarse sand portion of the sample was weighed to get relative abundance within the sample. Finally, 0.10 g of the sieved <1.0 mm sample was used in the Malvern.

The Malvern divided the soil samples into 100 size-class bins between 0.01 µm and 1,891.251 µm. The bins were sized by class of logarithm base 10 in microns with the corresponding numbers representing the mid-point of that bin. For example, the bin for 1.891 µm contains the percentage of grains that are between 1.7885 µm and 2.0065 µm in diameter. Oblong grains had the potential to be less than 1 mm along an axis and consequently make it through the 1 mm sieve. The Malvern does not measure a specific axis of the grains. Instead, it measures each sample three times and averages the results together. As a result, it is possible to have grains larger than 1 mm (1000 μm) in diameter appear in the results. The sample averages were used for the grain size distribution analyses.

The Malvern returns count data, not weight percent. To convert this to weight percent I used the following equations:

$$\text{Eq. 1: } volume = \frac{4}{3} * \pi * r^3$$

Equation 1 assumes that each grain is a perfect sphere. The radius used is half the size of the mid-point of each class bin in mm, which is the diameter of the grain sizes.

$$\text{Eq. 2: } weight = volume * 0.00265 g\ mm^{-3}$$

Equation 2 assumes the average density of rock is 2.65 E-03 g mm^{-3}. The weight is the product of this density and the volume calculated in Equation 1.

$$\text{Eq. 3: } weight\ \% = weight * count$$

Equation 3 then calculates the weight percent of each class size as the product of the weight calculated Equation 2 and count provided by the Malvern. The Malvern count data has a final sum of 100 and therefore can also be considered the count percent of each class size.

To determine the overall texture of each sample, I calculated the sum of the weight percentages of all the bins in each class. I based my classes on the U.S. Department of Agriculture (USDA) texture classes (Agvise, 2018). For the clay fraction of the soil sample, I summed all the bins between 1.55 E-05 mm and 2.01 E-03 mm in diameter. For the silt fraction of a soil sample, I summed all the bins between 2.01 E-03 mm and 0.05 mm in diameter. For the sand fraction, I summed all the bins between 0.05 mm and 2.00 mm in diameter. These three sums resulted in a total of 100%, representing the portion of the sample that passed through the 1 mm sieve. To include the 1 to 2 mm fraction that was sieved out, I calculated the weight percent of the sieved fraction of each sample. I summed this percent with the Malvern sand weight percent to get overall sand abundance. I then summed this percentage with the three class fraction percentages from the Malvern, resulting in percentages greater then 100%. I then divided each class fraction by the new percentage to normalize it. (For example, if the clay fraction from the Malvern for a sample was 15.55% and the new percentage was 103.55%, I divided the clay fraction by 103.55% to get the relative abundance of clay in the entire sample, which in this case would be 15.02%.) This method of normalization was necessary because of the small amount of subsample that was actually passed through the Malvern.

To plot the soil texture of the samples, I used the package “soiltexture” in R (Moeys, 2018). The program plots one point per sample on a texture triangle to show where the sample falls in the USDA classifications of different textures. The plot used is a USDA texture triangle plot (Figure 4). Each side of the triangle is an axis of 0-100% for one of the soil texture size fractions. The sum of the percentages equals 100 and allows the program to triangulate a point on the texture triangle.

Texture classifications were compared to the National Cooperative Soil Survey (NCSS) classification of the respective mapping unit at the mine or reference location. Since soil samples were collected to a depth of 20 cm, samples were only compared to the top 20 cm of the NCSS classifications. A subset of samples was also classified using the feel method, which classifies a soil on its ability to maintain a length of ribbon under its own weight and the feeling of how smooth or gritty the sample is. A soil that forms a ribbon 2.5-5.0 cm long that is very smooth to the feel is a silty clay loam, whereas a soil that forms a ribbon of similar length but does not feel particularly smooth or gritty is a clay loam (Thein, 1979).

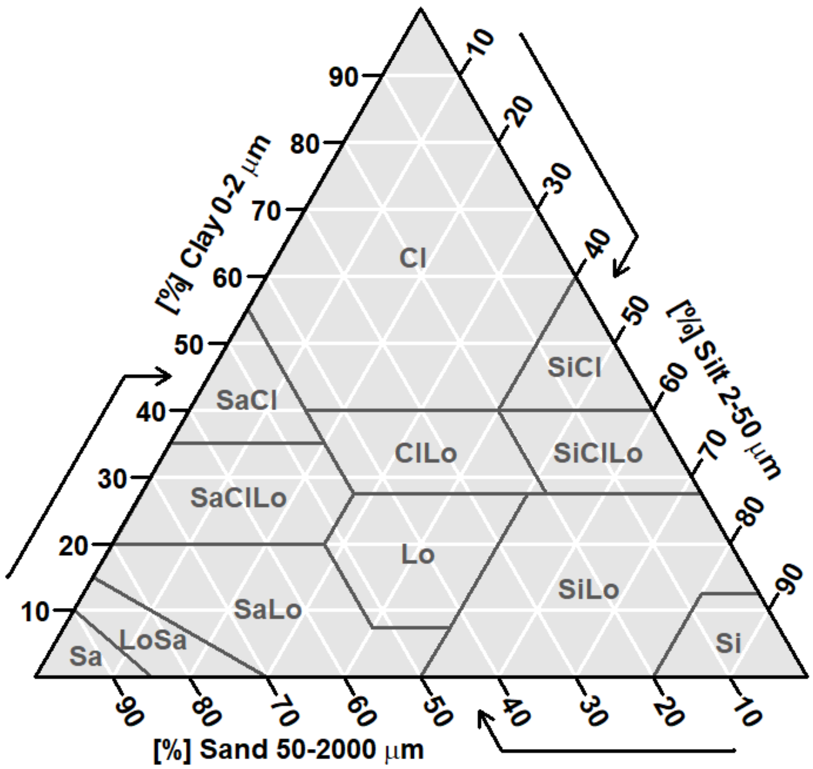

Figure 4: A blank texture triangle generated by the “soiltexture” package. The texture divisions are marked by solid black lines. The modifiers used are “Sa,” “Si,” “Cl,” and “Lo” for sand, silt, clay, and loam respectively. Modifiers are used in conjunction with one another for some textures. For example, “SaClLo” is a sandy clay loam and “SiLo” is a silty loam.

Near-Surface Bulk Density

Bulk density samples were collected from the top 5 cm of soil at 10 to 36 sampling points from each study area. Hereafter these samples are referred to as near-surface bulk density measurements. To compare the soil properties at Dover prior to deep-ripping treatment to the soil following deep-ripping treatment, I collected near-surface bulk density samples from every sampling point established during the 20 cm soil probe sample collection (n = 44). After ripping, I collected a second set of near-surface bulk density samples. I randomly sampled in cross-rips (n = 9), single rips (n = 13), on disturbed soil not in a rip (n = 6), and on undisturbed soil not in a rip (n = 6). The disturbed and undisturbed samples not in a rip were combined into one data set of samples not collected in a rip (n = 12). Sampling points that were not within the deep-ripped boundaries, as determined by the perimeter of the protective deer fence, were not resampled. Their pre-ripping counterparts were not included in statistical analyses. The final sample number used in the statistical analyses was 34. Due to time constraints, half of the 20 cm core sampling points at Snowville Quarry, Hines Hill Excavation, Cleveland Trust, and Rockside Road were sampled for near-surface bulk density. These points represent every second point on the grid (n = 21, n = 23, n = 21, and n = 17, respectively). Due to the small number of original sampling points at Dover Reference (n = 10), Snowville Reference (n = 11), Hines Hill Reference (n = 12), and Cleveland Trust and Rockside Road Reference (n = 12), I collected near-surface bulk density samples at all the 20 cm soil core sampling points at all these locations.

To collect bulk density samples, I used an AMS bulk density corer (parts 400.81 and 400.82). The AMS bulk density corer contains a removable sleeve measuring 5.08 cm tall and 5.08 cm in diameter (part 404.28). To collect a sample, I inserted the corer into the ground to a depth of 5.08 cm. After I removed the corer, I kept it horizontal while I unscrewed the chamber containing the sleeve. I gently pushed the sleeve out without disturbing the soil sample (Figure 5). I used a spatula to remove excess soil from the ends of the sleeve (Figure 5) and extruded the soil into a plastic, resealable bag. Samples were oven-dried at 105°C for >24 hours. Oven-dried samples were then weighed to the nearest 0.01 g. Bulk density was calculated by dividing the dry mass by the known volume.

Figure 5: Taking a near-surface bulk density sample using a bulk density soil corer. A sleeve is removed from the corer intact and held horizontal to prevent loss of sample (left). It is then carefully trimmed using a spatula so that the volume of the sample is equal to the volume of the sleeve (right) before transferring the entire sample to an airtight sample bag.

Bulk Density Depth Profiles

To determine if the near-surface bulk density samples were representative of bulk density at depth, I collected samples for bulk density profiles at Snowville Quarry and Snowville Reference. Snowville Quarry was chosen because Dover had already been ripped, with unknown consequences for bulk density. Snowville Quarry was the next site planned for deep-ripping, and collecting bulk density depth profiles there would allow for future assessment of the effects of ripping on bulk density below the top 5 cm.

Bulk density profiles were sampled from two soil pits at Snowville Quarry. One pit was on the sloped portion (41°16’58.9”N, 81°34’41.1”W) of Snowville Quarry and the second was on the flat (41°17’00.9”N, 81°34’40.6”W). Soil pits were dug to the point where it was either extremely difficult or impossible to continue using hand tools (~50 cm). One soil pit was dug to a depth of 35 cm in the Snowville Quarry Reference area (41°16’53.7”N, 81°34’53.7”W).

Before sampling, I took photographs of one pit wall and took notes of any changes in color, texture, or pore space. Using the same corer as for near-surface bulk density measurements, I sampled the soil profile in 5 cm increments by inserting the corer horizontally into the pit wall. Sampling in a zig-zag pattern ensured that samples taken in succession down the profile did not influence samples taken above or below them.

It was more difficult to get full penetration of the sampler horizontally in the pit wall than vertically from the soil surface, and 11 out of 21 samples were not completely filled. One sample, which was noted as the least intact in the field, produced a calculated bulk density (3.0 g cm^{-3}) greater than quartz, so that data point (Snowville, flat, 35 cm) was dropped from further analysis.

Saturated Hydraulic Conductivity

To determine the effects that SMCRA mine reclamation and deep-ripping have on water movement through soils, I measured saturated hydraulic conductivity (K_{sat}) of soil at a depth of 15 cm at the mine sites and reference locations. K_{sat} measurements are time-consuming, taking 0.5 to 2 hours per measurement, so the number of measurements obtained are more limited than for grain size or near-surface bulk density. To obtain a representative number of K_{sat} measurements within Dover in the time allotted prior to deep-ripping, I selected 8 of the 44 sampling points. To capture site-wide variability, these points were spread over the site, ensuring at least three were in each east-west row of the 20 cm soil core sampling grid. Two measurements were at either end of each row and one or two were approximately in the middle of each row. These were the same points at which I measured post-ripping K_{sat}. I repeated this method of selecting points for measurements so that I performed 8 measurements at Snowville Quarry, 8 at Hines Hill Excavation, 6 at Rockside Road, and 6 at Cleveland Trust. At each reference location, I performed 3 measurements at randomly selected 20 cm sampling points.

A Guelph permeameter, which is a constant-head infiltration device that relies on the Mariotte siphon principle, was used to determine to determine K_{sat}. I augered a well approximately 15 cm deep at each location and agitated the sides of the well with a wire brush to reduce the effect of clay smearing which could alter the infiltration rate of the natural setting (Bagarello, 1997). I inserted the Guelph into the well such that the bottom of the capped tube rested on the bottom of the well. Water level in the reservoir was recorded at equal time intervals until an approximate steady state was reached, as defined by three or more measurements with nearly equal rate of decline. Each measurement was started using the combined reservoir, but where the drop rate was very slow, I switched to the inner reservoir and discarded measurements from the combined reservoir. For each measurement, infiltration measurements were made using a 5 cm head and a 10 cm head in the same well.

The formulae to calculate K_{sat} come from the Guelph permeameter user's manual:

Eq. 4: $K_{sat}(m\ s^{-1}) = (0.0041)(X)(R_2) - (0.0054)(X)(R_1)$

Eq. 5: $K_{sat}(m\ s^{-1}) = (0.0041)(Y)(R_2) - (0.0054)(Y)(R_1)$

Equation 4 is used for measurements taken using the combined reservoir. X represents the combined reservoir cell constant of 35.22 cm^2. Equation 5 is used for measurements taken using the inner reservoir. Y represents the inner reservoir cell constant of 2.15 cm^2. In both equations, R_1 represents the water drop rate under the 5 cm head. R_2 is the water drop rate under the 10 cm head.

If 15 minutes passed with no noticeable drop (<0.1 cm) in the inner reservoir, a new well was augered within a meter of the original location. The Guelph permeameter was reset in the new well and the measurement started again. This process was repeated three times or until water level drop rate of >0.1 cm in 15 minutes could be measured. At seven sampling points, K_{sat} had to be estimated because three successive measurement attempts did not result in sufficient drop rates. All estimates are maximum K_{sat}, calculated as described in the following sentences. At the seven measurement points, if no water level changes occurred in 15 minutes under the 5 cm head using the inner reservoir it was assumed that the rate was 0 at 5 cm head. That rate was used for R_1 in Equation 5. The measurement then proceeded to the 10 cm head. At four of the seven points, a drop of at least 0.1 cm was recorded within 15 minutes and that value was used for R_2 in Equation 5. At the remaining three points, no water level changes occurred within 15 minutes under the 10 cm head. It was assumed the drop rate was 0.1 cm every 16 minutes. In the case where no water level drop was recorded at either head, the calculated Ksat was 1.47 E-08 m s^{-1}, which is therefore the minimum possible value for K_{sat} in this study.

STATISTICAL METHODS

All statistical calculations were performed in R Version 3.4.3 and RStudio Version 1.1.423.

Near-Surface Bulk Density

To determine if there was a significant difference in near-surface bulk density values between mine sites and reference locations, I constructed a linear mixed-effects model using the command “lme” in the “nlme” package. The continuous variable used was near-surface bulk density values of the samples and the discrete factor was whether the sample came from a mine site or a reference location. The broad sampling area (including both the mine and the reference location) was designated as a random effect. Broad study areas encompassed each mine site and its respective reference location, resulting in four broad study areas: Dover and Dover Reference, Snowville Quarry and Reference, Hines Hill Excavation and Reference, and Cleveland Trust, Rockside Road, and Reference. The linear model met assumptions of normality ($p = 0.95$). Probability plots demonstrated equal variance between the residuals. Data from Dover post-rip was not included in this analysis and was analyzed separately, as described below.

To test for significant differences in near-surface bulk density between Dover pre-rip and Dover post-rip, I performed a two-way analysis of variance (ANOVA) on the mean differences between Dover pre-rip conditions and Dover post-rip conditions. The continuous variable in this model was the difference in near-surface bulk densities between pre-rip and post-rip conditions at each sampling point. The type of rip (cross-rip, single rip, or no rip) that the sample was taken from during post-rip collection served as the discrete variable. A Shapiro-Wilk's test failed to reject normality for the model ($p = 0.34$). The residuals were linear with equal variance.

Saturated Hydraulic Conductivity

Since the K_{sat} values varied by several orders of magnitude, I transformed all the measurements using a base-10 logarithmic function prior to conducting any statistical analyses. To determine if there were significant differences in K_{sat} between mines and reference locations, I constructed a linear mixed-effects model with the general study area serving as the random effect. This model would allow me to determine if the effects of mining have an effect on K_{sat} in the greater CUVA area. The continuous variable used was the log of the K_{sat} measurements. The discrete factor was whether the measurement came from a mine site or a reference location. A Shapiro-Wilk's test on the residuals failed to reject normality for this model ($p = 0.1033$).

To determine if there were finer differences in K_{sat} between the mine sites and their respective reference locations, I performed three two-sample t-tests: Dover and Reference, Snowville Quarry and Reference, and Hines Hill Excavation and Reference. I also performed a one-way analysis of variance (ANOVA) on Cleveland Trust, Rockside Road, and Reference. Additionally, I performed a two-sample t-test: Snowville Quarry sloped portion and Snowville Quarry flat portion.

I constructed linear models of the data sets that would be used for the two-sample t-tests to test for normality. Shapiro-Wilk's tests on the residuals of these models failed to reject normality for all these tests. Dover and Reference had a p-value of 0.9851. Snowville Quarry and Reference had a p-value of 0.6414. Snowville slope and Snowville flat had a p-value of 0.1489. Hines Hill Excavation and Reference had a p-value of 0.7059. I also performed a Shapiro-Wilk's test on the ANOVA model for Cleveland Trust, Rockside Road, and Reference. It failed to reject normality for this model ($p = 0.7458$).

To determine if there were significant differences in K_{sat} between Dover pre-rip and Dover post-rip based on the number of rips measurements were conducted in, I constructed an ANOVA model comparing the log of the K_{sat} values to the number of rips the measurement was taken in. A Shapiro-Wilk's test failed to reject normality ($p = 0.9952$).

RESULTS

Site History

Dover (D)

Dover is an 8.41 ha topsoil mine located on the southern side of West Highland Rd in Northfield, OH, approximately 700 meters north of the Brandywine Ski Resort (Figure 6). It is an eastern facing hill with a 9.94% slope. The northern and southern edges of the western portion of the Dover site are much steeper at 12.70% and 22.47% slopes respectively. During the late 1990s, the Brandywine Ski Resort removed the top 3 m of the Dover site's soil for use in the construction and grading of their ski slopes (Davis, 2017). In 2001, the site was reclaimed by filling, grading, compacting, and seeding the remaining hillslope. The fill used was lake sediment dredged from the bottom of Brushwood Lake, streambed sediment from Furnace Run, and soil and floodplain material removed from Station Road during a parking lot installation. Much of this material sat unattended in piles on the site for an unknown number of years prior to grading (Norley, 2001; Tuckerman, 2001). In 2001, the bulk density of the soil at the Dover site at a depth of 25.4 cm was estimated to be between 2.04 and 2.68 g cm^{-3} (Davis, 2018). Tension cracks along the southern edge of the site in conjunction with a patch of bare earth approximately 26 m wide and 23 m long in the southwestern corner of the site indicate downslope mass movement. Vehicle trails, likely the result of mining and reclamation activities, are visible on the eastern and western edges of the site.

Prior to mining, Natural Resources Conservation Service (NRCS) classified the soil on Dover as belonging to the Geeburg silt loam series (Soil Survey Staff, 2018). The

Geeburg soils are aquic hapludalfs that are formed on clayey glacial till or lacustrine sediments. It is moderately well-drained with slow permeability (NCSS, 1986). The Geeburg series is described as silt loam to a depth of 7.62 cm, underlain by silty clay loam to a depth of 10 cm, underlain by silty clay to a depth of 152.40 cm. The Geeburg series soils are strongly acid or very strongly acid to a depth of 25.40 cm. Below this depth, the soils are medium acid to moderately alkaline (Ritchie & Steiger, 1974). Bedrock at the Dover site is Devonian black shale and shale (Slucher et al., 2006).

To eliminate competitive plant life on the Dover site prior to treatment, the Invasive Plant Management Crew at CUVA treated invasive species with glyphosate herbicide during the summer of 2017 (Davis, 2018). Glyphosate is a non-selective herbicide. It prevents the creation of proteins that are necessary for plant growth by blocking the shikimic acid pathway (Henderson et al., 2010). The team worked systematically with backpack sprayers, applying the herbicide to the leaves and stems of the most competitive invasive plants common reed, Canada thistle (*Cirsium arvense*), wild teasel (*Dipsacus fullonum*), and crownvetch. After the team finished spraying the invasive plants, they mowed the site using industrial push-mowers.

Deep-ripping took place over the course of two days, 18-19 September 2017. CUVA hired out the deep-ripping process to a private contractor. The contractor used a Cat® dozer with two plow-shaped 1 m shanks to rip the sites in a cross-hatch pattern (Figure 2). The contractor first ripped north to south, along the steep portion of the hill. He then ripped east to west, along the gradual portion of the hill. Ripping in this pattern, perpendicular to the topographic contours and then parallel to the topographic contours, was intended to prevent excessive runoff from the site by blocking the formation of rills and gullies. Tree-planting continued until 14 November 2018 and and the CUVA Invasive Plant Management Crew continues to selectively spray invasive plants with glyphosate herbicide during the growing season.

Dover Reference (DR)

The reference location for Dover is located on the western edge of the same hillslope as the Dover site but is vegetated with mature hardwood forest (Figure C1). Portions of the forest that appeared to be disturbed by large vehicle trackways were to the south of the delineated reference location.

The soil at the Dover Reference location is classified as a Cardinal-Mentor silt loam (Soil Survey Staff, 2018), which is a typic hapludalf that has properties similar to the Geeburg series found on the Dover site. NCSS describes Cardinal soils as having formed on Wisconsin age glacial till or lacustrine sediments and being moderately well drained with moderately slow permeability. It is a silt loam to a depth to 33 cm, underlain by silty clay loam to a depth to 71 cm, underlain by silty clay to a depth to 203 cm. The soil is very strongly acid in the upper horizons, moderately acid in the middle of the soil profile, and neutral to moderately alkaline in the bottom horizons (NCSS, 2005). Mentor soils are well-drained soils with moderately high permeability, formed on Wisconsin age glaciolacustrine or stream sediments. Mentor soils are a silt loam to a depth of 46 cm, underlain by a silty clay loam to a depth of 89 cm, underlain by a silt loam to 112 cm, underlain by loam to 127 cm. The bottom of the profile is a fine sandy loam, loam, and silt loam to a depth of 152 cm. The soil is neutral or slightly acid in the uppermost horizons, strongly acid at 28-127 cm, and slightly acid at the bottom of the profile (NCSS, 2016). Like the Dover site, the Dover Reference location is underlain by Devonian shale and black shale (Slucher et al., 2006).

Snowville Quarry (SQ)

Snowville Quarry is an 8.40 ha former sand and gravel quarry that was quarried beginning in the early 1950s until 1999, when it was reclaimed (Davis, 2017; NETR, 2018). It is located on the southern side of Snowville Road in Brecksville, OH, 400 meters from the intersection of Snowville Road and Riverview Road and 1.8 kilometers west, southwest of the Dover site (center of site to center of site) (Figure 7). Snowville can be considered in two pieces: with a sloped portion and a flat portion (Figure C2). Overall, the northeast facing hillslope has a slope of 12.44%, which can be broken down into 20.51% slope on the upper portion of the site and 6.00% slope on the flatter portion of the site. Prior to reclamation, Snowville exhibited sheer cut slopes and extensive gullying (Figure 8) (CVNRA, 1984). As of August 2018, a disturbed patch of bare earth approximately 8 m wide and 20 m long in the southeasternmost corner of site is indicative of some downslope mass movement, which is likely the result of incomplete SMCRA reclamation at this site (Davis, 2018).

When a soil survey of the area was published in 1978, most of the soil at Snowville was classified as pits and gravel, with a portion of the upper slope classified as part of the Ellsworth silt loam (Soil Survey Staff, 2018). The Ellsworth series is an aquic hapludalf that is moderately well-drained soil formed in glacial till with moderately low saturated hydraulic conductivity. The first 20 cm are a strongly acid silt loam underlain by a very strongly acid silty clay loam to a depth of 64 cm, underlain by strongly to slightly acid silt loam to a depth of 94 cm, underlain by a slightly alkaline silty clay loam to 152 cm (NCSS, 2015). The bedrock in this area is Devonian aged shale and black shale (Slucher et al., 2006).

Snowville Reference (SR)

The reference location for Snowville Quarry is on the southwestern half of the same hillslope as the Snowville Quarry (Figure C2). An intermittent stream delineates where the disturbed mine ends and the mature forest begins. The soil is classified as Cardinal-Mentor silt loam (Soil Survey Staff, 2018) (see Dover for description). Snowville Reference is also underlain by Devonian shale and black shale (Slucher et al., 2006).

Hines Hill Excavation (HH)

Hines Hill Excavation is a 6.60 ha construction borrow that was originally reclaimed in 1991. A portion of Hines Hill Excavation is relatively undisturbed with mature tree stands. It is likely this portion of the site was not part of the construction borrow and served as part of the access road during mining (CVNRA, 1984). The extracted material was used in the original construction of Interstate 271 in the 1960s (Cockrell, 1992; CVNRA, 1984; ODOT, 2016). It is located on the southeastern side of

Interstate 271, between West Hines Hill Rd and Boston Mills Rd (Figure 9). Access to Hines Hill Excavation is 0.57 km by foot from Boston Mills Road. It is 2.78 kilometers southeast of Dover (center of site to center of site). Hines Hill Excavation is a northeast facing hill with a slope of 21.17%. Gullying was taking place on site by the 1980s (Figure 10) and it continued to be a primary concern during the reclamation. In an attempt to control the extent of gullying, the reclamation team regraded the gully channel walls and deposited rip-rap in piles along the base of the gullies (Kopcak, 1991). By July 2018, Hines Hill Excavation had developed over 40 gullies, 54 rills, and 9 small areas of downslope mass movement with no clear paths of preferential flow.

The soil at Hines Hill Excavation mostly consisted of the same Ellsworth silt loam as Snowville Quarry. Approximately a quarter of the site in the northeastern portion also consists of the Chagrin silt loam (Soil Survey Staff, 2018). The Chagrin series is composed of well drained, moderately permeable silt loam formed from alluvium. The entire soil profile is a moderately acidic silt loam to a depth of 152.4 cm (NCSS, 1998). The bedrock in this area is Devonian shale and black shale (Slucher et al., 2006).

Hines Hill Reference (HR)

Hines Hill Reference area is in the wooded area to the southeast of Hines Hill Excacation, on the opposite side of a ravine (Figure C3). The area was chosen to minimize apparent invasive plants and anthropogenic disturbance. The soil consists of the same Ellsworth series described in the Hines Hill Excavation site (Soil Survey Staff, 2018). The bedrock in this area is also Devonian shale and black shale (Slucher et al., 2006).

Cleveland Trust (CT)

Cleveland Trust (Figure 11) is an 18.10 ha construction borrow (CVNRA, 1984) that was reclaimed in 2012, making it the most recent reclamation of the five sites in the FoSTER Project. It is a continuance of the Rockside Road construction borrow (described below). Reclamation records of this area are limited. A portion of the site was turned into a mitigated wetland by the Heartland Inventory & Monitoring Network (Bingham, 2018). Other than the wetland, it is unclear what other reclamation practices outside of SMCRA policy were used. Due to the presence of the wetland, only a portion of Cleveland Trust, measuring 3.50 ha in size, was studied.

Cleveland Trust is located 424 m southeast of the Rockside Road site (center of site to center of site) (Figure 12) (CVNRA, 1984). The access trail to Cleveland Trust begins at the parking lot to the Cuyahoga Valley Scenic Railroad Station located at 7900 Old Rockside Road, Independence, OH. The access road is usable by vehicles for the first 230 m to the south. At that point it becomes a footpath. The footpath follows a west-southwest orientation for 170 m to the northernmost corner of the site. The site itself is a northeast-facing hill with a slope of 13.46%. When the soil survey of Cuyahoga County was completed in 1978, the soil on the mine site had been described only as an udorthent, while the surrounding non-mined lands are mapped as a Brecksville silt loam (Soil Survey Staff, 2018). The Brecksville silt loam is described as a silt loam to a depth of

13.6 cm, underlain by a silty clay loam to a depth of 76.2 cm, underlain by shale. The entire profile is very strongly acid (NCSS, 2011a). The bedrock at Cleveland Trust is Devonian age shale and black shale (Slucher et al., 2006).

Rockside Road (RR)

Rockside Road is a 3.55 ha construction borrow that was reclaimed in 1984, making it the oldest reclamation of the five sites in the FoSTER Project. It is located on the southern side of Rockside Road in Independence, OH, 341 meters east of the intersection of Rockside Road and Brecksville Road (Figure 13). The access trail to the Rockside Road starts where the access trail to Cleveland Trust ends. The rest of the trail is a 280 m long northwesterly foot trail along the edge of the Heartland mitigated wetland; this edge is marked by pink NPS flagging tape attached to tree branches. The site is a northeast facing hill with a slope of 12.07%. West to east oriented gullies and rills are the dominant geomorphic features of this site. In 1978, the Rockside Road site was mapped in the same udorthent unit as Cleveland Trust (Soil Survey Staff, 2018). The surrounding non-mined lands are also mapped as the Brecksville silt loam described in Cleveland Trust (Soil Survey Staff, 2018). It is also underlain by the same Devonian shale and black shale bedrock as Cleveland Trust (Slucher et al., 2006).

Cleveland Trust and Rockside Road Reference (CRR)

Due to their proximity to one another, Rockside Road and Cleveland Trust share a reference location. The nearest, relatively mature forested area of similar slope and aspect within NPS boundaries is located 1.32 kilometers south-southeast of Cleveland Trust (center of site to center of reference location) (Figures B4-B6). The soil consists of Mitiwanga silt loam, Loudonville silt loam, and Ellsworth silt loam (Soil Survey Staff, 2018). The Mitiwanga silt loam, an aeric ochragualf, is a poorly drained, moderately permeable soil formed on 50-102 cm of till underlain by sandstone bedrock. It is a moderately acid silt loam to a depth of 22.86 cm, underlain by a very strongly acid loam to a depth of 40.64 cm, underlain by strongly acid clay loam to a depth of 63.5 cm where it meets hard sandstone bedrock (NCSS, 2011b). The Loudonville series, an ultic hapludalf, is a well-drained, moderately permeable loamy till that is underlain either by sandstone or siltstone. The first 33 cm are a very strongly acid silt loam, underlain by strongly acid loam to a depth of 96.52 cm where the soil profile meets bedrock (NCSS, 2004). (For description of the Ellsworth silt loam, see the Snowville Quarry site description.) The bedrock at CRR consists of Devonian sandstone and shale (Slucher et al., 2006).

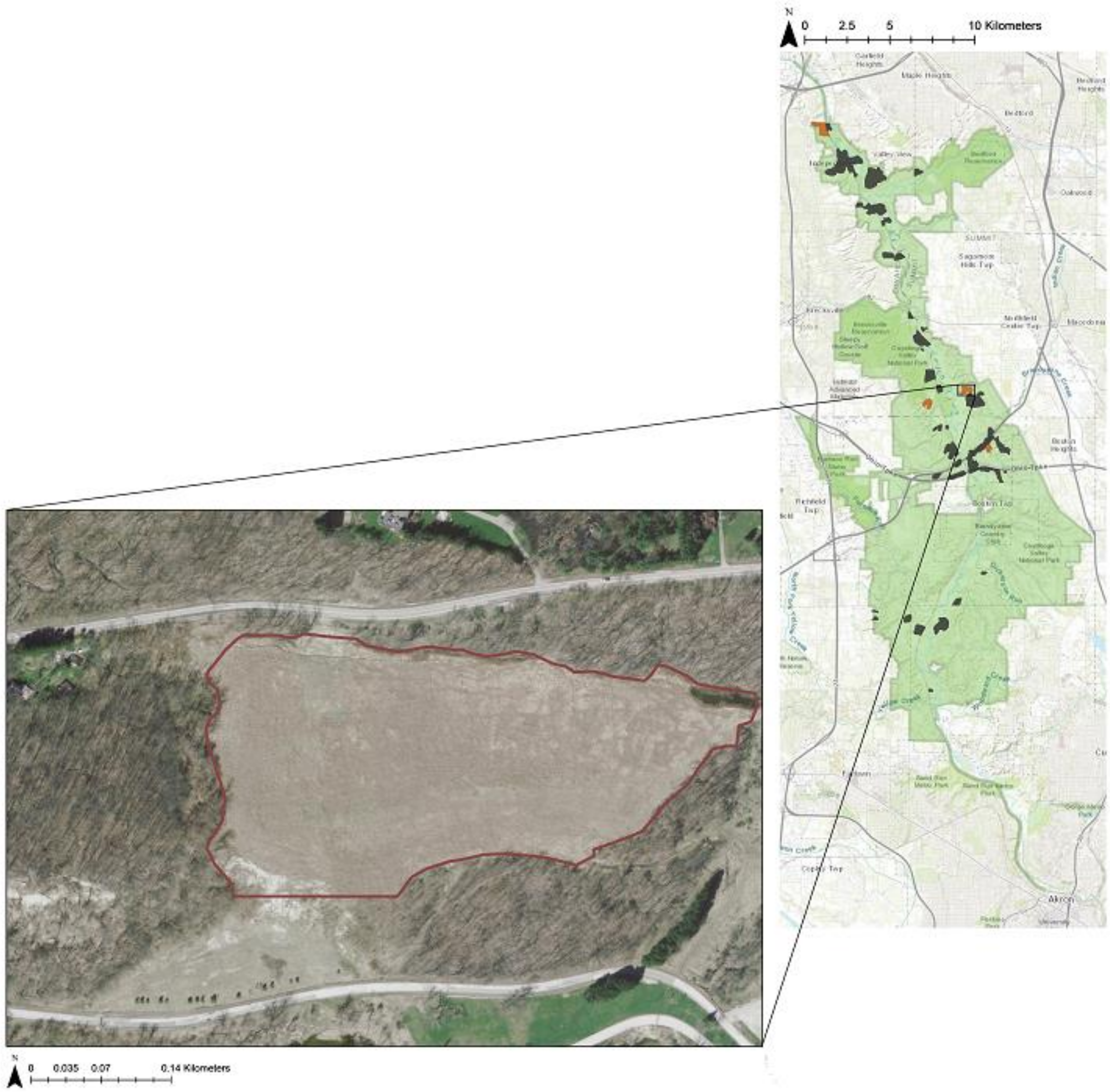

Figure 6: Dover topsoil mine in 2006. The brown border indicates the sampling area. West Highland Rd is to the north, running west to east. Note the gullied area in southwest corner of the site where the slope is extremely steep. Part of the access road is still visible, starting in the southeast corner of the site and running east before turning southwest. (See Figure C1 for a topographic map of Dover, Dover sampling points, original Dover boundaries, and Dover Reference sampling points.)

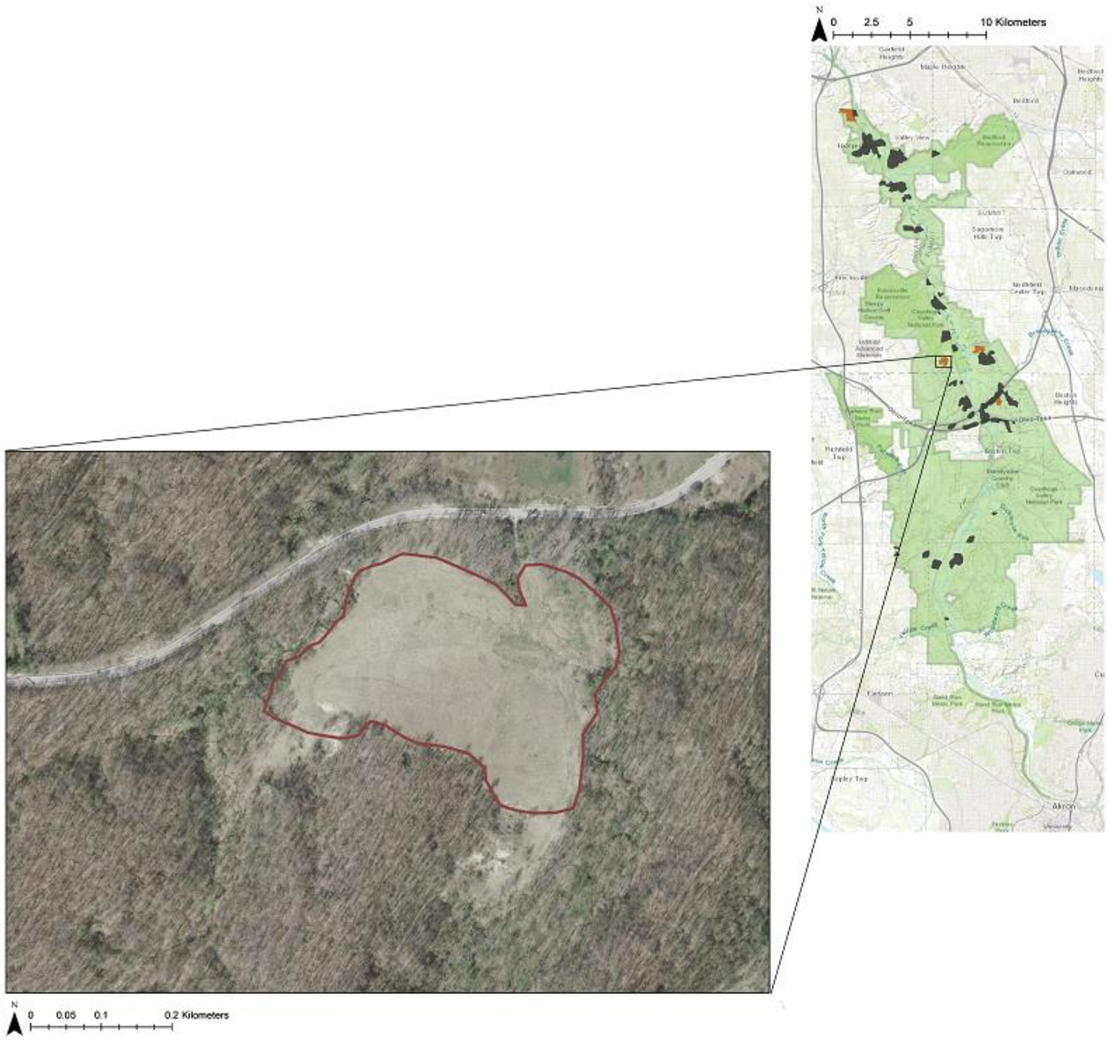

Figure 7: Snowville Quarry in 2006. Snowville Road is to the north. The brown border indicates the sampling area. The upslope portion of the quarry starts halfway into the site from the north, leading up toward the tree line in the south. (See Figure C2 for a topographic map of Snowville Quarry, Snowville Quarry sampling points, original Snowville Quarry boundaries, and Snowville Reference sampling points.)

Figure 8: Snowville Quarry (1980s) prior to reclamation in 1999. Top: Facing southwest toward the cut slope. Bottom: Facing south toward the top of the ridge. Note lack of vegetation and extensive gullying. Photo credit: Cuyahoga Valley National Park, Division of Resource Management Archives.

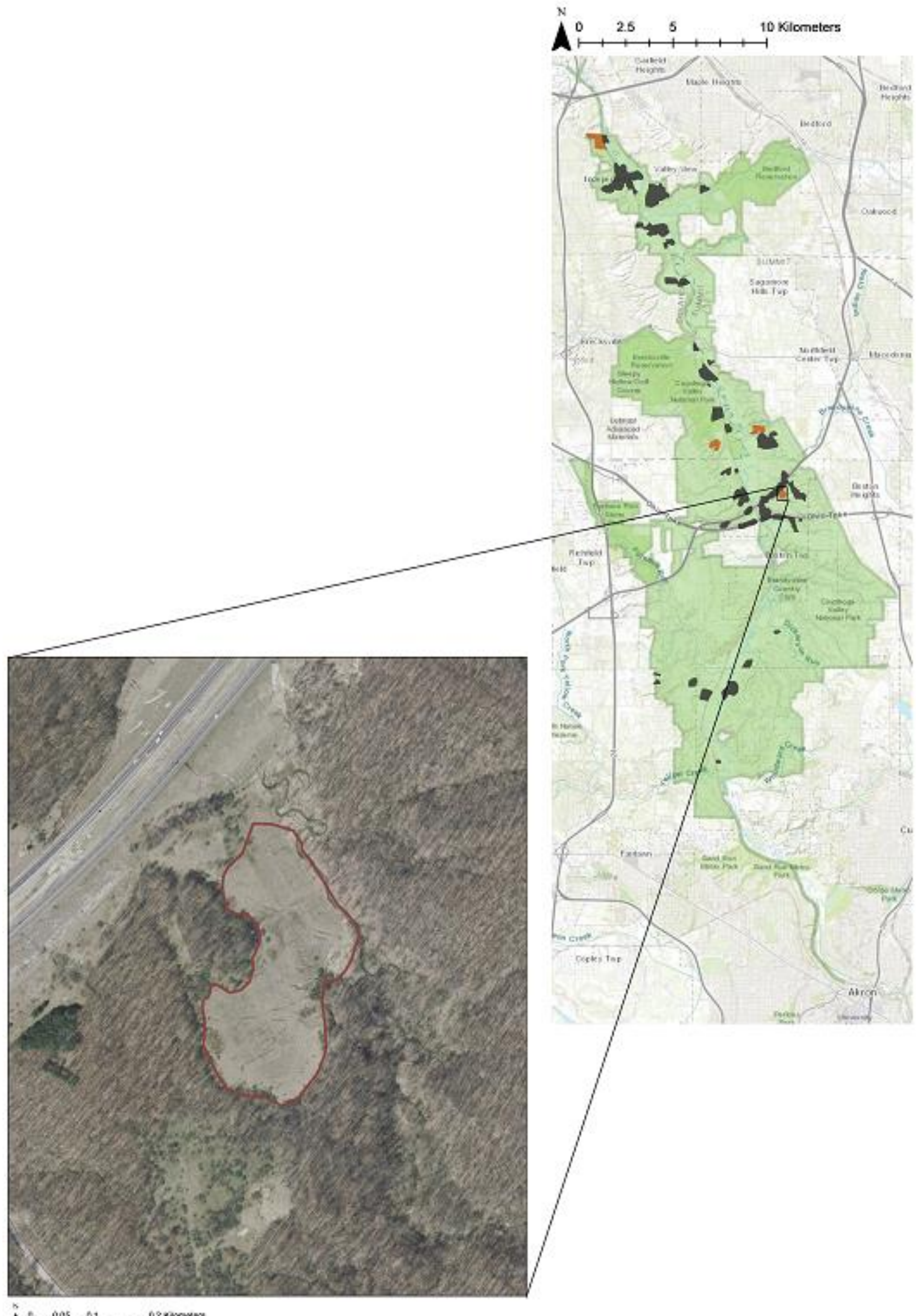

Figure 9: Hines Hill Excavation in 2006. The brown border indicates the sampling area. I-271 can be seen to the northwest, running southwest to northeast. Boston Mills Rd can be seen in the southwest, running northwest to southeast. Note the gullies. (See Figure C3 for a topographic map of Hines Hill Excavation, Hines Hill Excavation sampling points, original Hines Hill Excavation boundaries, and Hines Hill Reference sampling points.)

Figure 10: Hines Hill Excavation (1980s) prior to reclamation in 1991, facing east away from center of site. Note the establishment of gullies, trending toward the eastern (left) edge of the site. Photo credit: Cuyahoga Valley National Park, Division of Resource Management Archives.

Figure 11: Cleveland Trust (1980s) prior to reclamation in 2012. Picture taken from access road facing west-southwest toward site. Note extensive gullying. Photo credit: Cuyahoga Valley National Park, Division of Resource Management Archives.

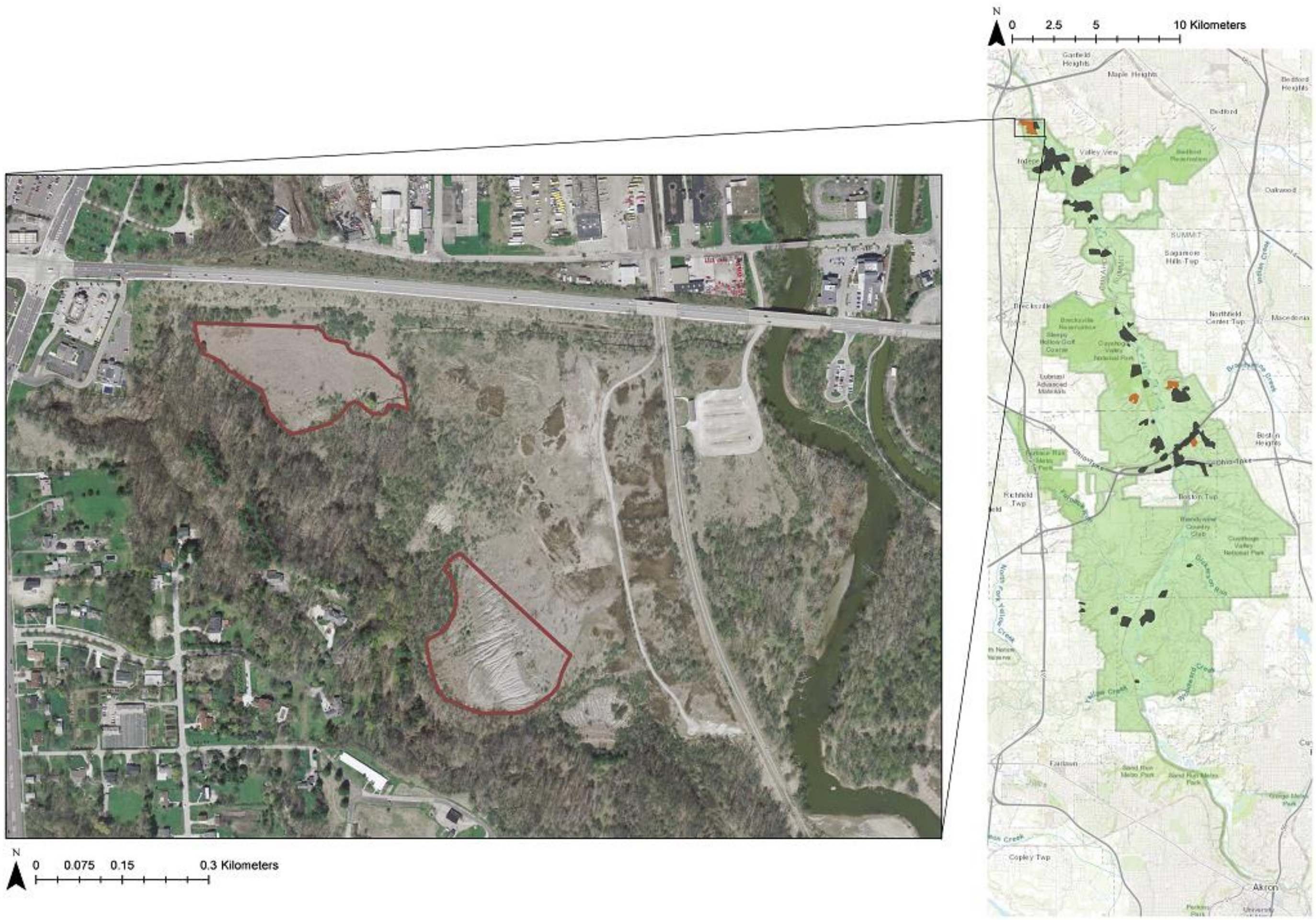

Figure 12: Rockside Road and Cleveland Trust in 2006. The brown borders indicate the sampling areas. Rockside Rd can be seen to the north, running east to west. The Rockside Road site is adjacent to it, to the south. Cleveland Trust is southeast of the Rockside Road site. The Cuyahoga River can be seen to the east, running south to north. (See Figure C4 a topographic map of Cleveland Trust, Rockside Road, and the Cleveland Trust Rockside Road Reference area. See Figures B5 and B6 for topographic maps of Cleveland Trust and Rockside Road, respectively.)

Grain size distribution

The soil samples in both the mines and the reference locations plotted primarily in the silt loam category of the texture triangle (Figures 13-16). There was a spread of textures, however, due to varying ratios of sand and silt. This caused some soil samples to plot in the loam portion of the texture triangle and a small subset to plot in the sandy loam portion.

Soil samples from Dover plotted primarily in the silt loam portion of the texture triangle. Some points also plotted in loam and two points plotted in sandy loam (Figure 13). NCSS classified the soil at the Dover site as a silt loam to a depth of 7.62 cm and a silty clay loam to a depth of 10 cm (Ritchie & Steiger, 1974; NCSS, 1986; Soil Survey Staff, 2018). The Dover Reference location plotted similar to this NCSS classification: half within silt loam and half within loam (Figure 13). NCSS classified Dover Reference as a silt loam to a depth of at least 33 cm, making them slightly finer than the site textures (Ritchie & Steiger, 1974; NCSS, 2005; NCSS, 2016; Soil Survey Staff, 2018). At the Dover site, long ribbons of soil could be formed, suggesting the soil is more likely a silty clay loam or a silty clay.

A majority of soil samples from Snowville Quarry plotted in the silt loam portion of the texture triangle, while some samples also plotted in the loam portion of the triangle (Figure 14). Where it wasn't classified as a pit, Snowville Quarry was classified as a silt loam to a depth of 20 cm and Snowville Reference was classified as a silt loam to a depth of 33 cm (Ritchie & Steiger, 1974; NCSS, 2005; NCSS, 2015; NCSS, 2016; Soil Survey Staff, 2018). Snowville Reference plotted almost entirely within the silt loam portion of the texture triangle, with one point plotting on the boundary between loam and sandy loam (Figure 14). Therefore, both Snowville Quarry and Snowville Reference, which both had most of their samples plot within the silt loam category, were relatively similar to each other and their respective NCSS soil classifications. The difference here is that Snowville Quarry also had some samples plot within the loam category. Like Dover, the feel test suggested the soil was more clay-rich, likely a silty clay loam or a silty clay, especially where soil was exposed at depth from deep-ripping in 2018.

Soil samples from Hines Hill Excavation plotted mostly in the silt loam portion of the texture triangle with some samples also plotting in the loam portion (Figure 15). Hines Hill Reference samples also plotted mostly in the loam portion of the texture triangle with some samples plotting in the silt loam and sandy loam portions of the triangle (Figure 15). Hines Hill Excavation and Hines Hill Reference were both classified as silt loams to a depth of 152 cm (Ritchie & Steiger, 1974; NCSS, 2005; NCSS, 2015; NCSS, 2016; Soil Survey Staff, 2018). Samples from Hines Hill Excavation plotted mostly within the silt loam category with some in the loam category. Hines Hill Reference plotted half within silt loam and half within loam. This suggests that Hines Hill Excavation is more similar to the NCSS classifications than the Reference location is. Samples from Hines Hill Excavation were more like a silty clay loam using the feel test.

Soil samples from Cleveland Trust plotted almost entirely within the silt loam portion of the triangle with some samples plotting in the loam and sandy loam portions of the triangle (Figure 16). Samples from Rockside Road had a similar distribution (Figure

16). Cleveland Trust and Rockside Road Reference plotted mostly within silt loam portion of the triangle with some samples plotting in the loam and sandy loam portions of the triangle (Figure 16). Cleveland Trust and Rockside Road were classified by the NCSS only as udorthents, with no attribution regarding their soil texture (Soil Survey Staff, 2018). Meanwhile, the Cleveland Trust and Rockside Road Reference location was classified by the NCSS as a silt loam to a depth of at least 20 cm (NCSS, 2004; NCSS, 2011b; NCSS, 2015; Soil Survey Staff, 2018). The samples from the reference location plotted primarily in the silt loam category, but some did plot within the loam category, making it similar to, but slightly coarser than, the NCSS classification. Cleveland Trust and Rockside Road plotted primarily within the silt loam category with some samples in the loam category. Additionally, Cleveland Trust had some samples plot within the sandy clay loam category. Therefore, in general, a majority of the samples from both Cleveland Trust and Rockside Road plotted similar to the reference location, though some samples were coarser. The feel test produced a wide range of results from Cleveland Trust and Rockside Road. Samples could be silt loams, silty clay loams, clay loams, or silty clay. At the reference location, samples analyzed using the feel test were predominantly silt loams or silty clay loams.

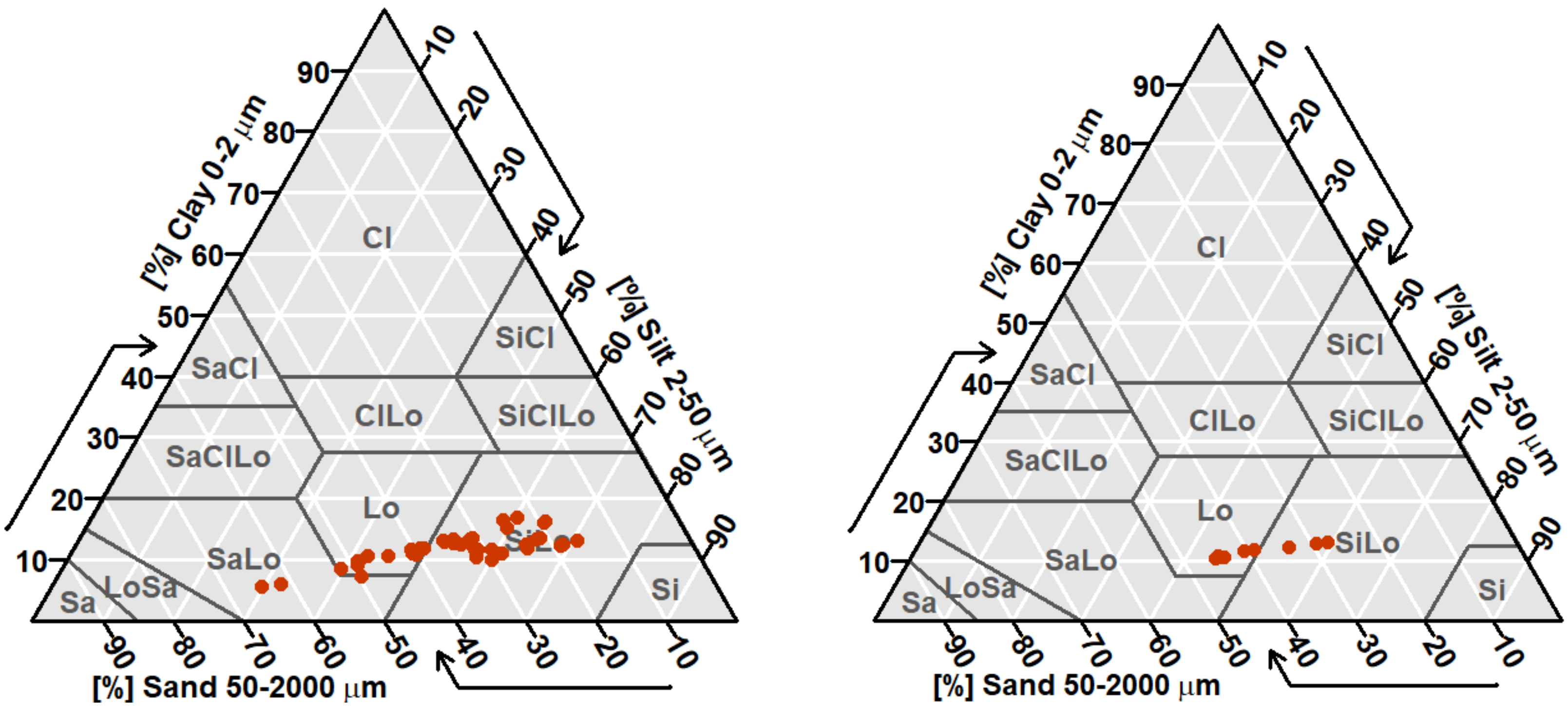

Figure 13: Grain size distributions for Dover (left) and Dover Reference (right). Red circles indicate individual sample results.

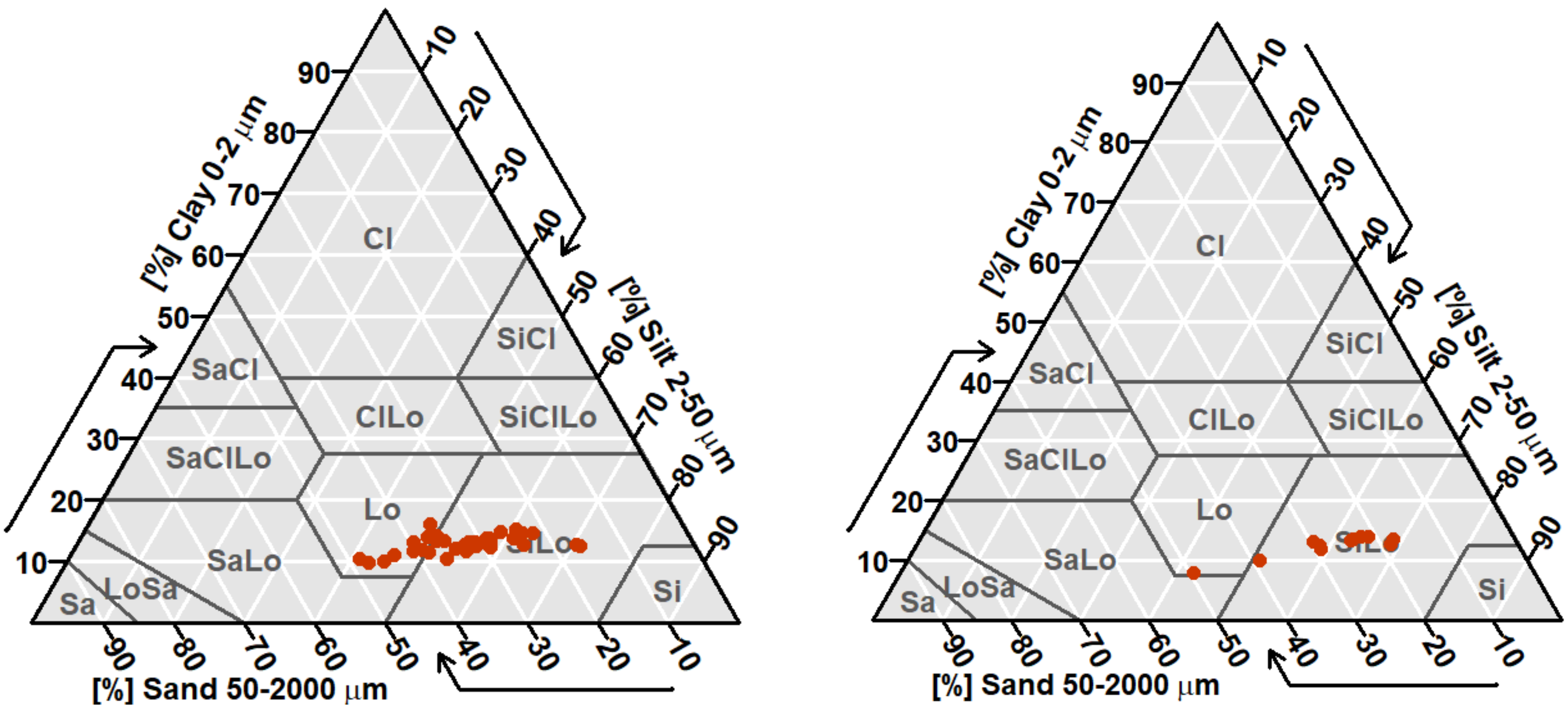

Figure 14: Grain size distributions for Snowville Quarry (left) and Snowville Reference (right). Red circles indicate individual sample results.

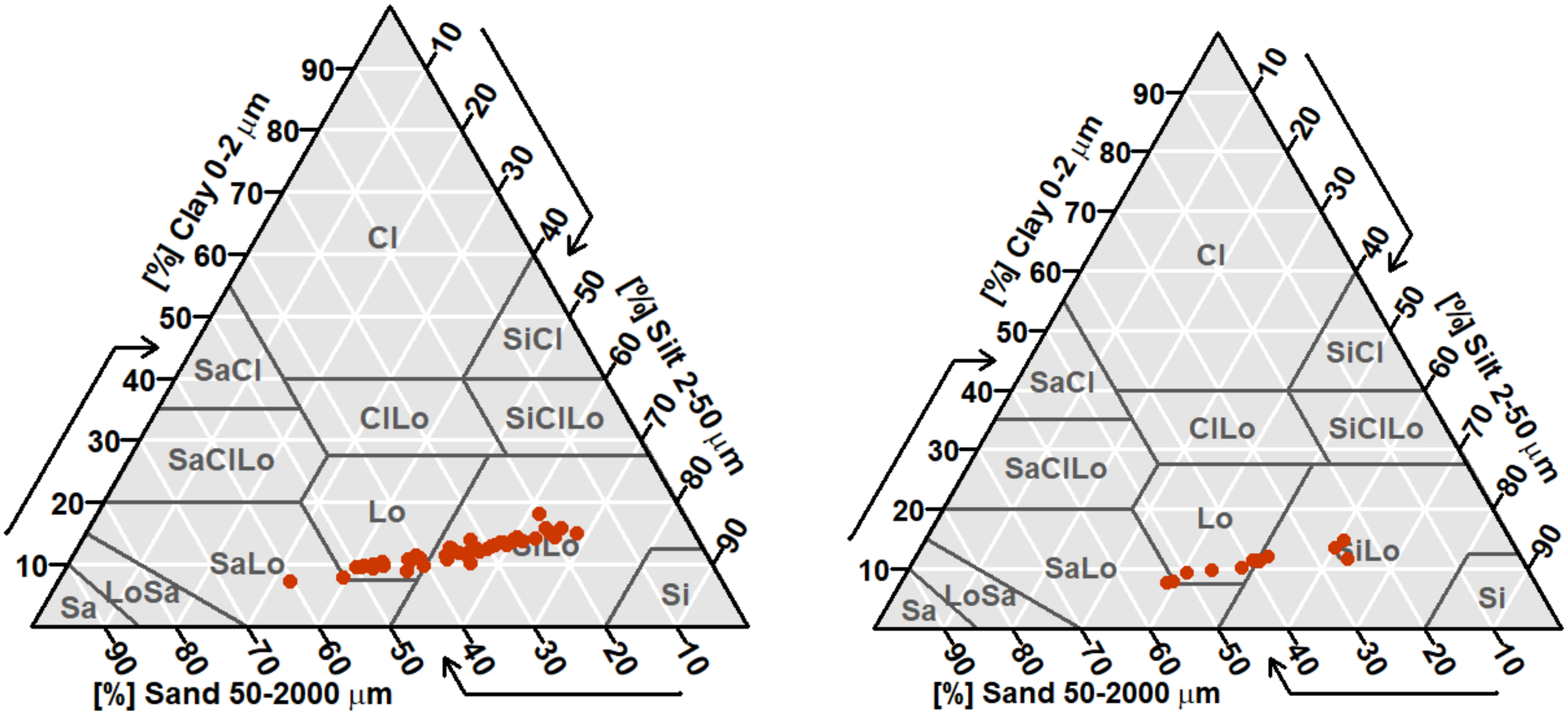

Figure 15: Grain size distributions for Hines Hill Excavation (left) and Hines Hill Reference (right). Red circles indicate individual sample results.

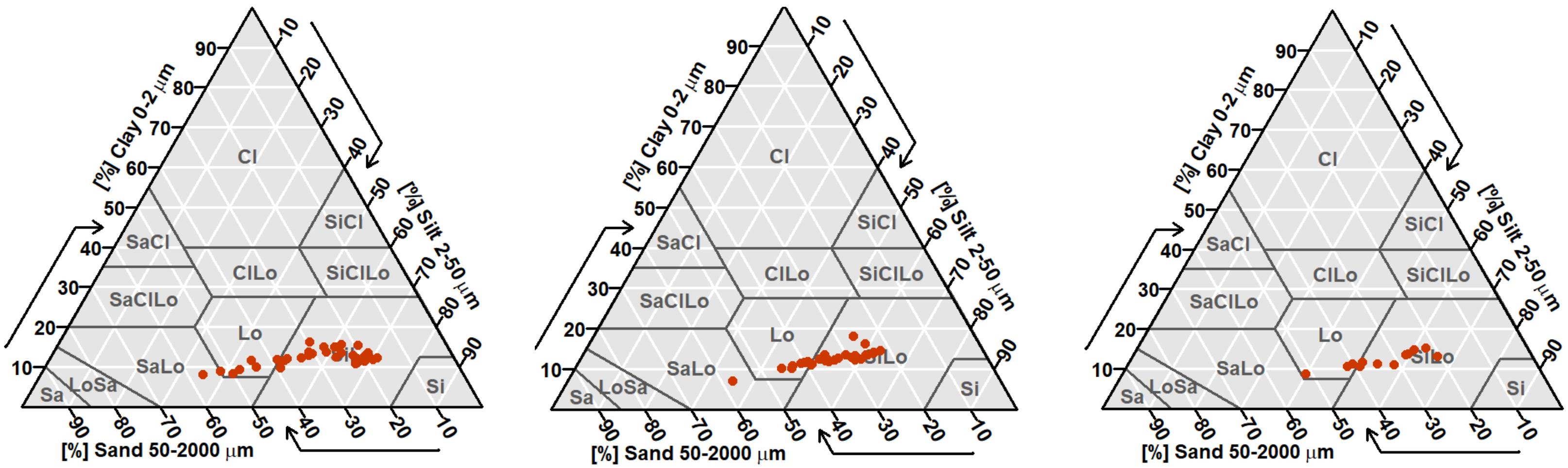

Figure 16: Grain size distributions for Cleveland Trust (left), Rockside Road Excavation (middle), and Cleveland Trust and Rockside Road Reference (right). Red circles indicate individual sample results.

Near-Surface Bulk Density

The near-surface bulk density samples on the mine sites contained a range of values between 0.51 and 1.65 g cm^{-3}. The mean value for these samples was 1.10 g cm^{-3} with a standard deviation of 0.20 g cm^{-3}. The near-surface bulk density samples in the reference locations contain a of range of values between 0.39 and 1.32 g cm^{-3}. The mean value for these samples was 0.86 g cm^{-3} with a standard deviation of 0.26 g cm^{-3}.

The effect on mine versus reference location on near-surface bulk density was significant ($p < 0.001$) (Figure 17). In general, the near-surface bulk density was significantly higher in the mine sites than it was in the reference locations. The fixed effects had a Pearson's r^2 value of 0.21. The fixed effects combined with the random effects had a Pearson's r^2 value of 0.28. The effect of general area of study was also significant.

The densest soils post-ripping occurred in the cross-rips (Figure 18). On average, Dover pre-rip samples were 0.31 g cm^{-3} denser than Dover post-rip samples located outside rips, 0.02 g cm^{-3} less dense than post-rip samples taken in a single rip, and 0.14 g cm^{-3} less dense than samples taken with cross-rips. The differences between the differences in means of single rips versus cross-rips were not significant ($p = 0.366$). The differences between the differences in means of single rips versus no rips were significant ($p = 6.74$ E-04). Similarly, the differences between the differences in means of cross-rips versus no rips were significant ($p = 5.40$ E-05) (Figure 19).

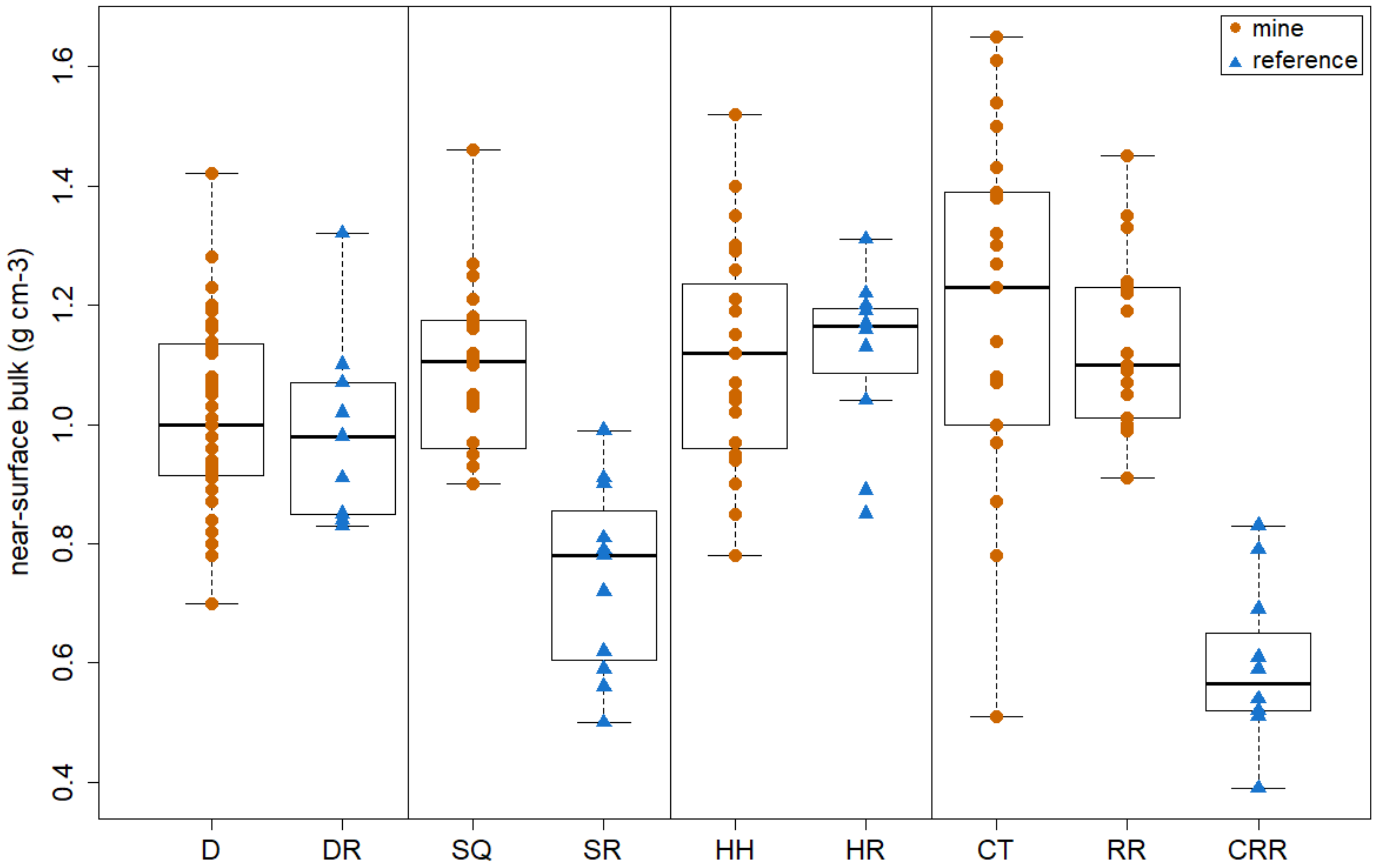

Figure 17: Near-surface bulk density by site. Boxplots are grouped by general study area such that reference locations are next to their respective mine sites. Orange circles are mine site samples and blue triangles are reference location samples.

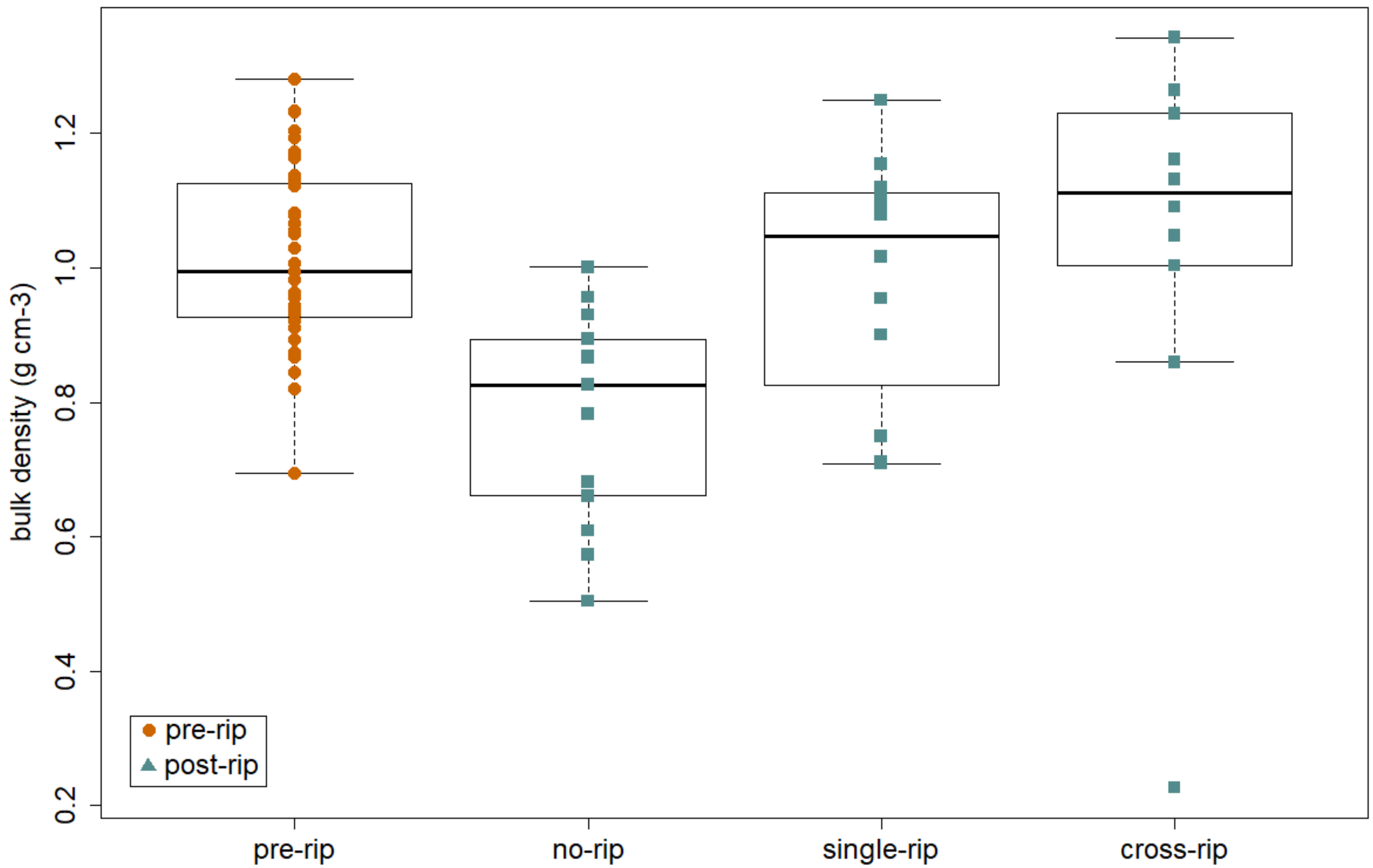

Figure 18: Near-surface bulk density at Dover pre- and post-ripping. Orange circles are pre-rip near-surface bulk density samples. Green squares are post-rip near-surface bulk density samples.

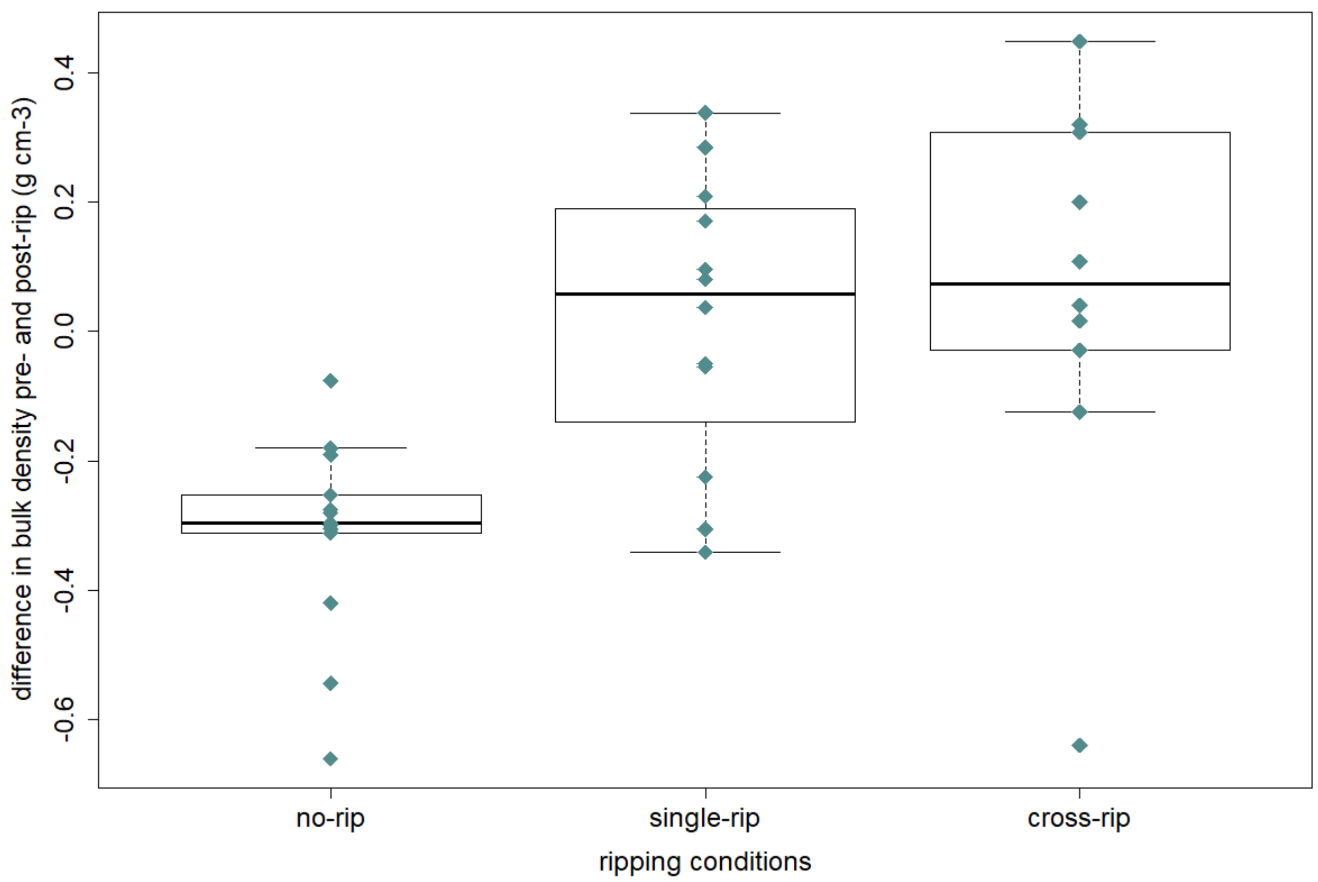

Figure 19: Differences in near-surface bulk density between Dover pre-ripping and Dover post-ripping. The y-axis is the difference between the post-rip sample and the pre-rip sample at each sampling point in g cm^{-3}. A value of 0 g cm^{-3} would represent no difference between the pre-rip sample and the post-rip sample. A negative value would indicate the post-rip sample was less dense than the pre-rip sample. A positive value would indicate the post-rip sample was denser than the pre-rip sample. Along the x-axis are the post-rip sample categories. 0 indicates the samples were not taken in a rip, 1 indicates the samples were taken in a single rip, and 2 indicates the samples were taken at the intersection of 2 rips (a cross-rip).

Deep Bulk Density

On the flat portion of the Snowville Quarry site, bulk density was non-root restrictive to a depth of 20 cm. On the slope, root-restrictive density occurred at 15 cm. The maximum bulk density occurred at 25 cm on the flat. In general, the bulk densities of Snowville Quarry were higher than those of Snowville Reference and were root-restrictive past 15 cm (Figure 20).

The 35 cm measurement on the flat portion of the site was not used in analysis because it was calculated to be 3.00 g cm^{-3}, which is physically impossible. Density of basalt ranges from 2.7 to 3.3 g cm^{-3} (Jones, 2007). This sample was the least intact sample during collection.

The soil within the Snowville Reference location pit had horizonation marked by wavy boundaries. The top 8-10 cm compose the first horizon. The soil is dark brown and very loose and porous in areas here. The next horizon is 3-10 cm thick. The soil in this horizon is grayish-brown. Where the first horizon is thicker, the second horizon is thinner and vice versa. Below the second horizon is a tan third horizon until the bottom of the soil pit at 35 cm. Fine and very fine roots are very common in the upper 10 cm and common in the next 5 cm. Very fine roots were rare throughout the rest of the profile. A tree root approximately 2 cm in diameter was present in the bottom of the pit. In comparison, the soil pits at Snowville Quarry, both on the slope and the flat, demonstrated very little horizonation. On both, the horizon was approximately 2 cm thick. Below this for the next 48 cm was the parent material. On the sloping portion of the site there was a color change in the soil approximately 15 cm down the profile, shifting from dark brown to reddish brown. On the flat portion of the site, there was no color change. Both profiles had fine roots common in the top centimeter of soil with very fine roots very rare throughout the rest of the profile.

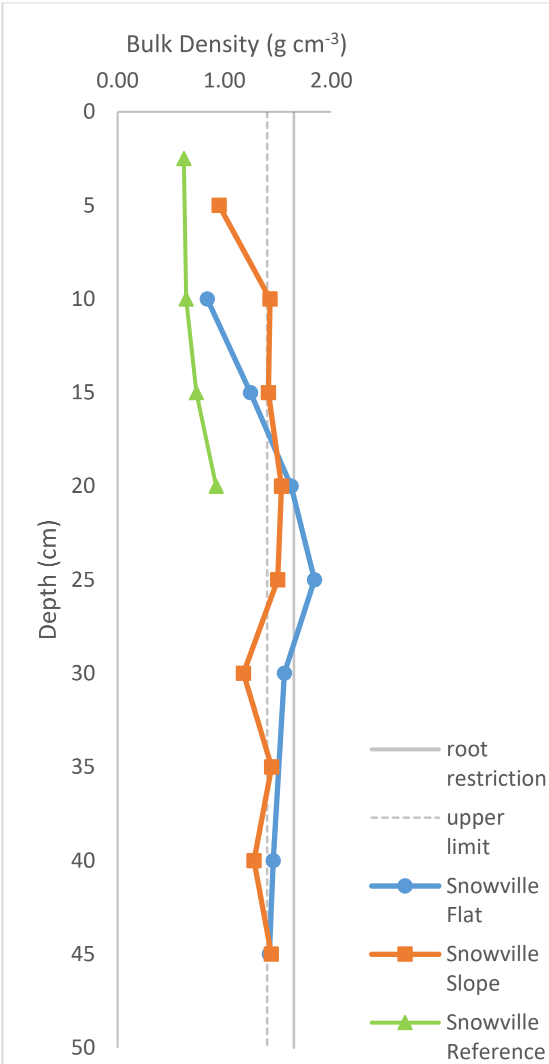

Figure 20: The bulk density at depth profiles for Snowville Quarry on the slope and on the flat in comparison to the bulk density depth profiles for Snowville Reference.

The green solid line with triangles marks the profile for Snowville Reference. Roots and hard soil prevented digging the Reference soil pit past 25 cm, despite multiple attempts. The blue solid line with circles indicates the soil profile for the flat portion of Snowville Quarry. The orange line with squares marks the soil bulk density profile for Snowville Quarry on the slope.

The faded gray dashed line in the background marks the upper limit of ideal soil compaction for plant growth in a silt loam or silt clay loam. The faded solid gray line in the background indicates the bulk density at which root elongation in severely restricted in silt loams and silt clay loams.

Saturated hydraulic conductivity

The K_{sat} on the mine sites contained a range of values between 1.47 E-08 and 1.63 E-04 m s^{-1}. The average K_{sat} on the mine sites was 1.48 E-05 m s^{-1} with a standard deviation of 3.60 E-05 m s^{-1}. These measurements were exceedingly slow and took 0.5 – 2.0 hours each to collect. The K_{sat} in the reference locations contained a range of values between 2.96 E-06 and 3.24 E-05 m s^{-1}. The average K_{sat} in the reference locations was 1.35 E-05 m s^{-1} with a standard deviation of 9.16 E-06 m s^{-1}. These measurements occurred at a much faster rate and took 25-40 minutes each to collect.

K_{sat} was significantly higher in reference locations than it was on mine sites ($p = 0.0027$). The effect of the general study area was also significant ($p < 0.001$) (Figure 21). There is no significant correlation between K_{sat} and near-surface bulk density at its respective sampling location (Pearson's $r^2 = 0.022$).

K_{sat} was not significantly higher on the Dover site than it was in Dover Reference ($p = 0.1906$). Likewise, K_{sat} was not significantly higher in Snowville Quarry than it was in Snowville Reference ($p = 0.5042$). K_{sat} was significantly higher in the sloping portion of Snowville Quarry than it was in the flat portion of the site ($p = 0.01146$). K_{sat} was not significantly higher on Hines Hill Excavation than Hines Hill Reference ($p = 0.1108$). There was a significant difference in the ANOVA for Cleveland Trust, Rockside Road, and Reference ($p = 0.0186$). There was no significant difference between Cleveland Trust and Rockside Road ($p = 0.7839$). Cleveland Trust was significantly slower than the Reference location ($p = 0.0166$). Rockside Road was also significantly slower than the Reference location ($p = 0.0443$) (Figure 22).

There was no significant difference in the rate of K_{sat} at Dover between pre-rip, single rip, cross-rip, and no rip conditions ($p = 0.0592$) (Figure 23), despite the visually apparent difference between the measurements as they were conducted.

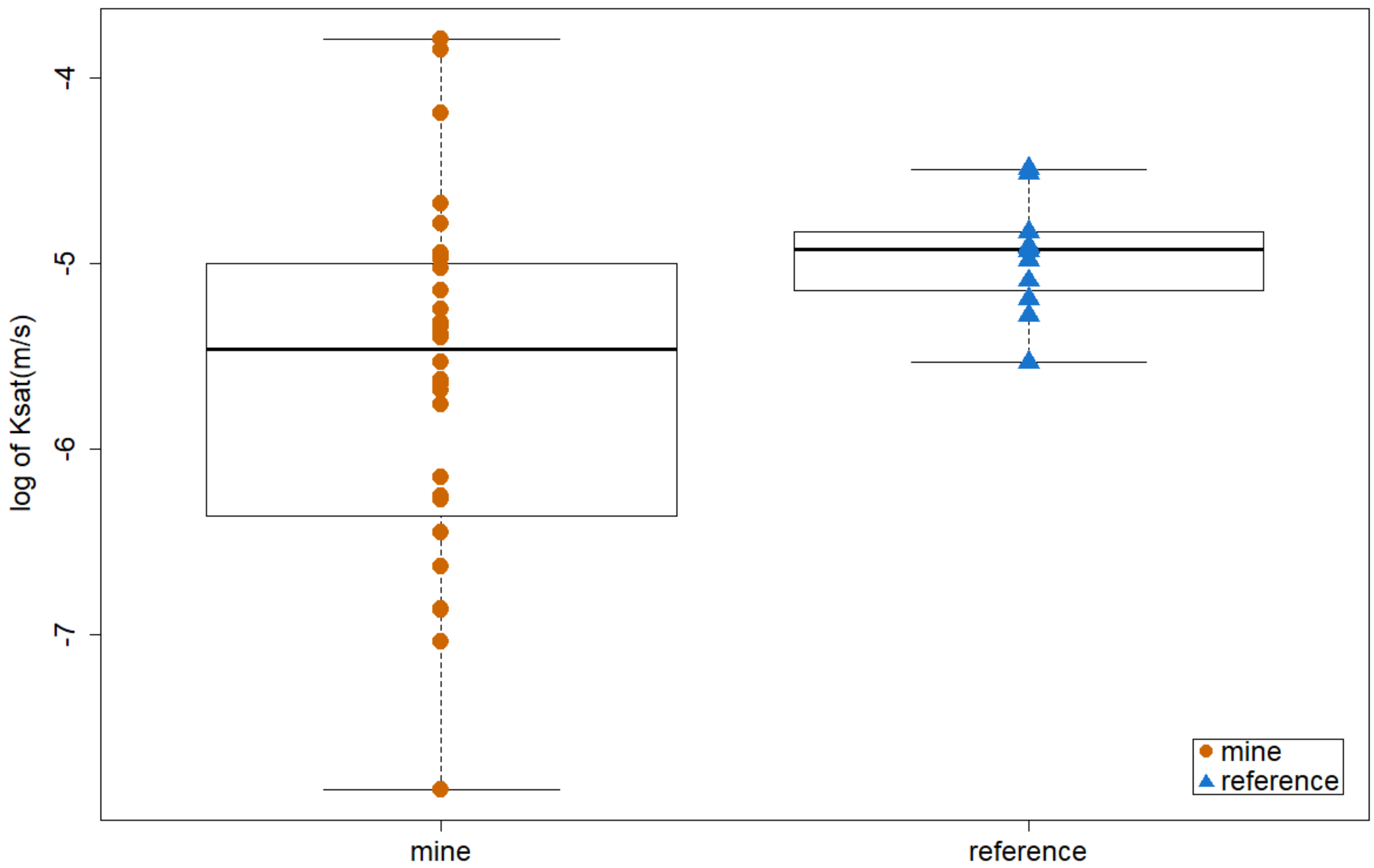

Figure 21: Saturated hydraulic conductivity for the nine study areas in CUVA, comparing mine sites and reference locations. The y-axis is the log of the K_{sat} (m s^{-1}) measurements. Orange circles are mine site measurements and blue triangles are reference location measurements.

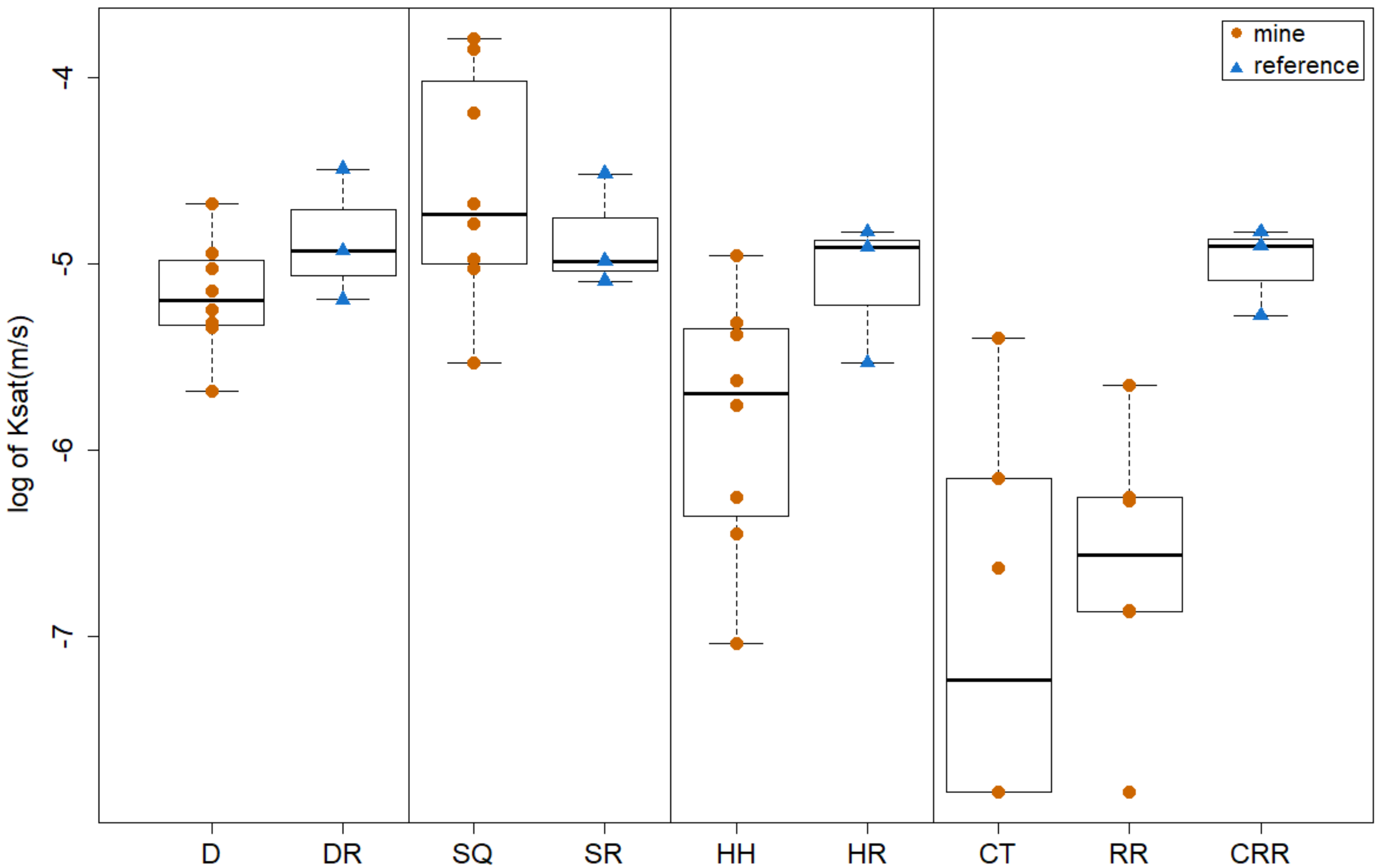

Figure 22: Saturated hydraulic conductivity for the nine study areas in CUVA, comparing mine sites and reference locations. Boxplots are grouped by general study area such that reference locations are directly next to their respective mine sites. The y-axis is the log of the K_{sat} (m s^{-1}) measurements. Orange circles are mine site measurements and blue triangles are reference location measurements.

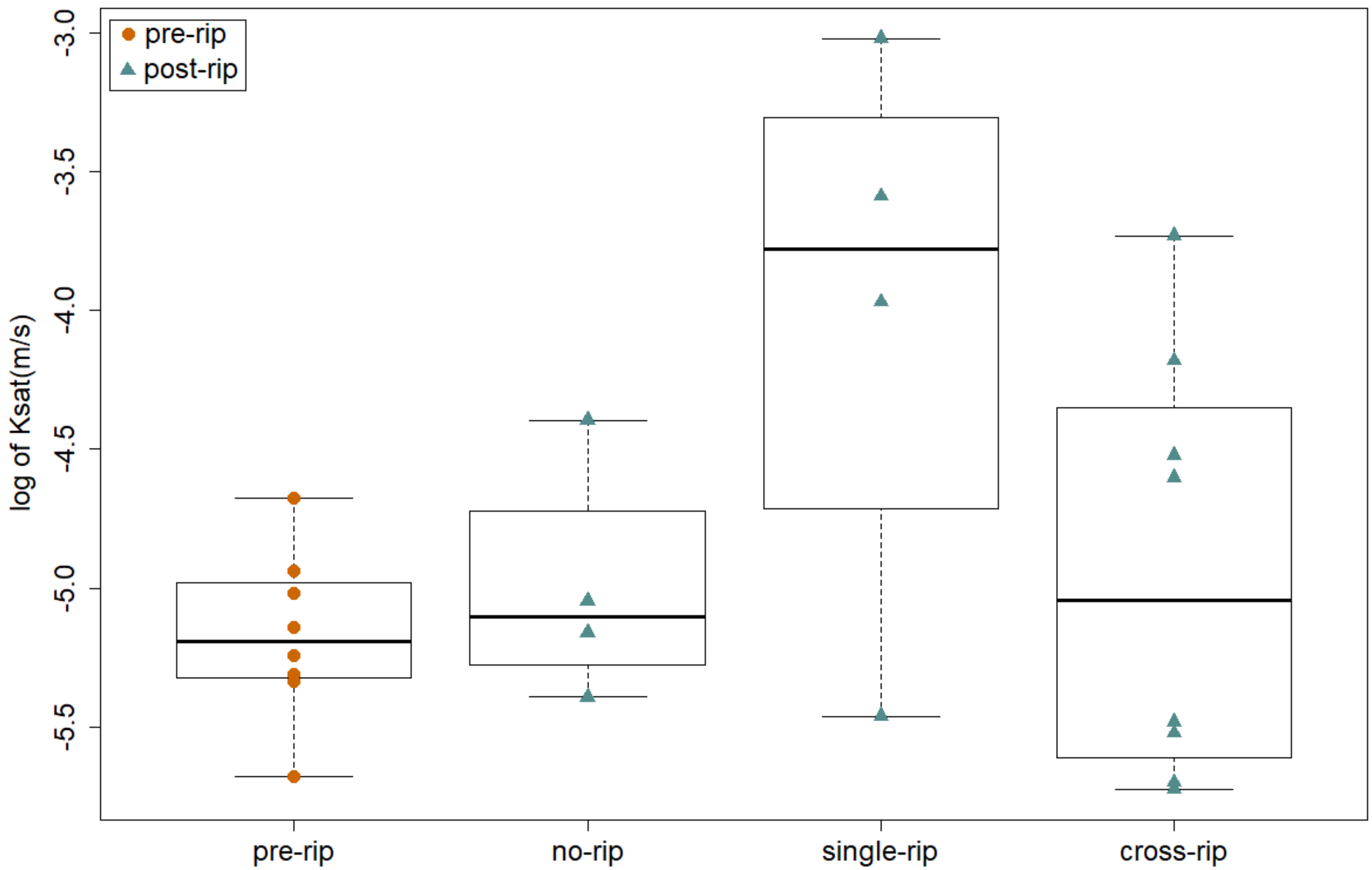

Figure 23: Saturated hydraulic conductivity for Dover pre- and post-rip. The y-axis is the log of the K_{sat} measurements. Orange circles are pre-rip measurements. Green triangles are post-rip measurements.

Discussion

It is difficult to piece together the full history of the mine sites as many important elements are undocumented or missing. It has become evident that assumptions about natural succession for reforestation were not valid for the mining and reclamation practices, although at the time of reclamation of four out of the five sites, the best practices of the FRA had not yet been published or otherwise communicated to CUVA staff. However, studying the conditions of the sites in comparison to reference locations lends clues as to which properties on these sites inhibit native tree growth and informs future restoration efforts.

Soil texture was not markedly different between the mine sites and the reference locations, though some mine and reference samples did differ from the NCSS classifications. Where reference location soils differ from NCSS classifications, a problem with either the NCSS mapping resolution or the methods used in this project may provide an explanation. In general, surprisingly little clay was present in the samples in comparison to how the samples responded to the feel method for identifying soil texture in the field (Thein, 1979). These observations suggest there may be an error in the texture data produced by the Malvern, likely caused by the soil's lack of disaggregation, especially of the clay fraction, during sonication.

Other explanations for the differences in soil textures between the mine sites and the NCSS could include the effects of mining or SMCRA reclamation. Mechanical mixing of layers during mining and reclamation could cause coarser material to move upward in the soil column from the C and R horizons. The source of the backfill used in reclamation, such as the stream and lake sediment used for backfilling Dover, is another potential factor in shifting the texture of a soil away from its original texture. Finally, at mine sites like Cleveland Trust and Rockside Road, the mining happened long enough ago that these sites were mapped only as udorthents. Given this, it is impossible to know whether the texture observed today is equivalent to the pre-existing soil conditions of those sites.

The idea of focusing on reclamation at these sites in lieu of restoration is significant. While restoration focuses on returning a post-mining landscape to its original pre-disturbance conditions and ecological functions, the activities undertaken at the FoSTER sites have been primarily concerned with creating geotechnical stability, followed by repopulation of original species. These strategies align with the goals of reclamation (Lima et al., 2016). Restoration would be ideal, but as noted earlier, our information about the pre-mining conditions of these sites is limited or missing. If the on-going anthropogenic processes of deep-ripping and tree-planting are successful, natural processes may eventually succeed in achieving restoration of ecological functions without further human intervention.

The prevailing hypothesis to explain the inability of native trees to populate the mine sites following initial restoration activities has been root restriction associated with high bulk density. This hypothesis is based both on the studies that are the foundation of the FRA and the preliminary observations at the FoSTER sites. Indeed, despite the similar soil textures at mine sites and reference locations, near-surface bulk density was significantly higher within the mine sites. Additionally, bulk density at depth was markedly higher within Snowville Quarry than it was in Snowville Reference. While the near-surface bulk density values were not high enough to contribute to root restriction at any of the mine sites, the deeper soil measured at Snowville Quarry was dense enough to contribute to root restriction past 20 cm in depth. This is further corroborated by the lack of roots, especially larger roots, past 2 cm within the quarry. Indeed, grass roots can penetrate at least 1 m into the soil in the right conditions (Canadell, 1996; Pennington, 2016). While tree-rooting depth varies with the soil density and moisture conditions present, survival of trees requires roots penetrating to a depth of at least 60 cm. Elongation of the main taproot in the deeper portions of the soil is most rapid during the first 2-3 years, tapering off as lateral roots branch out. Therefore, if a tree is prevented from achieving adequate root penetration at depth and the taproot and replacement root tips die, the tree itself will not survive (Dobson, 1995). Additionally, the lack of roots at depths >2 cm also means that the soil has little to no chance over the near-term of experiencing bioturbation to decrease bulk density over depth. The lack of roots also suggests that organic matter will be low throughout the soil profile. Bulk density has been shown to be strongly inversely related to organic matter content (Arvidsson, 1998).

High bulk density and lack of rooting to create macroporosity have consequences for the soils' ability to infiltrate and drain water, as measured using K_{sat} (Chong & Cowsert, 1997; Manning, 1997; Hillel, 2004). The NRCS has accepted values for the typical K_{sat} of soils of various textures, assuming normal values for bulk density. Knowing a soil texture can be used as a guide to predict the K_{sat} of that soil and vice versa (NRCS, 2018). Within the reference locations, K_{sat} was moderately rapid (n = 4), moderate (n = 7), and moderately slow (n = 1). These values correspond to sandy loams, loams, silty loams, and silt (NRCS, 2018). These values also correspond to the texture classes determined for these locations: silty loams, loams, and sandy loams (NRCS, 2018).

In comparison to the reference locations, K_{sat} in the mine sites was highly variable. Across the 45 measurements made at the mine sites, K_{sat} was very rapid (n = 4), rapid (n = 3), moderately rapid (n = 6), moderate (n = 6), moderately slow (n = 13), slow (n = 4), and very slow or impermeable (n = 9). The three fastest classes, which contain 29% of the mine site measurements, are typically associated with loamy and sandy soils. The moderate class typically represents sandy loams, silt loams, and silt, which is similar to the texture categories the soil samples in the mine sites tended to plot in. Yet only 13% of mine site measurements had moderate K_{sat} according to the data collected in this project. The moderately slow and slow measurements, representing 28% of the measurements, revealed slow K_{sat}, and these rates are typically measured in such soils as clay loam, silty clay loam, and clay. The very slow and impermeable K_{sat} values, as measured in 20% of the sampling spots, are typically only observed in dense C (Cd) horizons and fragipans (NRCS, 2018). The distribution of K_{sat} data at the mine sites is again suggestive that deeper soils may be more clay rich and denser than near-surface measurements capture.

Near-surface bulk density samples were taken at 5 cm whereas K_{sat} measurements were conducted at a depth of 15 cm. This can likely be attributed to the lack of correlation between the two datasets ($r^2 = 0.022$). As the soil pits at Snowville Quarry demonstrated, bulk density is likely to increase greatly with depth. If deeper bulk density samples were taken at all K_{sat} measurement sites, it is possible a correlation could be found between the K_{sat} measurements and soil bulk density. For this reason, a future study should incorporate more soil pits throughout the mine sites and the reference locations and include collecting soil bulk density samples at depths greater than 5 cm.

K_{sat} is also uncorrelated with measured clay ($r^2 = 0.0058$) or sand ($r^2 = 0.0176$) content in the soil samples taken at the same spot, even though those soil texture measurements were made from the top 20 cm of soil. The extremely low K_{sat} measurements at the mine sites are another potential indication that the mine site soils are actually more clay-rich than was determined by the Malvern. That potential error in Malvern measurements may contribute to the apparent lack of correlation between soil texture and K_{sat}. A multivariate approach that incorporates both soil texture and bulk density may also yield better predictive power for K_{sat}, despite the limitations in the measurements.

In general, the FoSTER sites presented properties similar to those sites studied for the FRA, despite being previously glaciated non-coal surface mines. The high bulk density and low saturated hydraulic conductivity values corroborate the findings of the FRA. This may suggest that following the FRA guidance on deep-ripping is appropriate and will yield desirable results.

The soil properties at the mine sites lend support to CUVA's approach to reclaiming the sites via deep-ripping. However, the absence of a significant effect of deep-ripping on near-surface bulk density and K_{sat} may be attributed to four factors: (1)

limitations of a single site for post-ripping measurements; (2) low statistical power of the K_{sat} measurements; (3) depth of the ripping effects versus those of the measurements; and (4) the potential for a rapid decline in the effects of ripping over time.

First, at the Dover site, where ripping occurred, the near-surface bulk density was the lowest of the five mine sites and Ksat was the second highest of the five mine sites. These measurements were also not significantly different from Dover Reference. It is possible that the effects of deep-ripping are subtler on sites where the pre-ripping conditions are not as extreme. Snowville Quarry, which was ripped in September 2018, presents an opportunity for additional post-ripping measurements, which would address this limitation with respect to site specificity, and also has the potential to address some of the following three points.

Second, K_{sat} measurements were limited, especially for pre- and post-ripping observations. Prior to deep-ripping, due to time constraints, only eight measurements were collected. Post-ripping, K_{sat} measurements focused on the cross-rips of the site. Therefore, measurements conducted in the single rips and not within the rips were limited. In general, the sample values for pre- and post-ripping were low, preventing a high statistical power for any tests conducted on K_{sat} measurements.

Third, it is likely that near-surface measurements are not representative of soil properties at depth, and ripping may create greater changes in the deeper soil properties than at the surface. The ripping shanks extended approximately 1 m into the soil, while all measurements in this study were taken in the top 20 cm. The profiles of bulk density at Snowville Quarry at depth demonstrate that bulk density can increase significantly past the first 10 cm where it would not increase as quickly in a mature forest like Snowville Reference. The post-ripping measurements do not account of any effects on bulk density at these greater depths. The K_{sat} measurements occur at a depth of 15 cm, though the saturated bulb formed by the permeameter extends deeper. It is likely that K_{sat} captures more of the deep effect of ripping than near-surface bulk density. However, it is possible that K_{sat} measurements were unable to capture the full effect of deep-ripping on water movement at the range of depths where root penetration will occur within the first year of tree growth. Evidently, future studies should aim to measure vertical profiles of bulk density and Ksat within non-ripped, single-ripped, and cross-ripped areas to cover the full potential depth profile of ripping effects.

Finally, it is possible that immediate density-decreasing effects of deep-ripping decline rapidly over time. Post-ripping samples were not collected until nine months following deep-ripping. This could have potentially allowed the in-filling of ripped areas with sediment from rainsplash and overland flow and the compression of pore space created by ripping (Parsons et al., 1993). If the effects of deep-ripping on soil properties decline rapidly over time, there are implications for the method's potential to enable reforestation at the sites. Tree-planting days have continued well over nine months after deep-ripping and trees grow their taproot down into the soil for the first 2-3 years of growth, suggesting that manipulations that do not produce long-lasting changes to bulk density will not be sufficient for reforestation. Future work in tracking bulk density and K_{sat} values immediately after deep-ripping and over time, in addition to tracking tree survival rate in relation to planting time after deep-ripping, is needed.

The post-ripping K_{sat} measurements suggest that deep-ripping does not have a significant effect on increasing K_{sat}, but this may be the result of a low number of measurements that result in low statistical power. In general, the measurements not taken within a rip look remarkably like the pre-rip samples. The samples taken in the cross-rips and single-rips are highly variable. The high variability and lack of statistical significance could be attributed to the small number of measurements in each ripping class. More K_{sat} measurements in post-ripping conditions could determine if there is indeed no significant difference pre- and post-ripping and if measurements taken within single rips are indeed faster than samples taken within cross-rips. In general, this study of the effects of deep-ripping in relation to the number of rips is unique and serves as a solid foundation from which to inquire further as to these effects.

Future Work

This research is still on-going through FoSTER. Some data have been collected to address questions that have arisen during the research conducted here that lie beyond the scope of this thesis. Primary among these questions are questions regarding changes in grain size distribution, bulk density at depth, and changes in hydrology and runoff from deep-ripped sites.

An unresolved methodological question that needs to be addressed is whether the grain size distributions calculated by the Malvern are accurate, given how cohesive the soils were. This question can be approached in three ways. First, it is possible to run samples of known grain size distributions on the Malvern. The Midwest GeoSciences group sells a USDA calibrated soil texture kit. The kit contains eight samples of known and common soil textures (Midwest GeoSciences Group, 2018). Subsamples of these kit samples could be run on the Malvern to determine how accurate the Malvern is in determining the textures of the samples. Second, the samples could be rerun on the Malvern with the addition of sodium metaphosphate to further disaggregate the soil particles. Third, the samples taken from the field sites could reanalyzed for grain size distribution using the hydrometer method (Ashworth et al., 2007). While the hydrometer method is low-tech, it has been accepted as accurate in determining the percent ratios of clay, silt, and sand. The results from this test could be compared to the results of the Malvern calculations. As this methodology is refined for this project, sample collection could continue in pre- and post-ripping conditions in areas along rips that are parallel and perpendicular to topography. Collection of these samples over an extended period of time could provide an understanding as to how deep-ripping and rip orientation can alter the movement of sediment fines through the site via eluviation and alluviation. This study could be further augmented by studying the geomorphic stability and presence and development of rills, gullies, and pipes on the sites following deep-ripping.

Soil probe samples have been collected at Dover post-ripping. These samples were collected in the same method as outlined in soil probe methods in this thesis. Samples were collected either in cross rips, single rips, or no rips in a fashion like the post-ripping near surface bulk density samples. These samples can be analyzed for grain size distribution to determine if finer sediments are being transported through the site differently than coarser sediments, essentially changing the soil texture on site and potentially contributing to sedimentation of nearby waterways.

More extensive bulk density sampling can be conducted at the sites. At Snowville Quarry, new soil pits can be dug to assess the changes in the bulk density profile following ripping. Additionally, this process can be repeated with greater resolution at the three remaining mine sites slated for deep-ripping within the FoSTER Project.

The nature of deep-ripping itself lends to a whole host of interesting geological and hydrological questions that could be researched as this study continues. Studying not only how K_{sat} changes with deep-ripping, but also how soil moisture changes with deep-ripping, especially within rips of different orientation, could be worthwhile. Additionally, I would be interested in how runoff and erosion from these sites change with time, following both SMCRA and deep-ripping reclamations. Similarly, studying the relaxation of the micro- and mesotopography over time following deep-ripping could reveal some interesting data for hydrology and geomorphology studies. Finally, because this process so extensively disturbs the soil on these sites, I would be interested in discovering how people involved in reclamation can start to grow a soil that is beneficial to reforestation and how do these soils compare with mature forested reference locations.

CONCLUSIONS

The establishment of CUVA was the result of the culmination of concerns for the geological, hydrological, and biological resources of the valley. As population and industry within the Cuyahoga Valley and surrounding lands increased, pollution of the waterways and degradation of geological and biological resources escalated. The surge in pollution and environmental degradation inspired the desire to protect and reclaim Cuyahoga Valley and its resources. The lands within CUVA are therefore the result of both the industrialization and the consequent attempts to reclaim the environmental quality.

Mining within the area that became CUVA caused profound environmental damage, as had the mining elsewhere that prompted the development of SMCRA requirements. Reclamation at the CUVA sites sought only to meet the policies of SMCRA, following the assumption that the priority action at these sites should be stabilization of the land surfaces. However, as reforestation has become the preference of CUVA in accordance with the desires of NPS to conserve "… the natural and cultural resources and values of the National Park System for the enjoyment, education, and inspiration of this and future generations" further action is needed to render these former mine sites amenable to reforestation with native trees (NPS, 2018c).

While soil textures at the mine sites and reference locations were similar, near-surface bulk density and bulk density at depth were significantly higher and saturated hydraulic conductivity was significantly lower in the mine sites compared to the reference locations. Bulk density was not root-restrictive near the soil surface, but at depths of >15 cm, the soils were too dense for optimum root growth, based on two profiles at one site. For soil texture and bulk density, variability within each individual mine site was large compared to the site-to-site variation. For K_{sat} site-to-site variation was large for the mine sites, yet the reference locations all had similar K_{sat} values.

None of the measured variables appear to be correlated with one another, possibly because of the differences in the depths at which measurements were made. However, it is likely that these factors individually or collectively restrict native tree recruitment and establishment in the mine sites. Other factors, unexplored in this project (e.g. nutrient status, herbivory), may also limit the success of reforestation at these sites.

No significant changes in soil bulk density or K_{sat} can directly attributed to deep-ripping. It is likely that observation of these variables over time would lend to a clearer pattern of the evolution of these sites following deep-ripping. Regardless, many of the groups of trees at Dover following deep-ripping have a 100% survival rate a year later (Ruggles, 2018). In comparison to nearly-complete tree mortality during the tree-planting in 2012 (prior to deep-ripping), this suggests that deep-ripping does have a positive impact on the conditions on the sites and allows for tree survival.

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APPENDIX A

SAMPLING LOCATIONS, GRAIN SIZE DISTRIBUTION, BULK DENSITY, AND SATURATED HYDRAULIC CONDUCTIVITY FOR MINES SITES AND REFERENCE LOCATIONS

Table A1: Sample names, latitude, longitude, percent clay, percent silt, percent sand, percent gravel*, near-surface bulk density (ρ_{bulk}), and saturated hydraulic conductivity (K_{sat}) of the mine sites and the reference locations.

*Percent gravel is taken from the entire sample. Percent clay, silt, and sand are from the 0-2 mm subsample used for grain size distribution in the fine earth fraction analyses.

[1]**SQMS**: **S**nowville **Q**uarry Soil **M**oisture on the **S**lope: This point was added to the Snowville Quarry site to mark soil moisture sensors that were installed to monitor the soil moisture at that point for pre- and post-ripping comparisons. While this data is still being collected and was not included in this thesis, this point was selected for one bulk density at depth profile (Figure 20) and one K_{sat} measurement (Figures 21-22).

[2]**SQMF**: **S**nowville **Q**uarry Soil **M**oisture on the **F**lat: This point was added to the Snowville Quarry site to mark soil moisture sensors that were installed to monitor the soil moisture at that point for pre- and post-ripping comparisons. While this data is still being collected and was not included in this thesis, this point was selected for one bulk density at depth profile (Figure 20) and one K_{sat} measurement (Figures 21-22).

Sample	Latitude	Longitude	% clay	% silt	% sand	% gravel	ρ_{bulk} (g cm^{-3})	K_{sat} (m s^{-1})
D02	N 41°17’20.6”	W 081°33’32.0”	11.00	61.07	27.93	21.79	1.23	9.55 E-06
D03	N 41°17’20.6”	W 081°33’30.5”	9.91	60.23	29.85	5.06	1.06	
D04	N 41°17’20.6”	W 081°33’28.8”	10.43	57.71	31.87	34.92	0.93	
D05	N 41°17’20.6”	W 081°33’27.2”	13.06	51.70	35.24	25.94	1.17	
D06	N 41°17’20.6”	W 081°33’25.6”	9.09	41.61	49.30	17.38	1.05	5.69 E-06
D07	N 41°17’20.6”	W 081°33’24.0”	12.59	54.56	32.85	17.53	1.19	
D08	N 41°17’20.6”	W 081°33’22.4”	11.55	48.94	39.51	8.02	0.96	
D09	N 41°17’20.6”	W 081°33’20.8”	9.89	41.14	48.96	2.29		
D10	N 41°17’20.6”	W 081°33’19.1”	10.55	42.21	47.24	2.32		
D11	N 41°17’19.4”	W 081°33’33.7”	12.70	53.38	33.92	10.84	1.19	
D12	N 41°17’19.4”	W 081°33’32.0”	9.84	41.38	48.78	20.71	0.94	1.15 E-05
D13	N 41°17’19.4”	W 081°33’30.5”	11.68	47.94	40.38	3.87	1.13	
D14	N 41°17’19.4”	W 081°33’28.8”	5.55	29.76	64.69	2.96	0.89	
D15	N 41°17’19.4”	W 081°33’27.2”	13.43	52.96	33.61	24.85	0.87	
D16	N 41°17’19.4”	W 081°33’25.6”	11.88	49.03	39.09	26.65	0.93	

Sample	Latitude	Longitude	% clay	% silt	% sand	% gravel	ρ_{bulk} (g cm^{-3})	K_{sat} (m s^{-1})
D17	N 41°17’19.3”	W 081°33’24.0”	6.03	32.14	61.84	10.70	0.98	2.09 E-06
D18	N 41°17’19.4”	W 081°33’22.4”	8.47	39.46	52.07	8.38	1.14	
D19	N 41°17’19.4”	W 081°33’20.8”	11.51	48.75	39.74	5.36	0.70	
D20	N 41°17’19.4”	W 081°33’19.1”	12.90	51.96	35.14	3.77	1.03	
D21	N 41°17’19.6”	W 081°33’17.2”	10.70	45.17	44.13	5.75		
D22	N 41°17’18.2”	W 081°33’33.7”	10.97	48.49	40.54	13.67		
D23	N 41°17’18.2”	W 081°33’32.0”	7.37	43.00	49.62	19.28	0.87	
D24	N 41°17’18.2”	W 081°33’30.5”	11.82	49.66	38.52	4.83	1.23	7.19 E-06
D25	N 41°17’18.2”	W 081°33’28.8”	10.85	48.93	40.22	6.68	1.07	
D26	N 41°17’18.2”	W 081°33’27.2”	12.40	56.12	31.48	48.45	0.98	
D27	N 41°17’18.2”	W 081°33’25.6”	16.17	64.63	19.20	20.51	0.92	
D28	N 41°17’18.2”	W 081°33’24.0”	16.12	64.47	19.41	21.89	1.08	4.87 E-06
D29	N 41°17’18.2”	W 081°33’22.4”	12.55	63.81	23.64	24.45	1.00	
D30	N 41°17’18.2”	W 081°33’20.8”	11.64	59.31	29.06	26.48	1.08	
D31	N 41°17’18.2”	W 081°33’19.1”	13.09	70.74	16.17	5.63	1.28	4.61 E-06
D32	N 41°17’16.9”	W 081°33’32.0”	11.88	64.31	23.82	14.20	1.12	
D33	N 41°17’16.9”	W 081°33’30.5”	12.47	69.02	18.51	10.68	0.87	
D34	N 41°17’16.9”	W 081°33’28.8”	12.37	68.69	18.94	3.04	0.96	
D35	N 41°17’16.9”	W 081°33’27.2”	13.56	65.23	21.22	27.45	0.82	2.10 E-05
D36	N 41°17’16.9”	W 081°33’25.6”	13.39	64.72	21.89	33.64	1.16	
D37	N 41°17’16.9”	W 081°33’24.0”	16.42	58.58	25.01	16.13	0.91	
D38	N 41°17’16.9”	W 081°33’22.4”	16.90	60.32	22.78	4.92	0.84	
D39	N 41°17’16.9”	W 081°33’20.8”	11.77	57.33	30.90	4.25	0.78	
D40	N 41°17’15.7”	W 081°33’32.0”	11.67	57.02	31.31	13.18	1.42	
D41	N 41°17’15.7”	W 081°33’30.5”	13.50	55.68	30.82	2.48	1.20	
D42	N 41°17’15.7”	W 081°33’28.8”	13.34	55.46	31.20	9.42	0.94	
D43	N 41°17’15.7”	W 081°33’27.2”	15.33	59.63	25.04	0.00	1.01	
D44	N 41°17’15.9”	W 081°33’32.1”				16.03	0.80	

Sample	Latitude	Longitude	% clay	% silt	% sand	% gravel	ρ_{bulk} (g cm^{-3})	K_{sat} (m s^{-1})
DR01	N 41°17’19.9”	W 081°33’37.5”	10.92	49.93	39.15	27.04	1.02	
DR02	N 41°17’20.0”	W 081°33’36.2”	11.80	49.34	38.86	3.24	0.83	
DR03	N 41°17’18.8”	W 081°33’37.7”	10.85	44.51	44.64	3.59	1.32	
DR04	N 41°17’18.7”	W 081°33’36.2”	10.67	44.75	44.57	37.28	1.07	
DR05	N 41°17’17.6”	W 081°33’37.8”	10.68	45.40	43.92	1.92	0.98	
DR06	N 41°17’17.6”	W 081°33’35.9”	11.62	47.86	40.52	5.64	0.91	6.46 E-06
DR07	N 41°17’16.4”	W 081°33’37.8”	13.13	59.37	27.50	0.97	0.84	3.24 E-05
DR08	N 41°17’16.6”	W 081°33’36.0”	10.39	44.36	45.25	5.62	0.85	
DR10	N 41°17’17.6”	W 081°33’39.4”	12.23	54.10	33.67	2.95	1.10	
DR11	N 41°17’18.8”	W 081°33’39.2”	12.91	57.72	29.37	27.91		1.18 E-05
SQ01	N 41°17’02.6”	W 081°34’35.2”	12.33	58.62	29.05	15.08		
SQ02	N 41°17’02.2”	W 081°34’33.6”	9.87	42.57	47.56	14.61	1.12	
SQ03	N 41°17’03.2”	W 081°34’41.8”	14.28	50.06	35.66	6.57		
SQ04	N 41°17’02.8”	W 081°34’40.2”	13.32	51.61	35.07	5.49	1.27	9.51 E-06
SQ05	N 41°17’02.4”	W 081°34’38.8”	11.68	47.98	40.34	14.58		
SQ06	N 41°17’01.5”	W 081°34’35.8”	12.33	58.62	29.05	24.97	0.97	
SQ07	N 41°17’01.0”	W 081°34’34.3”	9.87	42.57	47.56	52.26		
SQ08	N 41°17’02.5”	W 081°34’43.8”	14.28	50.06	35.66	11.55	1.18	
SQ09	N 41°17’02.1”	W 081°34’42.4”	13.32	51.61	35.07	5.92		
SQ10	N 41°17’01.7”	W 081°34’40.9”	11.68	47.98	40.34	10.56	1.10	
SQ11	N 41°17’01.3”	W 081°34’39.4”						
SQ12	N 41°17’00.8”	W 081°34’37.8”	13.95	48.84	37.21	12.82	0.93	
SQ13	N 41°17’00.3”	W 081°34’36.3”	13.55	50.20	36.25	25.84		
SQ14	N 41°16’59.9”	W 081°34’34.8”	11.04	45.65	43.31	6.98	0.95	2.96 E-06
SQ15	N 41°16’59.5”	W 081°34’33.3”	13.21	47.26	39.53	30.39		
SQ16	N 41°17’01.0”	W 081°34’44.3”	16.05	48.23	35.72	7.83	1.11	1.07 E-05
SQ17	N 41°17’00.9”	W 081°34’42.9”	13.43	50.44	36.13	4.81		
SQ18	N 41°17’00.6”	W 081°34’41.5”	10.04	44.66	45.30	4.79	1.12	

Sample	Latitude	Longitude	% clay	% silt	% sand	% gravel	ρ_{bulk} (g cm^{-3})	K_{sat} (m s^{-1})
SQ19	N 41°17’00.1”	W 081°34’39.9”	10.39	41.13	48.48	7.23		
SQ20	N 41°16’59.7”	W 081°34’38.4”	12.03	53.86	34.11	7.16	0.90	
SQ21	N 41°16’59.3”	W 081°34’36.9”	10.44	53.40	36.16	7.21		
SQ22	N 41°16’58.8”	W 081°34’35.5”	11.95	49.16	38.89	17.92	0.93	
SQ23	N 41°17’00.2”	W 081°34’44.8”	11.66	55.56	32.78	7.57		
SQ24	N 41°16’59.9”	W 081°34’43.5”	13.44	58.05	28.51	7.30	1.04	
SQ25	N 41°16’59.4”	W 081°34’42.0”	14.77	70.36	17.87	39.45		
SQ26	N 41°16’59.1”	W 081°34’40.5”	12.47	71.23	16.30	5.33	1.16	
SQ27	N 41°16’58.5”	W 081°34’39.0”	12.72	70.48	16.80	5.74		
SQ28	N 41°16’58.2”	W 081°34’37.5”					1.05	6.46 E-05
SQ29	N 41°16’57.7”	W 081°34’36.0”	14.77	58.77	26.45	3.78		
SQ30	N 41°16’57.2”	W 081°34’34.5”	12.47	56.52	31.01	11.76	0.93	
SQ31	N 41°16’59.6”	W 081°34’47.1”	12.72	54.85	32.43	4.00		
SQ32	N 41°16’59.2”	W 081°34’45.6”	13.09	55.96	30.95	3.23	1.03	
SQ33	N 41°16’58.7”	W 081°34’44.2”	12.97	55.86	31.17	2.62		
SQ34	N 41°16’58.3”	W 081°34’42.6”	14.54	62.03	23.43	1.66	1.25	1.63 E-04
SQ35	N 41°16’57.9”	W 081°34’41.1”	13.68	57.35	28.97	8.96		
SQ36	N 41°16’57.4”	W 081°34’39.6”	15.16	60.73	24.10	9.13	1.17	
SQ37	N 41°16’57.0”	W 081°34’38.1”	13.85	61.19	24.96	3.19		
SQ38	N 41°16’56.6”	W 081°34’36.5”	12.80	63.14	24.07	2.13		
SQ39	N 41°16’56.1”	W 081°34’35.0”	11.55	50.36	38.09	4.29		
SQ40	N 41°16’58.0”	W 081°34’46.2”	13.04	55.20	31.76	5.64	1.46	
SQ41	N 41°16’55.4”	W 081°34’37.2”	13.84	57.65	28.51	7.16		
SQ42	N 41°16’55.0”	W 081°34’35.7”	14.61	63.45	21.94	3.70	1.21	2.11 E-05
SQMS[1]	N 41°16’58.9”	W 081°34’41.1”						1.43 E-04
SQMF[2]	N 41°17’00.9”	W 081°34’40.6”						1.64 E-05
SR01	N 41°16’56.5”	W 081°34’50.7”	11.91	59.07	29.02	0.83	0.50	
SR02	N 41°16’54.8”	W 081°34’51.3”	13.95	64.84	21.21	0.00	0.99	

Sample	Latitude	Longitude	% clay	% silt	% sand	% gravel	ρ_{bulk} (g cm^{-3})	K_{sat} (m s^{-1})
SR03	N 41°16’53.7”	W 081°34’52.0”	13.42	62.61	23.97	3.37	0.90	
SR04	N 41°16’52.7”	W 081°34’52.4”	14.00	63.78	22.22	5.28	0.79	3.05 E-05
SR05	N 41°16’53.7”	W 081°34’53.7”	13.49	62.89	23.62	14.45	0.62	
SR06	N 41°16’54.8”	W 081°34’53.1”	13.64	68.57	17.79	3.19	0.59	8.10 E-06
SR07	N 41°16’56.3”	W 081°34’52.3”	12.72	68.82	18.46	0.00	0.81	
SR08	N 41°16’56.4”	W 081°34’54.0”	9.97	51.17	38.86	13.20	0.78	1.04 E-05
SR09	N 41°16’55.3”	W 081°34’54.5”	12.41	58.62	28.97	4.78	0.72	
SR10	N 41°16’54.1”	W 081°34’55.2”	7.85	42.61	49.54	7.17	0.91	
SR11	N 41°16’56.8”	W 081°34’55.5”	13.19	57.34	29.47	0.12	0.56	
HH01	N 41°16’59.3”	W 081°34’45.1”	9.82	41.31	48.87	6.49		
HH02	N 41°16’58.6”	W 081°34’45.0”	9.62	40.49	49.89	2.51	1.21	
HH03	N 41°16’58.6”	W 081°34’44.1”	12.58	52.31	35.11	10.20		9.18 E-08
HH04	N 41°16’57.8”	W 081°34’46.1”	18.17	61.61	20.22	3.32	0.85	
HH05	N 41°16’57.8”	W 081°34’45.1”	8.92	47.83	43.25	7.33		
HH06	N 41°16’57.8”	W 081°34’44.1”	12.81	51.89	35.30	4.14	1.26	
HH07	N 41°16’57.8”	W 081°34’43.0”	14.23	63.00	22.76	13.71		
HH08	N 41°16’57.0”	W 081°34’46.0”	13.13	59.68	27.19	9.15	1.19	
HH09	N 41°16’57.0”	W 081°34’45.1”	12.01	56.44	31.55	23.38		2.36 E-06
HH10	N 41°16’57.0”	W 081°34’44.1”	10.67	47.40	41.93	4.03	1.35	
HH11	N 41°16’57.0”	W 081°34’43.0”	11.22	55.25	33.53	4.93		1.76 E-06
HH12	N 41°16’56.2”	W 081°34’46.1”	13.55	58.98	27.47	7.54		
HH13	N 41°16’56.3”	W 081°34’45.1”	15.88	63.74	20.38	6.99	1.30	
HH14	N 41°16’56.3”	W 081°34’44.1”	9.93	42.61	47.46	14.14		
HH15	N 41°16’56.2”	W 081°34’43.0”	13.94	60.19	25.87	2.89	1.52	
HH16	N 41°16’56.2”	W 081°34’42.0”	9.33	42.82	47.85	2.31		
HH17	N 41°16’56.5”	W 081°34’44.1”	10.50	43.59	45.92	5.91	1.05	
HH18	N 41°16’56.5”	W 081°34’43.0”	11.83	53.67	34.50	4.73		
HH19	N 41°16’56.5”	W 081°34’42.0”	9.57	40.50	49.93	9.49	1.21	

Sample	Latitude	Longitude	% clay	% silt	% sand	% gravel	ρ_{bulk} (g cm^{-3})	K_{sat} (m s^{-1})
HH20	N 41°16’56.5”	W 081°34’41.0”	12.27	54.96	32.78	6.73		
HH21	N 41°16’54.7”	W 081°34’43.0”	12.96	57.49	29.55	2.16		5.58 E-07
HH22	N 41°16’54.8”	W 081°34’42.0”	9.77	49.74	40.49	3.08		
HH23	N 41°16’54.0”	W 081°34’43.0”	15.85	65.94	18.21	3.77	1.40	
HH24	N 41°16’54.0”	W 081°34’42.0”	13.54	58.51	27.95	4.68		
HH25	N 41°16’53.2”	W 081°34’44.1”	13.80	60.22	25.97	1.18	0.95	
HH26	N 41°16’53.2”	W 081°34’43.0”	15.19	64.54	20.27	1.12		
HH27	N 41°16’52.5”	W 081°34’47.1”	11.05	48.62	40.33	7.79	0.94	
HH28	N 41°16’52.5”	W 081°34’46.1”	10.81	52.41	36.78	2.90		
HH29	N 41°16’52.5”	W 081°34’45.1”	12.53	57.27	30.20	4.25	1.15	
HH30	N 41°16’52.5”	W 081°34’44.0”	13.43	59.56	27.01	3.45		
HH31	N 41°16’52.5”	W 081°34’43.0”	14.35	65.74	19.91	2.51	1.07	
HH32	N 41°16’51.7”	W 081°34’47.1”	13.92	60.75	25.33	7.92		
HH33	N 41°16’51.7”	W 081°34’46.1”	14.92	68.53	16.54	4.29	1.04	1.12 E-05
HH34	N 41°16’51.7”	W 081°34’45.1”	8.00	39.36	52.64	3.96		
HH35	N 41°16’51.7”	W 081°34’44.0”	13.78	61.43	24.79	3.55	1.21	4.85 E-06
HH36	N 41°16’51.7”	W 081°34’43.0”	14.41	60.43	25.17	0.99		
HH37	N 41°16’50.9”	W 081°34’47.1”	9.52	41.20	49.29	31.07	1.12	
HH38	N 41°16’50.9”	W 081°34’46.1”	10.94	46.90	42.16	5.73		
HH39	N 41°16’50.9”	W 081°34’45.1”	10.14	43.55	46.31	3.65	0.78	
HH40	N 41°16’50.9”	W 081°34’44.1”	13.30	59.36	27.33	0.88		
HH41	N 41°16’50.9”	W 081°34’43.0”	13.21	57.97	28.82	1.89	0.97	
HH42	N 41°16’50.2”	W 081°34’47.1”	11.55	47.76	40.69	5.07		
HH43	N 41°16’50.2”	W 081°34’46.1”	12.50	55.79	31.71	10.47	0.90	4.17 E-06
HH44	N 41°16’50.2”	W 081°34’45.1”	11.48	51.93	36.59	3.50		
HH45	N 41°16’50.2”	W 081°34’44.1”	10.28	55.95	33.77	1.19	1.02	3.58 E-07
HH46	N 41°16’50.2”	W 081°34’43.1”	9.91	43.96	46.13	4.65		
HH47	N 41°16’49.4”	W 081°34’49.4”	9.77	44.17	46.06	1.51	1.29	

Sample	Latitude	Longitude	% clay	% silt	% sand	% gravel	ρ_{bulk} (g cm^{-3})	K_{sat} (m s^{-1})
HH48	N 41°16’49.4”	W 081°34’49.4”	13.98	54.13	31.90	2.07		
HH49	N 41°16’49.4”	W 081°34’49.4”	7.21	32.38	60.41	3.75	0.85	
HR07	N 41°15’45.1”	W 081°32’41.8”	10.14	48.25	41.60	2.29	0.85	
HR08	N 41°15’45.1”	W 081°32’40.5”	13.65	60.11	26.23	1.04	1.04	1.49 E-05
HR09	N 41°15’45.1”	W 081°32’39.2”	11.40	50.25	38.35	1.97	1.16	
HR10	N 41°15’45.1”	W 081°32’37.8”	9.41	40.63	49.96	3.39	0.89	
HR11	N 41°15’44.1”	W 081°32’41.9”	7.72	38.68	53.60	5.50	1.19	2.96 E-06
HR12	N 41°15’44.1”	W 081°32’40.5”	11.21	50.36	38.43	6.71	1.16	
HR13	N 41°15’44.1”	W 081°32’39.2”	9.85	44.16	45.99	5.56	1.22	
HR14	N 41°15’44.8”	W 081°32’37.5”	12.16	51.15	36.69	7.29	1.31	
HR15	N 41°15’43.1”	W 081°32’41.9”	11.37	49.26	39.37	2.57	1.13	
HR16	N 41°15’43.1”	W 081°32’40.5”	7.97	39.39	52.64	4.46	1.20	
HR17	N 41°15’43.1”	W 081°32’39.2”	14.71	60.78	24.52	1.00	1.19	1.23 E-05
HR18	N 41°15’43.1”	W 081°32’37.8”	11.70	62.98	25.31	2.74	1.17	
CT01	N 41°23’27.2”	W 081°38’03.9”	15.09	57.87	27.04	9.77	0.97	
CT03	N 41°23’25.6”	W 081°38’04.0”	12.30	54.47	33.23	12.62	0.87	
CT04	N 41°23’26.4”	W 081°38’02.9”	16.30	54.23	29.47	20.39	1.23	
CT06	N 41°23’23.4”	W 081°38’04.9”	13.35	56.29	30.35	1.51	1.08	
CT07	N 41°23’24.2”	W 081°38’03.9”	15.39	65.20	19.41	27.40	1.27	
CT08	N 41°23’24.9”	W 081°38’02.9”	11.02	67.28	21.70	54.25	0.78	1.47 E-08
CT09	N 41°23’25.7”	W 081°38’01.9”	11.84	68.03	20.13	80.12	1.00	
CT12	N 41°23’22.7”	W 081°38’04.0”	11.80	70.28	17.92	1.72		1.47 E-08
CT13	N 41°23’23.4”	W 081°38’02.9”	11.40	68.67	19.93	7.24		
CT14	N 41°23’24.2”	W 081°38’01.9”	13.57	62.47	23.95	13.41		
CT15	N 41°23’25.0”	W 081°38’00.7”	13.56	68.23	18.21	16.05		2.35 E-07
CT20	N 41°23’21.9”	W 081°38’02.9”	12.03	66.64	21.34	2.23	1.39	
CT21	N 41°23’22.7”	W 081°38’01.8”	12.86	65.34	21.80	12.27	1.54	
CT22	N 41°23’23.4”	W 081°38’01.0”					1.61	4.03 E-06

Sample	Latitude	Longitude	% clay	% silt	% sand	% gravel	ρ_{bulk} (g cm^{-3})	K_{sat} (m s^{-1})
CT23	N 41°23’24.2”	W 081°38’59.7”	12.91	55.74	31.35		1.50	
CT28	N 41°23’21.1”	W 081°38’01.9”	13.80	59.22	26.99	1.50	1.30	
CT29	N 41°23’21.8”	W 081°38’00.7”	11.64	43.93	44.42	6.53	1.65	
CT30	N 41°23’22.7”	W 081°38’59.7”					1.32	
CT31	N 41°23’23.4”	W 081°38’58.7”	12.35	70.86	16.79	0.00	1.14	
CT33			12.71	68.04	19.26			
CT34	N 41°23’25.6”	W 081°38’04.3”	12.53	61.97	25.50	0.00		
CT35	N 41°23’23.0”	W 081°38’05.5”	11.48	67.42	21.09	0.00		
CT36	N 41°23’23.8”	W 081°38’04.5”	12.10	68.76	19.14	1.71		1.47 E-08
CT37	N 41°23’25.3”	W 081°38’02.4”	10.82	66.96	22.21	0.00		
CT38	N 41°23’22.7”	W 081°38’05.0”	11.59	51.13	37.28	1.34		
CT39	N 41°23’22.3”	W 081°38’04.5”	8.43	41.60	49.97	0.00	1.38	
CT40	N 41°23’23.0”	W 081°38’03.4”	9.76	51.18	39.06	0.00	1.07	
CT41	N 41°23’23.8”	W 081°38’02.4”	10.06	45.77	44.16	14.79	1.00	
CT42	N 41°23’24.5”	W 081°38’01.3”	12.09	51.53	36.38	0.00	0.51	
CT43	N 41°23’21.9”	W 081°38’04.0”	13.78	55.34	30.88	1.61		
CT44	N 41°23’21.5”	W 081°38’03.4”	11.33	50.51	38.17	5.49		
CT45	N 41°23’22.3”	W 081°38’02.4”				11.80		
CT46	N 41°23’23.0”	W 081°38’01.3”	11.80	49.39	38.80	10.78		
CT47	N 41°23’23.8”	W 081°38’02.6”	9.42	42.43	48.15	16.85		
CT48	N 41°23’21.5”	W 081°38’01.3”				6.09		7.07 E-07
CT49	N 41°23’22.6”	W 081°38’00.3”	8.02	35.13	56.85	11.99		
CT50	N 41°23’23.0”	W 081°38’59.2”	8.90	38.63	52.47	18.10		
CT51	N 41°23’21.5”	W 081°38’00.3”	15.74	61.42	22.84		1.23	
CT52	N 41°23’22.2”	W 081°38’59.2”	14.95	60.38	24.67	6.45	1.43	
CT53	N 41°23’24.5”	W 081°38’03.5”				9.17		
RR01	N 41°23’37.1”	W 081°38’18.6”	11.09	50.23	38.68	3.58		
RR02	N 41°23’37.1”	W 081°38’17.6”	13.49	60.68	25.83	0.23	1.05	

Sample	Latitude	Longitude	% clay	% silt	% sand	% gravel	ρ_{bulk} (g cm^{-3})	K_{sat} (m s^{-1})
RR03	N 41°23’37.0”	W 081°38’16.6”	12.80	55.16	32.04	5.29		
RR04	N 41°23’37.0”	W 081°38’15.6”	13.15	58.55	28.30	3.41	1.01	
RR05	N 41°23’37.0”	W 081°38’14.5”	13.01	58.55	28.44	10.13		
RR06	N 41°23’37.1”	W 081°38’13.5”	12.99	57.82	29.19	0.00	1.22	5.40 E-07
RR07	N 41°23’37.1”	W 081°38’12.3”	11.69	48.35	39.96	1.19		
RR08	N 41°23’36.3”	W 081°38’17.6”	16.27	59.11	24.62	2.34	1.07	1.36 E-07
RR09	N 41°23’36.2”	W 081°38’16.6”	11.83	53.60	34.56	1.01		
RR10	N 41°23’36.2”	W 081°38’15.5”	12.61	60.05	27.34	3.87	1.24	
RR11	N 41°23’36.3”	W 081°38’14.5”	10.17	46.47	43.36	5.57		
RR12	N 41°23’36.3”	W 081°38’13.5”	10.25	46.34	43.42	1.94	1.09	
RR13	N 41°23’36.3”	W 081°38’12.4”	13.29	58.54	28.17	0.20		
RR14	N 41°23’36.3”	W 081°38’11.3”	10.77	46.36	42.87	1.89	1.33	
RR15	N 41°23’35.5”	W 081°38’16.7”	11.94	49.10	38.96	10.12		
RR16	N 41°23’35.5”	W 081°38’15.6”	11.46	47.74	40.80	1.17	1.01	5.58 E-07
RR17	N 41°23’35.6”	W 081°38’14.6”	11.40	49.78	38.81	2.03		
RR18	N 41°23’35.5”	W 081°38’13.4”	11.73	49.16	39.10	4.31	1.12	
RR19	N 41°23’35.6”	W 081°38’12.4”	13.00	58.95	28.04	2.06		
RR20	N 41°23’35.5”	W 081°38’11.4”	18.17	55.66	26.17	2.31	0.99	2.25 E-06
RR21	N 41°23’35.5”	W 081°38’10.3”	11.66	48.99	39.35	0.83		
RR22	N 41°23’35.5”	W 081°38’09.3”	13.60	51.86	34.54	0.12	1.23	1.39 E-07
RR23	N 41°23’34.7”	W 081°38’15.5”	7.09	35.22	57.68	0.37		
RR24	N 41°23’34.8”	W 081°38’14.5”	12.40	58.88	28.72	1.34	0.91	
RR25	N 41°23’34.8”	W 081°38’13.4”	12.42	51.23	36.35	1.67		
RR26	N 41°23’34.8”	W 081°38’12.4”	11.34	50.29	38.36	0.00	1.00	
RR27	N 41°23’34.7”	W 081°38’11.4”	12.39	54.60	33.01	1.80		
RR28	N 41°23’34.7”	W 081°38’10.3”	12.02	52.80	35.18	1.54	1.45	
RR29	N 41°23’34.8”	W 081°38’09.2”	13.87	62.18	23.95	0.84		
RR30	N 41°23’34.8”	W 081°38’08.2”	10.27	44.15	45.58	1.71	1.19	

Sample	Latitude	Longitude	% clay	% silt	% sand	% gravel	ρ_{bulk} (g cm^{-3})	K_{sat} (m s^{-1})
RR31	N 41°23’34.0”	W 081°38’14.5”	12.21	53.26	34.52	1.36		
RR32	N 41°23’34.0”	W 081°38’13.5”	13.46	56.44	30.10	3.27	1.10	
RR33	N 41°23’33.3”	W 081°38’14.5”	14.55	63.33	22.12	1.29		
RR34	N 41°23’33.2”	W 081°38’13.5”	14.25	61.92	23.83	7.91	1.35	1.47 E-08
RR35	N 41°23’33.3”	W 081°38’12.4”	13.47	61.19	25.35	0.99		
CRR01	N 41°22’45.9”	W 081°37’58.9”	13.77	59.58	26.66	21.78	0.39	
CRR02	N 41°22’45.7”	W 081°37’56.7”	10.58	47.97	41.45	0.00	0.59	1.49 E-05
CRR03	N 41°22’45.6”	W 081°37’52.7”	10.73	50.61	38.66	0.00	0.51	
CRR04	N 41°22’44.2”	W 081°37’58.5”	8.67	39.77	51.57	16.04	0.52	
CRR05	N 41°22’44.2”	W 081°37’54.7”	15.28	62.55	22.17	4.29	0.79	
CRR06	N 41°22’44.2”	W 081°37’50.5”	14.82	60.27	24.91	2.63	0.83	
CRR07	N 41°22’42.7”	W 081°38’00.8”	11.29	48.61	40.10	0.00	0.52	
CRR08	N 41°22’46.6”	W 081°37’56.6”	11.77	50.63	37.60	10.76	0.54	
CRR09	N 41°22’42.6”	W 081°37’52.6”	13.47	59.12	27.40	3.89	0.69	1.25 E-05
CRR10	N 41°22’41.2”	W 081°37’58.9”	11.27	53.98	34.74	0.00	0.61	5.30 E-06
CRR11	N 41°22’41.2”	W 081°37’54.8”	11.06	57.75	31.19	6.70	0.54	
CRR12	N 41°22’41.2”	W 081°37’50.6”	13.08	66.27	20.66	0.00	0.59	

APPENDIX B

SAMPLING LOCATIONS, NEAR-SURFACE BULK DENSITY,

AND SATURATED HYDRAULIC CONDUCTIVITY

FOR DOVER PRE- AND POST-RIPPING

Table B1: Sample names, latitude, longitude, ripping condition of sample, near-surface bulk density, and saturated hydraulic conductivity of the Dover site for pre- and post-ripping conditions.

Sample	Latitude	Longitude	ripping condition	bulk density (g cm^{-3})	K_{sat} (m s^{-1})
D02	N 41°17’20.6”	W 081°33’32.0”	pre-rip	1.23	9.55 E-06
			no-rip	0.96	
			single-rip		1.07 E-04
			cross-rip		2.00 E-06
D03	N 41°17’20.6”	W 081°33’30.5”	pre-rip	1.06	
			no-rip		
			single-rip	0.75	
			cross-rip		
D04	N 41°17’20.6”	W 081°33’28.8”	pre-rip	0.93	
			no-rip		
			single-rip		
			cross-rip	1.13	
D05	N 41°17’20.6”	W 081°33’27.2”	pre-rip	1.17	
			no-rip	0.87	
			single-rip		
			cross-rip		
D06	N 41°17’20.6”	W 081°33’25.6”	pre-rip	1.05	5.69 E-06
			no-rip		6.90 E-06
			single-rip	0.71	
			cross-rip		2.50 E-05
D07	N 41°17’20.6”	W 081°33’24.0”	pre-rip	1.19	
			no-rip	0.89	
			single-rip		
			cross-rip		

Sample	Latitude	Longitude	ripping condition	bulk density (g cm^{-3})	Ksat (m s^{-1})
D08	N 41°17’20.6”	W 081°33’22.4”	pre-rip	0.96	
			no-rip	0.78	
			single-rip		
			cross-rip		
D12	N 41°17’19.4”	W 081°33’32.0”	pre-rip	0.94	1.15 E-05
			no-rip		4.50 E-06
			single-rip	0.71	
			cross-rip		6.59 E-05
D13	N 41°17’19.4”	W 081°33’30.5”	pre-rip	1.13	
			no-rip		
			single-rip		
			cross-rip	1.00	
D14	N 41°17’19.4”	W 081°33’28.8”	pre-rip	0.89	
			no-rip		
			single-rip		
			cross-rip	1.34	
D15	N 41°17’19.4”	W 081°33’27.2”	pre-rip	0.87	
			no-rip		
			single-rip	1.08	
			cross-rip		
D16	N 41°17’19.4”	W 081°33’25.6”	pre-rip	0.93	
			no-rip	0.68	
			single-rip		
			cross-rip		
D17	N 41°17’19.3”	W 081°33’24.0”	pre-rip	0.98	2.09 E-06
			no-rip		
			single-rip		2.57 E-04
			cross-rip	1.09	3.29 E-06

Sample	Latitude	Longitude	ripping condition	bulk density (g cm^{-3})	Ksat (m s^{-1})
D18	N 41°17'19.4"	W 081°33'22.4"	pre-rip	1.14	
			no-rip		
			single-rip	0.83	
			cross-rip		
D19	N 41°17'19.4"	W 081°33'20.8"	pre-rip	0.70	
			no-rip	0.50	
			single-rip		
			cross-rip		
D20	N 41°17'19.4"	W 081°33'19.1"	pre-rip	1.03	
			no-rip	0.61	
			single-rip		
			cross-rip		
D23	N 41°17'18.2"	W 081°33'32.0"	pre-rip	0.87	
			no-rip		
			single-rip		
			cross-rip	0.23	
D24	N 41°17'18.2"	W 081°33'30.5"	pre-rip	1.23	7.19 E-06
			no-rip	0.57	
			single-rip		3.45 E-06
			cross-rip		3.00 E-05
D25	N 41°17'18.2"	W 081°33'28.8"	pre-rip	1.07	
			no-rip		
			single-rip	1.02	
			cross-rip		
D26	N 41°17'18.2"	W 081°33'27.2"	pre-rip	0.98	
			no-rip		
			single-rip	1.15	
			cross-rip		

Sample	Latitude	Longitude	ripping condition	bulk density (g cm^{-3})	Ksat (m s^{-1})
D27	N 41°17’18.2”	W 081°33’25.6”	pre-rip	0.92	
			no-rip		
			single-rip		
			cross-rip	1.23	
D28	N 41°17’18.2”	W 081°33’24.0”	pre-rip	1.08	4.87 E-06
			no-rip		4.02 E-05
			single-rip		
			cross-rip	1.05	1.86 E-04
D29	N 41°17’18,2”	W 081°33’22.4”	pre-rip	1.00	
			no-rip		
			single-rip	1.09	
			cross-rip		
D30	N 41°17’18.2”	W 081°33’20.8”	pre-rip	1.08	
			no-rip		
			single-rip	1.12	
			cross-rip		
D31	N 41°17’18.2”	W 081°33’19.1”	pre-rip	1.28	4.61 E-06
			no-rip	1.00	
			single-rip		9.50 E-04
			cross-rip		3.00 E-06
D32	N 41°17’16.9”	W 081°33’32.0”	pre-rip	1.12	
			no-rip		
			single-rip		
			cross-rip	1.16	
D33	N 41°17’16.9”	W 081°33’30.5”	pre-rip	0.87	
			no-rip		
			single-rip	0.95	
			cross-rip		

Sample	Latitude	Longitude	ripping condition	bulk density (g cm^{-3})	Ksat (m s^{-1})
D34	N 41°17'16.9"	W 081°33'28.8"	pre-rip	0.96	
			no-rip		
			single-rip	0.90	
			cross-rip		
D35	N 41°17'16.9"	W 081°33'27.2"	pre-rip	0.82	2.10 E-05
			no-rip		9.00 E-06
			single-rip	1.11	
			cross-rip		1.88 E-06
D36	N 41°17'16.9"	W 081°33'25.6"	pre-rip	1.16	
			no-rip	0.87	
			single-rip		
			cross-rip		
D37	N 41°17'16.9"	W 081°33'24.0"	pre-rip	0.91	
			no-rip		
			single-rip	1.25	
			cross-rip		
D38	N 41°17'16.9"	W 081°33'22.4"	pre-rip	0.84	
			no-rip		
			single-rip		
			cross-rip	0.86	
D39	N 41°17'16.9"	W 081°33'20.8"	pre-rip	0.78	
			no-rip		
			single-rip	1.17	
			cross-rip		
D41	N 41°17'15.7"	W 081°33'30.5"	pre-rip	1.20	
			no-rip	0.66	
			single-rip		
			cross-rip		

Sample	Latitude	Longitude	ripping condition	bulk density (g cm^{-3})	Ksat (m s^{-1})
D42	N 41°17’15.7”	W 081°33’28.8”	pre-rip	0.94	
			no-rip		
			single-rip		
			cross-rip	1.26	
D43	N 41°17’15.7”	W 081°33’27.2”	pre-rip	1.01	
			no-rip	0.93	
			single-rip		
			cross-rip		

APPENDIX C

TOPOGRAPHIC SITE MAPS AND SAMPLING LOCATIONS

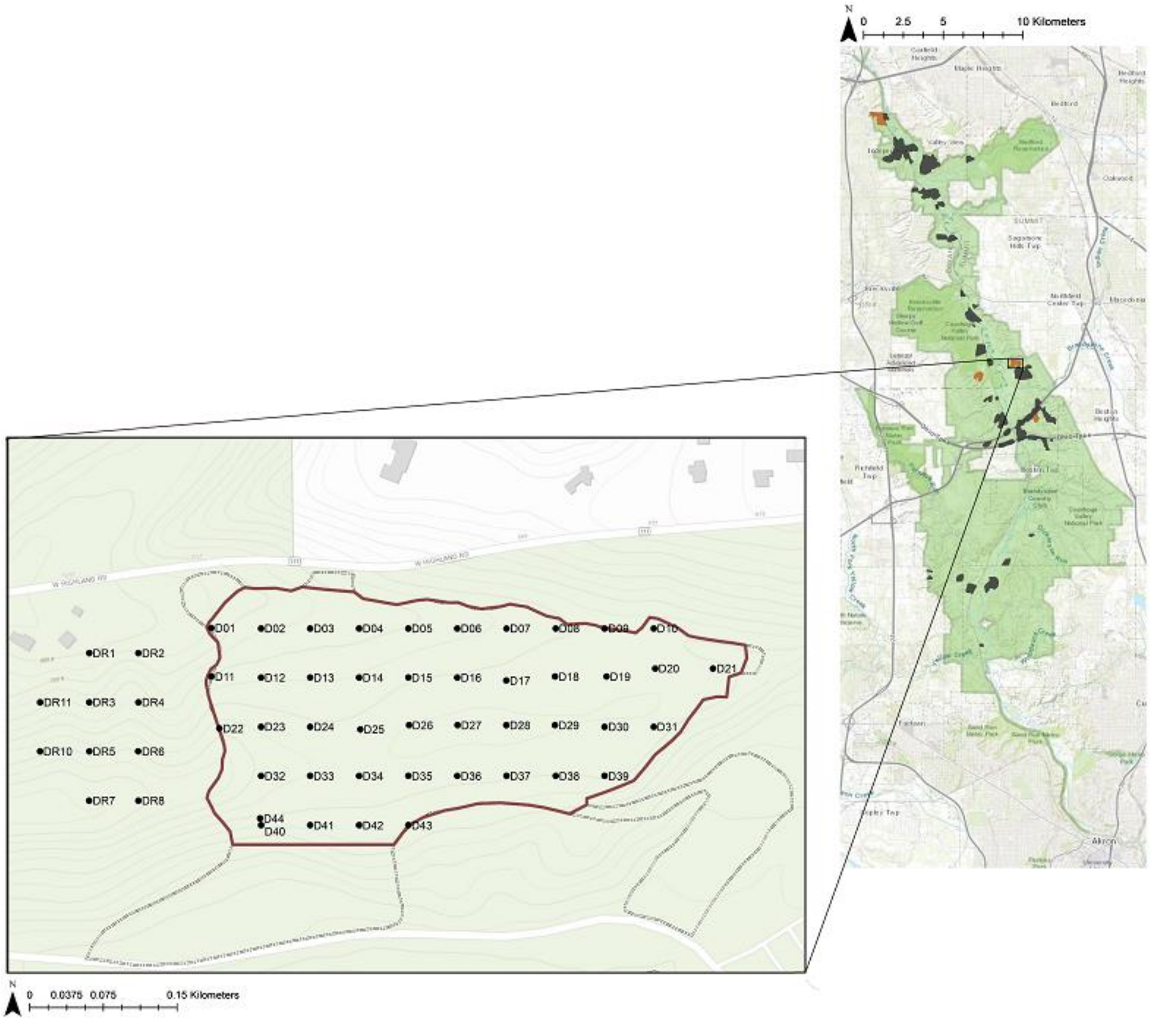

Figure C1: Topographic map of the Dover topsoil mine. W Highland Rd can be seen to the north, running west to east. The brown border indicates the sampling areas with individual sampling locations demarked by black points. The Dover Reference area is located to the west of the Dover site, with individual sampling locations demarked by black points outside of the Dover sampling area. The gray dashed line indicates the original disturbed area.

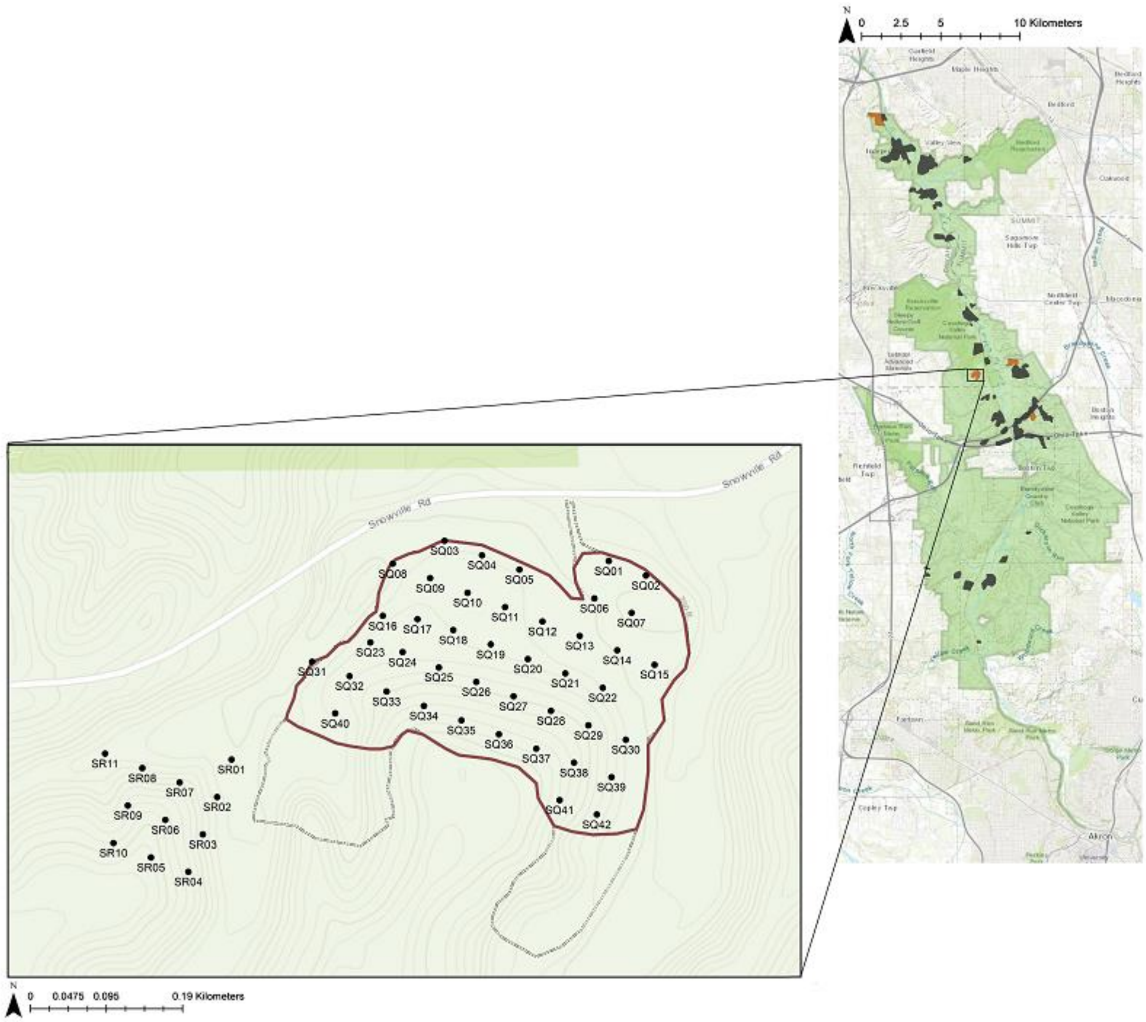

Figure C2: Topographic map of Snowville Quarry. Snowville Rd can be seen to the north, running southwest to northeast. The brown border indicates the sampling areas with individual sampling locations demarked by black points. The Snowville Reference area is located to the southwest of Snowville Quarry, with individual sampling locations demarked by black points outside of the Snowville Quarry sampling area. The gray dashed line indicates the original disturbed area.

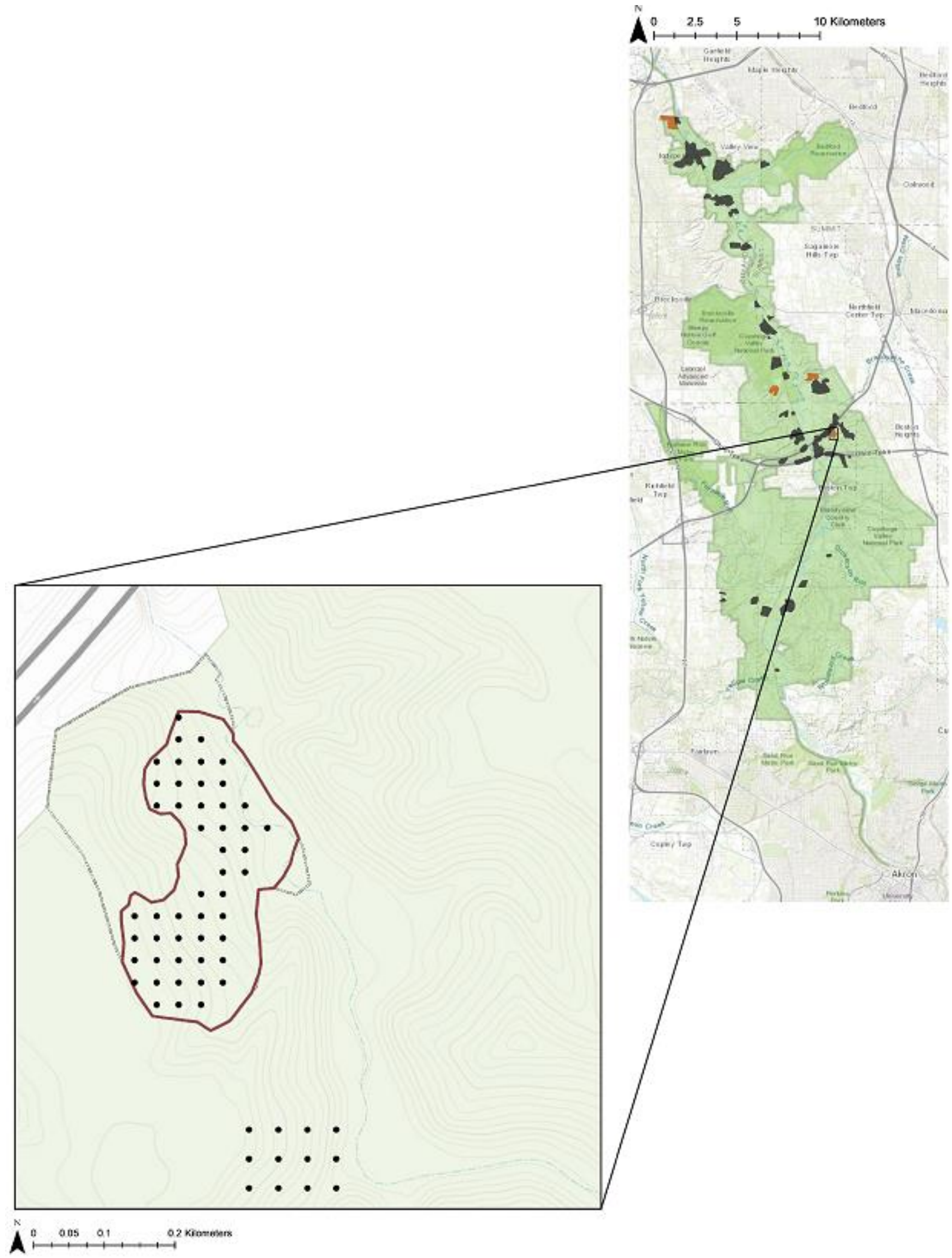

Figure C3: Topographic map of Hines Hill Excavation. The brown border indicates the sampling areas with individual sampling locations demarked by black points. I-271 can be seen to the northwest, running southwest to northeast. The Hines Hill Reference area is located south, southeast of Hines Hill Excavation, with individual sampling locations demarked by black points outside of the Hines Hill Excavation sampling area. The gray dashed line indicates the original disturbed area.

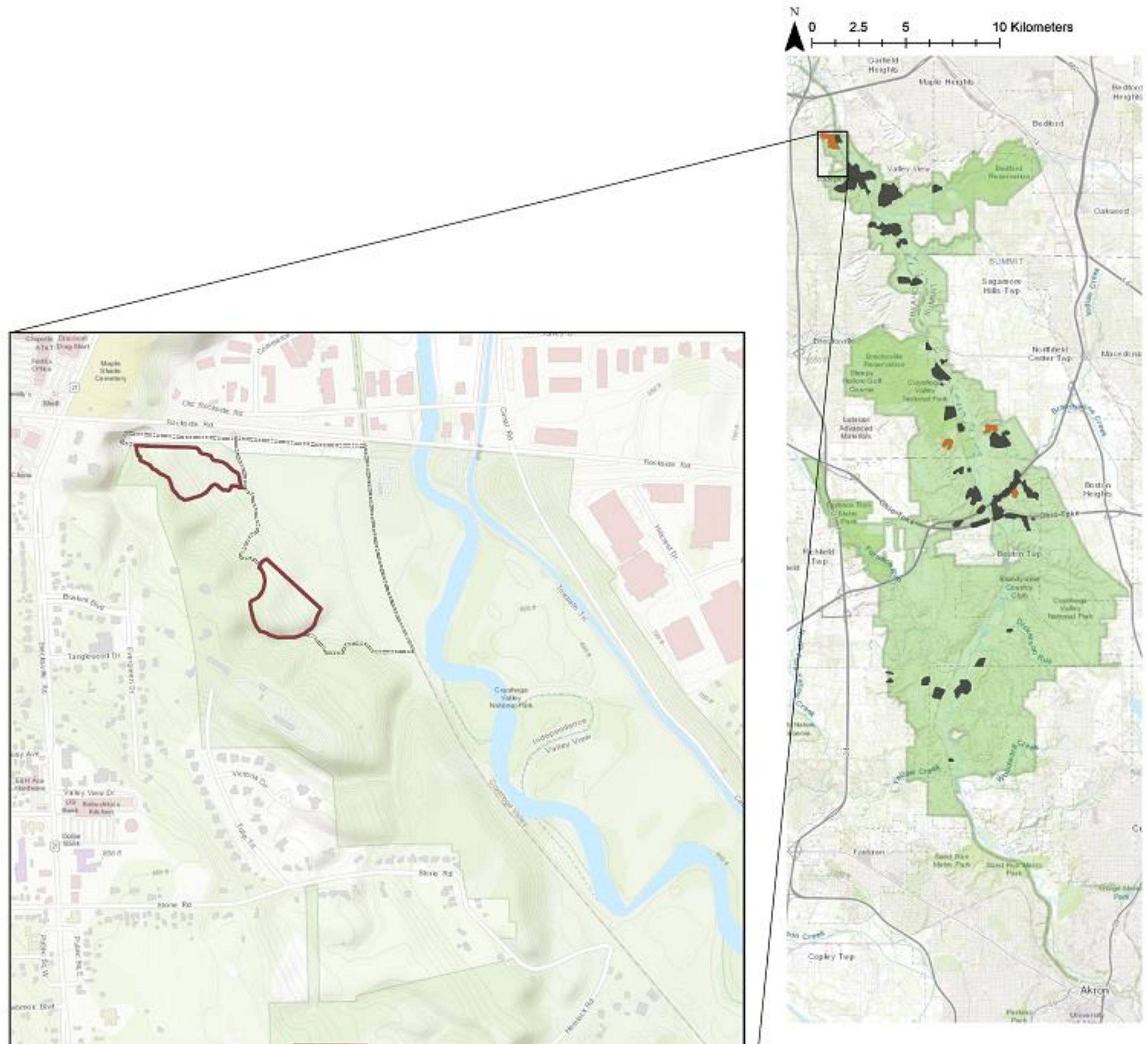

Figure C4: Topographic map of Cleveland Trust, Rockside Road, and the Cleveland Trust and Rockside Road Reference area. The Cuyahoga River can be seen on the eastern portion of the map, running south to north. The brown borders indicates the sampling areas. Rockside Road is the northernmost site. Cleveland Trust is southeast of Rockside Rd. The Cleveland Trust and Rockside Road Reference area is to the south of both sites. The original Rockside Road and Cleveland Trust disturbed areas are outlined with a gray dashed border.

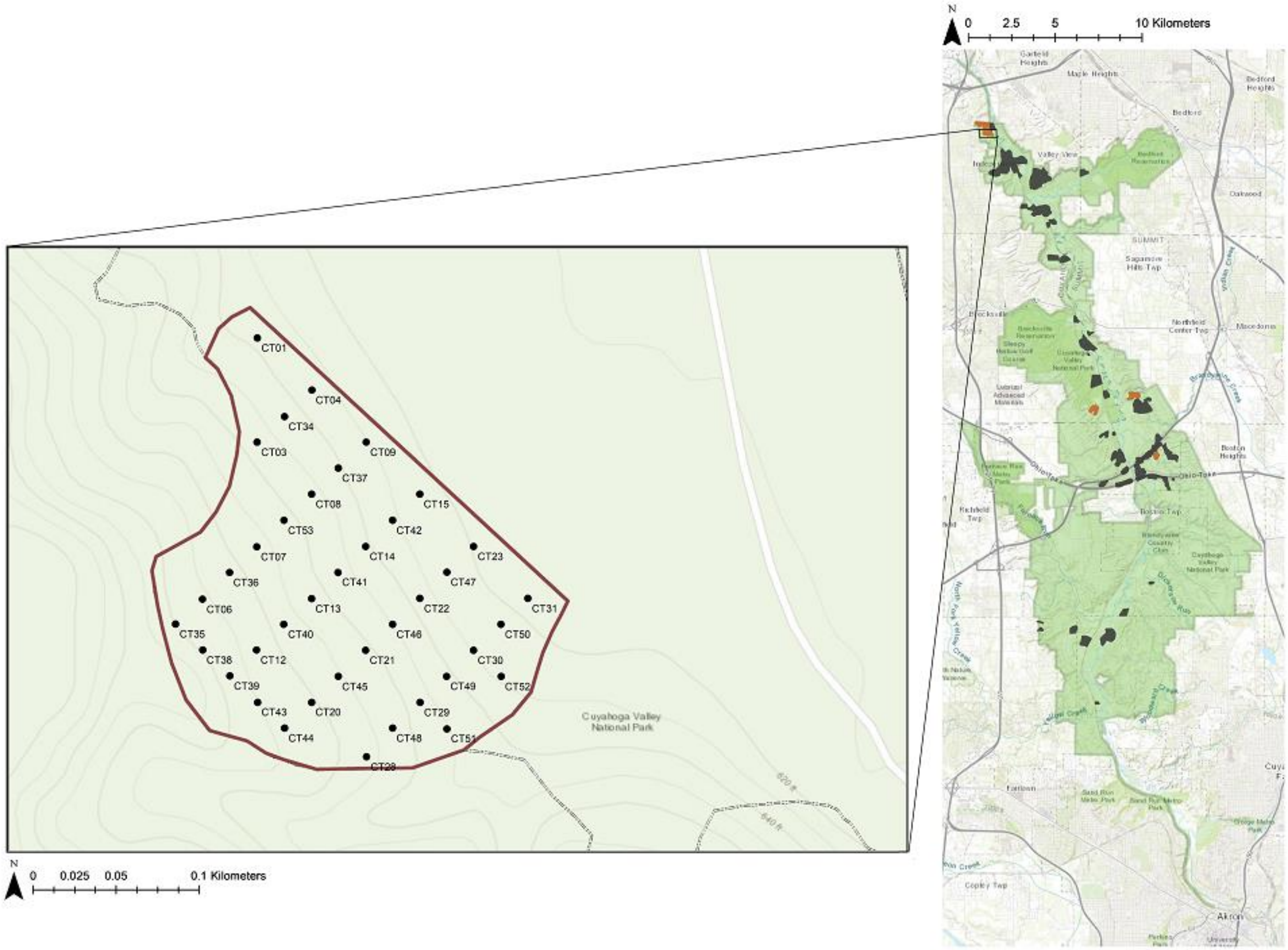

Figure C5: Topographic map of Cleveland Trust. The brown border indicates the sampling areas with individual sampling locations demarked by black points. The gray dashed line indicates part of the original disturbed area.

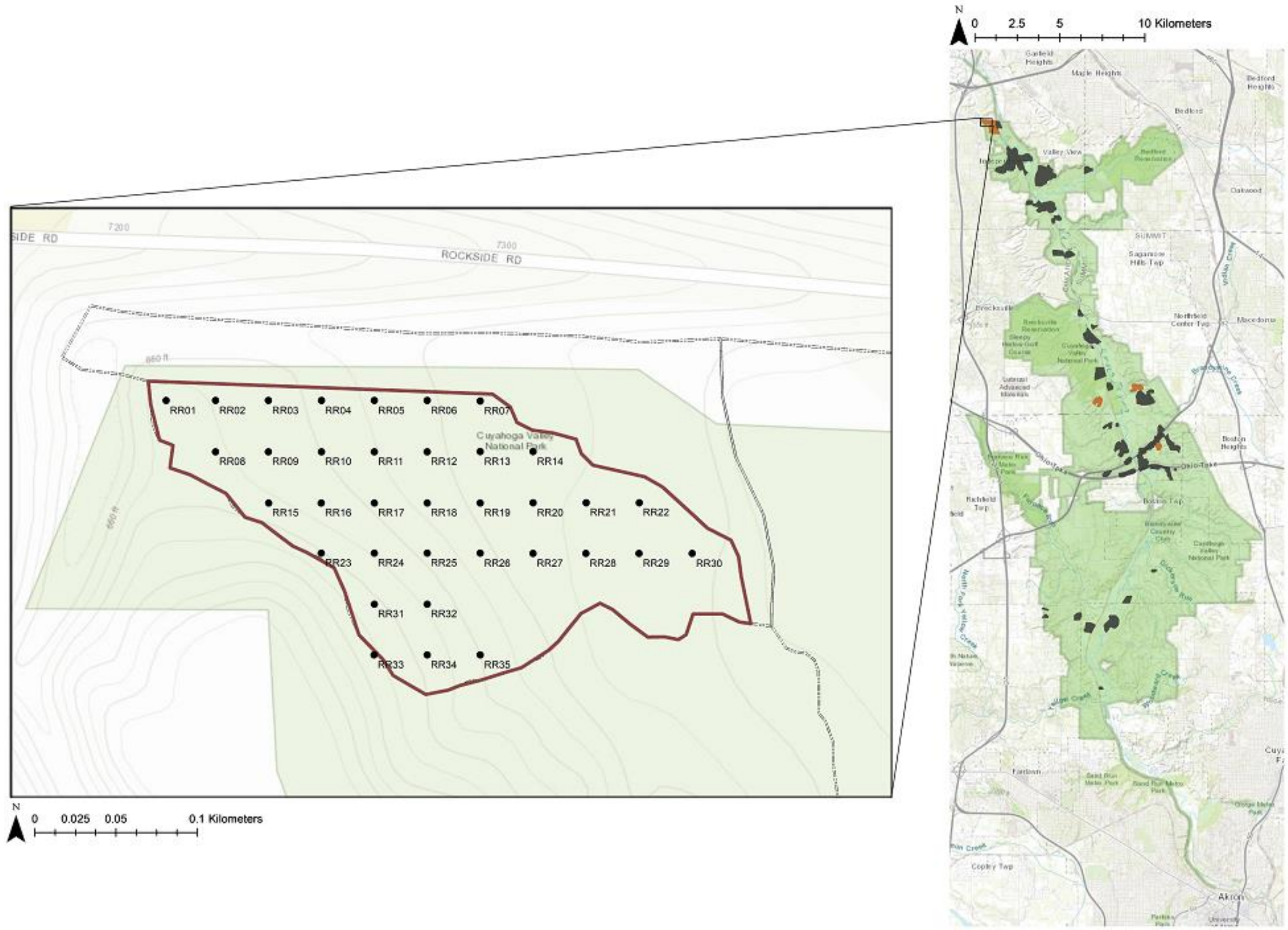

Figure C6: Topographic map of Rockside Road. Rockside Rd can be seen to the north, running west to east. The brown border indicates the sampling areas with individual sampling locations demarked by black points. The gray dashed line indicates part of the original disturbed area.