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Effects of reclamation and deep ripping on soil bulk density and hydraulic conductivity at legacy surface mines in northeast Ohio, USA

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Highlights.

- Mine reclamation compacted glacial parent materials, impeding reforestation.
- Deep ripping lowers soil bulk density within rips, below the surface.

- Deep ripping increases variability in hydraulic conductivity and creates pipes.
- Deep ripping may create soils that better support tree growth within, but not outside, the rips.

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Abstract.

Surface mining and reclamation activities can substantially affect the soil physical properties that mediate water movement and root growth, impeding the re-establishment of native vegetation and ecosystem function. Deep ripping is a promising approach to mitigate compaction using long shanks dragged through the soil, but little is known about its effectiveness in fine-textured glacial parent material. In five reclaimed surface mines and four reference forests on glacial parent material, we measured soil bulk density and saturated hydraulic conductivity. Two mine sites were subsequently subjected to deep ripping in a grid pattern and soil properties were remeasured within and outside of the rips. Before ripping, near-surface bulk density was higher and saturated hydraulic conductivity was lower at the reclaimed mines than the reference forests, and mine soils deeper than 20 cm were often denser than ideal for plant growth (>1.4 g cm^{-3}). Ripping increased variability in bulk density and saturated hydraulic conductivity, with the intersection of perpendicular rips becoming denser than pre-rip conditions in the top 5 cm. Below the surface, soils in the rips were generally less dense than pre-rip conditions, and soil piping was observed within some rips. Between the rips, bulk density decreased in the top 5 cm, but remained constant or increased relative to pre-rip conditions at greater depths. These results emphasize the importance of fine-scale, spatially explicit sampling when assessing the effects of mine reclamation and ripping. Our data support strategies of planting trees within rip intersections, though cast doubt on the potential for root expansion into areas between rips.

Keywords.

mine reclamation; soil properties; deep ripping; bulk density; saturated hydraulic conductivity; root restriction

1. Introduction

Removal of vegetation and topsoil layers and use of industrial equipment during sand, gravel, and topsoil mining has lasting impacts on soil properties. Reclamation activities on former mines often aim to retain key ecosystem services, but not necessarily to return the area to its original ecosystem. In contrast, restoration goals in post-mining landscapes often seek the reproduction of original species composition and ecosystem functions (Lima et al. 2016). However, efforts to reclaim or restore former surface mines may face ecological limitations imposed by the physical and chemical changes to the soil that occur during mining. Understanding how mining, reclamation, and restoration techniques affect soil structure and function is necessary to improve our ability to restore former mines to support native vegetation.

Physical characteristics of the soil play a key role in the ability for native plants to colonize legacy mines (Gilland and McCarthy, 2014). Soil bulk density and saturated hydraulic conductivity (K_{sat}) are used as key indicators of soil physical properties that affect root growth, water movement, and nutrient transport. Soil bulk density is largely a function of porosity and organic matter content (Robinson et al., 2022), and high bulk density can be a limiting factor for plant growth by restricting the penetration and spread of roots. Root-restrictive soil bulk density limits vary based on plant species and soil texture, but generally fall between 1.4-1.6 g cm^{-3} (Daddow and Warrington, 1983, NRCS 2019). In addition to bulk density, water infiltration and drainage are also key controls over root growth and distribution (Fan et al., 2017). Soils with K_{sat} lower than 1 x 10^{-6} m s^{-1} could limit plant growth due to inadequate ability of the soil to transport water. Bulk density typically increases while K_{sat} decreases with soil depth due to increased weight of surface layers, decreased organic matter, and less aggregate and pore formation (Brady and Weil, 2017). Thus, surface mining practices that expose deeper soil layers can result in higher soil bulk densities and lower K_{sat}, but this can also be exacerbated through mine reclamation practices.

Reclamation practices at mine sites commonly involve regrading to remove over-steepened slopes and compaction of the exposed soil and parent material, with hopes of maintaining stable topography (e.g., following the U.S. Surface Mining Control and Reclamation Act of 1977 (SMCRA)). After compaction, topsoil may be spread across the sites (Phelps and Holland, 1987). However, these actions leave soils with bulk densities greater than undisturbed areas and often higher than the root-restricting threshold (Shrestha and Lal, 2011). Finally, native and non-native grasses are seeded in order to further reduce runoff and retain nutrients at the sites. Although reducing nutrient and sediment loss is a key factor in the reclamation process, the use of non-natives and non-woody plants counters the goal of native forest restoration (Ruggles et al. 2021).

To counter the compaction found in many legacy surface mine sites, deep soil ripping (also known as deep tillage) has been used to break up dense layers throughout the soil profile by pulling 1-meter-long shanks along the landscape (Sweigard et al. 2007). This technique has been explored for use in conversion of legacy surface mines to both agricultural (Dunker et al. 1995) and restored forest land (Ashby, 1997). Some recent post-mining reclamation projects in the Appalachian region are using the “Forestry Reclamation Approach”, which incorporates deep ripping to promote reforestation (Zipper et al. 2013) and return soils to a compaction degree similar to undisturbed forests (Ampoorter et al., 2010). Angel et al. (2018) found a significant decrease in soil bulk density in restored coal mines where deep ripping was performed in a grid pattern compared to those with no ripping. Deep ripping has also been paired with disking and organic matter amendments to improve soil properties and promote revegetation (e.g., Batemen and Chanasyk, 2001; Angel et al., 2018). However, less research has been conducted on the effects of deep ripping of glacial parent materials exposed by mining and reclamation.

The aim of this research is to characterize the effects of mine reclamation and deep-ripping restoration methods on soil bulk density and saturated hydraulic conductivity of exposed glacial parent materials. We are motivated by the long-term goal of improving the success of reforestation with native tree species in highly compacted legacy mines. We hypothesize that: H1) traditional reclamation and passive management methods, following a decades-old approach, has increased bulk density and decreased hydraulic conductivity relative to reference (unmined forest) sites; H2) restoration practices using deep ripping will result in lower soil bulk density and higher saturated hydraulic conductivity, more closely resembling their adjacent reference forest soils than reclaimed mine areas between the rips; and H3) the bulk density through a depth profile within the ripped areas of the mine sites will more closely resemble forest soils.

2. Material and Methods

2.1. Site description

This research is part of the longer-term Forest Soils and Trees Ecosystem Restoration (FoSTER) project aimed at reforestation of legacy non-coal surface mines in the Cuyahoga Valley National Park (CVNP) in northeastern Ohio, USA. Five reclaimed mines, paired with four unmined reference sites, were selected for study of the mine reclamation and deep soil ripping restoration methods (Table 1, Figure 1). Reclaimed mine sites were selected based on restoration priority for the National Park Service. For each mine site, a reference site was chosen in an area of mature forest with minimal recent human disturbance as close as possible to the mine site and with similar slope and aspect. The Dover (DV), Snowville Quarry (SQ), and Hines Hill (HH) reference sites were on the same hill slopes as the mine sites. The Cleveland Trust (CT) and Rockside Road (RR) mine sites share a single reference site, 1.3 km from the mine sites, because there were no appropriate reference sites closer to the mine sites. Reference sites are noted by an R after the site initial (DVR, SQR, HHR, and CTR).

All mine sites are dominated by hillslopes which were disturbed by excavation for construction between the 1950s and 1990s. Surface mines in CVNP were primarily used for the extraction of topsoil, sand, and gravel to aid in construction of nearby roadways and facilities. Mine and reference hillslopes are mostly northeast facing, with DVR facing north and HHR facing east. Average slopes are 10-13% for DV, SQ, CT, and RR, and 21% for HH (Ruhm, 2018). For 1991-2020, mean annual temperature was 11.3°C, mean annual precipitation was 1042 mm at the Cleveland (Ohio) airport (Arguez et al., 2012). The region can receive snow from November to April.

All sites were glaciated during the Last Glacial Maximum, with till, glacial lake sediments, and outwash deposited mostly between 17,000 and 14,050 ybp (Pavey, 2002; Ford, 1987; White and Brown, 1984). Devonian shale and sandstone underlie the glacial deposits (Slucher et al. 2006). Prior to mining, soils at DV, SQ and HH were likely aquic Hapludalfs, similar to the surrounding Geeburg soil series near DV and

Ellsworth soil series near SQ and HH. The DVR and SQR reference sites have typic Hapludalf soils (in the Cardinal-Mentor soil association), while HHR has aquic Hapludalf soils (Ellsworth series). Soils at CT and RR were likely similar to the typic Dystrudept soils (Brecksville series), which surrounds them. The CTR reference site has three mapped soils, an aeric Ochraqualf (Mitiwanga series), an ultic Hapludalf (Loudonville series), and an aquic Hapludalf (Ellsworth series).

Reclamation at the mine sites occurred between 1984 and 2012, following modified SMCRA protocols. Mined areas were graded to remove gullies and over-steepened slopes, and the sites were compacted to reduce erosion. CVNP records indicate that fill was added to DV during reclamation, with a mixture of lake, streambed, and floodplain sediments applied prior to regrading (Ruhm, 2018). There are no records of imported materials at the other sites. Topsoil was not preserved during mining or replaced during reclamation. Following regrading and compaction, compost was applied to the soil surface, and the sites were seeded with fast-growing, non-native species. In 2018, a plant community composition survey at HH, CT, and RR showed that the sites are still dominated by herbaceous species, along with some invasive woody plants (Ruggles et al., 2021). DV and SQ had similar vegetation prior to deep-ripping restoration.

Table 1. Mine and reference site information.

Site Name	**Site Code**	**Site type**	**Area (ha)**	**Reclamation Year**
Dover	DV	mine	8.41	2001
Dover reference	DVR	reference	1.25	---

Snowville Quarry	SQ	mine	8.40	1999
Snowville Quarry reference	SQR	reference	1.63	---
Hines Hill	HH	mine	6.60	1991
Hines Hill reference	HHR	reference	1.02	---
Cleveland Trust	CT	mine	3.50	2012
Rockside Road	RR	mine	3.55	1984
Cleveland Trust reference[1]	CTR	reference	5.48	---

Table 2. Number and type of measurements taken at each site.

Site Code	**Pre-rip or reference near surface bulk density**	**Post-rip near surface bulk density**	**Pre-rip or reference K_{sat}**	**Post-rip K_{sat}**
DV	44	cross-rip: 9 single rip: 13 non-rip: 12	8	cross-rip: 8 single rip: 4 non-rip: 4
DVR	10	---	3	---
SQ	20	cross-rip: 12 single rip: 14 non-rip: 13	8	cross-rip: 6 single rip: 12 non-rip: 6
SQR	11	---	3	---
HH	23	---	8	---

[1] CTR is also the reference site for the RR mine site.

HHR	12	---	3	---
CT	21	---	6	---
RR	17	---	6	---
CTR	12	---	3	---

2.2. Ripping method

Deep-ripping restoration took place at DV in September, 2017 and at SQ in September, 2018. A bulldozer made passes in two directions across the site while dragging shanks sunk one meter deep to create rips in a grid pattern that covered the majority of the mine area at DV (8.41 ha) and SQ (8.40 ha). Parallel rips were ~2 m apart. The ripping method used was similar to that prescribed using the “forestry reclamation approach”, which was designed to create suitable substrate for tree survival (Sweigard et al., 2007).

2.3. Soil properties

A rectangular grid of sample points was established at each mine and reference site. Grid sizes varied based on site area but had between 5 and 13 sample points per hectare at the mine sites and between 2 and 12 sample points per hectare at the reference sites. Texture of 20 cm depth soil samples was measured by a laser diffraction particle size analyzer (Mastersizer 2000, Malvern Panalytical, UK), as described by Ruhm (2018). Percent clay and silt values have been adjusted according to DiStefano et al. (2010), which we also validated for our instrument (unpub. data).

Near-surface bulk density samples were collected from the top 5 cm of soil at a subset of sample points on the rectangular grid at each study site, using a 5.08 cm diameter AMS bulk density corer. Samples were refrigerated until being oven-dried at 105°C for >72 hours, and then weighed to the nearest 0.01 g. Bulk density was calculated by dividing dry mass by the known volume. All mine sites were sampled for bulk density before ripping occurred ("pre-rip"). Post-ripping samples were collected nine months after ripping DV and SQ within one meter of previously sampled points. At each of these points, we randomly chose to sample in one of three types of locations: within a rip furrow ("single-rips"), at the intersection of two rips ("cross-rips"), and in areas between rips ("non-rips").

To determine how bulk density changes with depth, we also collected samples from soil profiles before ripping (at HH and SQ), after ripping (at DV and SQ), and in reference sites (at HHR and SQR). The DV profile pit (n=1) was dug near the center of the site and located on the slope. This location had a saturated hydraulic conductivity measurement most similar to the site average. Similarly, pits at HH (n=1) and HHR (n=1) were dug on the major slope of each site. Two pre-rip soil pits were dug at SQ (n=2). One pit was on the sloped portion of SQ and the second was on a flat area, both near the midline of the site. Then, 9 months after deep-ripping SQ, new profile pits were dug at locations neighboring the pre-ripping pits, and an additional post-ripping pit was dug at a third site on the SQ slope to account for rips running in two directions - down slope and across the slope (n=3). Two soil pits were also dug at SQR on the same east facing slope (n=2).

Soil profile pits were dug to approximately 70 cm or until it became impossible to dig deeper. The profiles were approximately 1 meter long and 0.5 meters wide. Each post-rip pit was dug to expose the profile of a rip as well as an adjacent non-ripped area. We sampled bulk density by taking cores every 5 cm to a 60 cm depth, pushing the bulk density corer into the profile horizontally. The cores were taken in a staggered pattern down the profile to minimize pressure disruption of nearby soil areas that were not yet sampled. Soil horizonation, color, and root abundance were also described for each pit.

To assess soil hydraulic properties within the rooting zone, K_{sat} was measured using a Guelph permeameter, which is a constant-head infiltration device that relies on the Mariotte siphon principle. K_{sat} measurements were taken on the same rectangular grid as near-surface bulk density, but at a subset of sample points (Table 2). After augering each 6 cm diameter, 15 cm deep well, we agitated the sides of the well with a wire brush to reduce the effect of clay smearing which could alter the infiltration rate (Bagarello, 1997). For both 5 cm and 10 cm heads, water level in the reservoir was recorded at equal time intervals until an approximate steady state was reached. If <0.1 cm water level drop in the reservoir within 15 min, a new well was augered within 1 m of the original location. This process was repeated up to three times as needed. For a few measurement locations (3 at CT and 2 at RR) no water level drop occurred within 15 min with either head in any of the three tested wells. At these locations, K_{sat} values were truncated to 1.47×10^{-8} m s^{-1}, based on the assumption of a 1 mm drop in the 16 minutes at a 10 cm head. This truncated value thus represents the upper limit of Ksat assuming the wells were not affected by smearing.

2.4. Statistical analyses

All statistical analyses were performed in R version 4.1.1 “Kick Things”. To test H1, we used a linear mixed-effects model for analysis of pre-rip vs reference near-surface bulk density and K_{sat} using the “lme4” package. We used bulk density or log(K_{sat}) as response variables, site type (pre-rip mine vs reference) as a fixed factor, and a random factor that grouped the corresponding mine and reference site into one pair (e.g., SQ and SQR). To test the significance of the random factor, we ran a likelihood ratio test with the mixed effects model and a model without the random factor and chose the model with the lowest AIC (mixed effects model for both bulk density and log(K_{sat})). We then compared each mine to its neighboring reference forest using individual two-tailed t-tests for SQ, DV, and HH and a two-way ANOVA to include CT, RR, and their common reference forest. We used the “emmeans” package with a “holm” adjustment as the post hoc test. We used the cor.test() function to test for a significant correlation between bulk density and log(K_{sat}) measured at the same sample point across all projects.

Similarly, to test H2, a linear mixed-effects model for analysis of pre-rip vs post-rip near-surface bulk density and K_{sat} was performed under the “lme4” package (at DV and SQ). Bulk density or log(K_{sat}) were response variables. Rip type (pre-rip, non-rip, single-rip, or cross-rip) and site were fixed factors. Sample point was designated as the random factor to account for repeated sampling of individual sites. We used the “emmeans” package with a “holm” adjustment as the post hoc test.

We ran Moran’s I tests for spatial autocorrelation of pre-rip near-surface bulk density measurements taken at each mine site using the “gstat” package. Neighbors were identified with Euclidean distance across each respective mine site using the "dnearneigh()" function. We then modeled semivariance of these same measurements using the "variogram()" function.

3. Results

3.1. Soil horizons and texture

At the reference sites, soil horizonation appears to be consistent with Soil Survey mapping for the area (Soil Survey Staff, 2018). For example, at SQR, the dark brown, loose A horizon is 8-10 cm thick and underlain by a 3-10 cm, grayish brown E horizon. Below that, a dark yellowish-brown horizon extended to at least 33 cm. Fine roots are very common in the top 10 cm and common from 10-15 cm. Very fine roots were present throughout the profile. Large, woody tree roots were also present at depth.

Soils are poorly developed in the mine sites, with a thin A horizon above parent material moved or emplaced during mine reclamation 6-34 years prior to sampling. Fine roots are common in the top 1 cm of the mine soil, with rare very fine roots in the rest of the profile. For two pits dug at SQ, the dark A horizon was 2 cm thick. In the pit on the SQ slope, there was a color change from dark brown to reddish brown at 15 cm, but the pit in the SQ flat area had no color change.

At all of the mine sites, soil textures in the upper 20 cm are dominated by silt loams, with some loams and silty clay loams. For the reference sites, soil texture analyses indicate that the upper 20 cm of the soil profile is also mostly silt loams, with some loams and silty clay loams (Ruhm, 2018). This is consistent with NRCS Web Soil Survey classifications of soil texture at these locations (Soil Survey Staff, 2018).

3.2. Reclaimed mines compared to reference forests

Prior to ripping, near-surface soils at the mine sites were significantly denser than soils in the reference forest sites ($p < 0.001$). Across all sites, mine and reference sites had mean bulk densities of 1.10 g cm^{-3} (SD=0.20 g cm^{-3}) and 0.86 g cm^{-3} (SD=0.26 g cm^{-3}), respectively. There were large contrasts between mine and reference sites in near-surface bulk density at CT, RR, and SQ ($p<0.001$, Figure 2A). However, DV and HH soils had similar near-surface bulk densities as their respective reference sites ($p=0.74$ and $p=0.86$ respectively, Figure 2A).

Bulk densities at DV and RR were not spatially autocorrelated (although the test was based on only 17 samples from RR). However, soils at SQ, HH, and CT exhibited significant spatial autocorrelation, as shown by increasing semivariance over the first 100-200 m (Figure 3). SQ and HH soils exhibited highest bulk density on the north to northeast side of the site in both sloped and flat topography. CT had the highest soil bulk density in the southern portion of the site along the slope.

Examining soil bulk density by depth, SQR and HHR reference sites were the least dense in the top 5 cm, below which bulk density was mostly in the range of 1.1 to 1.4 g cm^{-3} (Figure 4A,B). Although similar at the surface, the profile at the SQR reference site shows a gradual increase in bulk density with depth, while the profile at the HHR site has more variability. None of the bulk density values measured in the SQR profile were >1.4 g cm^{-3}, and within the HHR profile, only soil at 60 cm depth exceeded 1.4 g cm^{-3}. Bulk densities <1.4 g cm^{-3} is considered ideal for plant growth in silty clay loam soils, while bulk densities >1.6 g cm^{-3} significantly restrict root growth (Daddow and Warrington, 1983, NRCS, 2019).

At the reclaimed SQ and HH mine sites, a rapid increase in bulk density at depths below 5-10 cm was seen prior to ripping, with the majority of deeper samples having bulk density measurements >1.3 g cm^{-3} (Figure 4A,B). At depths ≥20 cm, the soil in the flat portion of the SQ site had bulk densities greater than the range for ideal plant growth (M=1.58 g cm^{-3}, SD=0.167 g cm^{-3}, M=mean, SD=standard deviation), and digging by hand became impossible below 50 cm. On the SQ slope, bulk density was not as high (M=1.39 g cm^{-3}, SD=0.138 g cm^{-3}) at depths ≥20 cm. In both SQ mine profiles there was a local bulk density minimum at 30 cm depth, but there were no apparent soil color or texture changes at that depth. Compared to the SQ mine profiles, the HH mine soil was less dense, but still had bulk densities ≥1.4 g cm^{-3} over half of its profile.

Prior to ripping, log(K_{sat}) at the mine sites was significantly slower than at the reference sites (p=0.006) (Figure 2B). The significance of this effect was driven by the large difference in log(K_{sat}) values between mine sites CT and RR compared to their reference site (p=0.025 for CT, p=0.039 for RR), whereas log(K_{sat}) at mine sites SQ, DV, and HH was not statistically different from their respective reference sites (two sample t-tests, p=0.504 for SQ, p=0.191 for DV, and p=0.111 for HH). There was also significant variability among the geographic pairs of mines and their respective reference sites (likelihood ratio test of random effects p<0.001). Log(K_{sat}) was also statistically more variable in the mine sites, spanning 4 orders of magnitude, while measurements at the reference sites only varied about 1 order of magnitude (Levene's Test, p=0.005), though we had fewer measurements at the reference sites than at the mine sites.

There was no significant correlation between log(K_{sat}) and near-surface bulk density at specific sampling points, when all sites are combined (p=0.40). At the level of single sites, only DV and SQ had >4 pre-rip K_{sat} measurements, and the correlation with bulk density was also not significant (p=0.42 and 0.36, respectively).

3.3 Effects of ripping on reclaimed mines

After soil ripping treatment, near-surface bulk density differed among sites (SQ mine vs DV mine) and sample type (non-rip, single-rip, and cross-rip) within each site (Figure 5). Near-surface bulk density at Snowville was significantly higher than at Dover (p<0.001). In general, ripping appears to have increased near-surface bulk density where the ground was ripped, but decreased near-surface bulk density in non-ripped areas between rips (Fig. 5A). At Dover, non-rip samples had a significantly lower bulk density than single-rip, cross-rip, and pre-rip samples (p=0.01, p=0.003, and p=0.0004, respectively). At Snowville, non-rip and pre-rip samples both had significantly lower bulk density than cross-rip samples (p=0.0007 and p=0.0008 respectively).

Soil bulk densities across the depth profiles did not necessarily reflect the trends in near-surface bulk density. At depths greater than 20 cm, DV mine soil bulk density was less in the rip than in the non-rip (Fig. 4C). Soils within rips were at the high end of plant root tolerance at depths ≥35 cm, and non-rip soils were measured above the root restriction level (1.6 g cm^{-3}) at depths 55 and 60 cm. Non-ripped soils at DV between 35 and 50 cm depths were so dense that we were not able to push the soil corer into the profile. Soil bulk density at depths below 10 cm varied substantially among the 3 profile pits that we sampled at SQ. The soil bulk density in the flat portion of SQ mine (Figure 4D) did not differ between the non-rip and rip sample points at depth; however, both of those soil sample types were less dense than the pre-rip samples. The soil at the slope of SQ mine in a rip running downslope (Figure 4E) was similar to pre-rip conditions until 20 cm. At ≥20 cm depth, rip soils were substantially less dense (M=1.31, SD=0.045) than non-rip soils (M=1.45, SD=0.047), and generally less dense than pre-rip soils. Similarly, in a profile pit of a rip running horizontally to the slope, rip bulk density was generally lower than non-rip and pre-rip bulk densities (Figure 4F). In contrast, bulk densities in the non-rip at 25-45 cm depths were also so dense that we were not able to insert the soil corer.

After ripping, saturated hydraulic conductivity was not different between sites (Dover vs Snowville, p=0.21, Figure 5B). Also, there was no statistically significant difference between sample types (non-rip, single-rip, cross-rip) at either of the sites (p>0.05), although sample sizes were small so power was limited. However, the range of K_{sat} measured within rips was much larger than the range measured pre-rip. At DV, the greater range was due to higher K_{sat} in some places within rips, while at SQ, the K_{sat} range increased because of both higher and lower K_{sat} values than had been measured pre-ripping. The increase in variability is consistent with field observations of soil pipe formation within some rips.

4. Discussion

After years of disturbance, soils of legacy surface mines usually inhibit native and woody vegetation due to deleterious changes in soil physical properties (Feng et al. 2019). Even decades after reclamation, mine soils in our study did not resemble nearby forest soils. Reclamation techniques have left soils dense enough to, in some cases, restrict tree root growth and limit water flow and storage. Near-surface measurements of soil physical properties are not sufficient to determine the effectiveness of deep-ripping restoration; rather, properties at depth must also be considered if reforestation to native forest communities is a main restoration goal (Shrestha and Lal 2011, Ussiri et al, 2006). Nine months after deep soil ripping, restored mine soils showed little change in structural properties at the soil surface. However, deep ripping yielded promising results of loosening soils at depth, which could facilitate tree root expansion in ideal rooting depths and promote success after plantings. Pairing deep ripping with top soil improvement similar to the techniques used in the “forestry reclamation approach” (Burger et al. 2007) may be necessary to have the greatest chance of successful reforestation.

4.1. Reclaimed mine soils differ from reference forests

Soil texture is usually a key control on other soil physical properties, but while mine and reference soils had similar textures arising from their shared parent material, their bulk density and K_{sat} were often different. Prior to deep ripping restoration, near-surface soil bulk density was significantly higher in 3 out of the 5 studied mines sites compared to their neighboring non-mined forest soils, while 2 mine soils had a significantly lower K_{sat} than reference forest soils. There was less variability in bulk density among the five mine sites than there was among the four reference forests. Conversely, K_{sat} variability among the mines was much higher than among the reference sites, although fewer K_{sat} measurements were obtained at reference sites due to time limitations. These results echo findings that land use has a multi-decadal legacy in the mean and spatial variability of nutrients in forest soils, with differences attributed to both the human activity itself and the consequent differences in biological activity (Fraterrigo et al., 2005). Root systems of herbaceous species present at the mine sites may homogenize and lower near-surface soil density relative to the near surface in mature reference forests. At greater depths, the history of mechanical compaction and the absence of more deeply rooted species increases bulk density and decreases K_{sat} at the mine sites.

Near-surface pre-rip soil bulk density exhibited within-site spatial autocorrelation at 3 of the 5 mines. Topography can impart spatial autocorrelation in bulk density (Keshavarzi et al., 2021), but that doesn't appear to be the primary driver of the variation observed at our study sites. Alternative drivers of autocorrelation could be variability in the use of heavy equipment during mine reclamation (Phelps and Holland, 1987, Schroeder, 1988) or variation in plant communities that impart patterning on near-surface bulk density. The association between plant communities and soil bulk density is well established (e.g., Yimer et al., 2006, Lee et al, 2014, Kooch et al., 2016) though soils and plant communities typically co-evolve over much longer timescales than the few decades our study sites have had since mine reclamation (Berry et al., 2006). Future work could assess the relationship between the spatial variability of vegetation and soil physical and chemical properties at these and similar reclaimed mine sites. Huang et al. (2021) found significant spatial variability in bulk density at a reclaimed surface mine which was driven by vegetation cover and topography; however, at the ecosystem scale, trends in spatial distribution of bulk density at depth (>10 cm) did not follow trends observed near the surface. This further exemplifies the need for sampling soil physical properties throughout the profile, especially at sites with high spatial variability.

Near-surface measurements of bulk density underestimate the root restriction imposed by bulk density at depth. Most soils from both mine and reference sites had near-surface bulk densities below 1.4 g cm^{-3}, which is considered acceptable for root growth in silt loams (NRCS, 2019, Daddow and Warrington 1983) and is consistent with global averages found in the same textured soils (M=1.34 g cm^{-3}, n=618, Gupta et al., 2021). In all three depth profiles sampled at unripped mine sites, bulk density reached root restriction values around 10-20 cm depth. This could explain the survival of grasses and herbaceous plants with root structures better equipped for shallower and less developed soils, but mortality of deeper-rooted trees in some reclaimed areas that have not been ripped (Huang et al. 2015). The high bulk density would result in the inability for adequate root expansion at depths necessary for tree growth (Canadell et al., 1996). The biggest contrast between bulk density of pre-ripping mine soils and their reference counterparts is from 15-35 cm, where the mine soils are substantially denser than the reference soils. At 35-45 cm, we see convergence of the density values across all sites in the range of 1.3 to 1.45 g cm^{-3}. Similarly, soils at another reclaimed mine site, in southeastern Ohio, were significantly denser at 20-40 cm depth than undisturbed hardwood forests, though bulk densities were similar at 40-50 cm (Ussiri et al., 2006). Although additional deep sampling would be useful, these results suggest that lasting effects of earth moving and compaction during reclamation may be most pronounced over a narrow, but ecologically critical, range of depths.

At both mine and reference sites, most of the measured K_{sat} values fall within the typical range of silty loams, based on a global database with 810 measurements (M=~ 5 x 10^{-5} to 1 x 10-7 m s^{-1}, Gupta et al., 2021). This suggests that the commonly used Guelph permeameter produced reasonable results, despite uncertainties associated with the method (e.g, Gallichand et al., 1990, Salverda and Dane, 1993, Ghosh et al., 2019).

The truncated values at CT and RR are lower than expected for any of the measured soil textures and may suggest that smearing remained a problem despite brushing or that more intense compaction occurred at those sites during reclamation. Even if the truncated values are excluded, the remaining CT and RR pre-ripping K_{sat} values are lower than 92% (11 of 12) of the reference site K_{sat} values. Limitations of the Guelph permeameter technique and the relatively small number of measurements makes it likely that we are underestimating the full range of K_{sat} at both mine and reference sites. Nonetheless, the mine sites show greater K_{sat} variability than the reference sites, potentially reflecting differential compaction by heavy equipment during reclamation, as discussed above.

Lower K_{sat} in some of the mine sites relative to the reference soils is consistent with the greater bulk density in the 15-35 cm depth range and by the lack of pore spaces associated with biopores and macropores (e.g., Bailey et al., 2015, Germann and Beven, 1981). Lack of pore spaces as a factor influencing K_{sat} is supported by our observations of few roots and little soil aggregation within the soil pits at the mine sites. Residual compaction from the mine reclamation process likely limits the biological activities that would form pores at depth, thus lowering K_{sat}. Whatever the cause, low K_{sat} values may contribute to development of a transient, perched water table that could affect plant rooting depth (Fan et al., 2017) and potentially contribute to the success of shallow-rooted plant species at the reclaimed mines.

4.2. Effects of deep soil ripping restoration

Near-surface bulk density results after deep ripping restoration are intriguing and counterintuitive. Bulk density decreased in the areas between rips, and it was highest in the cross-rips. The decrease could partially be explained by exposure to wetting and drying cycles that facilitate creep of the soil monolith into the spaces created by the rips (e.g., Young, 1960; Fleming and Johnson, 1975). Additionally, rain splash and overland flow could cause fine particles to be washed from the non-ripped surfaces into the concave rips (Gabriels and Moldenhauer, 1978) increasing bulk density in those areas. Finally, shortly after ripping, we observed that at some locations, large soil clods produced by ripping settled into the concavity created at the intersection of the two ripping passes (i.e., the cross-rip sampling location). If the source of those clods was the compacted soil from >5 cm depth prior to ripping, the near-surface cross-rip bulk density measurements post-ripping could reflect the pre-ripping compacted conditions. Measuring bulk density changes over time and analyzing soil texture from samples in differing areas could be used to explore these potential mechanisms.

Below the surface, ripping tended to lower bulk density within the rips, but increase it in nearby non-ripped areas, particularly below 20 cm. Near the surface, the process of ripping caused upheaval of soil clods, whereas, at depth, the space for the ripping shank may have been partially accommodated by further compaction of the surrounding soil. This interpretation is consistent with previous observations of increased pore spaces adjacent to a rip in the upper 30 cm, but decreased pore spaces at greater depths in a clay-rich Australian soil (Koppi et al., 1994). Angel et al. (2018) found no significant interaction between ripping and depth for bulk density at a reclaimed mine in Texas, but that study did not specify where soil samples were collected with respect to rips. Our results suggest that soil bulk density within rips should be considered as a measure of success after deep-ripping restoration, but that near surface measurements alone are not sufficient, when restoration goals are aimed at reestablishing woody vegetation.

There were no significant differences between the K_{sat} measurements taken from non-rips, rips, and cross-rips, but there was a substantial increase in variability between measurements taken in the single-rips and cross-rips compared to non-rip and pre-rip conditions. A combination of ripping effects may explain the observed pattern. First, Guelph permeameter measurements, with a saturated bulb developing beneath the 15-cm borehole, likely produced K_{sat} values within rips that also include adjacent unripped areas. As discussed above, these deeper rip-adjacent areas became more compacted, and probably less permeable, during the ripping process. Additionally, there was clear development of soil piping and incipient gullying within some ripped areas, as described by Poesen (2018). We observed that some K_{sat} boreholes seemed to penetrate soil pipes and resulted in very rapid infiltration. Reportedly, having the second ripping pass be along the contour in sloped areas, as done here, is sufficient to prevent gullying (C. Davis, CVNP, pers. comm., 2019). Cross-ripping has also been used to disrupt pre-existing soil piping (e.g., Baillie et al., 1986). Nonetheless, our observations of piping and some uncharacteristically high K_{sat} values suggest that soil piping can be at least locally significant in sloped, fine soils subjected to ripping.

Future research should include a broader range of measures of soil hydrologic function to understand the effects of ripping on water movement at the profile to site scale. Bulk density, even through a profile, is not sufficient to characterize K_{sat} across ripped sites, and additional soil hydraulic property measurements in the rooting zone, along with K_{sat} depth profiles would be useful. Field measurements of K_{sat}, soil water content, and water table elevations over time would be useful to understand the evolution of hydrologic function in ripped landscapes. Dual porosity modeling approaches may also provide new insights (e.g., Gerke and van Genuchten, 1993), because ripped sites are likely to be characterized by significant preferential flow paths (Brouwer and Van De Graaff, 1988). Our results showing the high variability of bulk density and K_{sat} emphasize the need for fine scale measurements and model representations that are cognizant of the location of rips. Samples taken at >5 cm depth intervals or without reference to rip locations would not be sufficient to characterize the heterogeneous conditions found at our mine sites (e.g., Angel et al., 2018). This heterogeneity may be a critical determinant of the success of reforestation efforts.

4.3. Implications for reforestation

The main goal of soil ripping in restoration is reforestation by providing soil conditions more conducive to tree root growth. Previous studies on soil ripping have found positive effects on tree survival when compared to compacted soils or soils where only surface tillage was completed (Burger and Evans, 2010, Angel et al. 2018, Ashby, 1997). As part of the reforestation goal of CVNP, at the two ripped sites in this study, trees were planted in the cross-rips. Cross-rips were chosen to facilitate the 3-dimensional expansion of roots into loosened soils. Although our study revealed more dense soils near the surface of cross-rip areas, the decreased soil bulk density at depth should still allow for root expansion in multiple directions along the intersecting rips, providing adequate anchoring in the soil. Below 20 cm, expansion of roots into areas between rips is still likely to be limited by bulk density. Further work should be done to measure root distribution after planting in cross-rips. Additionally, measures of bulk density in future years will indicate whether areas between rips loosen over time due to tree root expansion. The influence of ripping on preferential flow, and the subsequent potential for water stress on young trees also requires further investigation.

Previous studies assessing the influence of deep ripping on reclaimed mine soils and vegetative establishment have largely focused on sites where topsoil was emplaced during reclamation (Szota et al., 2007) and/or where there were additional treatments of the surface layer around the time of ripping (e.g., Angel et al., 2018, Batemen and Chanasyk, 2001, Ashby, 1997). Our study sites are unique in assessing the effects of reclamation and ripping on glacial parent material exposed at the surface. The absence of topsoil, soil amendments, or tillage treatments may pose challenges to tree planting success at sites that cannot be fully ameliorated by deep ripping, but our sites provide opportunities for assessing whether deep ripping alone is sufficient to allow reforestation with native trees.

5. Conclusion

The reclamation and restoration of legacy non-coal surface mines impacts soil physical properties at depths critical for tree root growth. In the present study, we examined soil physical properties indicative of successful reforestation in reclaimed surface mines with exposed glacial parent material. Deep soil ripping lowered bulk density at depth but had the opposite effect on soils near the surface. Although measurements of bulk density throughout a soil profile can be difficult to collect, our results emphasize that near-surface samples are not sufficient for determining the effect of deep ripping. Saturated hydraulic conductivity of mine soils was generally slower than nearby forest soils and increased variability after deep soil ripping. The results of this study underline the importance of soil restoration in legacy surface mines, especially when the main goal is reforestation.

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Figure 1. Mine and Reference Site Locations

Location of studied mine sites within Cuyahoga Valley National Park and with respect to other disturbed lands in the park. Mine sites are labeled with two letter codes. Reference sites indicated with circles are not to scale. Note that CT and RR are adjacent and appear as one larger site at this scale, and the reference site is to the south. Inset map shows location of Cuyahoga Valley National Park within Ohio.

Figure 2. Pre-rip Mine and Reference Site Soil Properties

Near-surface bulk density (A) and saturated hydraulic conductivity (B) at 5 mine sites with their corresponding reference sites. Letters above boxes indicate significant differences among all sites using the Holm correction in post hoc analysis ($p \leq 0.05$).

Figure 3. Pre-rip Mine Bulk Density Semivariograms

Semivariograms of pre-rip soil bulk density with associated Moran's I and p-values for each mine site. Note that the semivariogram for CT has a different y-axis scale than the other sites.

Figure 4. Profile Bulk Density Measurements

Profile bulk density at 3 mine sites (SQ, HH, and DV) and 2 forested reference sites (SQR and HHR). "Non-rip" profiles describe areas in the mine after the ripping process occurred, but in areas between rips. (A) SQR compared to pre-ripping SQ mine on both flat and slope portions. (B) HHR compared to pre-ripping HH mine. (C) DV mine rip vs non-rip. (D) SQ mine rip vs non-rip vs pre-rip on the flat. (E) SQ mine rip (running north-south) vs non-rip vs pre-rip on the slope. (F) SQ mine rip (running east-west) vs non-rip vs pre-rip on the slope. Vertical dotted gray lines (1.4 g cm^{-3}) indicate the value at which bulk density is not ideal for root growth (Daddow and Warrington 1983, NRCS nd). At DV and SQ, soils at some depths were too dense to sample. Rather than excluding these depths, we assigned them a density of 2.0 g cm^{-3}, greater than any collected sample. The connections of these data points are represented by dashed, orange lines in panels C and F.

Figure 5. Post-rip Mine Soil Properties

Near-surface bulk density (A) and saturated hydraulic conductivity (B) at Dover (red) and Snowville Quarry (blue) mines after ripping. Comparison of cross-rip, single-rip, non-rip, and pre-rip measurements. Letters above bulk density boxes indicate significant differences among sample types at both sites using the Holm correction in post hoc analysis ($p \leq 0.05$). There was no significant difference among sample types for K_{sat}.

Figure 1

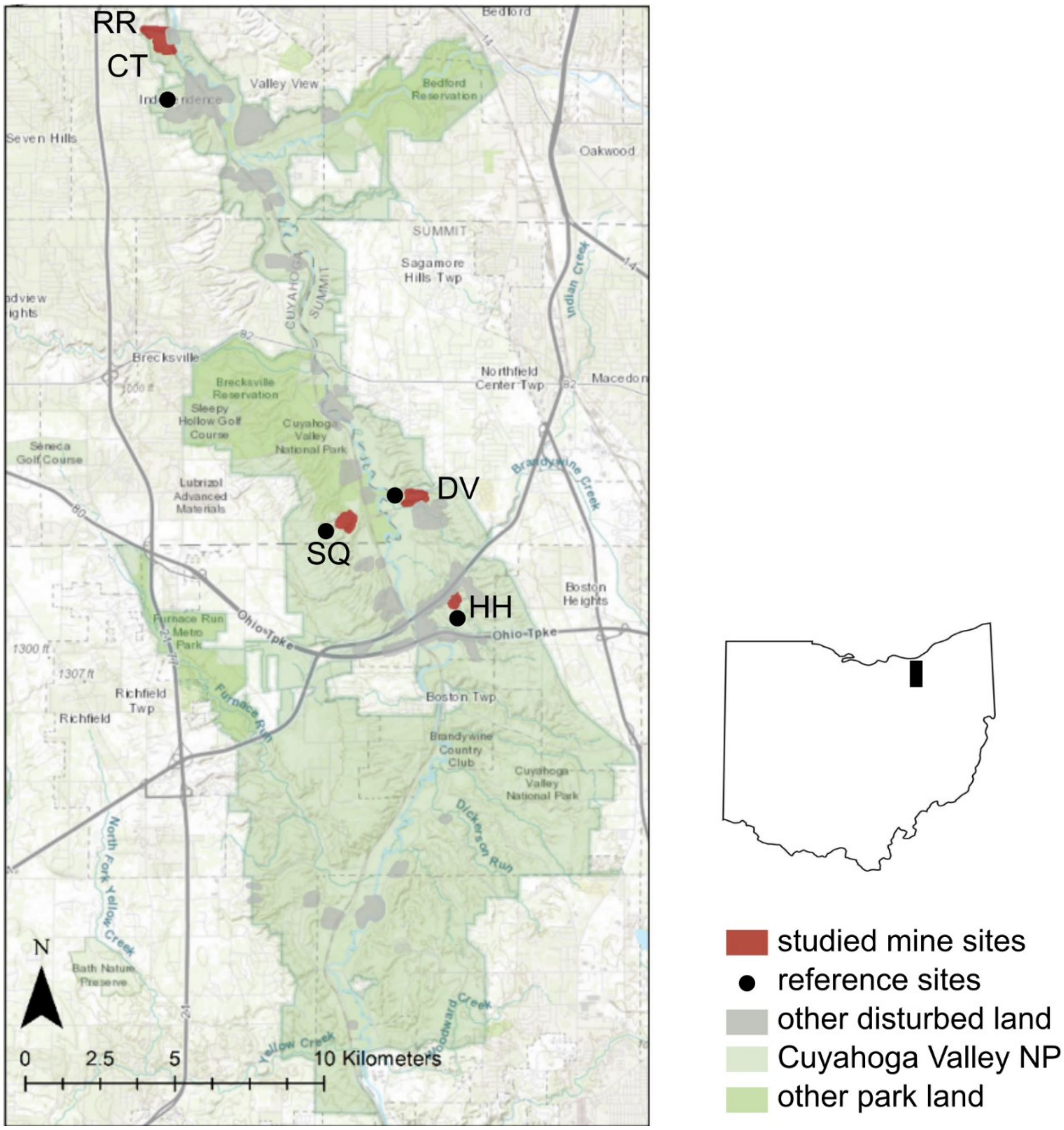

RR
CT
DV
SQ
HH
Bedford
Valley View
Bedford Reservation
Seven Hills
Oakwood
SUMMIT
Sagamore Hills Twp
CUYAHOGA
SUMMIT
Brecksville
Brecksville Reservation
Sleepy Hollow Golf Course
Cuyahoga Valley National Park
Northfield Center Twp
Macedon
Seneca Golf Course
Lubrizol Advanced Materials
Brandywine Creek
Indian Creek
Boston Heights
Ohio Tpke
Furnace Run Metro Park
Furnace Run
Richfield Twp
Richfield
Boston Twp
Brandywine Country Club
Cuyahoga Valley National Park
Dickerson Run
North Fork Yellow Creek
Bath Nature Preserve
Yellow Creek
N
0
2.5
5
10 Kilometers
studied mine sites
reference sites
other disturbed land
Cuyahoga Valley NP
other park land

Figure 2

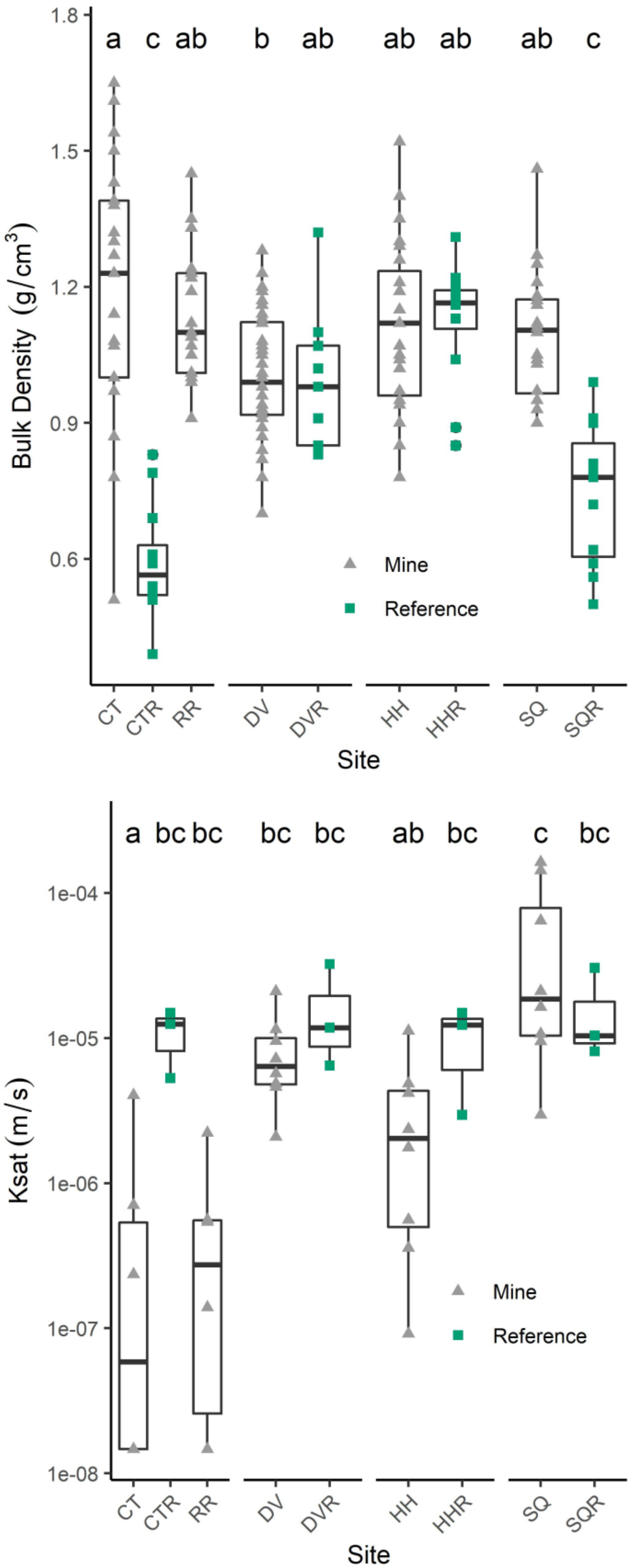
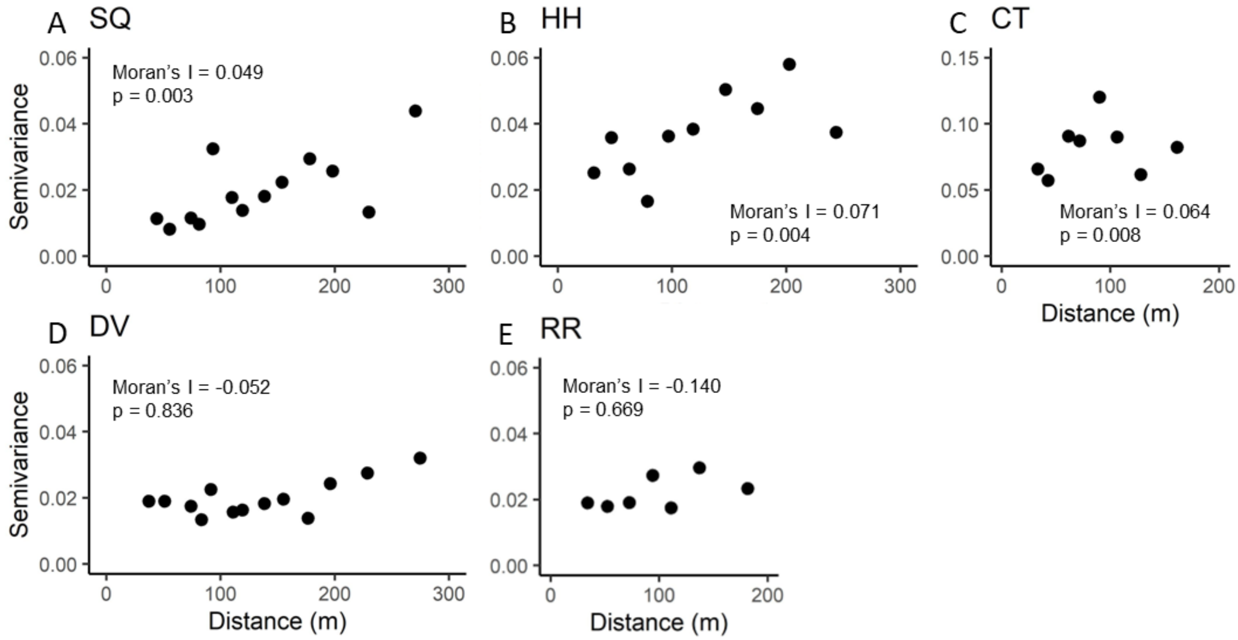

a c ab b ab ab ab ab c
1.8
1.5
1.2
0.9
0.6
Bulk Density (g/cm^3)
Mine
Reference
CT CTR RR DV DVR HH HHR SQ SQR
Site
a bc bc bc bc ab bc c bc
1e-04
1e-05
1e-06
1e-07
1e-08
Ksat (m/s)
Mine
Reference
CT CTR RR DV DVR HH HHR SQ SQR
Site

Figure 3



A SQ
Moran's I = 0.049
p = 0.003
B HH
Moran's I = 0.071
p = 0.004
C CT
Moran's I = 0.064
p = 0.008
D DV
Moran's I = -0.052
p = 0.836
E RR
Moran's I = -0.140
p = 0.669
Semivariance
Distance (m)

Figure 4

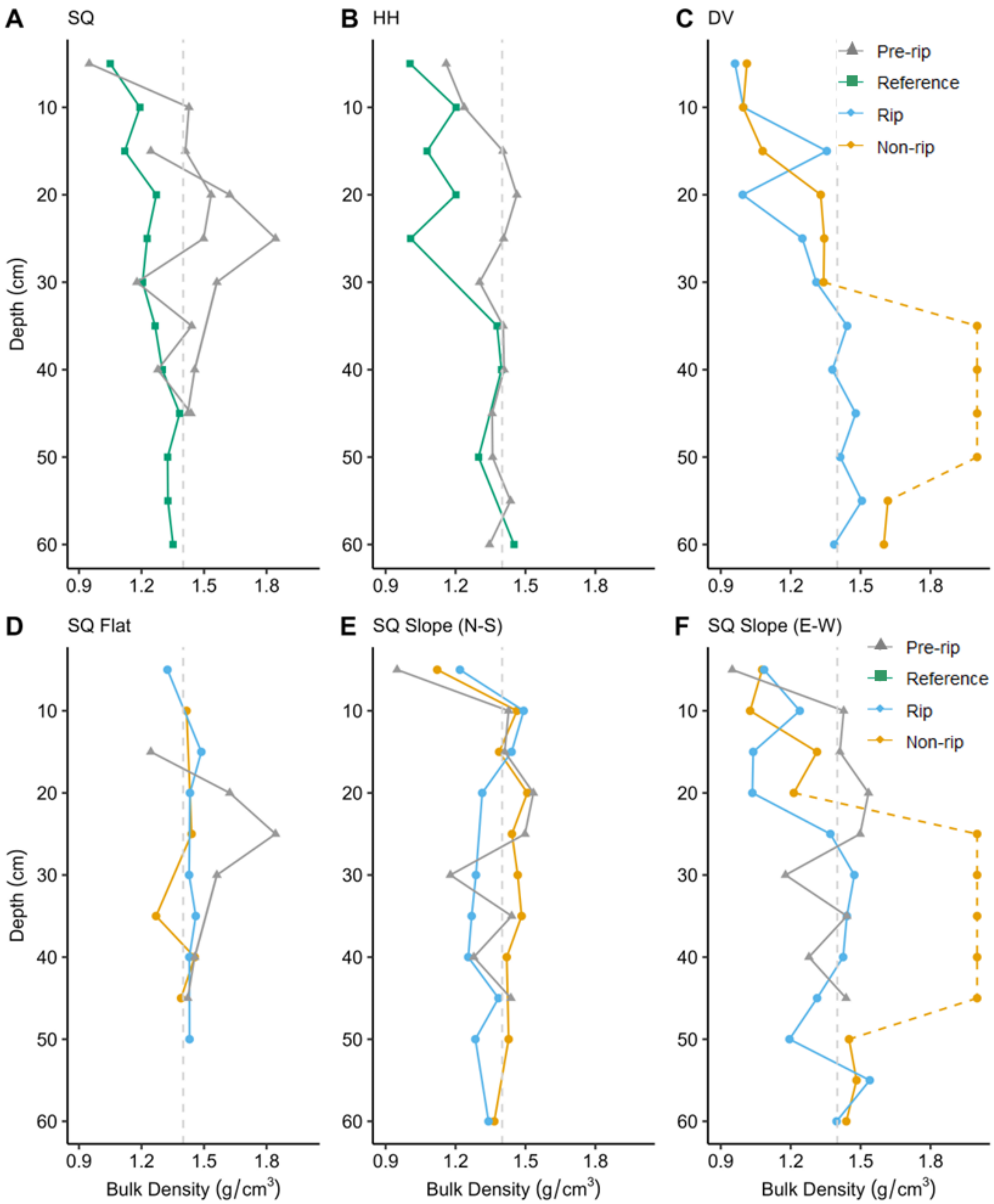
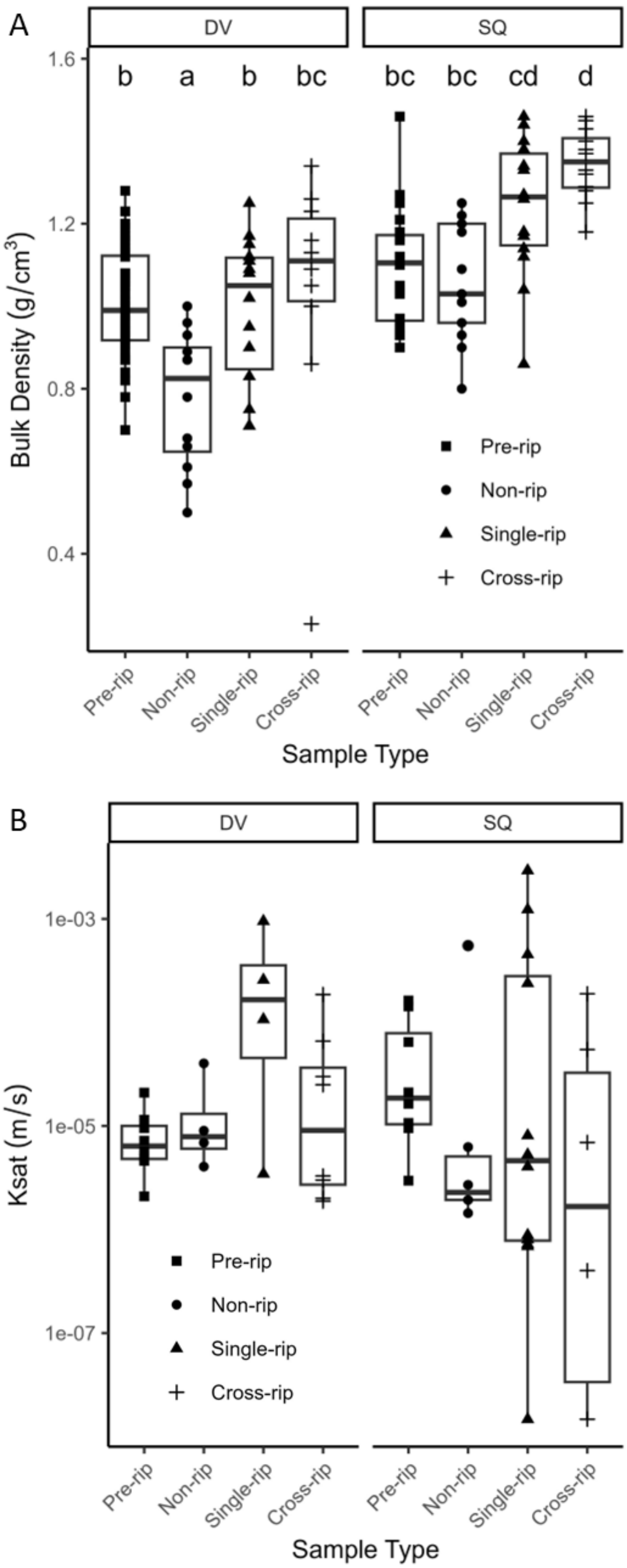

A
SQ
B
HH
C
DV
D
SQ Flat
E
SQ Slope (N-S)
F
SQ Slope (E-W)
Pre-rip
Reference
Rip
Non-rip
Depth (cm)
10
20
30
40
50
60
0.9
1.2
1.5
1.8
Bulk Density (g/cm³)

Figure 5



A
DV
SQ
b
a
b
bc
bc
bc
cd
d
1.6
1.2
0.8
0.4
Bulk Density (g/cm³)
Pre-rip
Non-rip
Single-rip
Cross-rip
Sample Type
B
DV
SQ
1e-03
1e-05
1e-07
Ksat (m/s)
Pre-rip
Non-rip
Single-rip
Cross-rip
Sample Type