Bulk Density of Rocky Mine Soils in Forestry Reclamation

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The Forestry Reclamation Approach (FRA) for reclaiming surface mined lands in Appalachia recommends minimal grading of mine soil materials to avoid surface compaction, which maintains an open and loose material for tree root expansion. To determine the level of compaction of mine soils, bulk density is measured. The traditional method of soil cores for measuring bulk density is difficult and prone to errors in rocky materials used for mine reclamation. We selected four methods (foam, frame, sand cone, and radiation) to determine bulk density at a depth of 15 cm in four mine soils and one forest soil, all having rock fragment contents > 30%. Bulk density values by sand cone were significantly lower (average of 1.35 Mg m^{-3}) than bulk densities determined by the other three methods (averages of 1.64–1.76 Mg m^{-3}). The sand cone was lower because the metal plate was sometimes not flush with the soil surface because of rock protrusions. For soils, the native forest soil showed an average bulk density across methods of 1.05 Mg m^{-3}, while the mine soils ranged from 1.70 to 1.84 Mg m^{-3}. Standard deviations for each method across soils (n = 25) ranged from 6% for radiation to 19% for the sand cone. In-field time efficiency was shortest for the radiation method at 6 min per sample, compared with 10 min for foam, 14 min for sand cone, and 27 min for the frame. The radiation method had the lowest standard deviation (better reproducibility) and better time efficiency than the other methods.

Abbreviations: ARRI, Appalachian Regional Reforestation Initiative; FRA, Forestry Reclamation Approach; SMCRA, Surface Mining Control and Reclamation Act.

Since the late 1970s and the passage of the Surface Mining Control and Reclamation Act (SMCRA), mined lands have commonly been reclaimed using smooth grading followed by the establishment of grasses and legumes (Groninger et al., 2007). Using this approach, the surface of reclaimed land is heavily compacted for soil stabilization, erosion control, and to provide a good seed bed for planting pasture and hay plant species. However, in the late 1990s landowners and coal operators began showing an increasing interest in reclaiming mined land to forest (Torbert and Burger, 2000). Even though the post-mining land use was different, the practice of heavily compacting soils has remained and heavy soil compaction has continued to be a primary reason for poor tree performance on reclaimed mine lands (Larson and Vimmerstedt, 1983; Sweigard et al., 2007). Compacted soils can lead to an increase in soil resistance to root penetration, poor aeration, slow movement of nutrients and water, and the buildup of toxic gases around the roots (Brady and Weil, 2002). One way to avoid negative effects to roots would be to limit compaction of the surface during the reclamation process.

In 2005, the United States Department of the Interior–Office of Surface Mining Reclamation and Enforcement began the Appalachian Regional Reforestation Initiative (ARRI) in conjunction with several Appalachian coal mining states. The ARRI was formed to encourage reclamation practices that would increase survival

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and growth of high value hardwood trees, and expedite the establishment of forest habitat through natural succession (Angel et al., 2005). To accomplish those goals, the FRA was adopted as a method for reclaiming mined land to forest. The FRA consists of the following five steps:

1. Create a suitable rooting medium for good tree growth that is no less than1.5 m (4 feet) deep and comprised of topsoil, weathered sandstone and/or the best available material;
2. Loosely grade the topsoil or topsoil substitute established in Step 1 to create an uncompacted growth medium;
3. Use ground covers that are compatible with growing trees;
4. Plant two types of trees: early successional species for wildlife and soil stability, and commercially valuable crop trees;
5. Use proper tree planting techniques (Burger et al., 2005).

Shallow soils in the pre-mining steep mountainous terrain of the Appalachian Coal Region make it difficult to obtain sufficient amounts of topsoil for forestry post-mining land uses or for safe topsoil removal by bulldozer operators. Thus, finding and saving suitable amounts of soil for placement on the surface as a rooting medium is dangerous, time-consuming, and expensive. Often a topsoil substitute comprised of weathered or unweathered sandstone overburden supplements any salvaged topsoil (Skousen et al., 2011). Typically, most of the weathered or unweathered topsoil substitute is coarse textured, with high levels of rock fragments and very little fine earth material. The rock fragment content in topsoil substitutes commonly ranges from 36 to 67% by weight (Emerson et al., 2009; Plass and Vogel, 1973; Showalter et al., 2010).

Step 2 of the FRA is achieved by minimizing grading of the mine soil during reclamation (Sweigard et al., 2007). Angel et al. (2006) showed that by minimizing compaction through decreased grading, the height and survival of white oak (*Quercus alba*, L.), eastern white pine (*Pinus strobus*, L.), northern red oak (*Quercus rubra*, L.), black walnut (*Juglans nigra*, L.), and yellow poplar (*Liriodendron tulipifera*, L.) were significantly greater compared with those grown in compacted mine soils. Zeleznik and Skousen (1996) found that leaving mine soil unleveled (uncompacted) increased the survival and height of white pine and yellow poplar. Understanding the relationship between compaction and tree performance is important for making management decisions. However, the ability to measure the level of compaction is critical to evaluating actual differences in tree performance in the field.

Soil compaction is evaluated in several ways. The most common way is by measuring soil bulk density. Soil bulk density is defined as the mass of a unit volume of dry soil in which both solids and pore space are included in the volume measurement (Brady and Weil, 2002). Five methods are available to determine bulk density. The first and most common way is by collecting an intact soil core of known volume (Blake and Hartge, 1986). This method is quick and accurate in agricultural soils containing no rocks. A second method for measuring bulk density is by removing large intact soil aggregates (clod method), which are dipped in saran or wax to coat the clod (Soil Survey Laboratory Staff, 1996). After drying and weighing, the coated clods are dipped in water and their volumes are determined by displacement. A third way is to excavate soil of a pre-determined area and depth, then measuring the length, width, and depth of the cavity with rulers to determine volume. This method is good when the edges of the excavated area are even and smooth. A fourth way is by excavating the soil and filling the excavated cavity with a material of known density such as sand or water, or with polyurethane foam in which the volume of the filling material can be determined (Grossman and Reinsch, 2002). This method is useful when the edges of the excavation are uneven and broken like those that result from soils containing rocks. A radiation technique using a nuclear moisture-density gauge is also a viable option for bulk density determination (American Society for Testing and Materials, 1999). However, a certified technician is required to conduct the readings due to the ^{137}Cs found in the moisture-density gauge.

To measure bulk density in rocky soils, such as mine soils, it is difficult to insert a soil core and extract the soil sample because of the presence of rock fragments. Any impedance or disturbance of the core sliding into the soil hinders the accurate measurement of soil volume because the material inside the core is often compacted or missing. The clod method only works well with soils having stable aggregates like those found in forest and fertile agricultural soils, not in organic matter-deficient soils like mine soils. Thus, one of several soil excavation techniques that allows for uneven edges is usually a better choice to determine bulk density in mine soils and other rocky soils (Childs and Flint, 1990). The objectives of this study were to determine bulk density and in-field time efficiency using three excavation methods (foam, frame, and sand cone) and one radiation method in five rocky soils.

MATERIALS AND METHODS

Study Area

This study was conducted at Catenary Coal's Samples mine (38°26′27″ N, 80°36′33″ W) near the town of Eskdale, in Kanawha County, WV (Fig. 1). We performed bulk density measurements on five soils. Four of the soils were located within a mined and reclaimed reforestation demonstration area and the fifth soil was located in an adjacent native forest (Table 1). In January 2005, Catenary Coal constructed two 2.8-ha demonstration plots consisting of weathered brown sandstone to a depth of 1.5 m and unweathered gray sandstone to a depth of 1.5 m. Plots were constructed by end-dumping the overburden material in closely adjacent piles. After dumping the soil material, one half of each plot was compacted using a D-10 Caterpillar dozer to completely cover the ground surface with tracks, while the other half was graded with only one or two passes of the same dozer to minimize compaction. The native forest soil (Dekalb [loamy-skeletal, siliceous, active, mesic Typic Dystrudepts]-

Pineville[fine-loamy, mixed, active, mesic Typic Hapludults]-Guyandotte [loamy-skeletal, mixed, active, mesic Typic Humudepts] association) was located adjacent to the demonstration plots on the permitted area.

Sampling

In July 2009 (5 yr after plot establishment), we determined bulk density of these soils with three excavation methods (foam, frame, and sand-cone) and one radiation method. Measurements were made in each soil at five randomly located sampling points. All four sampling methods were conducted close to each other (within a 4-m^2 square area) at each selected location within each soil. Five replications of each method were performed in each soil yielding a total of 100 bulk density measurements.

For the foam method, a 15-cm diam. hole was excavated to a depth of 15 cm using a hand trowel and the soil material was collected and weighed after drying. The excavated area was filled with polyurethane foam (Mueller and Hamilton, 1992). A piece of cardboard was placed over the hole to help push the foam into crevices in the hole. After curing and hardening overnight, the foam was trimmed off flush with the soil surface, carefully removed, and excess soil that adhered to the foam was brushed and picked from the surface of the foam form. The foam volume was determined by water displacement.

For the frame method, a wooden frame measuring 35 cm by 35 cm square (inside dimensions were 31.6 cm) with a plexi-glass cover plate, containing 40 evenly placed holes, was placed on the soil surface and secured with four metal rods (Grossman and Reinsch, 2002). After removal of vegetation, the distance from the plexi-glass plate to the soil surface was measured in each of the 40 holes. The plexi-glass plate was removed (the wooden frame being left in place) and the soil was excavated to a depth of 15 cm. After excavation, the plastic cover plate was replaced on the wooden frame and the distance from the plate to the bottom of the excavated area was measured in each of the 40 holes. The average difference in height between the two measurements was determined to obtain the volume measurement. The excavated soil was dried and weighed.

For the sand cone method, a metal plate was placed on the soil surface and soil was excavated from a 15-cm diam. hole in the plate to a depth of 15 cm (Blake and Hartge, 1986). The sand cone was weighed, then placed over the excavated hole and sand was allowed to fall and completely fill the excavated area. After filling the hole, the sand cone was reweighed to determine the amount of sand that had filled the hole. Volume was determined by the weight of sand divided by its density (measured sand bulk density = 1.70 Mg m^{-3}). The excavated soil was dried and weighed.

The radiation method (American Society for Testing and Materials, 1999) required contracting a private firm to conduct the soil bulk density sampling since a registered nuclear radiation technician must operate the device. The soil surface was prepared by removing any loose materials that would have prevented adequate contact between the density gauge and the soil surface. A small hole was made in the soil by pounding a 2.5-cm steel rod approximately 15 cm into the soil for the insertion of the density gauge probe. The probe (Troxler Moisture Density Gauge, Model 3430) was then placed in the hole to a depth of 15 cm and a 1-min reading was taken at each sampling point. Soil samples were collected to a 15-cm depth by the technician so density calculations could be corrected for soil moisture.

In-field time efficiency of each method was determined by measuring the amount of time it took to complete each method in the field from first breaking the soil surface with a small shovel or steel rod until all soil was excavated or the testing probe was removed from the soil.

Fig. 1. Map of West Virginia showing location of major cities in the state and the location of the Samples Mine where this research occurred.

Table 1. Soils used for bulk density determinations at a surface mine and an adjacent forest in West Virginia.†

Soil	Geology and preparation	Rock fragments	pH	EC	Ca	Mg	K
		%		dS m^{-1}	— cmolc kg^{-1} —		
1	Weathered brown sandstone-compacted	44	5.2	0.12	1.4	1.0	0.2
2	Weathered brown sandstone-uncompacted	45	4.7	0.17	1.2	1.3	0.2
3	Unweathered gray sandstone-compacted	61	7.6	0.10	1.8	1.5	0.1
4	Unweathered gray sandstone-uncompacted	63	8.3	0.11	2.7	1.4	0.1
NF	Native forest soil	31	4.5	0.06	0.2	0.1	0.1

† Data from DeLong, 2010.

Table 2. Average bulk density values and standard deviations for four methods and five soils at a surface mine in West Virginia.

Method	Bulk density
	Mg m-3
Foam	1.76 a † (0.456)
Frame	1.69 a (0.334)
Sand cone	1.35 b (0.378)
Radiation	1.64 a (0.285)
Soil‡	
1	1.76 a § (0.330)
2	1.84 a (0.211)
3	1.72 a (0.396)
4	1.70 a (0.213)
NF	1.05 b (0.162)

† Means for methods with the same letter are not significantly different at $P \leq 0.05$.

‡ Soil 1, brown sandstone-compacted; Soil 2, brown sandstone-uncompacted; Soil 3, Gray sandstone-compacted; Soil 4-gray sandstone-uncompacted; NF, native forest soil.

§ Means for soils with the same letter are not significantly different at $P \leq 0.05$.

Statistical Analysis

The study was a completely randomized design with five replications (four methods, five soils, and five replications). Statistical analyses were performed using SAS 9.1 software (SAS Institute, 2005). Using Proc GLM means statement, Least Significant Difference (LSD) tests were performed to test for differences at $P < 0.05$ in mean bulk density values and in-field time efficiency among methods and soils. Standard deviations were provided to assess reproducibility of the methods within and among soils.

RESULTS AND DISCUSSION

The four mine soils varied from 44% rock fragments for brown sandstone to 62% for gray sandstone (Table 1). The native forest soil averaged 31% rock fragments.

The foam, frame, and radiation methods produced similar bulk density results in each of the sandstone mine soils and native forest soil (Table 2). Relative standard deviations (std/mean × 100) ranged from 17% for the radiation method to 28% for the sand cone method. Chaudhuri et al. (2011) found standard deviations for sand cone bulk density measurements to be from 30 to 33% in mine soils in northern West Virginia, which deviations were similar to what we found in this study.

In this study, bulk density values determined with the sand cone method (average of 1.35 Mg m^{-3}) were significantly lower than values generated from the other three methods (range of 1.64–1.76 Mg m^{-3}). The significantly lower bulk density values for the sand cone method could have been due to the uneven ground surface of the sandstone mine soils. Uneven surfaces could hold the metal plate slightly above ground level which allows more sand to flow into the excavated area, thereby resulting in a larger volume and hence a lower bulk density value. In some of the mine soils, we noticed that rock protrusions caused the metal plate to be slightly elevated above the ground surface and efforts to push the metal plate down to make better contact with the soil surface were not always successful. This metal plate must be flush with the soil surface, and if rocks impede good contact then the plate should be moved to get better contact. Significantly lower bulk density values were found using the sand cone method in Soils 1 and 3 because of this problem (Table 3). Sand cone bulk density values in Soils 2 and 4 and the native forest soil were not significantly lower than the other methods, although there was a trend that these values were lower. Muller and Hamilton (1992) found little difference between the foam and sand cone methods when compared in two mine soils, so they must not have had problems with rock protrusions as we did in our study.

For mine soils, average bulk density values ranged from 1.70 to 1.84 Mg m^{-3}, while the forest soil average value was 1.05 Mg m^{-3} (Table 2). The bulk densities of the four mine soils and the native forest soil were comparable with other studies conducted on similar soils. Michels et al. (2007) found bulk densities of 1.60 to 1.72 Mg m^{-3} in sandstone mine soils in eastern Kentucky at a depth of 15 cm using a radiation method. Gorman et al. (2001) found bulk densities of 1.60 to 1.71 Mg m^{-3} in mine soils in northern West Virginia using the frame method. Bulk densities of 1.61 to 1.65 Mg m^{-3} were measured in mine soils of southern West Virginia using the soil clod method (Skousen et al., 1998).

The forest soil bulk density in our study was slightly lower than forest soil values reported by Page-Dumroese et al. (1999) for the foam and radiation methods in which the authors found bulk densities to be 1.10 and 1.24 Mg m^{-3} at 0 to 10 cm and 1.11 to 1.21 Mg m^{-3} at 10 to 20 cm. The Page-Dumroese et al. (1999) study found little difference in bulk density values between the foam and radiation methods in a rocky forest soil. On an older reclaimed forested site, bulk densities of 1.07 to 1.22 Mg m^{-3} were determined in the upper 15 cm using a core method (Zeleznik and Skousen, 1996).

No significant bulk density differences were found between the compacted and uncompacted sandstone mine soil treatments (Tables 1 and 2). When demonstration plots were established 5 yr before this testing, we could clearly see differences in the amount and degree of tracking done by bulldozers at the site and we assumed that this greater grad-

Table 3. Average bulk density and standard deviations for the interaction between each method and each soil on a surface mine and native forest in West Virginia.

Soil†	Methods: Foam	Frame	Sand cone	Radiation
	Mg m^{-3}			
1	1.97 a‡ (0.273)	1.92 a (0.196)	1.38 b (0.354)	1.78 ab (0.100)
2	1.88 (0.124)	1.90 (0.195)	1.76 (0.373)	1.82 (0.067)
3	2.12 a (0.204)	1.79 ab (0.104)	1.18 b (0.339)	1.78 ab (0.046)
4	1.86 (0.220)	1.74 (0.175)	1.46 (0.173)	1.74 (0.055)
NF	0.99 (0.297)	1.12 (0.081)	0.97 (0.060)	1.10 (0.069)

† Soil 1, brown sandstone-wcompacted; Soil 2, brown sandstone-uncompacted; Soil 3, Gray sandstone-compacted; Soil 4-gray sandstone-uncompacted; NF, native forest soil.

‡ Means for soils across methods with the same letter are not significantly different at $P \leq 0.05$.

ing intensity increased bulk density, although we did not measure bulk density at that time. Because of natural soil consolidation, freeze-thaw and vegetation establishment, the compaction treatment did not result in higher bulk densities in these mine soils after the fifth year. Relative standard deviations seemed to be lower for the uncompacted soils (Soils 2 and 4) at 12% compared with the compacted soils (Soils 1 and 3) at 20%.

Significantly different in-field time efficiencies were recorded for each of the four methods (Tables 4 and 5). The radiation method had the highest in-field time efficiency with an average time of 5.8 min per sample while the frame was the lowest in efficiency at 27 min per sample. Soils 1 and 2 (brown sandstones) required more time to sample than Soils 3 and 4 (gray sandstones) (Table 4), and the reasons for this difference is not clear. The gray sandstone may have required less time because it took less time to gather the slightly more abundant rocks compared with the brown sandstone mine soil. These differences were confirmed by evaluating interactions between methods and soils (Table 5).

Each method had benefits and drawbacks. The foam method in-field time efficiency was intermediate in time to conduct the initial part of the measurement (10.1 min.), but the foam had to cure for 8 h or left overnight and collected the following day. Plus, additional time was needed to excavate the foam from the soil and to brush off the soil particles. The added versatility of being able to use the foam on sloping and uneven areas was a benefit. The frame method allowed the sampling of a large volume of material that could lower the amount of error associated with rock fragments and sample size (Table 2; Vincent and Chadwick, 1994), but the larger sample required more time to collect in the field. The sand cone method averaged 14 min for each sample and the measurement was completed at one time, but it cannot be used on sloping areas. And as noted, special care should be taken on areas with high amounts of rock fragments because rocks protruding from the ground surface impede seating the metal plate flush with the soil surface to get accurate results. The radiation method needed the shortest time of the four methods and allowed a greater number of samples to be measured in a set period of time. It, however, required expensive equipment, training, and certification to conduct the method.

Table 4. Average in-field time efficiency for making bulk density measurements for four methods and five soils on a surface mine in West Virginia.

Method	In-field time efficiency
	Min.
Foam	10.2 c †
Frame	26.8 a
Sand cone	14.0 b
Radiation	5.8 d
Soil‡	**In-field time efficiency**
	Min.
1	17.2 a §
2	15.7 ab
3	12.5 c
4	11.9 c
NF	13.6 bc

† Means for methods with the same letter are not significantly different at $P \leq 0.05$.

‡ Soil 1, brown sandstone-compacted; Soil 2, brown sandstone-uncompacted; Soil 3, Gray sandstone-compacted; Soil 4-gray sandstone-uncompacted; NF, native forest soil.

§ Means for soils with the same letter are not significantly different at $P \leq 0.05$.

SUMMARY AND CONCLUSIONS

The foam, frame, and radiation methods for measuring bulk density produced similar results in the sandstone mine soils and native forest soil. Further, our values were comparable with bulk density values from other studies in rocky soils suggesting that all three methods provide accurate measurements of bulk density. Significantly lower bulk density values were recorded for the sand cone method compared with the others and the differences were due to poor contact between the metal plate and the uneven surface of the mine soils due to rock protrusions. The poor contact allowed more sand to flow into the excavated hole, giving a greater volume, and hence lowering the bulk density value. Relative standard deviations for each method ranged from 17 to 28%, indicating suitable reproducibility for these methods on these soils. The sandstone mine soils, with different compaction degrees, gave similar bulk density values of 1.70 to 1.84 $Mg\ m^{-3}$. The native forest soil had a bulk density of 1.05 $Mg\ m^{-3}$.

Each method was different for in-field time efficiency or the amount of time required to make the measurement. The frame method required almost 30 min per sample and the radiation method required about 6 min per sample. The other two methods, foam and sand cone, were intermediate and required approximately 10 to 15 min to complete.

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Table 5. Average in-field time efficiency for the interaction between each of the four methods on each of the five soils at a surface mine and native forest in West Virginia.

	Methods			
Soil†	**Foam**	**Frame**	**Sand cone**	**Radiation**
	Min./sample			
1	13.0 c‡	33.6 a	17.8 b	4.4 d
2	12.0 c	27.2 a	17.0 b	6.4 d
3	8.6 c	22.6 a	12.0 b	6.8 d
4	7.8 c	22.8 a	11.8 b	5.2 d
NF	9.6 c	27.6 a	11.2 b	6.0 d

† Soil 1, brown sandstone-compacted; Soil 2, brown sandstone-uncompacted; Soil 3, Gray sandstone-compacted; Soil 4-gray sandstone-uncompacted; NF, native forest soil.

‡ Means for each soil across methods with the same letter are not significantly different at $P \leq 0.05$.

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