RESEARCH BRIEF

An improved excavation method for measuring bulk density of rocky soil using terrestrial LiDAR

V. Polyakov, M. Nearing, M.H. Nichols, and M. Cavanaugh

Abstract: A new excavation method to estimate soil bulk density of rocky soil is presented. The method utilizes soil surface scanning with terrestrial Light Detection and Ranging (LiDAR). It allows measurement of several comparatively large volume samples at the same time. The experimental procedure also eliminates the need for scan reference points. All this contributes to low variability of measurements and decreases time in the field. The average bulk density of Luckyhill very gravely sandy loam from southern Arizona was 1.48 g cm^{-3} with standard deviation of 5.4% using LiDAR-measured volume, while a conventional excavation method yielded an average bulk density of 1.45 g cm^{-3} with standard deviation of 10.3%.

Key words: bulk density—excavation method—LiDAR—rocky soil—rangeland soils

Soil bulk density is the ratio of undisturbed dry soil mass per unit volume, where volume includes both solids and pore space. Bulk density is an important characteristic used in various aspects of soil and environmental research. Its accurate estimation is particularly critical when quantifying soil erosion and sedimentation using remote sensing techniques, such as laser scanning and photogrammetry. These techniques measure surface elevation and require conversion of volumetric changes into mass flux.

There are a number of traditional methods to determine bulk density of soils (Blake and Hartge 1986). The most common is the core method where a sample is extracted using a steel cylinder. Field measurement of bulk density in stony soils is problematic. Loose, stony soils make it almost impossible to obtain an intact core. In addition, the relatively small size of the sampler results in underestimation of bulk density in these conditions (Flint and Childs 1984). The clod method involves extraction, coating, and submergence of a natural clod to determine volume. This method only works with moist, cohesive, or organic soils (DeLong et al. 2012), and is intended specifically for clod density rather than total soil bulk density. The excavation method (Blake and Hartge 1986) includes digging a pit and determining volume of the cavity by filling it with water, sand, an inflated rubber balloon, or making a cast. An uneven surface and unstable walls of the soil pit make determining the excavated volume difficult and prone to errors. The radiation attenuation method requires handling of radioactive materials, special training, and certification, which is often impractical. It is also difficult to calibrate for nonhomogeneous media (Soane et al. 1971). A three-dimensional scanning method was tested in the laboratory (Rossi et al. 2008); however, extraction and transportation of the intact clod was still necessary. Several studies (DeLong et al. 2012; Page-Dumroese et al. 1999; Throop et al. 2012) compared core, excavation, and radiation techniques and found up to 24% statistically significant differences in bulk densities between methods.

Terrestrial Light Detection and Ranging (LiDAR) is a method that uses pulsed lasers to map the surface of remote objects (Vosselman and Maas 2010). The LiDAR instrument uses laser beam direction and travel time to calculate coordinates of the reflection. Terrestrial LiDARs provide very high resolution coverage (three-dimensional point cloud), millimeter accuracy, and collect data points at a rate in excess of 1 MHz. Today LiDARs have become increasingly common and are used by many scientists and institutions for a variety of environmental research tasks ranging from vegetation monitoring to measurement of soil erosion (Eltner and Baumgart 2015; Schmid and Hildebrand 2004; Turner et al. 2014). The goals of this experiment were (1) to test the feasibility of determining bulk density of a rocky rangeland soil using a terrestrial LiDAR scanner to measure excavated volume, and (2) compare the results to a conventional excavation method that uses water.

Materials and Methods

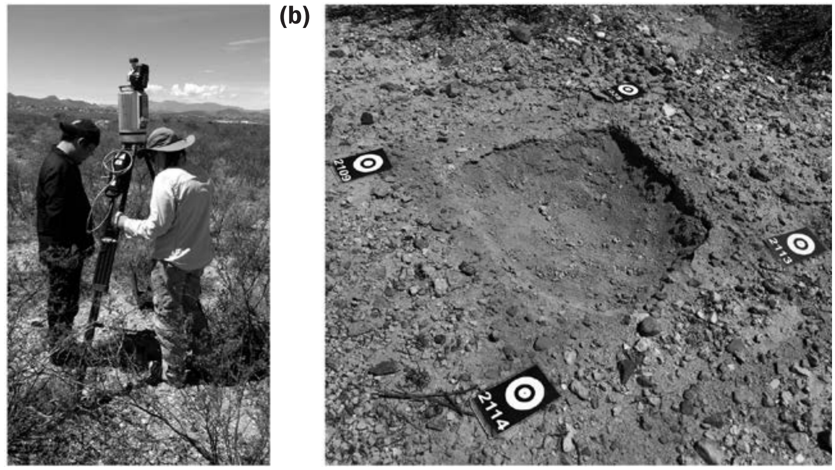
Experimental Area. The experiment was conducted in Lucky Hills area (31°44´42˝ N; 110°3´17˝ W) of USDA Agricultural Research Service Walnut Gulch Experimental Watershed located within San Pedro River basin in southeastern Arizona, United States. The climate is semiarid with annual precipitation of 290 mm and mean annual temperature of 17.7°C. Short duration, high intensity convective storms occurring in July through September account for 60% of annual rainfall. The experimental area was located on a 4% slope at 1,360 m above sea level. The soil series is Luckyhill (coarse-loamy, mixed, superactive, thermic Ustic Haplocalcids) very gravely sandy loam (USDA NRCS 2003) formed on a thick alluvial fan. It consists of approximately 69% gravel, 16% sand, 8% silt, and 7% clay. The organic carbon (C) content in the top 2.5 cm of soil ranges from 0% to 1.0%. Selective erosion processes on the site resulted in development of surface rock layer, which covers approximately two-thirds of the ground area (Nearing et al. 2007). These rocks with presumably greater density (2.7 g cm^{-3}) overlay a more cohesive soil that has lower bulk density. Vegetation is dominated by shrubs, namely creosote (*Larrea tridentata* [DC.] Coville) and whitethorn (*Acacia constricta* Benth.) with canopy cover reaching 25% during the rainy season.

Viktor Polyakov is a soil scientist at the Southwest Watershed Research Center, USDA Agricultural Research Service (ARS), Tucson, Arizona. **Mark Nearing** is a research agricultural engineer at the Southwest Watershed Research Center, USDA ARS, Tucson, Arizona. **Mary H. Nichols** is a research hydraulic engineer at the Southwest Watershed Research Center, USDA ARS, Tucson, Arizona. **Michelle Cavanaugh** is a hydrologic technician at the Southwest Watershed Research Center, USDA ARS, Tucson, Arizona.

Figure 1

Riegl VZ-400 terrestrial LiDAR scanner (a) on Lucky Hills experimental site, and (b) soil pit with reference targets.

(a) **(b)**



Experimental Procedure. Two locations with flat surfaces and patches free of vegetation were selected. A Riegl VZ-400 terrestrial LiDAR scanner (Riegl, Horn, Austria) was set up on a tripod approximately 2 m above the ground (figure 1). At each location, five sites with bare ground were selected 2 to 3 m away from the instrument. A 0.35 by 0.35 m plot was marked with spray paint at each site. Care was taken to ensure unobstructed view of each plot from the LiDAR scanner. Shrub branches were cut if necessary. First, a LiDAR scan of all five plots was conducted from one fixed position, which took approximately three minutes. The scan point spacing was 3.4 mm on average (approximately 86,500 points m^{-2}). Then, surface rocks greater than approximately 10 mm and not embedded into the soil were manually removed inside the marked perimeter. The rocks were placed into plastic bags for further analysis. A second scan of now bare (rock free) surface was conducted using the same instrument parameters.

Following the second scan, a shallow (~ 0.1 m) pit was excavated on each plot within the marked perimeter (figure 1). The wall of the pit facing the LiDAR had less than 40° slope. This ensured direct field of view of the entire excavated surface from the instrument and eliminated data shadows. The excavated soil was collected into plastic bags and later oven dried at 105°C, weighed, and passed through 2, 4, and 8 mm sieves to determine gravel size distribution. After the excavation the third and final scan was conducted. Then the entire procedure was repeated at the second location.

Because the scanner was not moved, and therefore the scan position did not change between scan sets, tie-points were not needed to align the three scans done at each of the two scan locations. In RiSCAN PRO (Riegl 2018), all data for each site were clipped to the same extent, approximately 10 cm beyond the area of excavation for each of the 10 total plots. The 10 cm band was to insure that the entire disturbed area is accounted for. All data were imported into Surfer 15 (Golden Software, LLC, Golden, Colorado, United States) for volume calculations. The data were gridded at a 4 mm spacing using the natural neighbor gridding method. A consistent X- and Y- direction minimum and maximum for the output grid geometry were set for each of the three scan sets to ensure that the grids line up without any noise along the edges. The change in volume between scan sets (i.e., loose rock surface, bare surface, and excavated surface) was determined using the Surfer Grid Volume tool.

Alternative measurements of soil bulk density were conducted prior to scanning in close proximity to the scanner setup using a more common excavation method using water as volumetric agent (Blake and Hartge 1986). A rigid wide frame lined with foam on the underside was placed on the ground cleared of surface rocks (see above), leveled, and secured in place. The frame opening was lined with plastic wrap and filled with water to a reference level indicated by a steel pin. The liner was spread such that it touched the ground avoiding air pockets underneath. The volume of water used to fill the void was recorded. Then the water and plastic were removed and a small pit approximately 300 to 500 cm^3 was dug in its place. The frame opening with pit in it was again lined with plastic wrap and filled with water to the previous level. The excavated volume was calculated as a difference between volumes of water used before and after excavation. Excavated soil was collected in plastic bag, dried, and weighed.

Results and Discussion

A total of 10 samples were obtained using LiDAR method, and 16 samples were obtained using the alternative water method. Total gravel content in the LiDAR samples varied between 57% and 74% (average 69%), and mean particle diameter of the soil was between 1.31 and 1.77 mm (average 1.45 mm). Neither of the variables was significantly correlated with the soil bulk density, probably due to small range of their values.

The average soil bulk density of the water method was 1.45 g cm^{-3} with standard deviation of 10.3% (table 1). It was slightly smaller than the LiDAR method value without surface rocks (1.48 g cm^{-3}). The difference between the mean values was not statistically significant; however, the smaller value shown by the water method might indicate the presence of air pockets between the membrane and the soil surface. The LiDAR method also reduced the standard deviation of the data (5.3%; table 1 and figure 2). In addition, the total range of values decreased more than twofold from 0.65 to 0.27 g cm^{-3}.

The decrease of variability could be attributed to the mass of LiDAR samples being on average larger (7,714 g) than the water method (434 g). When analyzing heterogeneous media, such as very gravely soils, greater sample size could be beneficial (Starr et al. 1995). In addition, measurement of pit volumes with LiDAR was conducted several at a time, providing consistency and leaving less room for human error. When performing volume measurements using water, 20% of samples were lost due to membrane failure or other mistakes.

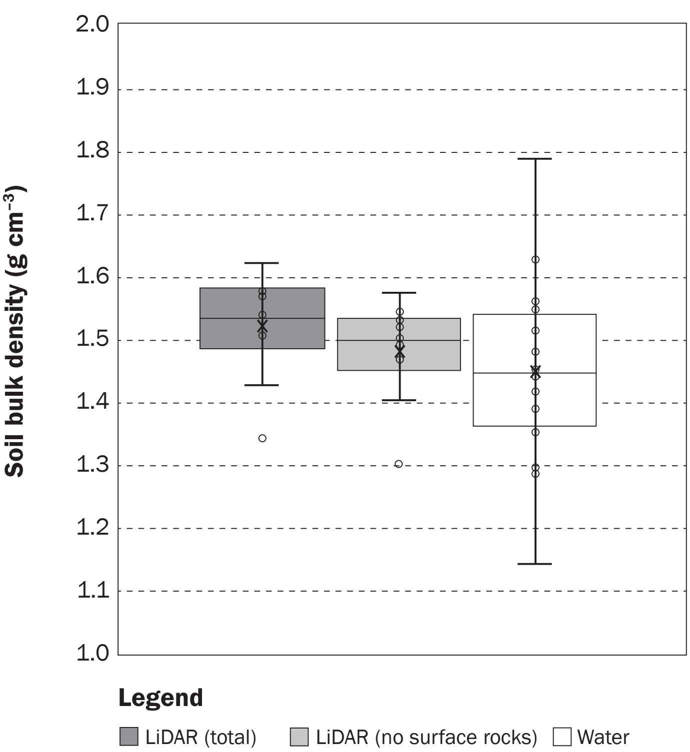
The bulk density of soil with surface rock layer (1.52 g cm^{-3}) was greater than without, as expected. Bulk density of surface rocks alone was overestimated and varied greatly from sample to sample. It appears that a single scan position and the current scan density

Table 1
Comparative statistics of two bulk density measurement methods.

	Volume measurement method		
Statistic	**LiDAR (total)**	**LiDAR (no surface rocks)**	**Water displacement**
Mean (g cm^{-3})	1.52*	1.48*	1.45*
Standard deviation (%)	5.4	5.3	10.3
Range (g cm^{-3})	0.28	0.27	0.65
Samples (*n*)	10	10	16
Average sample (g)	7,971	7,714	434

*There was no statistically significant difference between mean values at p = 0.95.

Figure 2
Distribution of soil bulk density values based on two measurement methods.



were inadequate to accurately interpolate the irregular surface of loose rocks. The overall profile was indeed heterogeneous from the bulk density perspective with denser rocks overlaying the bulk of soil. When conducting an experiment, one needs to decide which bulk density value (total, including rocks, or soil only) is relevant for a particular situation.

Summary and Conclusions

Terrestrial LiDAR can be used as a reliable tool for quantifying bulk density of noncohesive gravely arid soils. Traditional methods (Blake and Hartge 1986) are difficult to implement in this environment. Our experiment showed a slightly larger average bulk density and smaller variability of the LiDAR-based data than those obtained from a water-based method. Partially this is due to larger samples, which is beneficial when dealing with heterogeneous media. The LiDAR method is not limited by sample volume and could be used to incrementally measure bulk density of individual soil horizons if necessary. With the standard water method, it becomes impractical to use volumes greater than approximately 500 mL. In addition, lining the pit surface with a membrane while avoiding air pockets is a tedious and error-prone task.

While more computationally complex, the LiDAR method requires less time in the field, which can be desirable in certain climates. Multiple soil pits of virtually any size can be scanned in a single sweep from one position in a matter of minutes. Terrestrial LiDAR scanners are costly and require a skilled operator. However, today they have become increasingly common among research groups and institutions. This experiment demonstrates a good opportunity to expand the scientific tool kit using existing instrumentation. Finding optimal size and geometry of soil pit, number of samples, and their spatial distribution to best characterize the site would be a good topics for future testing.

References

Blake, G.R., and K.H. Hartge. 1986. Bulk density. *In* Methods of Soil Analysis. Part 1. Physical and mineralogical methods, ed. A. Klute, 363-375. Madison, WI: Soil Science Society of America.

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

Eltner, A., and P. Baumgart. 2015. Accuracy constraints of terrestrial LiDAR data for soil erosion measurement: Application to a Mediterranean field plot. Geomorphology 245:243-254, doi:10.1016/j.geomorph.2015.06.008.

Flint, A.L., and S. Childs. 1984. Delelopment and calibration of an irregular hole bulk density sampler. Soil Science Society of America Journal 48:374-378, doi:10.2136/sssaj1984.03615995004800020030x.

Nearing, M.A., M.H. Nichols, J.J. Stone, K.G. Renard, and J.R. Simanton. 2007. Sediment yields from unit-source semiarid watersheds at Walnut Gulch. Water Resources Research 43:W06426, doi:06410.01029/02006WR005692.

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

Riegl. 2018. RiSCAN PRO 2.0, Companoin Software to 3D Terrestrial Scanners. Horn, Austria: Riegl. http://www.riegl.com/products/software-packages/riscan-pro/.

Rossi, A.M., D.R. Hirmas, R.C. Graham, and P.D. Sternberg. 2008. Bulk density determination by automated three-dimensional laser scanning. Soil Science Society of America Journal 72:1591-1593, doi:10.2136/sssaj2008.0072N.

Schmid, T., and E. Hildebrand. 2004. A case study of terrestrial laser scanning in erosion research: Calculation of roughness and volume balance at a logged forest site.

International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences XXXVI-8/W2:114-118.

Soane, B.D., D.J. Campbell, and S.M. Herkes. 1971. Hand-held gamma-ray transmission equipment for measurment of bulk density of field soils. Journal of Agricultural Engineering Research 16:146-156, doi:10.1016/s0021-8634(71)80029-x.

Starr, J.L., T.B. Parkin, and J.J. Meisinger. 1995. Influence of sample siza on chemical and physical soil measurements. Soil Science Society of America Journal 59:713-719, doi:10.2136/sssaj1995.03615995005900030012x.

Throop, H.L., S.R. Archer, H.C. Monger, and S. Waltman. 2012. When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. Journal of Arid Environments 77:66-71, doi:10.1016/j.jaridenv.2011.08.020.

Turner, R.M., R. Panciera, M.A. Tanase, K. Lowell, J.M. Hacker, and J.P. Walker. 2014. Estimation of soil surface roughness of agricultural soils using airborne LiDAR. Remote Sensing of Environment 140:107-117, doi:10.1016/j.rse.2013.08.030.

USDA NRCS (Natural Resources Conservation Service). 2003. Soil Survey of Cochise County, Arizona, Douglas-Tombstone Part. Washington, DC: USDA Natural Resources Conservation Service.

Vosselman, G., and H.-G. Maas. 2010. Airborne and Terrestrial Laser Scanning. Caithness, Scotland: Whittles Publishing.