Correction of Bulk Density and Sampling Method Biases Using Soil Mass per Unit Area

Stewart B. Wuest*
USDA-ARS
Columbia Plateau Conserv. Research Center
PO Box 370
Pendleton, OR 97801

This study compared linear depth from the soil surface vs. equivalent sample mass for interpreting soil water content and concentration data. Our first experiment sampled soils that differed only in surface bulk density. A second experiment compared different soil sampling tools. In both cases, analysis by mass instead of depth corrected water content discrepancies caused by bulk density or sample compaction differences. In a third experiment, samples collected from an on-farm test resulted in many significant differences in soil moisture between tillage practices for linear depth data that did not exist when analyzed using equivalent sample mass. When it is important to avoid confounding bulk density, depth from the surface, or sampling method with quantitative measurements, sampling by mass instead of volume is more accurate and precise than many quantitative methods currently in use, and represents an important advance in our ability to make comparative measurements across time, treatments, locations, and equipment.

Most soil sampling techniques use distance from the soil surface as a primary metric. The soil surface, however, is a reliable datum only for measurement of concentration characteristics directly related to distance from the soil surface at the time of sampling. Examples might be soil temperature or water potential 10 cm below the current soil surface. Most quantitative or comparative measurements can suffer appreciable inaccuracies when using the soil surface as a datum due to the dynamic nature of surface bulk density and the resultant fluctuations in distance between the surface and features lower in the soil profile (VandenBygaart and Kay, 2004). In addition, different soil conditions, sampling equipment, or techniques can cause unintended biases in depth measurements, which may affect the accuracy of comparisons among data collected by different persons or at different times.

Many research efforts would benefit from improved sampling methods. Recent concern over the effects of small changes in soil C has prompted researchers to evaluate the accuracy of methods for quantifying soil constituents with time and across diverse soils and soil management conditions (VandenBygaart and Angers, 2006). In dryland cropping regions, seed-zone soil water content is vital to the success of crop establishment. Evaluation of soil management effects on moisture involves comparison of soils with different surface bulk densities. In addition, the bulk densities change with time.

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*Corresponding author (stewart.wuest@ars.usda.gov).

The fixed or equivalent mass method of soil sampling exchanges measurement of depth from the soil surface for measurement of the mass of soil per unit area (Smith et al., 2000). Adjusting each sample to the equivalent dry soil mass eliminates sensitivity to bulk density (McGarry and Malafant, 1987; Ellert and Bettany, 1995). Tests for accuracy in recovering added C demonstrated the benefits of the equivalent mass concept (Ellert et al. 2002), and reevaluation of older data demonstrated significant reinterpretation of depth-based studies when bulk density differences were removed as a factor (Gal et al., 2007).

Fluctuations in bulk density cause fluctuations in the elevation of the soil surface, and, as a result, the point in the soil profile to which soil is collected. This causes direct fluctuations in the total amount of a substance removed with the sample. This means that a sample removed to a certain depth at a time when bulk density is greater will sample more soil and to a greater depth than when the soil has a lower bulk density, even if the only bulk density changes are at the surface. This will cause a difference in the estimate of the total amount of a soil constituent contained in that soil to a fixed depth, varying in direct relation to the bulk density at the time of sampling. As in the choice of linear depths, the choice of the mass increments to use for data analysis is mostly arbitrary and will probably be based on rough equivalence to customary linear depth increments.

This bulk density influence on sampling depth might not seem to affect estimates where the goal is to compare the concentrations of soil constituents instead of total quantities. For any soil constituent that changes in concentration with depth, however, small differences in sampling depth can cause dilution or concentration of a constituent. This means that the influence of bulk density on sampling depth can produce a measurement bias even when concentration rather than quantitative results are desired.

This study compared the equivalent mass technique to linear depth for (i) making near-surface soil water measurements under conditions of varying bulk density, and (ii) reconciling artifacts caused by the use of different sampling equipment.

MATERIALS AND METHODS

The accuracy of depth-based and equivalent mass methods for comparing soil samples with identical soil moisture quantities but different surface bulk densities was tested on a Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll, with about 0.40 kg kg^{-1} sand, 0.54 kg kg^{-1} silt, and 0.06 kg kg^{-1} clay in the Ap horizon). The soil at the site was loosened by rototilling, which produced low soil bulk densities to depths of 16 to 19 cm. Soil samples were collected using a sample tube made from 51-mm o.d., 46-mm i.d. steel tubing, the bottom end of which had been hammered to reduce the opening to 44.8-mm inner diameter. The cutting edge was then sharpened without disturbing the 44.8-mm opening. Samples were collected in 14 pairs, one sample of each pair from the tilled soil, and the other within 30 cm of the first, but after gently and uniformly compacting the tilled soil with a 10-kg, 20-cm-diameter weight. The loose soil settled as the tubes were driven into the ground using a mallet, and the difference between the soil surface inside the tube and the original soil surface outside the tube was measured. Samples were divided into depth increments using the resulting surface of the soil core after sampling. The cores were divided into increments of 0 to 3 and 3 to 15 cm in 2-cm increments, and 15 to 30 cm in 5-cm increments. The core was divided with the aid of an electric sampler (Wuest and Schillinger, 2008), which holds the sample tube vertical and pushes the soil out the top in predetermined increments. For the soils tested to date, the 1.2 mm of clearance between the diameter of the soil core and the inner wall of the sample tube has been enough to allow the soil core to be pushed out of the tube without compression, but not so much as to allow loose soil to fall within the tube. Individual soil samples were weighed, dried, and reweighed to determine gravimetric soil moisture on a dry-weight basis. To analyze the data, the weight of soil water in each sample was successively summed from the surface downward to give cumulative soil water, and the same was done for dry soil mass.

To check the potential effect of substituting equivalent mass for depth in interpreting tillage treatment differences, soil water samples were collected in an on-farm test comparing several tillage methods for summer fallow. Four treatments (chiseling followed by rod-weeding, undercutter sweep followed by rod-weeding, undercutting alone, and no tillage) were compared in four replications on plots using commercial-sized equipment. Soil samples were collected, one from each plot, using the same tools and increments as in the first experiment described above.

To test the equivalent mass technique for comparisons among data from different soil sampling equipment, a set of 12 samples was collected from a no-till summer fallow field (Shano silt loam, a coarse-silty, mixed, superactive, mesic Xeric Haplocambid). Six samples were collected as described above, and another six using a square-tube incremental sampler designed by Pikul et al. (1979). The sampling tube of the electric sampler took cores with a cross-section of 15.71 cm^2, and the square-tube core cross-sections were 40.1 cm^2. Other differences included the amount of force required to drive the tubes into the ground, and the variance of bulk density determinations (Wuest and Schillinger, 2008). Samples were collected to 26-cm depth in 2-cm increments and then weighed and oven dried for gravimetric moisture content and oven-dry soil mass.

To adjust data to equivalent mass-depths, a dry soil mass per unit area was selected and water content data from each sample core adjusted by linear interpolation between the two nearest data points. Results of analysis of variance for each depth are presented as $p > F$, or designated as not statistically significant when >0.20.

RESULTS

In the first test, analysis of the amount of water in compacted and uncompacted sampling sites using linear depth from the soil surface indicates that more water was present in the compacted sites (Fig. 1). This could be interpreted as a soil water difference of about 1.4 kg m^{-2} in the top 30 cm (the horizontal distance between the two curves). Knowing there was no real difference in water content independent of bulk density differences, a better interpretation is that the two curves represent about 0.8 cm difference in the depth of sampling (the approximate vertical distance between the two curves). The lower graph in Fig. 1 is based on the mass of soil instead of the depth of the soil, and is therefore independent of soil bulk density. Compacted samples had slightly greater cumulative soil mass per unit volume or per fixed depth increment, but this does not distort a quantitative comparison between the two treatments at any mass-based location in the profile.

Average sample settling, measured after driving the sample tube but before pulling it from the ground, was 5.1 cm for

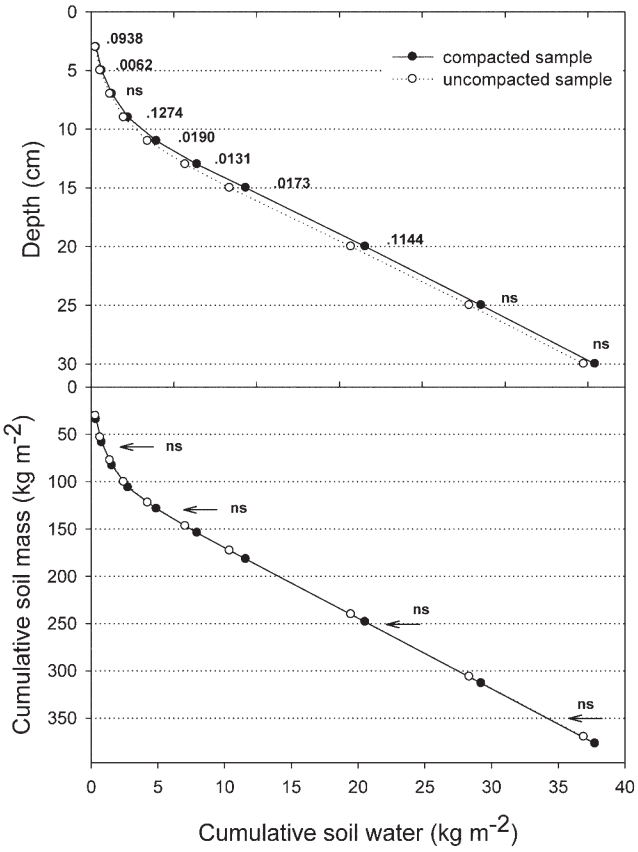

Fig. 1. Comparison of quantifying water contents by depth vs. by mass per unit area. Fourteen pairs of samples were collected from tilled soil. One sample was collected immediately after compacting the soil, the other in a nearby uncompacted area. The compacted samples show an average increase of depth of sampling of 0.8 cm (the vertical displacement needed to match the lines). Plotting by the mass of each sample instead of depth corrects the discrepancy. Probabilities of a greater *F* from analysis of variance at each depth are indicated, and also for water contents at example equivalent mass-depths; ns = not statistically significant.

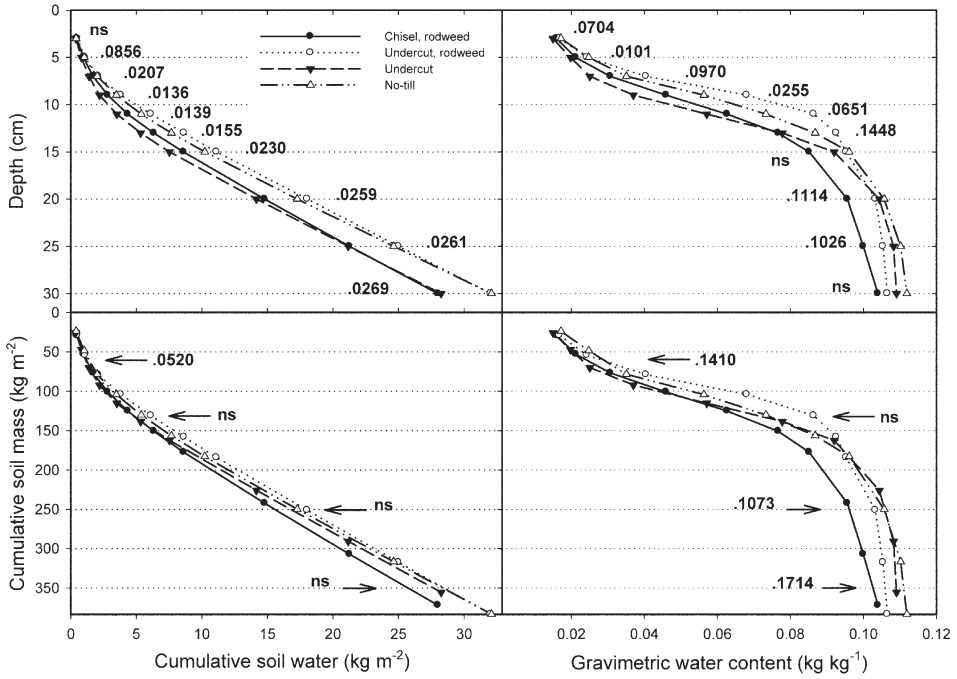

Fig. 2. Data demonstrating a difference in interpretation when using depth from the soil surface vs. soil mass per unit area. In the depth-based upper graphs, the undercut tillage treatment (solid triangle) appears to have the least cumulative soil water to the 20-cm depth and the lowest gravimetric water concentration to the 12-cm depth, but in equal mass per unit area, the undercut treatment is never substantially lower in cumulative water and only slightly lower in gravimetric water content between 50 and 100 kg m^{-2} soil mass. Probabilities of a greater *F* from analysis of variance at each depth are indicated, and also for water contents at example equivalent mass-depths; ns = not statistically significant.

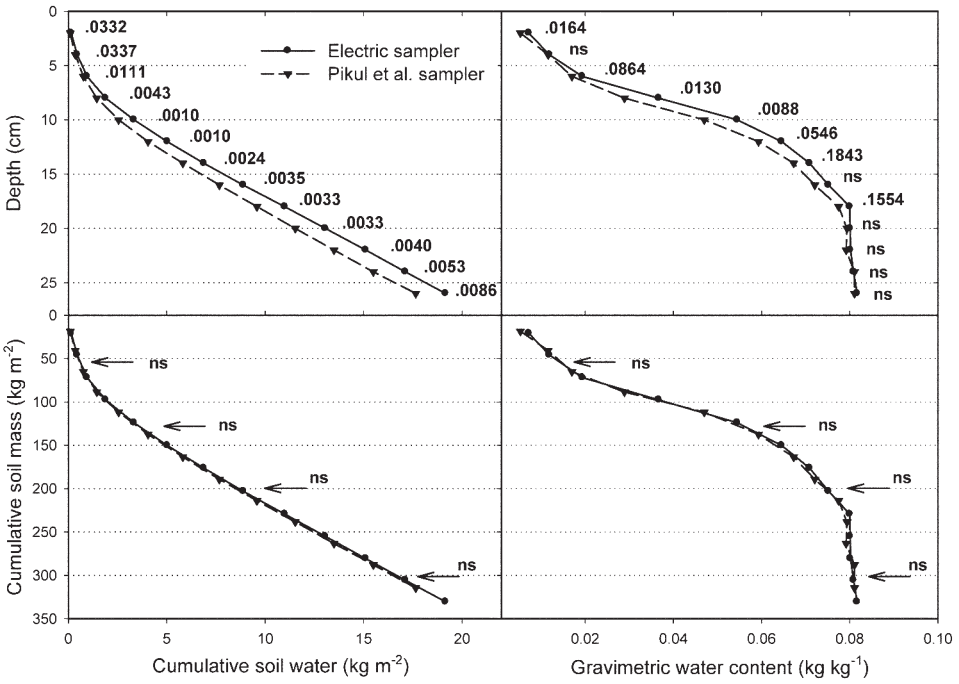

Fig. 3. Data from 12 cores from a no-till fallow field, six using a 15.71-cm^2 cross-section sample tube and an electric incremental sampler, and six using a 40.1-cm^2 cross-section square tube and incremented according to Pikul et al. (1979). Graphs on the left are cumulative soil water (moving down the soil profile) of samples plotted against sample depth and cumulative soil mass. On the right, gravimetric water concentrations are shown, again by depth and mass. Probabilities of a greater *F* from analysis of variance at each depth are indicated, and also for water contents at example equivalent mass-depths; ns = not statistically significant.

uncompacted and 2.4 cm for compacted samples. As might be expected, samples from uncompacted locations settled more while driving the tubes than samples from compacted locations. This disturbance of the cores during sampling was disregarded in measuring depth increments. If sampling had been performed with greater care to preserve the original bulk density of the cores (using a larger diameter tube with thinner walls, for example), then the depth-based differences demonstrated in Fig. 1 would have been even greater.

In the on-farm comparison of the effect of tillage methods on water loss during summer fallow, analyzing data by mass vs. depth resulted in differences in estimates of the quantity and concentration of soil water (Fig. 2). Cumulative water content by depth indicates two distinct groupings of treatments, but analysis by mass shows that these are mostly due to the surface bulk density and the depth of sampling. Even gravimetric water content, a concentration comparison, is substantially different when analyzed by mass vs. by depth.

Closely paired soil samples using different sampling equipment (Fig. 3) resulted in substantial differences in both quantitative water content and gravimetric water concentration when analyzed by depth increments. When analyzed in equal mass per unit area instead of depth from the surface, the two techniques were in very close agreement.

DISCUSSION

During periods of water loss to evaporation, soil water concentration tends to increase with depth. When sampling using the soil surface as a datum, the soil bulk density of the surface influences quantitative estimates of the soil water content regardless of sample depth. In studies of methods for soil C quantification, deeper samples (>30 cm) were found to give quite different conclusions from samples to 20 or 30 cm (Baker et al., 2007; VandenBygaart et al., 2003). This was because the deep C profiles dif-

fered between the treatments of interest. Even if a soil constituent becomes quite uniform at depth, deeper sampling will not completely overcome a bias caused by bulk density variations and the resultant change in soil surface elevation. The exception would be where the constituent is universally absent at lower depths.

Accurate determination of elevation using surveyors' methods has been proposed as the most accurate way to make quantitative measurements in situations where appreciable additions or subtractions to a site may occur due to erosion, deposition, or soil amendments (Chang et al., 2007). This is probably true, assuming that management has appreciably changed the soil mass and that a reference elevation can be found that takes into account local elevation differences inherent in the prevailing topography and uplift and subsidence issues. Where side-by-side comparisons are needed, or additions and subtractions to soil mass are not issues, sampling by mass instead of depth is probably the most accurate and simplest method available to avoid confounding with bulk density fluctuations.

Equivalent soil mass is not more difficult than traditional methods for quantifying soil constituents. Many researchers already routinely collect the necessary information to analyze their samples using equivalent mass. If the samples are taken using constant horizontal cross-sectional area, the additional information needed is the dry mass of each sample. Precision of the equivalent soil mass method is determined by the precision of the dry soil mass determination and concentration analysis of each sample. In the case of gravimetric water analysis, accurate balances and careful drying are all that is necessary. Soil swelling due to high moisture content (McGarry and Malafant, 1987), fractured cores, or settling or compaction of cores in the sample tube do not affect precision. Precise core length or depth determinations are not essential to the accuracy of equivalent mass determinations, which is a distinct advantage given the difficulty in measuring or verifying exact lengths, depths, or volumes of soil samples.

Absolute accuracy of soil constituent mass per unit area will depend on careful determination of the sample cross-sectional area, as this will be critical in converting to standard units such as kilograms per square meter or megagrams per hectare. Most soil bulk density measurement methods also require accurate determination of cross-sectional area, plus accurate length of the undisturbed core. The equivalent mass technique should therefore be more accurate than quantification of soil constituents based on bulk density measurements since it does not rely on the more difficult measurement of undisturbed core length. Unbiased soil bulk density measurement is difficult if not impossible, and different methods often give different results (Grossman and Reinsch, 2002).

In this study, soil cores were sectioned into small depth increments, which clearly described changes in mass with increasing soil depth. If only total quantities of a soil constituent to a standard mass-based depth are needed, the number of depth increments can be minimized. Gifford and Roderick (2003) suggested that two increments are all that is necessary to define the section of curve required to interpolate to the desired equivalent soil mass. For example, the upper increment defines the quantity of water or C down to a point slightly above the expected sampling depth necessary to accumulate the target dry soil mass. A second increment defines cumulative water or C to a point slightly below the target. After determination of the dry mass of each sample, interpolation between the two points is used to mathematically correct each soil sample to a predetermined soil mass in common with all samples intended for comparison. While this technique is technically correct and might be recommended as a minimum standard for regional or temporal comparisons, the small effort required to collect depth information for each sample is highly recommended because depth and bulk density estimates are often very useful in interpreting results and explaining changes with time.

Except for the case where the soil constituent has a limited and known location that can be entirely sampled, none of the methods discussed here overcome the methodological problem of uneven soil surfaces. A prime example is the condition of a tilled field where furrows and ridges are produced, but the same problem exists for any rough or cloddy surface. Differences between the thickness of the surface soil on ridges and in furrows will result in differences in the amount of surface vs. subsurface soil sampled, even if equivalent soil masses are analyzed. It may be best to level sample areas to produce an average soil surface. Since equivalent mass analysis is not sensitive to bulk density, soil disturbance does not change the results. Leveling the surface may be more accurate than attempting to estimate the average soil surface by calculating the various depths and bulk densities represented by the ridges and furrows.

Some disadvantages of the mass sampling method include the requirement for additional depth increments to be collected and analyzed as described above. This is an added expense. Estimates of bulk density are desirable if a target mass is to be matched in an unfamiliar soil. Also, in many cases variation in bulk density will be minor and differences between mass-based and linear depth-based results will be insignificant. Obviously, a great deal of research progress in soil science has been made based on linear depth from the soil surface at the time of sampling, with bulk density being treated as an independent measurement. The recent interest in mass-based sampling is driven by the need for unbiased, accurate, repeatable, near-surface soil C measurements. This study proves it is also very effective for soil water profile comparisons.

CONCLUSIONS

Equivalent soil mass (mass-depth) instead of linear depth can be used to correct for differences in soil bulk density, allowing more precise and accurate quantitative comparisons of soil constituents. It is also capable of correcting for artifacts due to differences in sampling equipment and sampling conditions, which is important for comparison of research conducted across different times, locations, soil conditions, and by different researchers.

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