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Precision, Accuracy, and Efficiency of Four Tools for Measuring Soil Bulk Density or Strength

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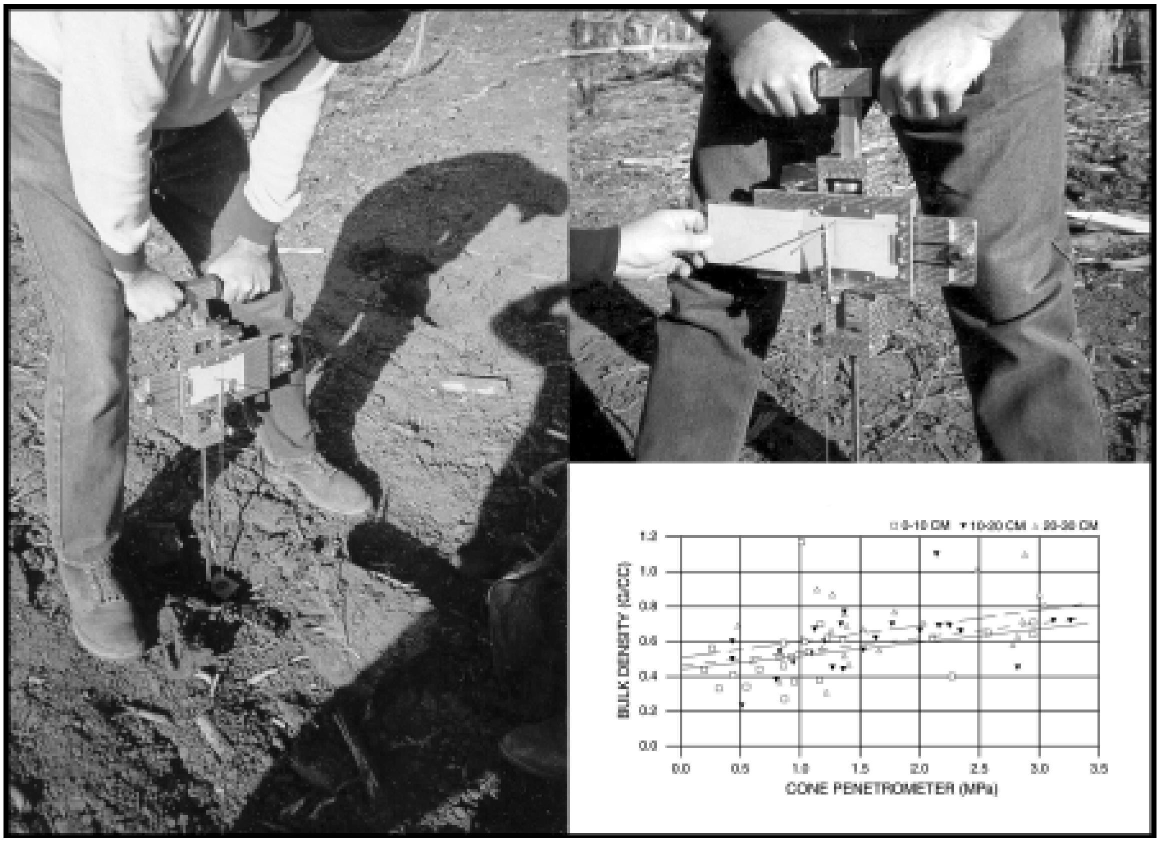

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Abstract

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Monitoring soil compaction is time consuming. A desire for speed and lower costs, however, must be balanced with the appropriate precision and accuracy required of the monitoring task. We compared three core samplers and a cone penetrometer for measuring soil compaction after clearcut harvest on a stone-free and a stony soil. Precision (i.e., consistency) of each tool at depths of 0-10, 10-20, and 20-30 cm was determined from two adjacent samples at 21 or more sampling points in each harvested location. Because one bulk density (D_b) sampler provided a continuous sample of each decimeter depth, it was designated as the standard; thereby, the relative accuracy and bias of the two shorter core samplers could be calculated. Both shorter samplers overestimated D_b as determined by the standard. At least 15 penetrometer samples could be taken and processed in the time required for three D_b samples to the same 30-cm depth. Precision of measurements taken by the cone penetrometer, however, was clearly less than that with any of the D_b samplers. Based on time requirements and precision of each tool, we examined the efficiency of double sampling (using a combination of penetrometer and core sampler) for estimating D_b. Results from the stone-free soil indicated an advantage in both precision and efficiency in applying double-sampling theory to estimate D_b rather than sampling exclusively by the more time-consuming core samplers.

Keywords: Bulk density, measurement precision, relative accuracy, cone penetrometer, soil strength.

Summary

Soil bulk density (D_b) is the ratio of mass of dry solids to bulk volume of soil. Bulk density, expressed as $Mg\bullet m^{-3}$ or $g\bullet cc^{-1}$, is commonly used to measure soil compaction. An increase in D_b indicates that movement of air and water within the soil has been reduced, and that the soil may be less favorable for plant growth or be more likely to erode. Soil compaction also can be indicated by a penetrometer (PEN), a device forced into the soil to measure its resistance to vertical penetration. Soil strength, as measured in kPa by a PEN, is related crudely to soil resistance as encountered by roots. Because PEN readings can be strongly dependent on soil moisture content, field sampling for comparative purposes should be done when soils are near field capacity.

Our general objective was to compare precision and efficiency of four tools conventionally used to monitor soil compaction. We compared three bulk density samplers and a cone penetrometer for measuring soil compaction over a range of sampling conditions in two young forests. Both stands had been planted after clearcutting and yarding by crawler tractors (D-8) in winter on wet silt loam soils. Both study locations were sampled during the spring rainy season; therefore, soils were probably at or near field capacity. Sampling points for each tool were assigned by subdividing each potential sampling plot, a 25- x 100-cm rectangle, into four equal-sized squares and randomly allocating a tool to each square. Two subsamples (replications) were taken within each square. Precision (i.e., consistency) of each tool was determined from two adjacent subsamples at depths of 0-10, 10-20, and 20-30 cm at 21 or more sampling points in each plantation.

Our PEN provided a continuous plotting of soil strength and soil depth to 40 or more cm unless impenetrable stone or wood was encountered. Bulk density sampling was restricted to the A-horizon of both soils. With the continuous volumetric sampler, the sampling tube was inserted and the soil was extracted sequentially at 10 cm-depth intervals

to 30 cm; each interval corresponded to a 100-cc sample. The extractor was re-inserted repeatedly to ensure complete removal of the soil for each depth interval. Because cores extracted by the two noncontinuous samplers were less than 10 cm long, samples were centered within each 10-cm-depth interval. We recorded the total time required to obtain each successful sample (including unsuccessful attempts) and to clean, sharpen, or adjust equipment in the field. Our three D_b samplers differed in length, diameter, and volume. Because one D_b sampler provided a continuous sample of each decimeter depth, it was designated as the standard; thereby, the relative accuracy and bias of the two shorter core samplers could be calculated.

Bulk density and resistance to penetration both increased with depth at both locations. In each decimeter depth, the continuous volumetric sampler (BD100) yielded the lowest D_b values, while the shortest and smallest volume sampler (BD46) yielded 17 to 28 percent greater D_b estimates. Relative to their respective mean values, precision of soil resistance measurements with the PEN were clearly less than that with any of the BD samplers. The shorter samplers (BD46 and BD136) extracted soil from only a portion of each 10-cm-depth interval. Because these noncontinuous corers sampled near the midpoint but not the full 10-cm depth, their D_b estimates would be expected to differ from those of BD100. Both noncontinuous samplers consistently overestimated D_b as determined by BD100 sampler, although the BD136 sampler was less biased.

The time required to obtain a D_b sample or PEN plotting differed by location and soil depth. Coarse fragment content at the Capitol Forest site necessitated repeated attempts to obtain an acceptable core sample or plotting. Time requirements for BD100 and BD46 were similar (a total of about 12 to 14 minutes to sample three successive 10-cm depths) and were less than the 16 to 19 minutes required to sample with the larger BD136 sampler. Although coarse fragments increased the time needed to secure a complete 0- to 40-cm plotting of soil strength with the PEN, less than 1 minute was needed at each sample point. In addition to these time requirements for field sampling, about 0.8 minute was required to digitize each PEN plotting and to compute soil strength by 1-cm-depth increments. To process each D_b sample in the laboratory required about 3.7 minutes or a total of 15.6 to 22.6 minutes for the 0- to 30-cm sampling. Thus, at least 15 PEN samplings could be taken and processed in the time required for three D_b samples to the same 30-cm depth.

If D_b could be reliably predicted from PEN data, then attendant cost savings could be used to increase sample size and distribution. The difficult question is how closely (precisely) must the PEN predict D_b to be an acceptable alternative. The answer to this question depends on the use of the results. If one is attempting to predict growth loss as a function of increased D_b, then close correspondence between the PEN and BD is needed; otherwise, the growth relation would be eroded by the imprecision of the D_b estimate. For a rough survey of compaction after management activities, however, the PEN may be sufficiently accurate, especially if sampling is done when soil is near field capacity or if soil moisture is determined concurrently and regression techniques are used to standardize PEN data to a common moisture percentage. An alternative would be to use measurements of both soil resistance and D_b. Thus, a large and less expensive sample of PEN measurements could be adjusted (by regression) from a smaller, more accurate, yet more costly sample in which both resistance and D_b are measured at adjacent points. This is the concept of double-sampling. Because soil moisture content affects the relation between bulk density and soil resistance, sampling should be conducted when soils are near field capacity so that penetrometer readings are least influenced by differences in soil moisture.

Good correlation between data from the two tools on the stone-free soil, even without corrections for moisture percentage, however, supported the feasibility of a double-sampling application to increase sampling efficiency. One could apply this double-sampling technique when quantifying the effect of timber harvesting on soil bulk density or soil resistance at one or more harvested areas. For example, one would sample soil resistance at 30 to 60 sample points and concurrently and randomly subsample D_b at about one-third of these sample points. If sampling was accomplished when soil was near field capacity, then bulk density at the 20 to 40 points, where soil resistance only was measured, could be estimated from the regression between bulk density and resistance. If, however, sampling in drier soil were necessary, then soil moisture should be measured at all 30 to 60 sampling points, so that PEN readings could be adjusted to an oven-dry basis (as are bulk density measurements). Exclusive use of the PEN in either soil was not an adequate substitute for measuring D_b; there was too much unexplained variation, especially in the stony soil. The results on the stone-free soil indicated the advantage in applying double-sampling theory to estimate D_b rather than sampling exclusively by any of the more time-consuming core samples. We believe this approach could be successfully taken with other soils, perhaps to even greater advantage, especially if soil moisture is concurrently measured and used to adjust PEN readings for differences in soil moisture.

Introduction

Bulk density (D_b) is widely used for converting water or nutrient percentages by weight to water or nutrient content by volume. Bulk density, expressed as Mg•m^{-3} or g•cc^{-1}, also is commonly used to measure soil compaction. An increase in D_b, if reliably measured, indicates that movement of air and water within the soil has been reduced; the soil therefore may be more likely to erode or be less favorable for plant growth.

Soil D_b is the ratio of mass of dry solids to bulk volume of soil. Bulk volume includes the volume of the solids and of the pore space (Blake and Hartge 1986). Mass is determined after drying to constant weight at 105 ^{o}C, and bulk volume is determined by a sampling core or excavation. Presence of gravel or stones complicates D_b measurement and also comparisons of bulk (whole-soil) D_b between soils or horizons with differing amounts of coarse mineral or organic fragments. Because the real density of these fragments differs from that of the bulk density of the fine soil (< 2 mm), whole-soil D_b as conventionally determined (Blake and Hartge 1986) will invariably be greater when gravel is present. Although fine-soil (< 2mm) D_b is an alternative measure of compaction or soil density, necessary corrections for weight and volume of gravel and coarse organic matter are not consistently made or documented.

Assessment of soil D_b by cores or excavations is time consuming and, as stated by Freese (1962), all methods differ in accuracy (success in estimating the true value of D_b), precision (clustering of sample estimates about their own average), and bias (the systematic distortion of estimates for the true value). Although equipment for core sampling is relatively inexpensive and durable for field usage, little is known about the relative accuracy (precision plus bias) and efficiency (cost per unit of precision) of various core samplers, which could be used to quantify changes in soil D_b caused by heavy equipment or to correlate these changes with tree growth.

Soil compaction also can be indicated by a penetrometer (PEN), a device forced into the soil to measure its resistance to vertical penetration (Bradford 1986). Soil strength, as measured by a PEN (units = 1 kg•cm^{-2} = 98.1 kPa = 0.0981 MPa = 14.2 psi), is related crudely to soil resistance as encountered by roots. Maximum root pressure of many plants to expand in soil lies between 0.9-1.3 MPa (Richards and Greacen 1986). Sands et al. (1979) report that root penetration of radiata pine (*Pinus radiata* D. Don) in sandy soils in South Australia was severely restricted at 3.0 MPa resistance. Rapidly obtainable PEN readings may be reliable estimators of soil D_b in soils with few interfering coarse fragments. Because PEN readings can be strongly dependent on soil moisture content, field sampling for comparative purposes should be done when soils are near field capacity (Davidson 1965). When soils with different moistures are being compared, concurrent soil moisture determinations can be used to adjust PEN readings to a common or to a standard moisture percentage. Choice of soil sampling tool may depend on the intended use of the results. Quick, less accurate methods may be adequate for conducting field surveys, whereas highly accurate, more time-consuming measurements may be necessary for sampling research plots.

We evaluated a PEN and three commonly used core samplers that differed in diameter, length, and volume of the extracted core. These four tools were compared in a stone-free soil as well as in a stony soil. In gravelly and stoney soils, penetration by a penetrometer is frequently interrupted and core extractions can be difficult or impossible. Because core samplers usually provide an unsatisfactory measure of soil mass and volume when more than an occasional stone is present in the soil (Blake and Hartge 1986), other methods are suggested for such situations (Flint and Childs 1984, Vincent

Table 1—Abbreviations for and descriptions of tools

Abbreviation	Description[a]
BD100	100-cm-long, continuous volumetric core sampler with an internal diameter of 3.58 cm and an internal volume of 1000 cc (Altanasiu and Beutelspacher 1961)
BD136	6-cm-long core sampler with an internal diameter of 5.37 cm and an internal volume of 136 cc (Soil Moisture Equipment, Santa Barbara, CA)
BD46	2.6-cm-long core sampler with an internal diameter of 4.80 and an internal volume of 46 cc (Art's Machine Shop, American Falls, ID)
PEN	Recording penetrometer with a 30º cone tip of 2.02 cm in diameter; shaft length adjustable to about 90 cm (DELMI, Shafter, CA)

[a] Mention of commercial products does not imply endorsement by the USDA.

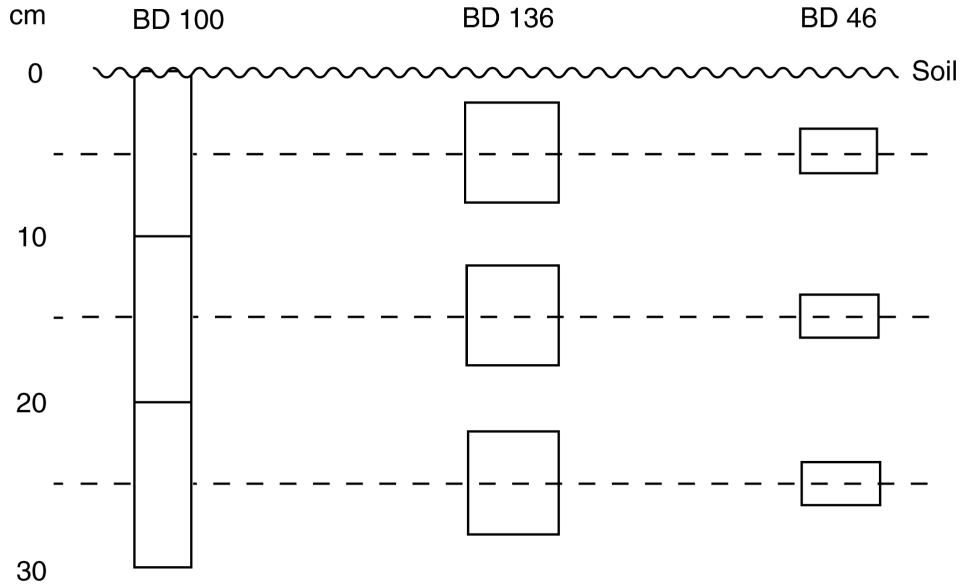
and Chadwick 1994). Our general objective was to compare precision and efficiency of four tools conventionally used to monitor soil compaction. Specifically, we wanted to accomplish the following:

- Compare the precision of each tool based on two adjacent samples at each sampling point and depth within two young forests planted after clearcutting and tractor yarding.
- Use our potentially most accurate core sampler as the standard and calculate relative accuracy and bias of two other core samplers for estimating average $D_{b;}$ determine if bias was related to soil depth. The standard tool was designated before comparisons by choosing the one that could sample the full range of the targeted 10-cm-depth interval.
- Determine the average time requirement per sample unit for each tool.
- Determine the relation and correlation between PEN measurements and D_b as measured by the core samples.
- Examine double sampling (PEN and a core sampler) as a more efficient way to estimate mean D_b than sampling with a core sampler alone; calculate optimum ratios of samples by each method.

Materials and Methods

Tools

The four tools we evaluate are described in table 1. The continuous volumetric sampler (BD100) can sample soil to a 1-m depth. Its sampling tube is inscribed at 10-cm intervals to indicate 100-cm^3 increments. The tube is pushed to the first desired depth, and the soil is removed with a screw-type extractor, which disturbs the sample. Unless large rocks or roots are encountered, successive depths can be extracted continuously without removing and reinserting the sampling tube. The other two samplers (BD136 and BD46) remove relatively undisturbed soil cores, but each has a different length and diameter; consequently they do not sample the same soil depth and volume as the continuous sampler. These samplers must be removed and reinserted nearby to sample at continuous depths. This relocation adds sampling error above that of a continuous sample. Alternatively, these noncontinuous samplers can provide a D_b centered on the 10-cm-depth interval sampled by the continuous sampler (fig. 1).



Sampler	BD 100 Continuous	BD 136 Core	BD 46 Core
Sample:	Disturbed	Undisturbed	Undisturbed
Volume (cc)	100	135.7	46.1
Diameter (cm)	3.57	5.37	4.80
Depth (cm)	10.0	6.0	2.6
Distance from cutting edge to core (cm)	0	3.3	1.7
Sampling depths and midpoint (cm):	0-10 (5.0)	3.3 - 9.3 (6.3)	3.7 - 6.3 (4.9)
	10-20 (15.0)	13.3 - 19.3 (16.3)	13.7 - 16.3 (14.9)
	20-30 (25.0)	23.3 - 29.3 (26.3)	23.7 - 26.3 (24.9)

Figure 1—Soil sampling depths and specifications.

The PEN has a 30° cone-shaped tip. When this 2.02-cm diameter tip is pushed into the soil, our PEN provides a continuous plotting (on a standard 3- by 5-inch card) of soil strength (as kg•cm^{-2}) and soil depth, unless impenetrable stone or wood is encountered. These plottings were digitized for summary, by 1- and 10-cm classes, and subsequent statistical analysis.

Study Locations

Central Park

This study location with practically stone-free soils and 0- to 5-percent slopes is near Central Park, WA. The soil is Le Bar silt loam (currently classified as medial ferrihydritic mesic Typic Haplodrand) formed in old alluvium (Pringle 1986). This deep, well-drained soil has an A-horizon of silt loam texture and strong granular structure averaging 30 cm in depth and a B-horizon of friable, silt loam with a subangular blocky structure. Organic matter averages 10 to 15 percent in the A-horizon. With few exceptions, depth to the C-horizon exceeds 150 cm.

Timber on the area was clearcut and then yarded by crawler tractors (D-8) in winter on wet soil. Eight years after logging and planting with coniferous seedlings, soil compaction was measured at predesignated locations by sampling four disturbance conditions:

- Skid trails with topsoil removed
- Skid trails with topsoil churned and compacted
- Scarified but nonburned areas between skid trails
- Nonscarified (logged only) areas

Each condition was sampled at five or more places, totaling 21 sample points. The replications for each condition were chosen to represent that condition over the entire clearcut.

Capitol Forest

This study area is on 0- to 10-percent slopes near Olympia, Washington. The soil is Raught cobbly silt loam (currently classified as: fine parasesquic mesic Typic Palehumults) formed on basalt (Pringle 1990). This moderately deep, well-drained soil has an A-horizon of cobbly silt loam averaging 30 cm in depth and a B-horizon of silt loam. Both A- and B-horizons have strong, subangular, blocky structure. Organic matter averages 5 to 15 percent in the A-horizon. Total soil depth to the C-horizon exceeds 150 cm.

The original mixed hardwood-conifer stand was clearcut and then yarded with crawler tractors. After broadcast slashburning, the area was planted with Douglas-fir seedlings. One year after harvest and planting, a total of 24 places were sampled on four transects within two 1-ha portions. The two portions were selected to represent the level and the sloping terrain of the entire clearcut. The two transects (at right angles across skid trails) sampled average conditions in each slope type. Individual sampling points were systematically located on these transects to sample skid-trail and non-skid-trail soil conditions.

Soil Sampling

Silt loam soils at both study locations were sampled during the spring rainy season; therefore, soils were probably at or near field capacity. Penetrability testing at field water-capacity is recommended because this water content occurs from time to time within a given season and from season to season (Bradford 1986). Sampling points for each tool were assigned by subdividing each potential sampling plot, a 25- by 100-cm rectangle, into four equal-sized squares and randomly allocating a tool to each square. Two subsamples (replications) were taken within each square.

Sampling depth differed by tool (fig. 1). The PEN provided a continuous plotting of soil strength and soil depth to 40 cm unless impenetrable stone or wood was encountered. With the continuous volumetric sampler, the sampling tube was inserted and the soil was extracted sequentially at 10-cm depth intervals to 30 cm; each interval corresponded to a 100-cc sample. The extractor was reinserted repeatedly to ensure complete removal of the soil for each depth interval. Hence, bulk density sampling was restricted to the A-horizon of both soils. Because cores extracted by the two noncontinuous samplers were less than 10 cm long, samples were centered within each 10-cm depth interval. After extraction, however, cores frequently were slid inside the sampling cylinder to obtain complete filling of each core; this adjustment usually shifted actual sampling about 1 cm lower than the decimeter midpoint. Cores were retaken occasionally when heavy roots or buried wood were encountered or when a core had obvious voids. Individual samples were placed in cans with tightly fitted lids or in sealable, plastic-lined paper bags. We recorded the time required to obtain each successful sample (including unsuccessful attempts) and to clean, sharpen, or adjust equipment in the field.

Laboratory Procedures

Fresh soil weight was determined on the day of collection by using an electronic balance that measured to the nearest 0.01 g. Soil and containers then were dried at 105 °C to constant weight in a forced-draft convection oven, cooled, and reweighed to determine moisture percentage and dry weight. Samples were screened through a 2-mm sieve to separate gravel and coarse organic matter for weighing and subsequent determination of their average weight-to-volume relations and conversion to volume. Bulk soil densities were corrected for weight and volume of gravel and coarse roots or wood totaling 1 cm^3 or more per sample. Hence, these are D_b of the fine-soil fraction (< 2 mm).

Data Summary and Analysis

Data for the two locations were analyzed separately because of their differing soil conditions. Precision of each tool was determined by summing the squared differences between the two replicates (order of measurement) at each sample point. Arithmetic differences between replications (values with signs) also were summed to determine if any consistent difference existed between the paired replicates. A consistent difference indicates that measurement 1 was affected by measurement 2. The sum of arithmetic differences should be approximately zero, if replications 1 and 2 were of equal consistency.

Relative accuracy and bias of the BD136 and BD46 tools were determined by comparing their means (of the two replications) at each sampling place with the corresponding means of the BD100 tool (our standard). Scattergrams were plotted to observe visually the correlation between tools as well as trends in variation. Before statistical analyses, however, a few outliers on preliminary plottings were removed from the data because the very low D_b observed in these samples was not realistic for mineral soil. Bias was estimated as the mean of the differences between tools; relative accuracy was calculated as the sum of the squared differences from the standard tool. Relative accuracy or bias of the PEN could not be judged because this tool measures in different units, so no direct comparison was possible. Instead, the correlation between BD100 and PEN was our measure of the adequacy of the PEN to reproduce BD100 measurements.

Time requirements for each tool (including field and laboratory phases) were averaged to determine time per sampling unit. By using time requirements and variances for each D_b sampler and the PEN, the correlation required to improve the efficiency of D_b estimates was computed for double sampling with both tools (Cochran 1977). Comparison of this calculated correlation with the actual correlation determined whether double sampling was more efficient in either soil than was sampling only by cores. Where double sampling was more efficient, the optimum sampling ratio between the two tools was calculated by using double-sampling theory.

Results and Discussion

Bulk density and resistance to penetration both increased with depth at both locations (table 2). In each decimeter depth, the continuous volumetric sampler (BD100) yielded the lowest D_b values, while the shortest and smallest volume sampler (BD46) yielded 17 to 28 percent greater D_b estimates. Conversely, variability (coefficient of variation) in D_b at each depth among the sampling points was least with BD46 and greatest with BD100. Coefficients of variation (CV%) in D_b within 10-cm depths at both locations ranged between 12 and 37 percent among the three core samplers; this compared to a CV of 36 to 67 percent in soil resistance as measured with the PEN (table 2).

Precision of Measurements (Rep. 1 vs. Rep. 2)

The precision of each tool was measured by the average squared difference between replicate measurements at each sampling point (21 points at Central Park and 24 at Capitol Forest). Relative to the respective mean values for each tool, precision of soil resistance measurements with the PEN was clearly less than that with any of the BD samplers (table 2). As will be discussed later, this lesser precision must be balanced against the rapidity by which individual PEN samples can be taken.

Recall that two replicate samplings with each tool were made within each 25- by 25-cm sampling subplot. Our measure of “consistency” responds to a potential concern that some of the difference between the two ordered replicates may be due to the influence of the first replicate on soil conditions for the second. For example, as the PEN tip is pushed through nonsaturated soil, surrounding soil is compressed to accommodate the probe. For penetrometers, the area of compressed soil is 6 to 10 times the probe radius (Fritton 1990). With the 2-cm diameter cone tip, soil within 6 to 10 cm of the tip could be compressed, suggesting that duplicate samples should be 6 to 10 cm apart to be independent of each other. Adequate spacing may not have occurred at a few sample plots when more than two probings were necessary to secure two replicates. We assume soil compression also occurred near the D_b samplers, but find no reference to support calculations of the zone of external compression. If measurable compression had occurred in our sampling, then the difference (rep. 1 – rep. 2) would be negative. Our consistency values do not support a concern for this potential bias (table 2).

The Noncontinuous Core Samplers as Estimators of Bulk Density

Our three D_b samplers differed in length, diameter, and volume. The shorter samplers (BD46 and BD136) extracted soil from only a portion of each 10-cm-depth interval (fig. 1). Because these noncontinuous corers sampled near the midpoint but not the full 10-cm depth, their D_b estimates would be expected to differ from those of BD100. Cutting-edge diameters were 3.58 cm (BD100), 4.80 cm (BD46), and 5.37 cm (BD136). Because its smaller diameter could cause soil compression inside the sampler, the BD100 sampler was likely to overestimate true D_b and provide greater D_b estimates than the larger diameter samplers. Our results (table 2), however, are opposite: BD100 estimates were consistently less than those of BD46 and 136. As expected, the lesser volume BD46 estimates usually exceeded those of BD136.

Costantini (1995) confirms earlier research that a small but significant reduction in estimated D_b is associated with increased sampler diameter. For his four, thin-walled samplers (inside diameters ranging from 3.48 to 9.12 cm), however, the absolute differences in mean D_b estimates for the largest and smallest samplers averaged less than 3 percent of the mean for all samplers. Holt (1979), as cited by Costantini (1995), identifies 5 cm as the practical lower diameter for core samplers and notes that incomplete filling of the cylinder or shattering during penetration can especially bias D_b estimates of small-diameter samplers and, possibly, of small-volume samplers.

Table 2—Mean, consistency, and precision of measurements, by location, soil depth, and tool[a]

Soil depth	Tool	Mean	Mean	CV	Precision[b]	Consistency[c]
Cm		*Mg•m*$^{-3}$	*Relative*[d]	*%*	*Mg•m*$^{-3}$	*Mg•m*$^{-3}$
			Central Park			
0-10	PEN[e]	0.724	—	47	0.944	0.056
	BD100	.48	(100)	27	.01	.00
	BD136	.56	(117)	21	.00	.03
	BD46	.60	(125)	20	.01	-.01
10-20	PEN[e]	1.224	—	46	2.136	.118
	BD100	.60	(100)	37	.02	-.02
	BD136	.70	(117)	21	.01	.00
	BD46	.76	(127)	18	.00	.00
20-30	PEN[e]	1.225	—	36	1.288	.017
	BD100	.65	(100)	29	.02	.00
	BD136	.76	(117)	24	.01	.00
	BD46	.76	(117)	25	.01	.00
			Capitol Forest			
0-10	PEN[e]	1.216	—	67	1.880	.223
	BD100	.54	(100)	33	.02	.00
	BD136	.54	(100)	22	.01	.04
	BD46	.64	(119)	22	.01	-.01
10-20	PEN[e]	1.603	—	51	2.268	.172
	BD100	.58	(100)	22	.02	.01
	BD136	.70	(121)	14	.02	.03
	BD46	.74	(128)	20	.02	-.01
20-30	PEN[e]	1.761	—	47	2.936	.00
	BD100	.66	(100)	26	.01	.03
	BD136	.72	(109)	14	.02	-.03
	BD46	.80	(121)	12	.02	-.04

[a] Sample locations: 21 at Central Park and 24 at Capitol Forest.
[b] Precision = average squared difference between replicates.
[c] Consistency = average arithmetic difference between “ordered” replicates (rep. 1 – rep. 2).
[d] BD100 = 100.
[e] Penetrometer resistance measured in MPa.

Regression and Correlation

Bulk densities determined with BD136 and BD46 tools were correlated significantly with BD100, our standard tool. Although not tabulated here, correlation coefficients for each decimeter depth were generally greater at the stone-free Central Park site (r = 0.68-0.86 vs. 0.27-0.72 at Capitol Forest).

Accuracy and Bias

The BD136 sampler was more accurate than the BD46 sampler for estimating assumed true D_b in both soils (table 3). These results were expected because the larger volume corer sampled 60 percent (6 cm/10 cm) of the standard 10-cm depth compared to 25.5 percent sampled by BD46 (2.55 cm/10 cm) (fig. 1). Both noncontinuous samplers consistently overestimated D_b as determined by BD100 sampler (table 2), although the BD136 sampler was less biased (table 3). This bias could be due to the trend of increasing D_b with depth (table 2). If this trend is not linear, then samples from the midpoint of the depth interval will give a biased estimate of D_b as measured by the continuous sampler. Moreover, our field procedure of sliding most soil cores lower in the sampling cylinder to obtain a filled lower end of the core would have (1) shifted the actual sampling lower than the decimeter midpoint and (2) biased D_b positively. Our results confirmed this suspicion; the bias was consistently positive, although it did not increase or decrease in magnitude with depth (table 3). Because the tools being compared do not actually sample the same soil volume, we do not have good statistical test of tool bias. A test of the true correlation, p = 1, is influenced by inaccuracy of the tools (Freese 1962).

Time Requirements

The time required to obtain a D_b sample or PEN plotting differed by location and soil depth (table 4). Coarse fragment content at the Capitol Forest site necessitated repeated attempts to obtain an acceptable core sample or plotting. Time requirements for BD100 and BD46 were similar (a total of about 12 to 14 minutes to sample three successive 10-cm depths) and were less than the 16 to 19 minutes required to sample with the larger BD136 sampler (table 4). Although coarse fragments increased the time needed to secure a complete 0- to 40-cm plotting of soil strength with the PEN, less than 1 minute was needed at each sample point. In addition to these time requirements for field sampling, about 0.8 minute was required to digitize each PEN plotting and to compute soil strength by 1-cm-depth increments. To process each D_b sample in the laboratory required about 3.7 minutes or a total of 15.6 to 22.6 minutes for the 0- to 30-cm sampling. Thus, at least 15 PEN samplings could be taken and processed in the time required for three D_b samples to the same 30-cm depth.

If other tools are used, less time will be required to quantify soil resistance to penetration. For example, the recommended insertion rate for the Rimik CP20 Cone Penetrometer with a standard cone is 200 cm/min (Rimik Agricultural Electronics 1944),[1] or about twice as fast as we inserted our PEN. Moreover, the time required to convert field data to an analyzable database also can be accelerated by newer technologies. For example, the Rimik penetrometer has an electronic data-logger enabling files to be transferred electronically for editing, summarization, and analysis. Bradford (1986) cites a penetration rate of 180 cm/min in field investigations when using the Corps of Engineers cone penetrometer. This rate of penetration is also faster than ours (80 cm/min). He notes, however, that “an increase in penetration rate…can increase, decrease or not influence probe resistance depending on soil properties and water conditions. The relationship of penetrometer resistance to penetration rate is influenced to a large degree by the pore water pressure generated by the advancing cone, the rate of dissipation of these pressures, and the dilatency [sic] properties of the soil under shear” (Bradford 1986: 464).

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[1] The use of trade or firm names in this publication is for reader information and does not imply endorse-ment by the U.S. Department of Agriculture of any product or service.

Table 3—Bias and accuracy of BD136 and BD46 as compared with BD100 at two locations[a]

		Replicate 1		Replicate 2		Mean	
Depth	BD tool	Bias	Accuracy	Bias	Accuracy	Bias	Accuracy
Cm	*Cm*^{3}	– – – – – – – – – – – – – – – – – – – *Mg•m*$^{-3}$– –					
			Central Park				
0-10	136	0.08	0.33	0.07	0.33	0.08	0.01
	46	.11	.35	.13	.36	.12	.36
10-20	136	.11	.39	.09	.40	.10	.36
	46	.17	.44	.15	.41	.16	.41
20-30	136	.10	.35	.11	.30	.10	.33
	46	.11	.35	.11	.39	.11	.36
			Capitol Forest				
0-10	136	.03	.33	-.03	.33	.00	.09
	46	.10	.41	.11	.41	.10	.39
10-20	136	.13	.39	.10	.36	.12	.36
	46	.15	.44	.17	.45	.16	.42
20-30	136	.04	.41	.11	.41	.06	.39
	46	.11	.36	.19	.48	.14	.16

[a] Example: bias = Σ (BD136 – BD100/n; accuracy = root mean square deviation or square root of Σ (BD136 – BD100)^2/n.

Table 4—Average time and number of attempts required in the field to obtain an acceptable sample, by tool, location, and soil depth

	Tool[a]			
Depth	BD100	BD136	BD46	PEN
Cm	– – – – – – – – – – – *Minutes (number of attempts)* – – – – – – – – – – – – –			
		Central Park		
0-10	3.86 (1.10)	4.69 (1.05)	4.29 (1.57)	– –
10-20	3.86 (1.10)	6.96 (1.05)	4.38 (1.14)	– –
20-30	4.18 (1.00)	7.30 (1.05)	3.82 (1.05)	– –
All	11.90 (– –)	18.95 (– –)	12.49 (– –)	0.51 (1.00)
		Capitol Forest		
0-10	5.61 (1.54)	4.13 (1.09)	4.24 (1.54)	– –
10-20	5.05 (1.26)	5.68 (1.21)	5.08 (1.25)	– –
20-30	3.64 (1.25)	6.33 (1.25)	4.30 (1.21)	– –
All	14.30 (– –)	16.14 (– –)	13.62 (– –)	.80 (1.49)

[a] Additional lab time for weighing BD samples, digitizing plottings of soil resistance, and calculations averaged 3.7 minutes for each BD sample (10-cm-depth intervals) and 0.8 minute for each 0- to 30-cm PEN sample.

The Penetrometer as an Estimator of Bulk Density

Soil density is conventionally characterized by D_b; yet, soil density is related to soil resistance, which can be measured with a PEN much more rapidly than D_b can be measured. If D_b could be reliably predicted from PEN data, then attendant cost savings could be used to increase sample size and distribution. The difficult question is how closely (precisely) must the PEN predict D_b to be an acceptable alternative. The answer to this question depends on the use of the results. If one is attempting to predict growth loss as a function of increased D_b, then close correspondence between the PEN and BD is needed; otherwise, the growth relation would be eroded by the imprecision of the D_b estimate. For a rough survey of compaction after management activities, however, the PEN may be sufficiently accurate, especially if sampling is done when soil is near field capacity or if soil moisture is determined concurrently and regression techniques are used to standardize PEN data to a common moisture percentage.

An alternative would be to use measurements of both soil resistance and D_b. Thus, a large and less expensive sample of PEN measurements could be adjusted (by regression) from a smaller, more accurate, yet more costly sample in which both resistance and D_b are measured at adjacent points. This double-sampling concept (Cochran 1977) is discussed later.

Regression and Correlation

To examine double sampling, we quantified the relation between the PEN and the BD100. Our comparative sampling with these tools was accomplished in spring when soil was at or near field capacity.

Bulk densities from BD100 were correlated significantly with PEN values at all 10-cm depths of the stone-free soil to 30 cm, but only at the 10- to 20-cm depth of stony soil at Capitol Forest (table 5). For both soils, slopes of regression lines were similar for each soil depth, but the slopes were steeper for the stone-free soil (table 5 and fig. 2). The two-factor equation, which included both PEN and gravimetric moisture percentage, provided a more precise estimate of bulk density than the one-factor equation (PEN) for each depth and both areas (table 5). Mathematically removing the influence of differing moisture contents among the wet-season PEN samples reduced the slope of the regression line and increased R^2. Hence, if soil moisture at the time of the PEN sampling is measured and standardized among samples, a lower mean D_b would be estimated. Presumably this reduction in mean D_b results because dry soil increases soil resistance more than a concurrent effect on bulk density.

Because soil moisture content affects the relation between bulk density and soil resistance, sampling should be conducted when soils are near field capacity so that penetrometer readings are least influenced by differences in soil moisture. Good correlation between data from the two tools on the stone-free soil, even without corrections for moisture percentage, however, supported the feasibility of a double-sampling application to increase sampling efficiency. The relation between D_b and soil resistance without standardization of moisture was examined further by covariance analysis for the three soil depths combining both locations. Preliminary analyses (to determine how many slope coefficients were needed) indicated that the overall regression relationship was highly significant, but the interaction of the six slope coefficients with locations and depths was nonsignificant, thereby suggesting that all relations were parallel (fig. 2). Subsequent ANOVA assumed a common slope of regression lines at both locations and compared differences in adjusted D_b means for two factors (location and depth) and their interaction (table 6).

Table 5—Regressions and correlation coefficients among D_b (Mg•m^{-3}) and soil strength (MPa), by location and soil depth

Variables			Number of	Coefficients			
Dependent	Independent	Depth	samples	A	B	C	R^2
		Cm					
			Central Park				
BD100	PEN	0-10	20	0.296	0.0239	—	0.48 **
		10-20	20	.236	.0272	—	.57 **
		20-30	20	.387	.0196	—	.27 *
BD100	PEN + % water[a]	0-10	20	.650	.0154	-0.00345	.69 *
		10-20	20	.454	.0237	-.00214	.71 **
		20-30	20	.776	.0205	-.00559	.67 *
			Capitol Forest				
BD100	PEN	0-10	24	.444	.0076	—	.11 ns
		10-20	23	.450	.0082	—	.26 *
		20-30	23	.512	.0088	—	.17 ns
BD100	PEN + % water[a]	0-10	24	.669	.0089	-.00272	.30 *
		10-20	24	.702	.0092	-.00342	.53 **
		20-30	24	.995	.0101	-.00794	.34 *

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.

[a] Percentage of soil moisture (w/w basis) was included as a second variable in multiple regression analysis.

Table 6—Abbreviated summary of covariance analysis of bulk density related to soil resistance, by location and soil depth

Source	D.f.	Adjusted mean squares	F-value	P-value
Location (whole plot)	1	0.00250	0.07[a]	ns
Depth	2	.11036	11.95[b]	0.001
Location x depth	2	.00578	.63[b]	ns

[a] Tested with whole-plot error term, consisting of 41 degrees of freedom (d.f.) and mean square error of 0.03571.

[b] Tested with error term consisting of 82 d.f. and mean square error of 0.00926.

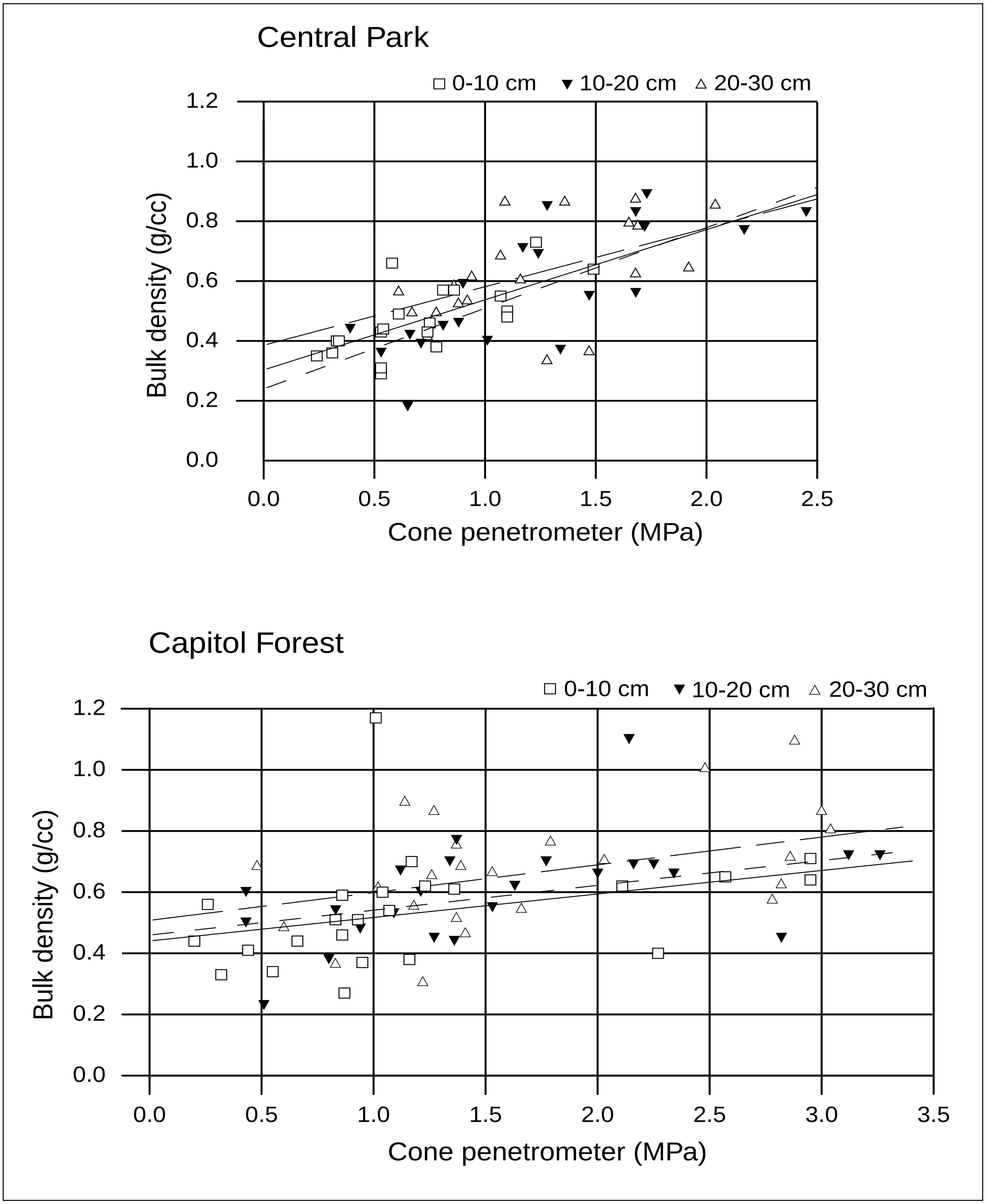

Figure 2—Relation between D_b (BD100) and resistance to a cone PEN in moist soil by soil depth in a stonefree (A) and a stony (B) soil.

The results indicate that average bulk density (0- to 30-cm depth) in the two locations did not differ. Although texture of the topsoil at both locations was silty loam, the soils represented two different suborders within the Inceptisol order (Andept vs. Umbrept). Depths, however, were significantly different, meaning that the adjusted means of bulk density differed among the three depths; no interaction existed between location and depth. A practical inference from this analysis is that bulk density could be estimated from penetrometer readings taken during the wet season at a reasonably wide range of soil conditions. Separate estimation equations would be desirable for successive soil depths, however.

Allbrook (1986) reports good correlation ($R^2 = 0.67$) between PEN resistance and D_b as determined by a double-probe, nuclear densitometer (which estimates bulk or whole-soil D_b). His analysis pooled five soil depths and four positions in a single transect on and near a skidtrail. He did not, however, attempt to remove soil depth as a source of variation.

Double Sampling with Two Tools

The efficiency of double sampling was compared with simple random sampling by using the following inequality (Cochran 1977, eq. 12.64):

$$\frac{c_2}{c_1} > \frac{\left[1 + (1 - p^2)^{1/2}\right]^2}{p^2} \qquad (1)$$

where c_1 and c_2 are average time requirements of methods 1 (PEN) and 2 (BD100), which were 1.057 and 7.56 minutes, respectively. Rho (p) is the correlation between the two methods; r = 0.693 is the sample estimate of p (at Central Park, 0-10 cm depth). When r, c_1, and c_2 are substituted in the inequality equation (1), we obtain $7.15 > 6.16$. Thus, double sampling is more efficient at this location and depth because the ratio of the time of method 2 to method 1 exceeds the right side of Cochran's inequality (table 7).

Having established that double sampling is more efficient (at this location and depth) for estimating mean D_b than analyzing only by core samples, we can calculate the optimum ratio of soil measurement by each method using the following relation (Cochran 1977, eq. 12.59):

$$\text{Optimum ratio}\left(\frac{n_2}{n_1}\right) = [c_1/c_2\,(1 - p^2) / p^2]^{1/2} \qquad (2)$$

where n_1 and n_2 are the number of samples for methods 1 and 2, c_1 and c_2 are respective times, and p (rho) is the correlation defined earlier.

The optimum ratio as computed by equation (2) is 0.389. Inverting this ratio results in a ratio of 2.57. This means the optimum number of PEN samples is 2.57 times larger than the number of BD100 samples. The results indicated an advantage in applying double-sampling theory and in using both analyses to estimate mean D_b for specified soil depth rather than sampling exclusively by the more time-consuming core sampler (direct sampling). We believe this approach could be used successfully with other soils, perhaps with even greater advantage. Our optimum ratio was 2.6:1 in the 0- to 10-cm depth, but this might differ in other depths and locations. If the regression relationship or the variance of either method or the time ratio changes, the efficiency of double sampling is affected. As a result, sampling efficiency may be higher or could be so low that core sampling only would be more advantageous, as we found in the stony soil (table 7).

Table 7—Data used to determine the efficiency of double sampling (D) compared with simple random sampling (S), by soil depth, tool, and location

Soil depth	Tool	Total time per sample C_1 (PEN)	Total time per sample C_2 (PEN)	Correlation, r	More efficient	PEN/ BD100
Cm						
			Central Park			
0-10	PEN vs. BD100	1.06	7.56	0.693	D	2.4
	PEN vs. BD136	1.06	8.39	.639	D	2.2
	PEN vs. BD46	1.06	7.99	.703	D	2.6
10-20	PEN vs. BD100	1.14	7.56	.755	D	2.8
	PEN vs. BD136	1.14	10.66	.461	S	—
	PEN vs. BD46	1.14	8.08	.716	D	2.6
20-30	PEN vs. BD100	1.31	7.88	.517	S	—
	PEN vs. BD136	1.31	11.00	.440	S	—
	PEN vs. BD46	1.31	7.52	.490	S	—
			Capitol Forest			
0-10	PEN vs. BD100	1.20	9.31	.338	S	—
	PEN vs. BD136	1.20	7.83	.314	S	—
	PEN vs. BD46	1.20	7.94	.154	S	—
10-20	PEN vs. BD100	1.34	8.75	.514	S	—
	PEN vs. BD136	1.34	9.38	.500	S	—
	PEN vs. BD46	1.34	8.78	.443	S	—
20-30	PEN vs. BD100	1.60	7.34	.411	S	—
	PEN vs. BD136	1.60	10.03	.017	S	—
	PEN vs. BD46	1.60	8.00	.291	S	—

One could apply this double-sampling technique when quantifying the effect of timber harvesting on soil bulk density or soil resistance at one or more harvested areas. For example, one would sample soil resistance at 30 to 60 sample points and concurrently and randomly subsample D_b at about one-third of these sample points. If sampling was accomplished when soil was near field capacity, then bulk density at the 20 to 40 points, where soil resistance only was measured, could be estimated from the regression between bulk density and resistance. If, however, sampling in dry season were necessary, then soil moisture should be measured at all 30 to 60 sampling points, so that PEN readings could be adjusted to an oven-dry basis (as are bulk density measurements).

Conclusions

- Precision of soil resistance measurements with the cone PEN was lower than that with any of the D_b samplers.
- The two shorter, noncontinuous samplers consistently overestimated D_b as determined by the longer, continuous sampler. This bias could be due to a nonlinear trend of increasing D_b within the 10-cm-depth intervals. If this trend is not linear within a given depth interval, then midpoint samples will produce biased estimates.
- The time required to obtain a D_b sample or PEN reading differed by location and soil depth. Coarse fragment content at the Capitol Forest location necessitated repeated attempts to obtain an acceptable D_b sample or PEN plotting. At both locations, at least 15 PEN samples could be taken and processed in the time required for three D_b samples to the same 30-cm depth.
- Exclusive use of the PEN in either soil was not an adequate substitute for measuring D_b; there was too much unexplained variation, especially in the stony soil. The results on the stone-free soil indicated the advantage in applying double-sampling theory to estimate D_b rather than sampling exclusively by any of the more time-consuming core samples. We believe this approach could be successfully taken with other soils, perhaps to even greater advantage, especially if soil moisture is concurrently measured and used to adjust PEN readings for differences in soil moisture.

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English Equivalents

When you know:	**Multiply by:**	**To find:**
Centimeters (cm)	2.540	Inches
Metric ton (Mg)	1.102	Ton
Cubic meter (m^3)	35.3	Cubic feet
Megapascal (Mpa)	0.145	Pounds per square inch
Megagram per cubic meter ($Mg•m^{-3}$)	1.00	Gram per cubic centimeter ($g•cm^{-3}$)

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