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Soil Sampling Bulk Density in the Coastal Lowlands of South-East Queensland

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Abstract

Bulk density is commonly measured in compaction, cultivation, land evaluation and site classification studies in forestry. Typically, measurements are made using a small-diameter core sampler (an integral open drive sampler) which is manually driven into the soil profile. The study reported in this paper was designed to determine the effects of sampler size on bulk density estimates, and to identify optimal sampling intensities for the coastal lowlands of south-east Queensland. Four sampler sizes were tested (internal diameters of 3·48, 4·83, 5·98 and 9·12 cm, and all approximately 10 cm in length).

All sampler sizes provided consistent estimates of bulk density for a range of soil types and conditions. The accuracy of bulk density assessment was not improved by increasing sampler diameter beyond 5·98 cm. The results suggested that the core sampler technique can be used efficiently in a wider range of soil conditions than that recommended in the literature.

Comparison of variances estimated for the four sampler sizes indicated no significant differences between either sampler size or site, and no significant 'site by sampler size' interaction. A single pooled estimate of variance was therefore used to recommend sampling intensities for coastal lowland soils. With any of the samplers used in this study, five replications will provide a point estimate of bulk density with a precision of $\pm 0 \cdot 1$ g cm^{-3} at the 95% probability level.

Keywords: bulk density, sampling intensity, coastal lowlands, core samplers, forest management.

Introduction

Bulk density (g cm^{-3}) is defined as the oven dry mass of soil from a core (g) divided by the core volume (cm^{-3}) of the moist soil. It is an index of both porosity and compaction and, as a result, affects both root development potential and solute/gaseous movement. Because of its impact on the plant root environment and hence on total crop production, bulk density (BD) is of interest to forest managers. Estimates of BD are used in compaction, cultivation, land evaluation and site classification studies.

Core sampling methodology is widely used to assess BD (McIntyre and Loveday 1974; McIntyre 1974). McIntyre (1974) suggested that different core sampling systems be preferred depending upon soil strength and cohesiveness conditions. Indeed, for the range of soil conditions that could be expected in the Queensland Department of Primary Industries Forest Service (QDPI-FS) *Pinus* plantation estate in the coastal lowlands of south-east Queensland, five different systems are preferred.

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Multiple sampling systems are however, impractical for forest managers. A single sampling system is required: one that is accurate, whilst at the same time being robust, simple to use, and effective where shrub and tree cover is heavy. Because of the high risk of cutting edge damage with repeated use in the coastal lowlands, the sampler should also be low cost. The integral open drive sampler described by Hvorslev (1949) and modified at the cutting edge in the manner described by McIntyre and Loveday (1974) has these qualities, and is widely used by the QDPI-FS in both cultivated and uncultivated soils which are relatively free of stone intrusions. The sampling system uses short core length samplers (5–15 cm) which are manually driven into the soil. Following the guidelines of Raper and Erbach (1985), samplers are pushed into loose soil and hammered into more compact soils. McIntyre and Loveday (1974) have noted that hammering with a rubber mallet is satisfactory for bulk density sampling. This is particularly the case where short length samplers are used and collection of an undisturbed soil core is not critical.

Hughes (undated) has reported that core samplers typically have internal diameters of 8–10 cm, though cylinders with internal diameters as small as 2·5 cm can be used for 'favourable' soil profiles that are moist, stone-free, weakly structured and of medium texture. Most BD sampling in the forest environment is conducted when the soil condition is less favourable. There are, however, ease of use and cost and time benefits to be gained from using smaller diameter samplers. Smaller samplers are easier to drive into the soil profile, to control when the penetration depth is reached, and to extract whilst ensuring that sample soil is not lost. Collected samples are lighter to carry and transport.

The study reported in this paper was designed to determine the effect of sampler size upon BD estimates for a range of non-stone forest soils in the coastal lowlands of south-east Queensland where the QDPI-FS manages a 110 000 ha *Pinus* plantation resource (Qld For. Serv. 1992). An important objective of the study was to test a range of soil structural, textural, cultivation and wetness conditions so that the findings would have universal application within the *Pinus* estate. A secondary objective of the study was to determine optimal sampling intensity. The study was designed so that observed variability reflected the natural variability for a specific profile depth over a relatively small area. It was not designed to determine BD variation over a large area. The estimated standard error of the mean therefore can be used to calculate an optimal sampling intensity for a point estimate of BD.

Methodology

Four core samplers (Table 1), with internal diameters at the cutting edge of 3·48, 4·83, 5·98 and 9·12 cm, were used in the study. They were fabricated from stainless steel pipe, sharpened in the manner described by McIntyre and Loveday (1974), and cutting-tip hardened. The hardening process slightly reduced the cutting diameter compared with the internal diameter of the sampler. The four sampler types were designed with a nominal length of 10 cm.

Seven soil profiles (Table 2) were selected for the study. Soils at sites 1 and 2 were fine to medium textured and moderately well structured. Sites 3 to 6 were medium to coarse textured and apedal, massive. Whereas sites 1 to 6 were uncultivated, site 7 was cultivated three times to form high mounds similar to those described by Foster and Costantini (1991*a*). Site 7 was assessed six weeks after mounding was completed.

Table 1. Description of core samplers used in the study
Following McIntyre (1974), the area ratio was calculated as $[(OD^2-CD^2)/CD^2]$; the inside clearance was calculated as $[(OD-WG)/CD]$. (CD, cutting edge diameter; OD, outside diameter; WG, wall gauge)

Sampler	CD (cm)	OD (cm)	WG (mm)	Inside clearance (%)	Area ratio (%)	Length (cm)	Vol. (cm^3)
1	3·48	3·81	1·2	0·3	20	10·10	96·1
2	4·83	5·08	1·2	0·2	11	9·79	179·4
3	5·98	6·32	1·6	0·3	12	10·20	286·4
4	9·12	9·47	1·6	0·3	8	10·05	656·5

Table 2. Description of soil types tested in the bulk density sampling study

Site	Soil type		Details of soil layer tested				
	Stace *et al.* (1968)	Isbell (1993)	Horizon	Depth (cm)	Texture[A]	Vol. moist.[B] Mean	s.d.
1	Krasnozem	Red Dermosol	A1	20	LC	10·8	1·9
2	Krasnozem	Red Dermosol	B2	50	LC	12·7	1·8
3	Yellow earth	Brown Kandasol	A1	20	SCLFS	20·3	1·4
4	Yellow earth	Brown Kandasol	B2	60	CLFS	21·6	1·5
5	Red earth	Red Kandasol	A1	30	SCL	16·7	1·5
6	Red earth	Red Kandasol	B2	70	CLFS	15·5	1·4
7	Yellow podzolic	Brown Kurasol	AP2	20	SCL	12·3	1·7

[A] LC, light clay; SCLFS, sandy clay loam fine sandy; CLFS, clay loam fine sandy; SCL, sandy clay loam.
[B] Volumetric moisture content (%).

Assessment sites used in the study were selected on the basis that constant depth, uniform soil horizons were available for measurement. A generalized randomized complete block design, with seven sites, four sampler sizes and ten replications of each sampler size at each site, was used in experimentation. Core samplers were driven horizontally into the profile after the soil profile walls were carefully prepared with a shovel blade. Typically, a 6–8 m length of profile wall was randomly sampled at each site. Soil samples were immediately placed in press-seal plastic bags and transported to the laboratory for oven dry weight (105°C for 48 h), volumetric moisture content and BD determination.

BD data were subjected to analysis of variance using the model described by Steel and Torrie (1981) for a generalized randomized complete block design. Significant differences were located with a Fisher's protected least significant difference test. The plot of residuals indicated that BD observations were normally distributed. A response surface analysis was used to determine if any relationship between sampler size and BD estimate existed.

Analysis of variance techniques were also used to compare the variances of BD estimates for each core sampler size. Two approaches were used. In the first approach, a randomized complete block design with seven sites and four sampler size estimates (each estimate of variance based on ten replications) was used to detect site and sampler size main effects. In the second approach, two estimates of variance, one based on replications 1–5 and the other on replications 6–10, were analysed as a generalized randomized complete block with seven sites, four sampler sizes and two observations. This enabled a 'site by sampler size' error term to be defined. It was necessary to log transform variance data in order to satisfy the assumptions of homoscedasticity.

Results

Pooled BD estimates ranged from $1 \cdot 34\ \mathrm{g\ cm^{-3}}$ for the newly tilled site 7 to $1 \cdot 69\ \mathrm{g\ cm^{-3}}$ for the 'B2' horizon of the red earth at site 6 (Table 3). Site and sampler size main effects for BD were highly significant ($P < 0 \cdot 001$) and significant ($P < 0 \cdot 05$) respectively. There was no significant site by sampler size interaction.

Table 3. Mean site bulk density ($\mathrm{g\ cm^{-3}}$) for various sampler sizes (mean of 10 observations)

Sample size Vol. ($\mathrm{cm^3}$)	Diam. (cm)	Study site 1	2	3	4	5	6	7	Overall mean[A]
96	3·48	1·57	1·56	1·53	1·51	1·50	1·71	1·33	1·53 v
179	4·84	1·49	1·55	1·44	1·53	1·49	1·71	1·32	1·51 vw
286	5·95	1·50	1·54	1·42	1·50	1·47	1·65	1·33	1·49 w
647	9·12	1·45	1·52	1·44	1·49	1·50	1·69	1·35	1·49 w
Overall mean:[A]		1·50 c	1·54 d	1·46 b	1·51 cd	1·49 bc	1·69 e	1·34 a	—

[A] Postscripts denote significant differences; l.s.d. 5% for sampler size overall means = 0·028; l.s.d. 5% for study site overall means = 0·037.

The response surface analysis of the relationship between sampler size and BD estimate indicated a significant ($P < 0 \cdot 01$) linear component. The overall BD estimates for all sites pooled ranged from $1 \cdot 53\ \mathrm{g\ cm^{-3}}$ for the smallest diameter sampler to $1 \cdot 49\ \mathrm{g\ cm^{-3}}$ for the largest (Table 3). This difference was significant at the 0·05 level.

Comparison of variances estimated for the four sampler sizes indicated no significant differences between either sampler size or site, and no significant site by sampler size interaction. Over the range of observed BDs, variance was unrelated to mean. All data were therefore pooled and a single estimate of variance $[0 \cdot 0071\ (\mathrm{g\ cm^{-3}})^2]$ was determined.

The formulae presented in Steel and Torrie (1981) were used to calculate the standard error of the mean ($S_{\bar{X}}$). For the purpose of determining optimal sample size, absolute error was calculated as

$$\mathrm{CL}_{95\%} = t_{0 \cdot 05(n-1)}\, S_{\bar{X}}\ (\mathrm{g\ cm^{-3}}),$$

where $\mathrm{CL}_{95\%}$ is the estimated 95% confidence limit of the mean, and $t_{0 \cdot 05(n-1)}$ is the Student's t at the 0·05 probability level with $n-1$ degrees of freedom (Fig. 1).

The relative error of the mean (RE) is defined as the absolute error divided by the mean, expressed as a percentage. For the lowest recorded mean BD, the relative error is

$$\mathrm{RE} = \{(t_{0 \cdot 05(n-1)}\, S_{\bar{x}})/1 \cdot 34\}100\%$$

and, for the largest recorded mean BD,

$$\mathrm{RE} = \{(t_{0 \cdot 05(n-1)}\, S_{\bar{x}})/1 \cdot 69\}100\%$$

These relationships are depicted in Fig. 2.

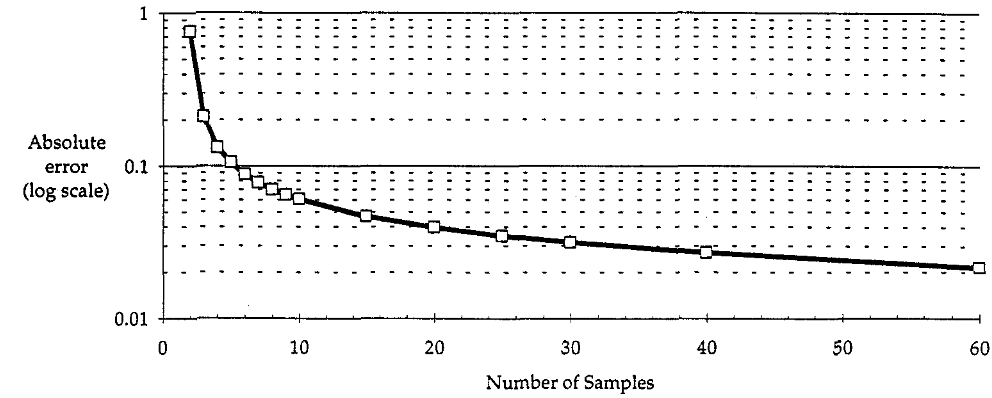

Fig. 1. Absolute error of the mean for bulk density estimates (g cm^{-3}).

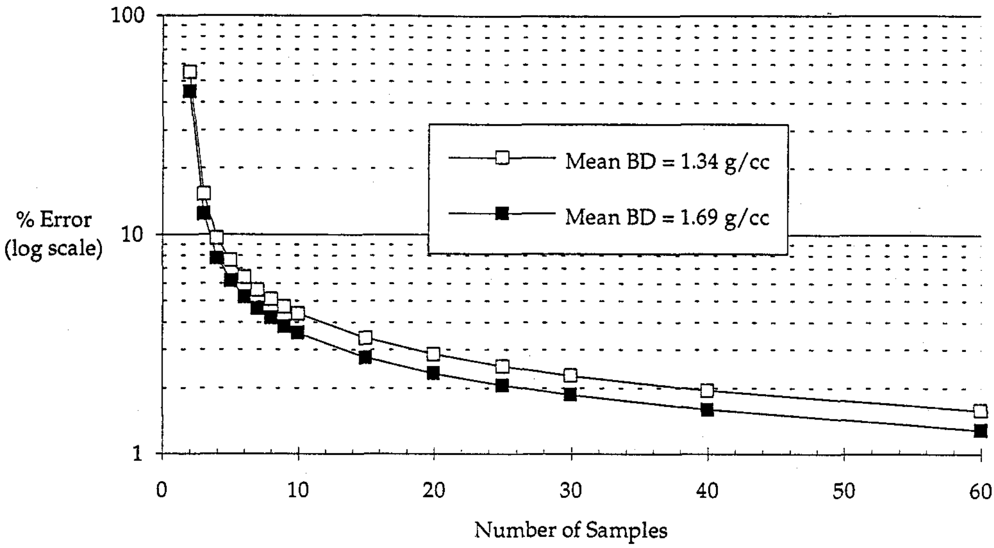

Fig. 2. Relative error of the mean for bulk density estimates.

Discussion

Soils included in the study are representative of those found in the coastal lowlands of south-east Queensland (see Foster and Costantini 1991*b*). They included a range of textural (sandy clay loam fine sandy–light clay), structural (massive–highly structured), cultivation (cultivated–not cultivated) and moisture (10·8%–21·6%) conditions (Table 2). Across this range, a small but significant reduction in estimated BD (Table 3) was associated with increased sampler size. The absence of a site by sampler size interaction indicated that this trend was consistent for the range of soils tested.

Whilst the linear component of the response curve for BD estimates *v.* sampler size is significant, the absolute differences in mean BD estimates are small (0·04 g cm^{-3}, or less than 3% of the mean on average, for the largest and smallest samplers). The slightly higher BD estimates from the two smaller samplers (Table 3) may be due to compaction around the cutting edge.

Hvorslev (1949) and McIntyre (1974) cautioned that compaction around the cutting edge increases as the area ratio, or the amount of soil which is displaced when the sampler is forced into the ground, increases. Both prescribed an upper limit for the area ratio of 10%. Only the 9·12 cm diameter sampler meets this standard. It is difficult to fabricate robust smaller diameter samplers that satisfy the area ratio requirement. As a result, the area ratios are marginal for the 4·83 and 5·98 cm diameter samplers and double the recommended maximum for the 3·48 cm diameter sampler (Table 1). The high observed BD estimates for the 3·48 cm diameter sampler are consistent with its high area ratio. The impact of the marginal area ratios on BD estimates has differed between the 4·83 and the 5·98 cm diameter samplers. Limited compaction is observed with the 4·83 cm diameter sampler but not with the 5·98 cm diameter sampler. The data suggest that an acceptable area ratio for sampler design may increase with sampler size.

McIntyre and Loveday (1974) reported that sampler diameter should be at least 7·5 cm and preferably 10 cm, but noted that a diameter of 5 cm might be sufficient for purposes not requiring high accuracy. The results of the present study indicate that bulk density estimates have not been improved by increasing sampler internal diameter beyond 5·98 cm. This result is reasonably consistent with the findings of Holt (1979) who identified 5 cm as the practical lower diameter for core samplers.

Notwithstanding the probable compaction associated with the large area ratios of the smallest sampler, the results of this study contrast with those reported by Hughes (undated). Hughes found that larger diameter samplers (8–10 cm) provided higher BD estimates than smaller diameter samplers (2·5 cm); that relative differences in the estimate of the mean for larger and smaller samplers were as high as 20%; and that a significant 'site (soil moisture) by sampler size' interaction existed. Hughes attributed the lower BD estimates of small samplers to incomplete filling of the cylinder and/or shattering during penetration. In the present study, the sampler design (relatively thin walls, sharpened and tapered cutting edges) may have avoided these difficulties. The results described by Hughes would, however, be expected if soil profiles contain dense root mats and/or incorporated wood that cannot be cleanly cut by the sampler.

In their study, Terry *et al.* (1981) found that crop roots (which comprised 2–3% of samples) did not compromise core sampler efficiency. In the coastal lowlands of south-east Queensland, root mats of sufficient density to cause problems for core samplers are likely to occur in the surface 0–20 cm of heavily grassed sites. In these situations, larger core samplers should be preferred. Regardless of the sampler size used, soil surveyors should be able to recognize problems (root mats, incorporated wood, stones, excessively loose soil) that can compromise the efficiency of core samplers.

McIntyre (1974) suggested that the integral open drive sampler be preferred for firm cohesive soils and for dry and moist non-cohesive soils. Hughes (undated) suggested that core samplers were suited to moist, medium and coarse textured soils which are either stone free or only moderately stony. Unlike McIntyre (1974), Hughes (undated) did not recommend core samplers for use in any dry soils. The findings of this study suggest that the core sampler technique can be used in a wider range of conditions than that preferred by McIntyre (1974) and recommended by Hughes (undated). In addition to the soils recommended in Hughes (undated), core samplers are shown to be suited to moist fine textured soils and relatively dry fine, medium and coarse textured soils. The utility of any core sampler will be limited in very dry soils where either core penetration is difficult and/or a lack of soil consistence makes extraction of the sampler together with the sample difficult.

Peck (1983) reported that observed variance of many soil physical characteristics typically decreases before ultimately reaching a limit as sampler size increases. A representative elementary volume (REV) is defined as the smallest sample size which results in a constant variance being estimated. By using this definition, the smallest sampler trialled in the present study exceeds the REV for BD assessment in the coastal lowlands of south-east Queensland.

In this study, the normal distribution provided a good fit to the BD estimates. This is consistent with findings from other studies (e.g. Peck 1983). The sample estimate of variance, $0 \cdot 0071$ $\{\mathrm{g}\,(\mathrm{cm}^{-3})^2\}$, is also consistent with estimates reported in the literature (see e.g. Warrick and Nielsen 1980), though, higher estimates of variance could be expected if larger, more heterogeneous sampling areas are used (Peck 1983).

The estimate of variance reported in this paper can be used to guide future BD assessments. For typical soils in the coastal lowlands of south-east Queensland, a sampling intensity of five replications can be expected to provide a point estimate of bulk density with an error interval of $\pm 0 \cdot 1\ \mathrm{g\,cm^{-3}}$ at the 95% confidence level (Fig. 1). The five estimates can be expected to provide a relative error for the mean of $7 \cdot 5$% and 6% respectively for a cultivated soil with a mean BD of $1 \cdot 34\ \mathrm{g\,cm^{-3}}$ and an uncultivated heavy soil with a mean BD of $1 \cdot 69\ \mathrm{g\,cm^{-3}}$.

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