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Comparison of techniques for estimating soil bulk density in arid and semi-arid rangelands: implications for estimation of soil carbon stocks

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Abstract

In Australia, arid and semi-arid rangelands cover vast areas, and contribute to the livestock industry, carbon market, and provision of other ecosystem services. Because of their extent, even minor changes in rangeland soil organic carbon (SOC) stocks on a per-area basis may significantly impact the terrestrial carbon budget. Estimation of SOC stocks from soil C concentrations requires estimates of gravel content, sampling thickness and soil bulk density (*BD*). However, *BD* is a major source of uncertainty, and determination of SOC stocks is often limited by challenges in *BD* estimation. In the absence of measured *BD* values, alternatives such as digitally mapped spatial layers are used to derive *BD* but these values are at relatively low resolution, are static and have relatively high uncertainty. Due to inherently low SOC stocks in rangeland ecosystems, accurate estimation of *BD* is important to detect temporal change.

The most effective method for measuring *BD* will depend on factors such as soil type and moisture conditions at sampling. Here we compared estimates of *BD* to 50 cm sampling depth across several rangeland sites derived from different field methods including: i) the mass of whole soil and volume of carbon concentration cores, corrected for oven-dry moisture content; ii) the mass of whole soil and volume of brass rings collected from soil pits corrected for oven-dry moisture content; and iii) *in situ* gamma-neutron gauge measurements of dry density adjacent to a subset of the cores. Under relatively dry soil conditions, the soil core method gave inconsistent and sometimes spurious results. By comparison, the other methods gave more consistent results. These differences have significant implications for the subsequent estimation of SOC stocks. Our results inform optimal pathways for estimating *BD* in arid and semi-arid rangelands to allow more accurate calculation of stocks and change detection over time.

Introduction

Arid and semi-arid rangelands cover vast areas of Australia and contribute to the livestock industry, carbon market, and provision of other ecosystem services (Department of the Environment 2014; NRMMC 2010; Woinarski et al. 2007). Because of their extent, even minor changes in rangeland soil carbon stocks on a per-area basis may significantly impact the terrestrial carbon budget (Conant et al. 2017).

Estimation of SOC stocks (Mg C ha^{-1}) from soil C concentrations requires estimates of gravel content and soil bulk density:

$$C_s = C_m \times BD \times D \times (1\text{-}G/100) \qquad \text{(Eqn 1)}$$

where C_m is the mass of soil organic C in the soil (%), *BD* is the soil bulk density (g cm^{-3}), *G* is the gravel content (%), and *D* is the thickness of the layer (cm). *BD* is a major source of uncertainty (e.g. Poeplau et al. 2017; Taalab et al. 2013), and determination of SOC stocks in arid and semi-arid rangelands is often limited by challenges in *BD* estimation.

BD can be estimated from 'direct' methods, such as core, clod, and excavation sampling, or 'indirect' methods including radiation and regression approaches such as pedo-transfer functions (Al-Shammary et al. 2018). Digital soil maps can also be used to derive BD but are typically of relatively low resolution, are static and have relatively high uncertainty. The most effective method for measuring *BD* will likely depend on the soil type and moisture conditions at the time of sampling. For example, if soils are dry and crumbly, cores may not be fully intact, resulting in large variation between cores, potentially resulting in spurious estimates. Using rings collected from soil pits largely removes the issue of crumbling cores, but typically lacks spatial coverage. Spatial representation could be addressed through excavating multiple pits, but this is time consuming and expensive. Indirect methods such as using gamma-radiation attenuation may be useful for increasing spatial representation in a more time- and cost-effective way, but accuracy is influenced by soil depth (Alam et al. 2001). Therefore, the aim of this study was to compare and assess the utility of three alternative methods for estimating *BD* and subsequent estimation of SOC stocks to inform future sampling strategies in arid and semi-arid rangelands.

Methods

Field sampling and measurement

The study sites included six long-term experimental trials in Australian rangelands (Table 1). Sampling was undertaken between September 2023 and August 2024 to compare three methods for determining soil bulk density (*BD*):

i. Soil was sampled from 12-30 random locations per plot depending on plot size using a corer (internal diam. 43 mm) to 50 cm depth, with three depth intervals 0-10, 10-30 and 30-50 cm;

ii. Soil was sampled from a single excavated pit per plot, with pit ledges at 0, 10 and 30 cm. Where soils were dry and crumbly, pits were irrigated overnight to 'wet up' the soils prior to sampling. Three brass rings (internal diam. 98.5 mm) were collected from each of three depth intervals 0-10, 10-30, 30-50 cm per plot;

iii. *In situ* measurements of BD were taken using a surface gamma-neutron gauge (Troxler Model 3440+, Troxler Electronics Laboratories, Inc, NC, USA) at 4-12 locations per plot depending on plot size adjacent to a random subset of cores from method i., at three depths (10, 20 and 30 cm). Deeper measurements were also made on each of the pit ledges from method ii), corresponding to depths of 10, 20 and 30 cm, 20, 30 and 40 cm and 40, 50 and 60 cm for the pit ledges at 0, 10 and 30 cm, respectively.

Sample processing and BD estimation

For i., soil samples were air-dried (40°C oven until constant weight) and bulked into 4-5 composite samples per depth per plot. For each bulked sample, peds were crushed using a mortar and pestle, and sieved to <2 mm to remove gravel and large organic matter (e.g. woody roots). The moisture content in the <2 mm soil samples after air drying was quantified gravimetrically by oven drying a 20-30 g subsample at 105°C for 48 hours. For each >2 mm sample, gravel was separated from organic matter and the weight recorded. Gravel content (*G*, %) was calculated as:

$G = G_m/W_m \times 100$ (Eqn 2)

Where G_m is the mass of the gravel in the >2 mm sample and W_m is the oven-dry corrected mass of the whole (>2 mm + <2 mm) soil sample.

For ii., the fresh weight of each sample was recorded before drying at 105°C to constant mass. For iii., the gauge measures BD by gamma source and moisture by neutron source, correcting wet BD to dry BD.

Using these data, we estimated *BD* (g cm^{-3}) of each depth interval in three ways:

i. *Core BD.* From the mass of the whole soil (fine and gravel fractions) and volume of the cores, corrected for oven-dry moisture content, as recommended in the Guidelines for the Soil Carbon Measurement Methodology (Australian Government 2021);

ii. *Pit BD*. From the mass of the whole soil (fine and gravel fractions) and volume of the rings collected from a single soil pit per plot corrected for oven-dry moisture content;

iii. *Gauge BD.* From *in situ* gamma-neutron gauge measurements of dry density.

To provide a preliminary test of the implications of differing *BD* estimates in the estimation of SOC stocks, alternative estimates of carbon stocks were derived (Eqn 1) using a consistent total carbon concentration for each of the 0-10, 10-30 and 30-50 cm depths layer as 4, 3 and 2 mg g^{-1}, respectively. Two contrasting sites – one with dry soils at the time of sampling (Wapweelah), and another with relatively moist soils at the time of sampling (Boatman) were compared.

Data analysis

Bland-Altman analysis (Bland and Altman 1999) measures the agreement, and quantifies the difference, between two methods compared with correlation and regression analyses where only the association between two methods is assessed. Here, Bland-Altman plots (also called Tukey mean-difference plots) of the differences against the averages of the alternative methods for the plot-level data were used to evaluate bias between the mean differences, and to estimate an agreement interval, within which 95% of the differences of the second method, compared to the first one, fall. The 95% limits of agreement were estimated by mean difference ±1.96 standard deviation of the differences. Because three measurement methods were compared here, plots were compared for each pairwise combination (Core vs. Pit, Core vs. Gamma, and Pit vs. Gamma). Data were checked for the assumption of normality. All analyses were performed using R statistical software (R 4.4.1) (R Core Team 2024).

Results

BD obtained from individual cores gave inconsistent and sometimes spurious results, with values ranging from 0.49-3.46 g cm^{-3} (Figure 1a). By comparison, *BD* obtained from individual rings (method ii) or individual gauge measurements (method iii) gave more consistent results in the range 1.21-1.88 g cm^{-3} (Figure 1b) and 1.09-1.86 g cm^{-3} (Figure 1c), respectively. Plot means for *BD* obtained from cores, pits and gauge measurements were 1.17-2.15 g cm^{-3}, 1.27-1.83 g cm^{-3} and 1.18-1.86 g cm^{-3}, respectively.

Bland-Altman analysis of the Pit BD and Gamma BD methods (Figure 2a) showed the mean difference was 0.10 and the 95% limits of agreement ranged from -0.10 to 0.31. There was no clear proportional bias, indicating that the difference between the two methods was consistent across the average bulk densities. By comparison, Bland-Altman analysis of the Core BD and Pit BD methods (Figure 2b) showed the mean difference was 0.01 and the 95% limits of agreement ranged from -0.37 to 0.39. Although the mean difference was close to zero, the plot indicated a proportional bias, with the difference between the two methods varying as the average soil bulk density increased. Analysis of the Core BD and Gamma BD methods (Figure 2c) showed the mean difference was 0.09

and the 95% limits of agreement ranged from -0.19 to 0.38. The Bland-Altman plot indicated a proportional bias, with the difference between the two methods varying as the average soil bulk density increased, although less steeply than for the Core and Pit BD comparison.

SOC stocks at 0-10, 10-30 and 30-50 cm depth estimated at a site where soils were dry at the time of sampling, were 15.1%, 9.5 and 0.1 % higher, respectively, using *BD* estimated from individual cores compared with the plot mean for the pit. By comparison, at a site where soils were relatively moist at the time of sampling, SOC stocks at 0-10, 10-30 and 30-50 cm depth were 18.8%, 8.8 and 16.3 % lower, respectively, using BD estimated from individual cores compared with the plot mean for the pit.

Table 1. Site characteristics, experimental designs and previous studies relating to the experiments used in this study.

Site name	State[1]	Latitude	Longitude	Experiment type	No. of plots[2]	Year trial established	Vegetation type
Oakvale	NSW	-30.95	146.46	Grazing exclosure	4	1975	*Eucalyptus* woodland
Wapweelah	NSW	-29.26	145.32	Grazing exclosure	4	1996	*Acacia* woodland
Croxdale	QLD	-26.46	146.13	Grazing exclosure	3	1981	*Acacia* woodland
Lanherne	QLD	-26.74	145.09	Grazing exclosure	3	1984	*Acacia* woodland
Boatman	QLD	-27.24	146.98	Thinning trial	7	1963	*Acacia* woodland
Monamby	QLD	-26.64	145.38	Thinning trial	6	1965	*Acacia* woodland

[1] NSW = New South Wales, Qld = Queensland; [2] number of plots sampled for bulk density. May not represent all plots in the experiment.

Discussion

A key finding of this study was that *BD* obtained from individual cores (method i) gave inconsistent and sometimes spurious results, while *BD* obtained from individual rings (method ii) or individual gamma-neutron gauge measurements (method iii) gave more consistent values within the expected range for soils. Although the plot means derived for core *BD* were more reasonable, in some cases they were still erroneously high (>2 g cm^{-3}). Further, because SOC stocks are typically calculated based on individual cores (or several cores where samples are bulked), SOC stock estimates using *BD* estimates from cores are likely to be significantly affected. This was demonstrated by the differences between SOC stocks using *BD* estimated from cores versus pits, particularly in the surface 10 cm of soil. The Soil Carbon Measurement Methodology Guidelines (Australian Government 2021) specify estimation of *BD* volumetrically using cores. Our results suggest that, depending on the soil conditions at sampling, alternative methods should be considered for determining *BD* in rangeland soils.

Results here confirmed that *BD* samples from pits that were irrigated overnight to 'wet up' the soils prior to sampling removed the issue of crumbling cores in dry soils. However, pit sampling lacked spatial coverage across the plots, and sampling multiple pits would be time consuming and expensive. Here, data from the gamma-neutron gauge provided better spatial coverage and more consistent *BD* estimates than cores. Although *BD* estimates from pit rings were typically higher than those from the gamma-neutron gauge, Bland-Altman analysis indicated that bias was relatively constant. By comparison, Bland-Altman analysis of core and pit estimates of BD showed that although the mean difference was close to zero, bias was proportional, with the difference between the two methods varying as the average soil bulk density increased. Bland and Altman (1999) recommended that 95% of data points should fall within 2 standard deviations of the mean difference. The method only defines the intervals of agreements, and not whether those limits are acceptable or not, therefore acceptable limits must be defined a priori (Giavarina 2015).

The main outcome of this work has been to progress knowledge on the trade-offs between three approaches to measurement of soil bulk density in rangelands. Although not sampled in this study, vertosols are a relatively common soil type throughout parts of the Australian rangelands. Determining *BD* in vertosols has the additional challenge of periodic swelling and cracking of these soils in relation to moisture content (Yule 1981), and further work is required to test the utility of methods in vertosols.

It should be noted that in the Soil Carbon Measurement Methodology Guidelines (Australian Government 2021), stocks are expressed on an equivalent soil mass (ESM) basis rather than on a specific thickness basis. The next phase of this work will investigate whether the ESM approach can avoid these differences in stock estimates resulting from different *BD* measurement approaches.

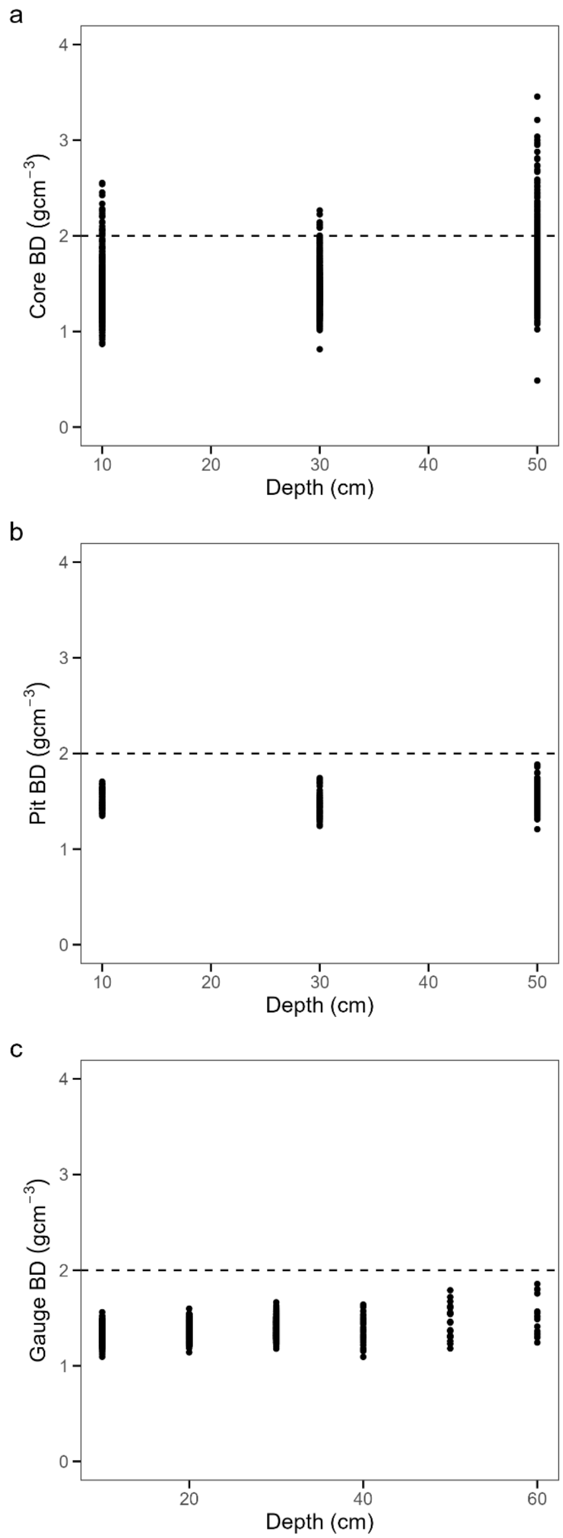

Figure 1 Scatterplots of individual soil bulk density (BD) estimates obtained from: a) individual cores (method i), b) individual gamma-neutron gauge measurements (method iii), and c) individual rings (method ii) by lower depth of sample (Depth). The dashed line indicates a value of 2 g cm^{-3}, the typical upper limit for soil.

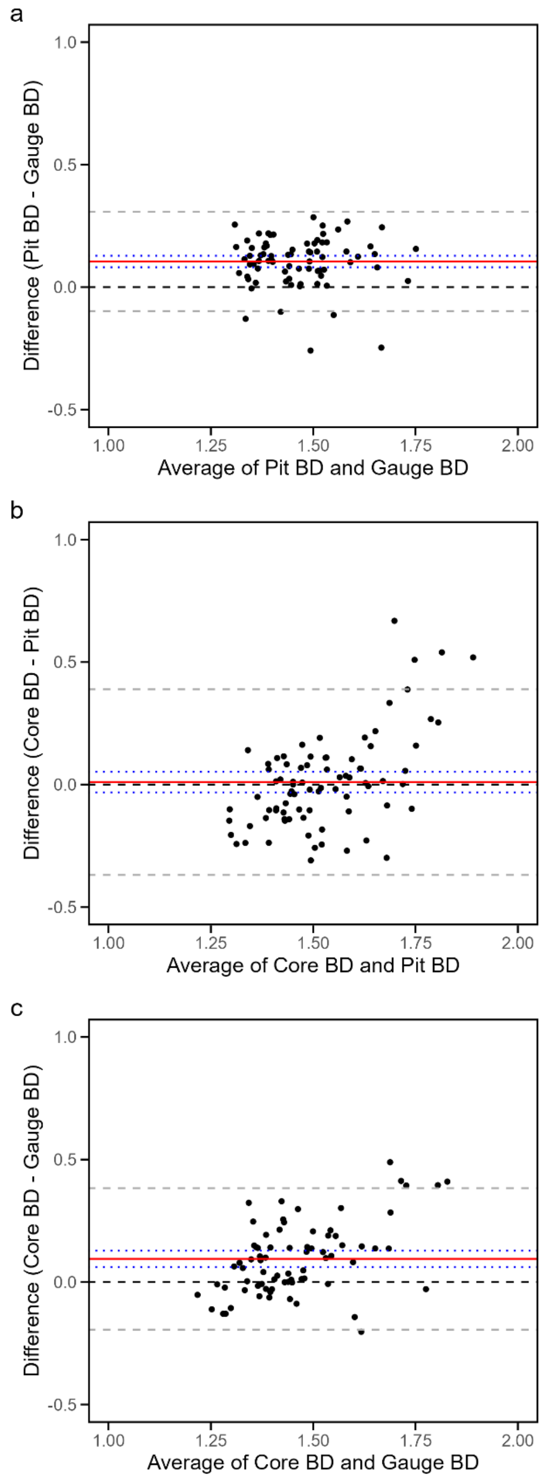

Figure 2 Bland-Altman plots showing the difference between pairs of bulk density (BD) methods plotted on the y-axis against the average of the methods on the x-axis for: a) Pit BD and Gauge BD, b) Core BD and Pit BD, and c) Core BD and Gauge BD. Solid red horizontal line shows the mean difference, dotted blue lines show the 95% confidence interval of the mean difference, dashed grey lines show limits of agreement (±1.96 standard deviation of the differences) and dashed black line shows the line of equality (zero difference). Difference and average values are calculated from three depth intervals (0-10, 10-30 and 30-50 cm) at each of the 27 plots across the six rangeland sites.

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