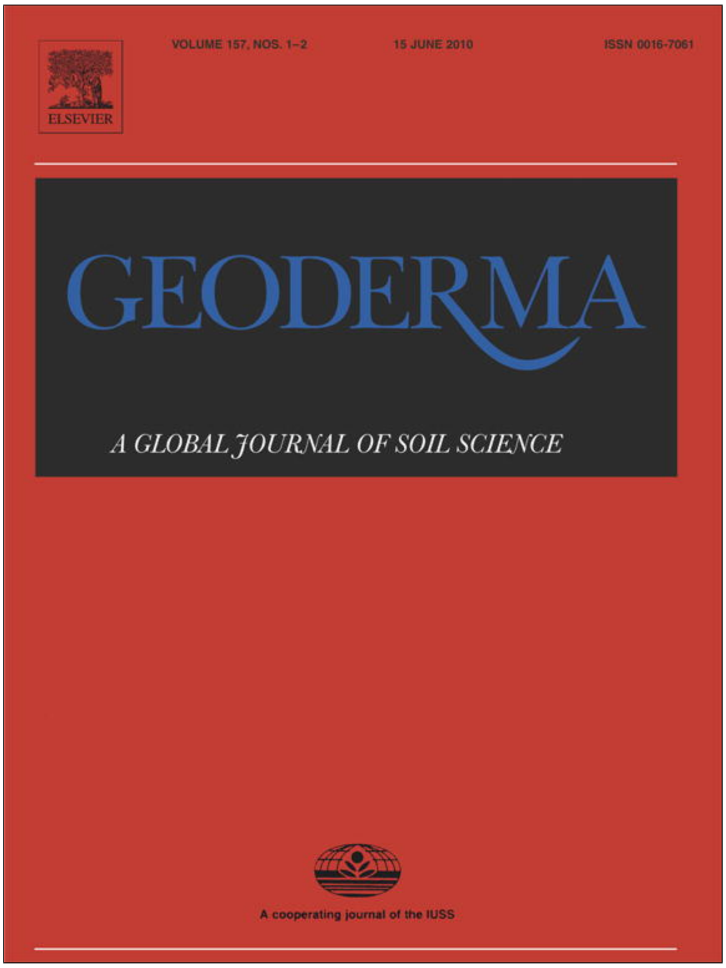
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Correcting bulk density measurements made with driving hammer equipment

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ABSTRACT

Accurate measurement of dry bulk density is critical for determining stocks of elements such as carbon or nitrogen, in soils. During investigations of changes of soil carbon with time, we resampled soil profiles for bulk density using two methods, namely the driving hammer method and the carving method. The carving method involves gently pressing a metal ring down into a carved pedestal of soil while the hammer method uses percussion to insert a metal ring into the top of a soil layer. We consider the carving method to be more accurate because the soils are less disturbed using carving. The hammer method generally underestimated bulk density by about 5% in comparison with the carving method – depending on soil order and horizon. Most of the bulk density data in the New Zealand National Soils Database (originally collected in moist soils for water release characterisation) were obtained with the hammer method and can now be corrected to the equivalent of data obtained by carving. With data from 44 soil profiles comprising 388 horizons, we showed that a greater correction is needed for soils in the Allophanic (+10%) and Melanic soil orders than for other soil orders. The Brown Soils were separated from the remaining soils and a correction factor of about +9% was required for their A and AB horizons and +3% for their subsoil horizons. The remaining soils required a correction factor of +6% for their A and AB horizons and +3.5% for their subsoil horizons. The correction factor for the A horizons for the Allophanic Soils was similar to their subsoil horizons, suggesting that the influence of aluminium and allophane was overriding that of soil carbon. The Melanic Soils required a correction factor of +13% for their A horizons but their subsoil horizons responded differently to other soils possibly because of high smectite contents. These differences in bulk density, attributed to change in sampling method, were often greater than changes in soil carbon that would be considered important. Although we used New Zealand soils, we believe that our conclusions will apply to many soils world-wide because most of our soils have equivalents within the FAO and USDA systems of soil classification. This study shows the importance of assessing bulk density methodology, and the possible need for other workers to amend the carbon stocks calculated from the hammer method.

1. Introduction

Since dry bulk density (BD) values for different mineral soils may have, at least, a two-fold range, it is important that BD values are used in conjunction with concentrations of soil nutrients in ecological studies. In assessing stocks of carbon in soils, BD is also required for quantifying carbon on an area basis (e.g., Schipper et al., 2007; Hopkins et al., 2009).

The method of determining BD is important (Harrison et al., 2003; Page-Dumroese et al., 1999; Stone, 1991; Vanremortel and Shields, 1993). Harrison et al. (2003) used four methods to measure BD in forest soils that contained stones, and found that the sand displacement method did not contain any bias. At the New Zealand Soil Bureau, staff used the displacement method where soils contained >15% volume content of gravels (size >10 mm). However, for both forest and agricultural soils with <15% of gravel, they used driving hammer equipment from Soil Moisture Equipment Corp, where two brass cylinders (with a 1-cm spacer) are hammered into the soil (Blake and Hartge, 1986). This slide hammer method was used in the past because it was somewhat faster than carving, and the primary purpose for collecting intact soils samples in brass cylinders was to measure water release curves for a soil profile (Blake and Hartge, 1986) rather than BD. Water release characterization required the collection of small (5.4-cm diameter) core samples, whereas BD measurement alone would normally use a larger volume of soil. It was recognised that soils could shatter if they were too dry (Blake and Hartge, 1986) so most measurements were carried out in spring when the soils were at field capacity.

A variation of the method where a thin walled cylinder is pressed into the soil (Blake and Hartge, 1986) is the method of carving soils to obtain BD (Gradwell, 1972). Here the operator carefully carves away the soil, to form thin pedestals of soil, and then progressively presses a

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cylinder over the pedestals until the cylinder is over-full and the top and base can be carved back to planar surfaces, yielding a perfect cylinder of soil filling the internal volume of the metal cylinder. We consider the carving method to be more accurate because the soils become less disturbed using carving (Blake and Hartge, 1986).

Comparison of the driving hammer method with the carving method for soils under pasture showed that the driving hammer method gave low BD values, indicating that cracking or expansion of the soil fabric occurred. Correction factors were therefore required to report C and N stocks accurately (Schipper et al., 2007). In this study, we collected a larger data-set of side-by-side comparisons of bulk densities using hammer and carving methodology across a broader range of soil orders. Our data allowed us to calculate robust correction factors to be applied to the 4000 observations of BD, measured with the hammer method, in the New Zealand National Soils (NSD) database – and originally collected for water release characterisation. These corrections are needed to better assess stocks of carbon and other elements in New Zealand soils.

2. Methods

During resampling of NSD soils under pasture, 44 profiles were investigated. Six of these profiles contained 1% by weight of stones in the lower horizons. Soil pits were excavated to about 1 m depth. BD samples were taken with the driving hammer 0200-core sampler (Soil Moisture Equipment Corp, Santa Barbara, California), which uses a small slide hammer to drive a coring barrel into the soil. The coring barrel was fitted with a wedge shoe. The coring barrel contains two brass cylinders, 5.4 cm in diameter and 3.0 cm high (volume of each is 68.2 cm^3). There were spacers above, between and below the rings. Samples were taken from horizontal "shelves" of soil and the hammer was in a vertical position.

For comparison, samples were also taking by carving: a brass cylinder of the same dimensions was placed on the same shelf, the soil carefully and sequentially carved away outside the cylinder to form a pedestal of soil. The cylinder was then progressively pressed down over the pedestal of soil as it was carved until about 1 cm of soil was above the top of the cylinder. The soil was cut 1 cm below the cylinder, which was then removed. The soil in the cylinder was carved so that it was flush with the top and bottom of the cylinder. Two carved cores were collected at the same depths as for the hammer method. This was repeated for each soil horizon. The soil was dried at 105 °C for 24 h, weighed and the BD calculated. Where stones were present these were not separated since they represented only 1% by weight.

The data-set included bulk densities by carving and hammer method, sample top and bottom depth, and water content (WC) at the time of sampling (% w/w), for 388 unique samples, together with NSD data on soil order, sample horizon designation (Ap, Bw, etc.), carbon, P-retention, CEC, extractable aluminium, iron, and silicon. The data for clay were incomplete and were not used. Stepwise multiple linear regressions were carried out in Genstat to examine which soil properties could be used in addition to the hammer values to correct BD, and thus to predict BD by carving. Differences in mean BD measured and calculated by different methods were compared to those by carving using root mean square errors (*RMSE*):

$$RMSE = \sqrt{\frac{\sum_i (P_i - O_i)^2}{n}}$$

where P_i = the model prediction, O_i = the observed value and n = number of observations.

Different statistical models using soil order and soil horizon were run in Genstat to test for the best model using generalized linear models in regression analysis with accumulated ANOVA. Linear regressions of BD values collected using the two methods were carried out in Genstat for the whole dataset, for separate soil orders and soil horizons based on NZ soil classification (Hewitt, 1998). Assessment of the % correction required was determined using the means of the bulk densities obtained by the different methods.

3. Results and discussion

The soil orders (and their equivalent classifications (Table 1)), number of samples, and the maximum depths of the profiles are reported in Table 2 together with the maximum, mean, and minimum values of BD by both the hammer and carving method. The bulk densities obtained from the carving method (BD_Carved) were plotted against bulk densities from the hammer method (BD_Hammer) for all soil orders (Fig. 1). Generally, greater BD was obtained by carving and the mean values were significantly different (P = 0.009), presumably because there was less disturbance to the soil structure than that caused by hammering the barrel corer and wedge shoe. The simple regression equation was:

$$BD_{\text{Carved}} = a*(BD_{\text{Hammer}}) + c \quad (1)$$

a and c are given in Table 3. This equation can be used for correcting the BD obtained by the hammer method to the BD obtained using the carving method, and gives a general correction of about +5% for the means of the data set of 388 samples.

The stepwise multiple linear regression analysis showed that the most successful equation for the whole data set was:

$$BD_{\text{Carved}} = a*(BD_{\text{Hammer}}) - b*WC + c \quad (2)$$

a, b and c are given in Table 3, where WC is the gravimetric water content (%) at the time of sampling. Regression analysis (generalized linear models) showed that the differences between the carving and hammer method was significantly (P<0.0001) related to WC. The *RMSE* was lower with this equation (0.074) than with the simple regression (0.110) (Table 3) and the mean predicted BD was 1.218 Mg m^{-3}, was nearly identical compared with 1.216 Mg m^{-3} obtained by carving (Table 4).

The Allophanic Soils (low bulk densities), however, generally have a large WC and require a correction of about 10%. Although WC provided a suitable correction based on regression statistics, the WC data are not always available and depend on rainfall before sampling. Therefore, we sought to replace WC with more invariant parameters to obtain a reliable correction equation.

If only one extra term was added to hammer BD data, regression analysis demonstrated that soil order was the best term to use – giving the highest R^2 value of 94.7% (P<0.001). Horizon designation was the second best term to use (R^2 = 94.6; P<0.001). The horizon designation, however, covered a wide range of designations from Ap to Cg. We substituted "A" for all horizons beginning with A (e.g., Ap, AB, etc.), and, since there were few C horizons, for the remainder (B and C horizons) we substituted "subsoil" in the regression analysis, and obtained a similar result to that using all horizon designations. We also tested two generalized regression models that included soil order either with or

Table 1
New Zealand Soil orders, Soil Taxonomy (Soil Survey Staff, 2006) and IPCC equivalent.

NZ Soil order	Soil Taxonomy	IPCC
Allophanic	Andisols (Udands)	Andisols
Brown	Inceptisols (Ochrepts)	Sandy soils
Gley	Aquepts, Aquents	Aquic soils
Melanic	Mollisols	Soils with high clay activity
Oxidic	Oxisols	Soils with low clay activity
Pallic	Alfisols	Soils with low clay activity
Recent	Entisols, Inceptisols	Sandy soils
Semi-arid	Aridisols	Soils with high clay activity

Table 2
Soil orders, number of samples, maximum depths of the profiles, maximum, mean, and minimum values of dry bulk density (BD) by both the hammer and carving method.

Soil order	Profiles	Maximum depth	Samples	BD Hammer	BD Hammer	BD Hammer	BD Carving	BD Carving	BD Carving
				Minimum	Mean	Maximum	Minimum	Mean	Maximum
		cm		$Mg\ m^{-3}$	$Mg\ m^{-3}$	$Mg\ m^{-3}$	$Mg\ m^{-3}$	$Mg\ m^{-3}$	$Mg\ m^{-3}$
Allophanic	9	100	69	0.44	0.63	0.91	0.42	0.69	1.00
Brown	12	104	120	0.79	0.89	0.96	0.98	1.05	1.14
Gley	7	106	66	0.69	1.24	1.80	0.62	1.31	1.80
Melanic	3	105	29	0.71	1.27	1.69	0.79	1.32	1.64
Oxidic	1	36	6	0.88	1.34	1.68	1.07	1.47	1.71
Pallic	4	85	27	0.68	1.22	1.70	0.77	1.25	1.71
Recent	4	110	37	0.77	1.19	1.59	0.78	1.24	1.70
Semi-arid	4	100	34	0.89	1.42	1.77	1.04	1.52	1.84

without soil horizon to determine if they were an improvement over the simple regression model in Fig. 1. Both of these models had $P<0.001$ for soil order in the accumulated ANOVA. The P value for soil horizon was also <0.001 when it was included. The two models both had $R^2=94.5$. This shows that both these models are an improvement over the simple regression model.

Since the Allophanic, Melanic and Brown soil have different mineralogy (Hewitt, 1998) they have been grouped separately from the other soil orders; and since A and AB horizons contain more organic matter they have been separated from subsoils. Regression equations were developed for these groups that give correction factors for BD obtained with the hammer method, and they are shown in Fig. 2. The greatest correction was required for soils in the Allophanic and Oxidic (about +10%), and Melanic (A horizon) soil orders (about +13%). The Brown Soils required a correction of about +9% for their A and AB horizons but only +3% for their subsoil horizons. The remaining soils could be grouped together and required a correction factor of +6% for their A and AB horizons and +3.5% for their subsoil horizons.

The parameters that give the corrections are presented in Table 5 for the regression equations with the form:

$$BD_{\mathrm{Carved}} = a*(BD_{\mathrm{Hammer}}) + c$$

The A horizons for the Allophanic and Oxidic Soils had similar correction factors as those for their subsoil horizons, and these are grouped together (Fig. 2A). The mean values of BD by both methods were significantly different ($P=0.009$). This regression equation had a lower *RMSE* than the equation using WC (Table 4). These soils have aggregates stabilised by large amounts of aluminium hydrous-oxides, iron oxides and/or allophane (Hewitt, 1998). Hammering and the shock wave associated with hammering may cause a rearrangement of these aggregates, resulting in a greater porosity within the cylinder in comparison with soil in the profile. We speculate that this arises from the variable charges on these materials (Parfitt, 1990), which may "lock in" the rearrangement. Since the A and subsoil horizons behave in a similar manner, the presence of the variable charge materials appears to override the effect of soil organic matter.

The Melanic Soils required a correction factor of about +13% for their A horizons but their subsoil horizons responded differently from other soils and no correction factor could be obtained (Fig. 2B). This effect possibly arises from the presence of smectite in the subsoil horizons (Hewitt, 1998), which may reduce friction and the effect of hammering as the soil moves through the brass cylinder. The mean values of BD by both methods were significantly different ($P=0.005$).

The Brown Soils, which usually contain iron oxides (Hewitt, 1998), were separated from the remaining soils; a larger correction factor (about +9%) was required for their A and AB horizons than for their subsoil horizons (about +3%) (Fig. 2C, D). The mean values of BD by both methods were significantly different ($P=0.05$).

The remaining soil orders also required a larger correction factor (about +6%) for their A and AB horizons than for their subsoil horizons (about 3.5%) (Fig. 2E, F). Both the soil carbon concentration and the concentration of plant roots are greater in the A horizons than the subsoils, therefore the different behaviour of A horizons during sampling with the two methods could be influenced by soil carbon and plant roots. The lower BD results obtained during hammering may be caused by resistance of plant roots to hammering and/or binding of soil organic matter to mineral particles that may "lock in" the rearrangement of aggregates. The mean values of BD by both methods were significantly different ($P=0.04$).

Our BD values range from 0.44 for Allophanic Soils to 1.80 for Gley Soils (Table 2). Therefore, measurement of BD (as well as % carbon) is essential in assessing carbon stocks in New Zealand. Our data also demonstrate that it is important to assess the methods used for obtaining BD, and correction factors may be required for some data sets. An underestimate of 5% in BD measurements would, on average, result in a 5% underestimate in total C stocks in soil. Given that pasture soils can often contain between 100 and 300 t C ha^{-1} (Conant et al., 2001; Schipper et al., 2007), a 5% underestimate of BD could equate to 5–15 t C ha^{-1}. If not corrected, this change in soil C is greater than changes in soil C attributed to many changes in land management practices over a number of years (Conant et al., 2001; Schipper et al., 2007). Particular care should be taken when combining datasets

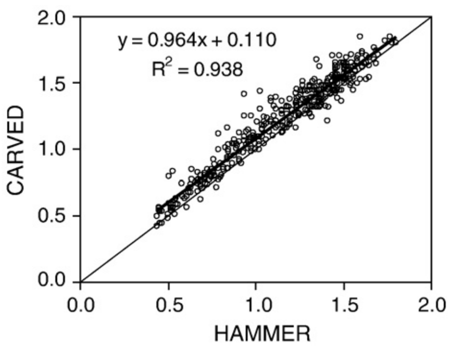

Fig. 1. Linear regression of bulk density by both methods for all samples; together with 1:1 line (units are $Mg\ m^{-3}$).

Table 3
Parameters used in simple regression equation ($BD_{\mathrm{Carved}}=a*(BD_{\mathrm{Hammer}})+c$) and multiple regression equation ($BD_{\mathrm{Carved}}=a*(BD_{\mathrm{Hammer}})-b*WC+c$) using water content.

Equation #	Parameter	Value	Std Err
Simple regression 1	*a*	0.964	0.013
Simple regression 1	*c*	0.110	0.015
Multiple regression 2	*a*	0.867	0.0223
Multiple regression 2	*b*	0.0014	0.00027
Multiple regression 2	*c*	0.274	0.0349

Table 4
Mean values of dry bulk density by the hammer and carving method, and corrected using water content (C1) and using soil order and horizon equations (C2). *RMSE* = root mean square error.

Soil order	*n*	BD Hammer Mean $Mg\ m^{-3}$	BD Carving Mean $Mg\ m^{-3}$	BD Corrected Mean C1 $Mg\ m^{-3}$	BD Corrected Mean C2 $Mg\ m^{-3}$	*RMSE* Ham–Carve	*RMSE* Ham–C1	*RMSE* Ham–C2
All	388	1.148	1.216	1.218		0.110	0.074	
Allophanic/Oxidic	75	0.650	0.719	0.723	0.719	0.096	0.078	0.066
Melanic A	10	1.108	1.276	1.193	1.275	0.174	0.085	0.047
Brown A	43	1.033	1.139	1.127	1.138	0.144	0.096	0.097
Brown B	77	1.358	1.400	1.419	1.400	0.095	0.065	0.080
Other A	59	1.069	1.142	1.153	1.142	0.112	0.086	0.085
Other B	106	1.390	1.440	1.446	1.440	0.089	0.061	0.073

C1 Corrected using equation $BD_{Carved} = a*(BD_{Hammer}) - b*WC + c$.
C2 Corrected using equations for soil order and horizon.
Ham = Hammer.

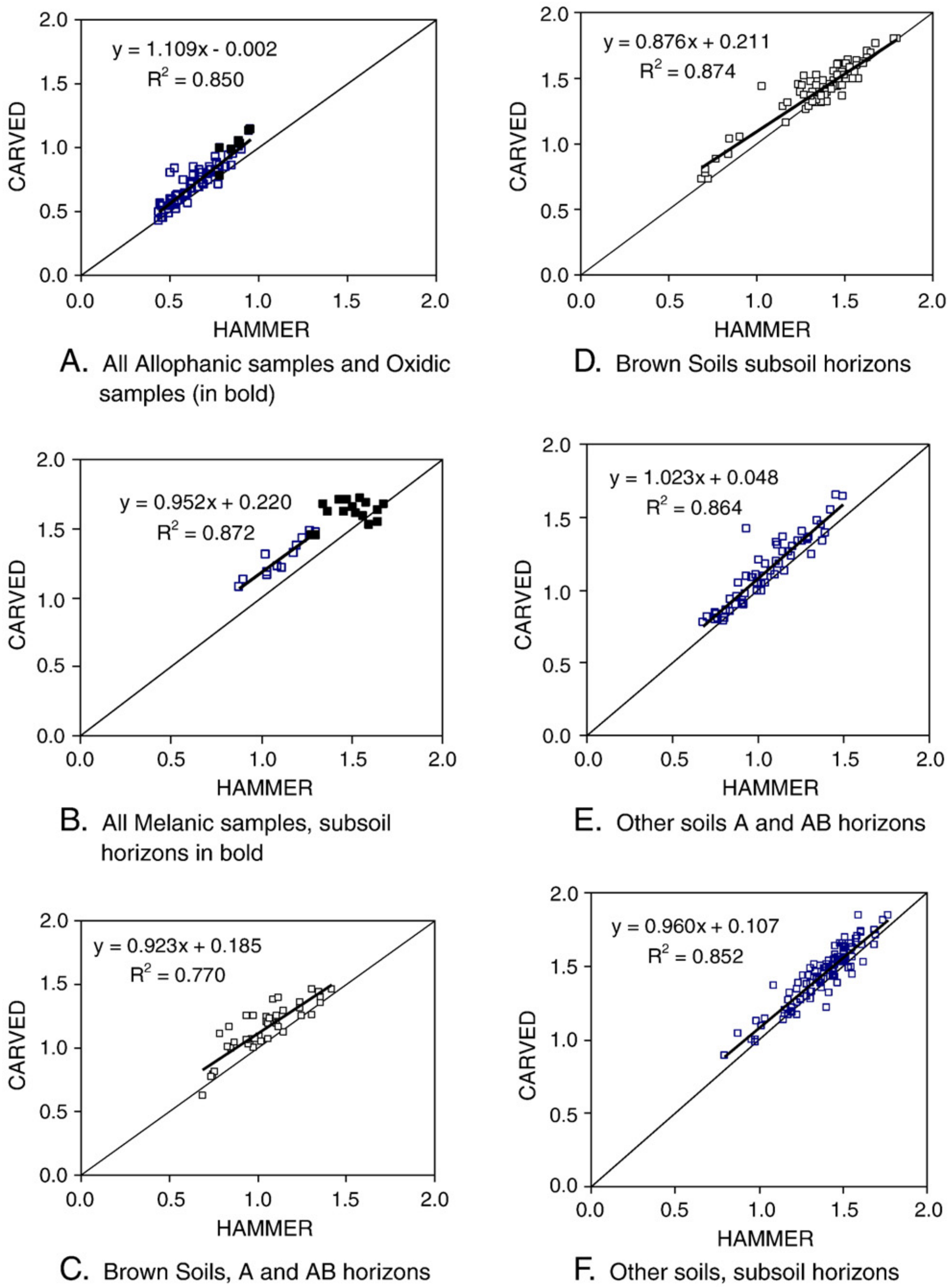

Fig. 2. Linear regressions of bulk density by both methods for groups of soils; together with 1:1 line. A. All Allophanic samples and Oxidic samples (in bold). B. All Melanic samples, subsoil horizons in bold. C. Brown Soils, A and AB horizons. D. Brown Soils subsoil horizons. E. Other soils A and AB horizons. F. Other soils, subsoil horizons (units are $Mg\ m^{-3}$).

Table 5
Parameters used in simple regression equations ($BD_{Carved} = a*(BD_{Hammer}) + c$) for different soil orders.

Equation #	Horizon	Parameter	Value	Std Err
Allophanic 3	A, B, C	*a*	1.109	0.054
Allophanic 3	A, B, C	*c*	−0.002	0.036
Melanic 4	A	*a*	0.952	0.138
Melanic 4	A	*c*	0.220	0.151
Brown 5	A, AB	*a*	0.923	0.079
Brown 5	A, AB	*c*	0.185	0.083
Brown 6	B, C	*a*	0.876	0.038
Brown 6	B, C	*c*	0.211	0.053
Others 7	A, AB	*a*	1.023	0.055
Others 7	A, AB	*c*	0.048	0.059
Others 8	B, C	*a*	0.962	0.039
Others 8	B, C	*c*	0.103	0.055

collected with both methods in national systems for soil C monitoring (Tate et al., 2003, 2005).

We recommend that the carving method be used rather than the driving hammer method. The method is suitable for both forest and agricultural soils that have few gravels (<15% by volume). We prefer to use a thin walled cylinder (100 mm diameter) to capture a larger volume of soil, such as has been used for measurements of hydraulic conductivity (Blake and Hartge, 1986). With this larger cylinder, soils containing few gravels with size <20 mm can be sampled. Sampling of the whole soil profile using the carving method takes about 30 minutes longer than the driving hammer method. It is suitable for organic soils and unconsolidated materials such as sands.

4. Conclusions

Staff at the New Zealand Soil Bureau traditionally used driving hammer equipment where a brass cylinder was hammered into the soil to obtain core samples for water release characterisation. The BD data from those measurements are now being used to assess stocks of carbon and nutrients. BD was found to be higher when collected by the more accurate hand carving method. We obtained the regression equations that give the corrections that need to be applied to the BD observations within the New Zealand National Soils database. Our results have several implications. First, soil carbon stocks in New Zealand, that were calculated with the hammer method, need to be corrected. Second, although we used New Zealand soils, we believe that our conclusions will apply to many soils world-wide. This includes agricultural and forest soils. Most of our soils have equivalents within the FAO and USDA systems of soil classification and they occur in other places in the world. Third, we would recommend that carving is used for forest and agricultural soils that have <15% volume of gravel; if more gravel is present then displacement methods should be used. Finally, our results in combination suggest that workers should carefully consider methodology before collecting BD data, and corrections may be needed globally where the hammer method was used.

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