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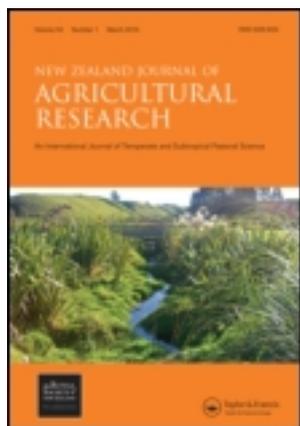
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SHORT COMMUNICATION

Use of shallow samples to estimate the total carbon storage in pastoral soils

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Using data from pastoral soils sampled by horizon at 56 locations across New Zealand, we conducted a meta-analysis. On average, the total depth sampled was 0.93 ± 0.026 m (\pm SEM), and on a volumetric basis, the total C storage averaged 26.9 ± 1.8 , 13.9 ± 0.6 and 9.2 ± 1.4 kg C m⁻² for allophanic ($n=12$), non-allophanic ($n=40$) and pumice soils ($n=4$), respectively. We estimated the total C storage, and quantified the uncertainty, using the data for samples taken from the uppermost A-horizon whose depth averaged 0.1 ± 0.003 m. For A-horizon samples of the allophanic soils, the mean C content was 108 ± 6 g C kg⁻¹ and the bulk density was 772 ± 29 kg m⁻³, for non-allophanic soils they were 51 ± 4 g C kg⁻¹ and 1055 ± 29 kg m⁻³, and for pumice soils they were 68 ± 9 g C kg⁻¹ and 715 ± 45 kg m⁻³. The C density—a product of the C content and bulk density—of the A-horizon samples was proportional to their air-dried water content, a proxy measure for the mineral surface area. By linear regression with C density of the A-horizon, the total C storage could be estimated with a standard error of 3.1 kg C m⁻², 19% of the overall mean.

Keywords: soil; carbon; allophane; pastoral; New Zealand

Introduction

Sustainably increasing the storage of organic carbon (C) in pastoral soils has the potential to ‘offset’ greenhouse gas emissions from pastoral agriculture. Determining C storage provides a baseline from which change can be assessed. This can be done by excavating soil samples and, generally, the deeper the sample, the smaller the C density. Thus, sampling depth can affect C storage, yet pastoral soils have commonly been sampled shallowly to determine the fertility (e.g. Sparling & Schipper 2004). This mismatch led us to ask how large would be the uncertainty if data from shallow samples (for example, based on soil samples taken from the surface to a depth of 0.1 m) were used to estimate the total C storage to a

deeper depth. For this purpose, we will reanalyse data reported earlier by Schipper et al. (2010) for pastoral soils sampled at 56 locations across New Zealand by horizon to a depth that averaged 0.93 m.

Materials and methods

The sampled soils were classified into nine orders according to New Zealand’s system described by Hewitt (2010). The orders included 12 allophanic and four pumice soils, and 40 others comprising 17 pallic, 14 brown, three gley, three recent, and one each of the granular, melanic and oxidic soils. Allophane is an amorphous, clay-sized mineral identified by ‘greasiness’, and for the allophanic order, clay

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content must be 10%–25% and a profile includes ≥ 0.35 m depth with allophane in the uppermost 0.6 m. Although pumice order soils can also contain allophane, their clay content is generally less than 10%. Soils with allophanic clay often have a relatively high C concentration which has been attributed to reactions with aluminium, and C storage in tiny pores, small enough to exclude hydrolytic enzymes and provide protection against microbial attack (Mayer 1994; Percival et al. 2000; von Lützow et al. 2006; Parfitt 2009). The other soils had no allophane, so hereafter, are grouped as non-allophanic. The sampled sites were located in nine regions, along a north–south transect spanning most of New Zealand's North and South Islands, approximately 1900 km long from 35.3–46.1°S. Distribution by regional council boundaries of the allophanic soil sites included Taranaki (seven sites), Waikato (three) and Manawatū-Wanganui (two). The pumice soils were sampled in Waikato, while the 40 non-allophanic soils sites included Manawatū-Wanganui (10), Gisborne (six), Otago (six), Southland (six), Canterbury (five), Waikato (three), Wellington (two), Northland (one) and Taranaki (one).

The sampling procedure began with excavation of a pit, and a soil sample taken by inserting and carving a 54 mm inside-diameter by 30 mm long brass ring into the centre of each horizon following Parfitt et al. (2010). The sample was dried for 16 h in an oven (105 °C), weighed and bulk density determined from the ratio of soil mass and sampled volume. Another sample was taken by scraping soil from each horizon for the measurement of C concentration, hereafter C content. This sample was sieved (2 mm mesh) and weighed and dried in the dark at 30 °C for 48 h before being weighed again to determine the air-dried water content (Parfitt et al. 2001). A subsample was oven-dried and analysed for C content by a combustion method (model FP2000 analyser, LECO Corporation, MI, US).

The vertical integration of C density from soil samples to determine total C storage can be

done on volumetric and equivalent mass bases. Vertical integration was done on a volumetric basis from the surface to the deepest depth sampled and to a depth of 0.3 m. The depth of 0.3 m has been recommended by the Intergovernmental Panel on Climate Change (2006). For choosing agricultural soils, the basis for a depth of 0.3 m was arable effects on the total C storage, this depth considered beyond a cultivated layer by full inversion tillage and mould-board ploughing (Dr J Baldock, pers. comm., 4 May 2012). Vertical integration was also done on an equivalent mass basis. Statistical analyses were done using Minitab (v 15) including linear regression and group comparisons by T-test assuming unequal variance and, where means have been reported, error bounds were \pm standard error of the mean (SEM).

Results and discussion

For the uppermost A-horizon, the sampling depth averaged 0.1 m (± 0.003 m), while the total sampling depth averaged 0.93 ± 0.026 m. On a volumetric basis to a mean depth of 0.93 m, total C storage of the seven non-allophanic soil orders were not statistically different from one another ($P > 0.05$), so hereafter, these data will be treated as a single group (mean = 13.9 ± 0.6 kg C m⁻², to convert kg C m⁻² to t C ha⁻¹, multiply by 10). Corresponding means of the allophanic and pumice soils were statistically significantly different from one another ($26.9 \pm 1.8 > 9.2 \pm 1.4$ kg C m⁻², $P < 0.05$) and the non-allophanic soils. For A-horizon samples of the allophanic soils, the mean C content was 108 ± 6 g C kg⁻¹ and the bulk density 772 ± 29 kg m⁻³, for non-allophanic soils they were 51 ± 4 g C kg⁻¹ and 1055 ± 29 kg m⁻³, and for pumice soils they were 68 ± 9 g C kg⁻¹ and 715 ± 45 kg m⁻³. Linear regressions between C density of the A-horizon, a product of the C content and bulk density, and total C storage yielded no significant differences between the three slopes ($P = 0.36$ for allophanic versus non-allophanic and 0.87 for pumice versus non-allophanic). Regression analysis using a

common slope of 0.23 ± 0.03 and different intercepts for the allophanic, non-allophanic and pumice soils was statistically significant, and yielded a standard error for the estimate of total C storage of 3.1 kg C m^{-2} , equivalent to 19% of the mean (16.3 kg C m^{-2} , Fig. 1).

The total C storage was then recalculated on a volumetric basis to a depth of 0.3 m. Compared with calculation to a mean depth of 0.93 m, recalculation to 0.30 m reduced the mean for total C storage of the pumice soils by 14% (i.e. to $7.9 \pm 1.0 \text{ kg C m}^{-2}$) and the non-allophanic soils' mean by 29% (to $9.9 \pm 0.4 \text{ kg C m}^{-2}$), respectively, indicating the latter soils had a lesser proportion of the total C stored between the surface and a depth of 0.3 m. Moreover, on this basis, the means for total C storage in the top 0.3 m for these two groups of soils were not significantly different. For the allophanic soils, the mean for total C storage was reduced by 35% (to $17.9 \pm 0.8 \text{ kg C m}^{-2}$) and this was significantly greater than that of the non-allophanic and pumice soils. Linear regressions between C density of the A-horizon

and total C storage recalculated to a depth of 0.3 m yielded no significant differences between the three slopes ($P=0.16$ for allophanic versus non-allophanic and 0.13 for pumice versus non-allophanic, data not shown). Regression analyses with a common slope of 0.16 ± 0.01 yielded significantly different intercepts of 4.7 ± 1.1 , 1.7 ± 0.7 and 0.1 ± 0.9 for the allophanic, non-allophanic and pumice soils, respectively, and a standard error for the estimate of total C storage of 1.3 kg C m^{-2} , equivalent to 11% of the mean. Thus, reducing the sampled depth from c. 0.9 m to 0.3 m corresponded with the total C storage estimate's standard error reducing from 19% to 11% of the mean.

Alternatively, C storage can be determined by vertical integration on an equivalent soil mass basis (e.g. Ellert et al. 2002). For the allophanic, non-allophanic and pumice soils, from the surface to a mean sampling depth of c. 0.9 m, the mean cumulative soil mass was 762 ± 63 , 1274 ± 51 and $559 \pm 73 \text{ kg m}^{-2}$, respectively. Recalculation on an equivalent mass basis, using the pumice soil's mean cumulative mass, reduced mean C storage of the allophanic soils by 10% (to $24.2 \pm 1.3 \text{ kg C m}^{-2}$) and the non-allophanic soils by 17% (to $11.5 \pm 0.6 \text{ kg C m}^{-2}$), respectively. On this basis, total C storage of the pumice and non-allophanic soils was not significantly different, but that of the allophanic soils was significantly greater. Linear regressions between C density of the A-horizon and these recalculated total C storage values yielded a standard error for the total C storage estimate equivalent to 16% of the mean (data not shown). Recalculation on the basis of the allophanic soil's mean cumulative mass reduced mean C storage of the non-allophanic soils by 11% (to $12.4 \pm 0.6 \text{ kg C m}^{-2}$). On this basis, total C storage of the allophanic soils was significantly greater than that of the non-allophanic soils. Linear regressions between C density of the A-horizon and these recalculated total C storage values yielded a standard error for the total C storage estimate equivalent to 19% of the mean (data not shown).

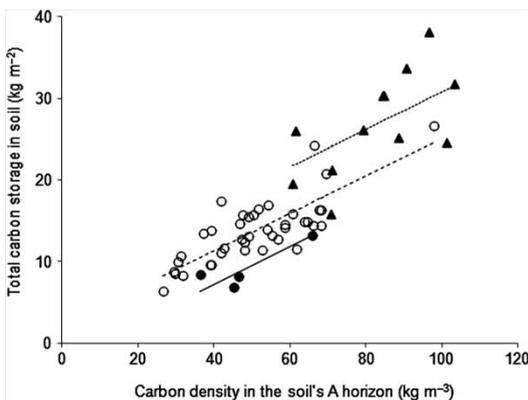


Figure 1 Relation between carbon (C) density in the soil's A-horizon and total C storage for pastoral soils classified into allophanic (\blacktriangle), pumice (\bullet) and non-allophanic (\circ) orders as described in the text. Regression analyses yield a common slope of 0.23 ± 0.03 and intercepts of 7.8 ± 2.6 for the allophanic soils (short-dashed line), -2.0 ± 2.1 for the pumice soils (—) and 2.1 ± 1.6 for the non-allophanic soils. To convert kg C m^{-2} to t C ha^{-1} , multiply by 10.

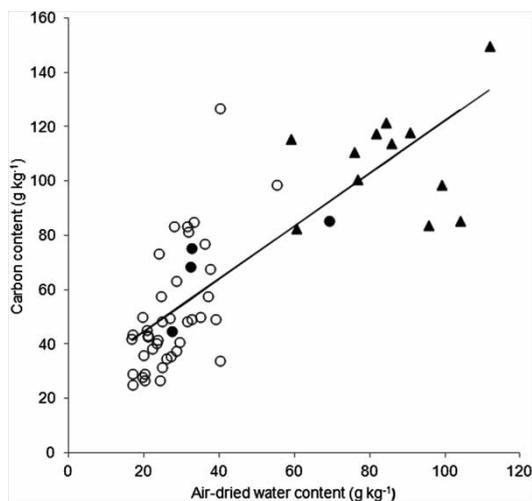


Figure 2 Relation between air-dried water content, a proxy for the specific surface area, and corresponding values of the carbon (C) content for A-horizon samples of pastoral soils classified into allophanic (\blacktriangle), pumice (\bullet) and non-allophanic (\circ) orders as described in the text. The regression line was based on analysis of all these data ($P < 0.001$, $n = 56$, slope = 1.0 ± 0.1 , intercept = 25.3 ± 4.7 , standard error of the estimate = 18.7 g C kg^{-1} , 29% of the mean C content).

The C density of A-horizon samples has been used as an independent variable to estimate total C storage in pastoral soils across New Zealand. To gain a better understanding of the C content component of our independent variable, we considered the data analysis of Mayer (1994) which yielded a consistent, linear relation between C content and the sample's specific surface area. This was interpreted to indicate the samples had the 'equivalent' of a mono-layer of organic matter, recognizing there was no evidence to suggest the organic matter had been evenly dispersed and measurements showed much of the surface area was contained in tiny pores of width $< 8 \text{ nm}$.

Parfitt et al. (2001) showed the specific surface area of soil samples could be determined from measurements of the sample's air-dried water content. On these bases, we postulated the measured air-dried water con-

tent of our A-horizon samples would be positively correlated to corresponding measurements of the C content. We tested our hypothesis by linear regression analysis which yielded a statistically significant, linear relation with a slope of $1.0 \pm 0.1 \text{ g C g}^{-1}$ (water), and based on the results of Parfitt et al. (2001), the slope would be equivalent to $0.5 \pm 0.05 \text{ mg C m}^{-2}$ (Fig. 2). Finally, by another linear regression with air-dried water content of A-horizon samples, the total C storage could be estimated with a standard error equivalent to 31% of the overall mean, a substantially greater error than for C density of A-horizon samples as the independent variable.

In conclusion, by linear regression with C density of the A-horizon, total C storage of the studied soils could be estimated with a standard error equivalent to 19% of the overall mean. Samples from the A-horizon of allophanic soils had the greatest C density, and these soils stored significantly more C to a depth of c. 0.9 m than the non-allophanic and pumice soils. Despite significant differences between the three groups of soils, the total C storage could be estimated by statistical analysis using a single regression slope.

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