

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/263493550>

An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers

Article in *European Journal of Soil Science* · February 2013

DOI: 10.1111/ejss.12002

CITATIONS

259

READS

5,894

2 authors:



John Wendt

International Fertilizer Development Center (IFDC)

36 PUBLICATIONS 1,832 CITATIONS

[SEE PROFILE](#)



S. Hauser

International Institute of Tropical Agriculture

155 PUBLICATIONS 3,148 CITATIONS

[SEE PROFILE](#)

An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers

J. W. WENDT^a & S. HAUSER^b

^aInternational Fertilizer Development Center, Nairobi, Kenya, and ^bInternational Institute of Tropical Agriculture, Ibadan, Nigeria

Summary

Soil carbon stocks are commonly quantified at fixed depths as the product of soil bulk density, depth and organic carbon (OC) concentration. However, this method systematically overestimates OC stocks in treatments with greater bulk densities such as minimum tillage, exaggerating their benefits. Its use has compromised estimates of OC change where bulk densities differed between treatments or over time periods. We argue that its use should be discontinued and a considerable body of past research re-evaluated. Accurate OC estimations must be based on quantification in equivalent soil masses (ESMs). The objective of this publication is to encourage accurate quantification of changes in OC stocks and other soil properties using ESM procedures by developing a simple procedure to quantify OC in multiple soil layers. We explain errors inherent in fixed depth procedures and show how these errors are eliminated using ESM methods. We describe a new ESM procedure for calculating OC stocks in multiple soil layers and show that it can be implemented without bulk density sampling, which reduces sampling time and facilitates evaluations at greater depths, where bulk density sampling is difficult. A spreadsheet has been developed to facilitate calculations. A sample adjustment procedure is described to facilitate OC quantification in a single equivalent soil mass layer from the surface, when multiple-layer quantification is not necessary.

Introduction

Historically, soil organic carbon (OC) has been quantified to a fixed depth as the product of soil bulk density, depth and concentration. This method has been employed in the vast majority of publications comparing OC stocks between treatments or over time periods. It is designated as 'good practice' by the Intergovernmental Panel on Climate Change (IPCC, 2003) and subsequently used in protocols of global importance to assess OC stocks, such as that of the European Union (Stolbovoy *et al.*, 2007). However, the fixed depth method has been shown to introduce substantial errors when soil bulk density differs between the treatments being compared, such as between till and no-till treatments or different land-use systems (Ellert & Bettany, 1995; Ellert *et al.*, 2002; Murty *et al.*, 2002; Deen & Kataki, 2003), or when bulk density has changed substantially over a monitoring period. More accurate methods quantify OC in an equivalent soil mass (ESM) (Jenkinson, 1971; Ayanaba *et al.*, 1976; Jenkinson & Johnson, 1976; Ellert & Bettany, 1995; Gifford & Roderick, 2003). Nevertheless, ESM methods, while increasingly used, are not widely employed. Ellert & Bettany (1995) concluded that '...recent publications indicate a serious and persistent lack of awareness about the influence of soil mass on estimates of nutrient storage'.

Correspondence: J. W. Wendt. E-mail: jwendt@ifdc.org

Received 6 June 2011; revised version accepted 25 October 2012

To clarify the differences between the two methods, the following hypothetical example, an elaborated version similar to that presented by Ellert & Bettany, is shown to highlight the systematic error bias that can occur when the fixed depth method is used. In Figure 1, the effect of tillage on OC is evaluated in two treatments that have the same OC content. One soil is left untilled, while the other is tilled to a depth of 25 cm. This tillage results in a change in soil bulk density from 1.20 to 1.00 g cm⁻³, with the effect that the 0–25-cm soil layer in the previously untilled soil now occupies 0–30 cm in the tilled soil. OC is quantified in a 0–30-cm sample in both soils. The example assumes that no changes in OC have occurred as a result of tillage.

The quantity of OC at a fixed depth soil layer of 0–30-cm in the untilled soil, calculated as the product of OC concentration, bulk density, and depth, is:

$$30 \text{ cm} \times 1.2 \frac{\text{g}}{\text{cm}^3} \times \frac{20 \text{ g OC}}{\text{kg}} \times \frac{100 \text{ kg}^2 \text{ cm}^2}{\text{g}^2 \text{ ha}} = \frac{72000 \text{ kg OC}}{\text{ha} - 30 \text{ cm}}, \quad (1)$$

whereas in the soil after tillage, the calculation yields:

$$30 \text{ cm} \times 1.0 \frac{\text{g}}{\text{cm}^3} \times \frac{20 \text{ g OC}}{\text{kg}} \times \frac{100 \text{ kg}^2 \text{ cm}^2}{\text{g}^2 \text{ ha}} = \frac{60000 \text{ kg OC}}{\text{ha} - 30 \text{ cm}}. \quad (2)$$

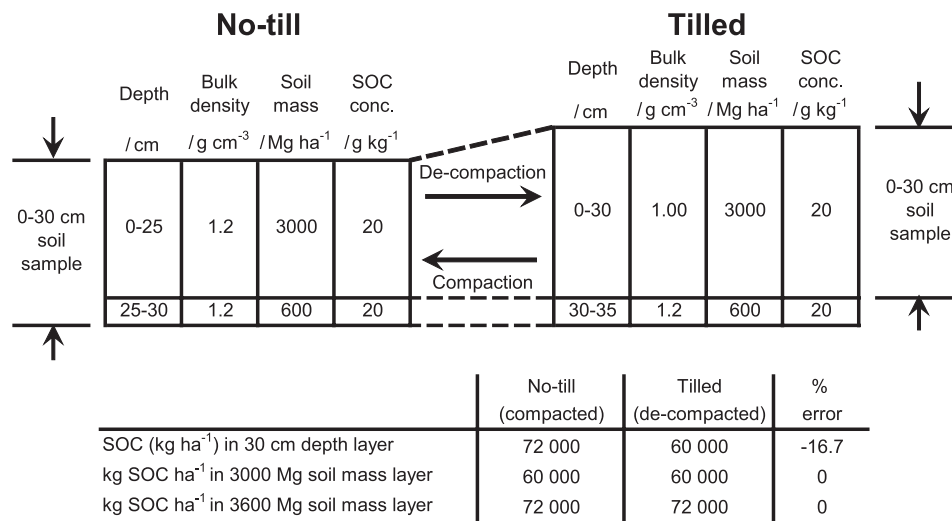


Figure 1 Error bias induced by quantifying soil OC stocks at fixed depths when differences in bulk density exist.

Using this formula, therefore, the quantity of OC in a 30-cm soil layer over 1 ha is 12 000 kg OC less in the tilled soil, representing a substantial decrease of 16.7%. This would lead to a false conclusion that tillage decreased the quantity of OC by 12 000 kg ha⁻¹ or, conversely, that not tilling increased the quantity of OC by 12 000 kg ha⁻¹, when in fact no change at all has occurred.

The source of this error is that OC stocks are being compared at fixed depths that contain different soil masses. The products of the first two terms in the fixed depth equation, bulk density and depth, actually calculate the soil mass, which when multiplied by the third term, OC, determines the OC mass. It is clear that if bulk densities differ, soil masses will differ, resulting in an unequal basis for comparison. In the above example, OC in 3000 Mg soil ha⁻¹ in the tilled soil is compared with OC in 3600 Mg soil ha⁻¹ in the soil before tillage, resulting in a substantial error.

After tillage, sampling the 0–30-cm soil layer omits the soil in the 25–30-cm layer before tillage. In most mineral soils, the sub-surface depth layer will have a lesser OC concentration than the surface soil. In the example above, if the sub-surface depth layer had half the OC concentration of the surface layer (10 g kg⁻¹), the error induced would be 6000 kg OC ha⁻¹. In other circumstances such as drained swamps or soils with buried or spodic horizons, the sub-surface horizon may have a greater concentration of OC than the surface horizon, and consequently an induced error greater than that shown in Figure 1. In all cases, the nature of the error is the same: OC is always over-estimated in the greater bulk density soil relative to the lesser bulk density soil. The over-estimate error is equal to the quantity of OC contained in the sub-surface soil mass that is not included in the sample with the lesser bulk density. Mathematically, the over-estimate error of OC mass ($M_{OC(EROR)}$, kg OC ha⁻¹) is calculated as:

$$M_{OC(EROR)} = (\rho_G - \rho_L) \times z \times C_{SUBOC(L)} \times 100, \quad (3)$$

where z is the depth (cm), ρ_G and ρ_L are the greater and lesser soil bulk densities in (g cm⁻³), and $C_{SUBOC(L)}$ (g OC kg⁻¹ soil)

is the C concentration of the sub-surface soil mass not included in the sample with the lesser bulk density.

From Equation (3), it is clear that if bulk density differences are small, or if the OC concentration in the unsampled sub-surface mass of the soil with the lesser bulk density is small, then the error will be small and perhaps negligible. It is important to re-evaluate past research that employed the fixed depth method to determine if the bulk density error substantially affected experimental interpretation. Errors are usually more pronounced when comparing tillage treatments or land-use changes, where bulk density differences are commonly considerable.

For single-layer evaluations, $C_{SUBOC(L)}$ is not known, and must be estimated from the surface soil C; therefore the error cannot be exactly calculated but can often be reasonably estimated. Re-evaluation is further complicated by the fact that the majority of publications that use the fixed depth method do not report actual bulk densities but only the results of the fixed depth calculation, rendering reassessment impossible. Because of errors inherent in the fixed depth method and the difficulties involved with re-evaluating fixed depth data, we argue its use should be discontinued.

Figure 1 also shows that OC content can be quantified consistently when one uses the same (or equivalent) soil mass as the basis for comparison. In a soil mass of 3000 Mg ha⁻¹, the OC content is 60 000 kg ha⁻¹ both before and after tillage. Similarly, in a soil mass of 3600 Mg ha⁻¹, the OC content is 72 000 kg ha⁻¹, irrespective of tillage. The soil mass used as the basis for comparison (in the example above, either 3000 or 3600 Mg soil ha⁻¹) is referred to as the reference soil mass.

Equivalent soil mass procedures

As is evident from Figure 1, the depth to achieve a particular ESM varies with soil bulk density, which may vary between treatments, sampling times and naturally within a plot or field. Nevertheless,

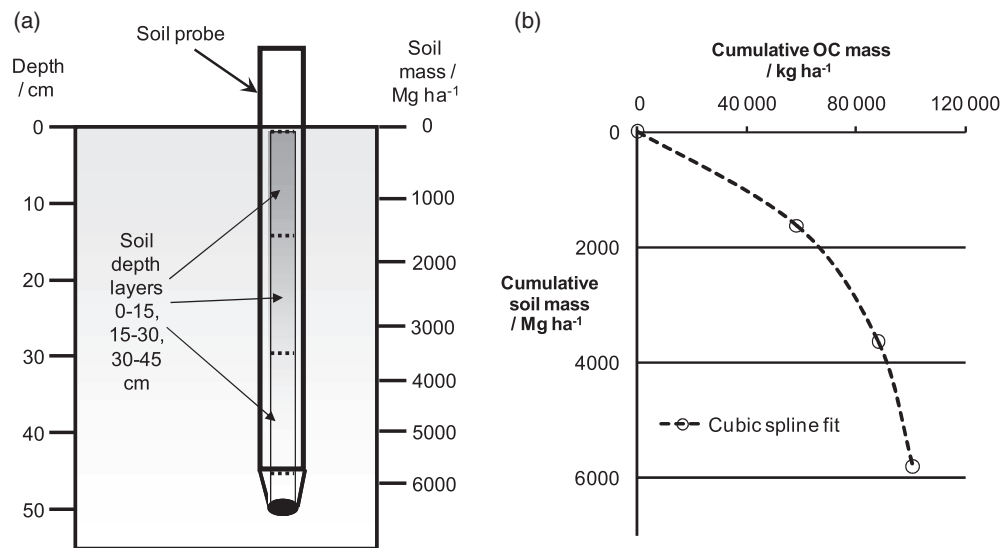


Figure 2 (a) Soil-depth layers and soil-mass layers. (b) A cumulative soil mass/OC mass profile.

stocks of OC and other soil properties in a given reference mass can be determined very accurately. Equivalent soil mass procedures are best understood by visualizing soil profiles in terms of soil mass layers instead of soil depth layers (Figure 2a). Soil mass layers (such as 0–1000, 1000–2000, 2000–3000 Mg ha⁻¹) are similar to soil depth layers (0–10, 10–20, 20–30 cm), but the mass of soil in a given depth layer will vary with bulk density, whereas the mass of soil in a soil mass layer, by definition, is fixed, and provides a consistent basis for comparing OC changes and differences.

An exact correspondence exists between the mass of a soil sample depth layer (g) and its soil mass. Dimensionally, soil mass is mass per unit area, or Mg ha⁻¹. To calculate the soil mass represented by a soil sample depth layer (*DL*), one only needs to divide the dry sample mass ($M_{\text{SAMPLE}(DL)}$, g) by the area sampled by the probe or auger, which is the cross-sectional area of its inside diameter, or $\pi(D/2)^2$. If multiple soil cores are combined to form one sample, then the area sampled is $\pi(D/2)^2 \times N$, where N is the number of cores sampled. A small error is associated with combining sub-samples into a single sample, which is discussed later. If D is expressed in mm, then the mass of the soil ($M_{\text{SOIL}(DL)}$, Mg ha⁻¹) in each depth layer is calculated as:

$$M_{\text{SOIL}(DL)} = \frac{\text{mass}}{\text{area}} = \frac{M_{\text{SAMPLE}(DL)}}{\pi \left(\frac{D}{2}\right)^2 \times N} \times 10000. \quad (4)$$

The OC mass in the depth layer ($M_{\text{OC}(DL)}$, kg ha⁻¹) is the product of its soil mass and OC concentration, $C_{\text{OC}(DL)}$ (g kg⁻¹):

$$M_{\text{OC}(DL)} = M_{\text{SOIL}(DL)} \times C_{\text{OC}(DL)}, \quad (5)$$

The cumulative soil and OC masses are calculated by summing their respective depth layer masses, calculated in

Equations (4) and (5) to any given depth; for example, the cumulative soil and OC masses to 30 cm are the sum of their respective masses in the 0–15 and 15–30-cm layers, and the cumulative masses to 45 cm are the sum of their respective masses in the 0–15, 15–30 and 30–45-cm layers. Data in Table 1 demonstrate these calculations and are graphically represented in Figure 2(b). A fitted curve, in this case a cubic spline, provides good estimates of cumulative OC contents for any chosen reference soil mass in the profile. The cubic spline function fits a smooth curve to a series of points with a piecewise series of cubic polynomial curves. For cumulative reference masses of 0–2000, 0–4000 and 0–6000 Mg ha⁻¹, from the data in Table 1, the cubic spline estimates of OC content in the soil mass layers are 67 831, 90 540 and 101 960 kg ha⁻¹, respectively. Intermediate reference mass layers are calculated by subtraction: for example, the OC in the 2000–4000 Mg ha⁻¹ soil layer $M_{\text{OC}(2000-4000)} = M_{\text{OC}(0-4000)} - M_{\text{OC}(0-2000)}$, and $M_{\text{OC}(4000-6000)} = M_{\text{OC}(0-6000)} - M_{\text{OC}(0-4000)}$. Thus calculated, the OC masses in the 0–2000, 2000–4000 and 4000–6000-Mg ha⁻¹ soil layers are 67 831, 22 709 and 11 420 kg OC ha⁻¹, respectively. The procedure described requires no bulk density sampling and thus avoids imprecision in its determination that occurs through compaction or core fracturing during sampling.

Some error is associated with bulking sub-samples into a single sample, because each core sub-sample will have a slightly different sample mass, and therefore will be either over- or under-represented in a bulked sample. We have evaluated this error for several soils by taking individual cores, analysing each depth layer from each core separately, and then calculating the OC concentrations in combined depth layers from a replication or land area using their weighted averages. The difference between ESM determinations from combined cores relative to the average of separate cores is approximately $\pm 1\%$ when the number of cores is four or more, with the error being randomly distributed. This

Table 1 Demonstration of calculations of cumulative soil and OC masses

Base data				Calculations of increment and cumulative soil masses					
Depth layer	No. of cores per soil sample	Probe diameter	Soil sample mass	OC conc.	Soil mass in increment	OC increment mass	Cumulative depth layer	Cumulative soil mass to bottom of depth increment	Cumulative OC mass to bottom of depth increment
/ cm		/ mm	/ g	/ g kg ⁻¹	/ Mg ha ⁻¹	/ kg ha ⁻¹	/ cm	/ Mg ha ⁻¹	/ kg ha ⁻¹
0–15	4	21.5	234.34	36.35	1614	58 658	0–15	1614	58 658
15–30	4	21.5	295.78	14.46	2037	29 452	15–30	3650	88 109
30–45	4	21.5	313.20	5.95	2157	12 833	30–45	5807	100 942

Data source: Rhodic Ferrallitic Nitosol (FAO, 1998) under primary forest, Mbira, Uganda.

Probe diameter, mm	21.5
# of cores per sample	4

Reference soil mass layers, Mg ha ⁻¹	1500 3000 4500 6000	Average calculated depth to reference mass, cm	13.3 24.5 35.8 47.1
---	------------------------------	--	------------------------------

Depth	Profile ID	Sample mass	Soil OC conc.	ESM layer	OC mass
/cm		/g	/g kg ⁻¹	/Mg ha ⁻¹	/Mg ha ⁻¹
8	MFCF1	123.2	24.29	0-1500	29.7
16	MFCF1	139.2	12.68	1500-3000	13.9
32	MFCF1	306.1	8.71	3000-4500	11.9
48	MFCF1	292.2	6.97	4500-6000	10.2
8	MFCF2	122.7	28.77	0-1500	32.6
16	MFCF2	144.3	10.65	1500-3000	11.0
32	MFCF2	300.8	7.70	3000-4500	11.5
48	MFCF2	315.1	6.61	4500-6000	9.6
8	MFCF3	117.5	20.68	0-1500	25.2
16	MFCF3	143.5	11.28	1500-3000	13.2
32	MFCF3	306.5	8.53	3000-4500	12.0
48	MFCF3	303.6	7.09	4500-6000	10.4

Figure 3 An example of the spreadsheet used for calculating OC stocks in multiple soil layers using the cubic spline procedure. Hidden columns are used for calculations.

small error will have a minor impact on statistical assessments of differences and is usually justifiable when sampling a plot or field.

A web-accessible Excel™ spreadsheet (Wendt, 2012) allows easy calculation and incorporates a cubic spline macro function developed and distributed freely by SRS1 Software LLC (<http://www.srs1software.com>). The spreadsheet requires the input of sampler-probe diameter, number of soil cores per soil sample, soil sample masses, OC concentrations for each soil sample depth layer and desired reference soil mass layers. The spreadsheet also calculates the average depth to the reference soil mass, which is useful for reporting purposes (Figure 3).

Comparison with other ESM methods

The method developed above builds upon the procedure developed by Gifford & Roderick (2003), which uses cumulative soil/OC mass profiles to calculate OC contents in reference soil masses from the soil surface. Rather than using a cubic spline function, they employed linear interpolation to calculate the OC mass in any reference soil mass from the soil surface using the formula:

$$M_{\text{OC}(0-\text{ref})} = M_{\text{OC}(0-a)} + \frac{(M_{\text{SOIL}(0-\text{ref})} - M_{\text{SOIL}(0-a)})}{(M_{\text{SOIL}(0-b)} - M_{\text{SOIL}(0-a)})} \times (M_{\text{OC}(0-b)} - M_{\text{OC}(0-a)}), \quad (6)$$

where $M_{\text{SOIL}(0-\text{ref})}$ is the reference soil mass from the soil surface (used as the basis for comparison between soils), $M_{\text{OC}(0-\text{ref})}$ is the OC mass in the reference mass, $M_{\text{SOIL}(0-a)}$ and $M_{\text{OC}(0-a)}$ are the respective cumulative soil and OC masses of the soil layers above which the reference mass is achieved, and $M_{\text{SOIL}(0-b)}$ and $M_{\text{OC}(0-b)}$ are the respective cumulative soil and OC masses of the soil layer directly below a , in which the reference mass is achieved, as illustrated in Figure 4(a). For the data in Table 1, the OC masses in the cumulative reference soil mass layers 0–2000, 0–4000 and 0–6000 Mg ha⁻¹ are calculated by linear interpolation to be 64 236, 90 183 and 102 086 kg OC ha⁻¹, respectively. Though Gifford & Roderick (2003) did not calculate OC masses in intermediate soil mass layers (for example, 2000–4000 and 4000–6000 Mg soil ha⁻¹), this is easily accomplished by subtraction as described above for the cubic spline method. Thus calculated, the OC masses in the 2000–4000 and 4000–6000 Mg ha⁻¹ soil mass layers estimated by using linear interpolation are 25 946 and 11 904 kg OC ha⁻¹, respectively.

Linear interpolation assumes implicitly that the OC concentration in a soil-depth layer is constant throughout that layer, and then changes abruptly at the next sample depth layer (Figure 4a). Each sample depth layer is represented by a line on the graph; the slope of each line is its OC mass divided by the soil mass, which is the OC concentration. The curve fitting function that we prefer assumes that OC concentrations change gradually throughout each layer. Figure 4(a,b) shows the same soil sampled at

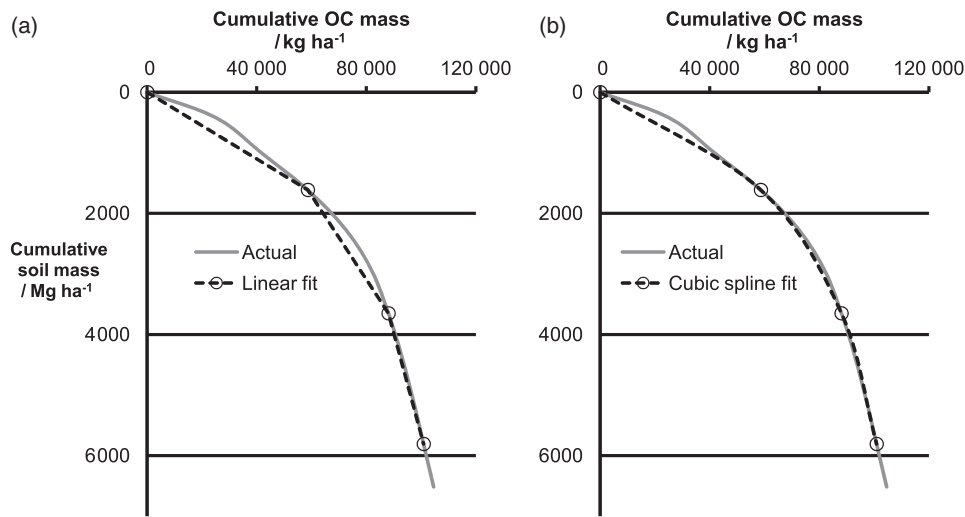


Figure 4 Estimation of OC masses using linear interpolation (a) and a cubic spline fit (b).

15-cm depth layers, and how estimates by both methods correspond to the 'actual' OC distribution, which was determined from 5-cm depth layers; the 'actual' estimates were 67 584, 23 022 and 11 330 kg ha⁻¹ in the respective 0–2000, 2000–4000 and 4000–6000 Mg ha⁻¹-soil layers, which corresponds better to cubic spline estimates than to linear estimates, as calculated above. We believe that cubic spline estimates will generally be more accurate, particularly when larger depth layers are employed.

Equation (6) can be further reduced. The difference of the cumulative soil masses $M_{\text{SOIL}(0-b)} - M_{\text{SOIL}(0-a)}$ is equal to the soil mass of the depth layer $a - b$, or $M_{\text{SOIL}(a-b)}$. Similarly for the OC masses, $M_{\text{OC}(0-b)} - M_{\text{OC}(0-a)} = M_{\text{OC}(a-b)}$. The OC mass of any depth layer divided by its soil mass is its OC concentration, or $C_{\text{OC}(a-b)}$; therefore:

$$\frac{(M_{\text{OC}(0-b)} - M_{\text{OC}(0-a)})}{(M_{\text{SOIL}(0-b)} - M_{\text{SOIL}(0-a)})} = \frac{M_{\text{OC}(a-b)}}{M_{\text{SOIL}(a-b)}} = C_{\text{OC}(a-b)}, \quad (7)$$

which when substituted into Equation (6) yields:

$$M_{\text{OC}(0-\text{ref})} = M_{\text{OC}(0-a)} + (M_{\text{SOIL}(0-\text{ref})} - M_{\text{SOIL}(0-a)}) \times C_{\text{OC}(a-b)}. \quad (8)$$

The method of Ellert & Bettany (1995) is perhaps the most commonly used ESM method, currently cited in over 200 publications. In its original application, the thickness T (cm) of a sub-surface soil layer is calculated, which, when added to the surface layer, results in the specified reference soil mass, using the equation:

$$T = \frac{(M_{\text{SOIL}(0-\text{ref})} - M_{\text{SOIL}(0-a)})}{\rho_{(a-b)}} \times 0.01, \quad (9)$$

where $M_{\text{SOIL}(\text{ref})}$ is the reference soil mass from the surface, $M_{\text{SOIL}(0-a)}$ (Mg ha⁻¹) is the soil mass in the surface soil depth

layer above which the reference soil mass is obtained, and $\rho_{(a-b)}$ the bulk density in g cm⁻³ of the sub-surface depth layer below the surface-sample depth layer, in which the equivalent soil mass is achieved. Once calculated, T is multiplied by the sub-surface soil bulk density and OC concentration in the layer below the surface depth layer, $C_{\text{OC}(a-b)}$, to obtain the quantity of OC in T , which is then added to the OC in $M_{\text{SOIL}(0-a)}$ to obtain the OC in the reference soil mass, $M_{\text{OC}(0-\text{ref})}$.

Equation (9) can be simplified. The soil mass of the sub-surface soil layer needed to adjust the surface layer to the reference mass, $M_{\text{SOIL}(a-\text{ref})}$, is the product of T and $\rho_{(b)}$; therefore:

$$M_{\text{SOIL}(a-\text{ref})} = M_{\text{SOIL}(0-\text{ref})} - M_{\text{SOIL}(0-a)}, \quad (10)$$

and the OC stock in the reference soil mass is calculated as:

$$M_{\text{OC}(0-\text{ref})} = M_{\text{OC}(0-a)} + M_{\text{OC}(a-\text{ref})} = M_{\text{OC}(0-a)} + M_{\text{SOIL}(a-\text{ref})} \times C_{\text{OC}(a-b)}, \quad (11)$$

which, when combined with Equation (10), yields:

$$M_{\text{OC}(0-\text{ref})} = M_{\text{OC}(0-a)} + (M_{\text{SOIL}(0-\text{ref})} - M_{\text{SOIL}(0-a)}) \times C_{\text{OC}(a-b)}, \quad (12)$$

which is the same as Equation (8), a reduction of Gifford & Roderick's original equation. Therefore, calculation by either method yields the same OC mass for any reference soil mass. As originally applied, the method described by Ellert & Bettany (1995) was used to calculate OC contents in soil masses from the soil surface. Thus one can use Equation (12) first to calculate OC in reference masses from the soil surface, and then take the difference of the cumulative OC masses to calculate the OC in intermediate reference mass layers, as previously described.

In its original application, Ellert & Bettany (1995) calculated the soil mass as the product of the depth layer bulk density and sampling depth. This yields the same result as Equation (4) provided that the soil sampled from the probe to calculate bulk density is used. Ellert and his colleagues (Ellert *et al.*, 2001) recognized that bulk densities used in equivalent soil mass calculations should be determined from the actual cores sampled for analysis and not from separate field bulk-density samples. An unfortunate consequence of the use of the method described by Ellert & Bettany (1995) is that because bulk density sampling is time-consuming, many researchers take only one or two field bulk density samples per plot and then take many samples separately (though at the same time) for OC determination. Because fewer samples are employed, the average bulk density determination is less representative and more variable. When samples are taken at considerable depth, pits are commonly dug, and the mid-section of a large depth layer is sampled and taken to be the average of the depth layer, which is time-consuming and less accurate than sampling the entire depth layer. All of this is in fact unnecessary, as the soil mass can be directly determined from sample masses, as per Equation (4). Soil can be sampled easily to depths of 50 cm or more. Gifford & Roderick (2003) noted that when the soil mass is calculated from a probe sample, its determination is effectively as accurate as one can weigh the soil sample (easily within $\pm 0.5\%$) and inaccuracies and added sampling time associated with field soil bulk density sampling are eliminated.

Reporting results on an ESM basis

Rather than reporting the actual ESM layers in which OC was evaluated, Ellert & Bettany (1995) reported the depth at a particular sampling time at which the ESM was achieved. Commonly referred to as the 'mass-equivalent depth', this has since become the convention in many publications using ESM methods, such that the reference ESM layer or layers (in Mg ha^{-1}) in which OC stocks are determined are not commonly reported. It is essential to report the actual ESM layers in which OC stocks are evaluated, rather than only reporting the approximate depth layer or layers represented. When the ESM layer is recorded and reported, it allows the possibility of returning to the same sampling site at a later date and calculating OC stocks at that soil mass, which is necessary when monitoring changes in soil OC over time.

Choosing soil reference soil masses and depth-sampling layers

To determine change of soil C stocks as a result of a change in land management, sampling should go as deeply as soil C changes are expected, which is at least as deep as the rooting depth. This can be up to a metre or more, especially where trees, shrubs and deep rooting pasture species are growing. Sampling depths of less than 30 cm can result in flawed conclusions regarding OC changes induced by tillage and land-use practices (Davidson &

Ackerman, 1993; Murty *et al.*, 2002; Baker *et al.*, 2007). Deeper OC stocks may contribute substantially to long-term OC changes. Omonode *et al.* (2006) found that 40% (over 17 000 kg ha^{-1}) of the soil OC lost from conventional tillage compared with no-till treatments came from soil layers below 30 cm.

While soil mass layers should represent at least the upper 30 cm of soil, it is not possible to suggest exact reference soil mass layers that apply to all soils. For example, soil bulk densities in the 0–30-cm range may vary from less than 1.0 to over 2.0 g cm^{-3} ; this would represent soil masses from 3000 to 6000 Mg ha^{-1} . We suggest that it is best to sample depth layers in which OC differences are to be compared, and then choose reference soil mass layers that represent those layers after sampling. Reference mass layers can be chosen to be equal (for example, 0–2000, 2000–4000, 4000–6000 Mg soil ha^{-1} and so on), which facilitates comparisons between soil layers, or alternatively can be chosen to correspond to the average soil masses of the depth layers sampled. Reference masses can also be chosen to represent zones of OC accumulation and depletion.

The exact reference soil masses chosen are not critical. What is essential is that consistent reference masses are used for all comparisons between treatments and sampling times, and that the reference masses fall within the depth layers sampled. However, reference soil masses should not be considerably less than the soil mass represented in the first depth layer, nor appreciably greater than the cumulative soil mass represented by the deepest layer. For the profile represented in Figure 4, for example, reference soil mass layers in a range from 1500 to 6000 Mg ha^{-1} are suitable, as they lie within a reasonable extrapolation zone.

Single-layer compared with multiple-layer assessments

Multiple-layer assessments require multiple-layer samples, which are more expensive than single-layer assessments. Multiple-layer assessments are useful for investigative research purposes. For routine monitoring for greenhouse gas mitigation accounting purposes, reducing costs is critical, as sampling and measurement costs detract from the potential value of the C sequestered. For many monitoring purposes, single layer assessments are sufficient.

The cubic spline method described above is not applicable to single-layer assessments, because it does not result in a good curve fit from two soil depth layers. The methods of Gifford & Roderick (2003) or Ellert & Bettany (1995) can also be applied to single-layer assessments, but both require the analysis of both surface and sub-surface soils. Next we describe a procedure that, while requiring the sampling of surface and sub-surface depths, requires analysis of only one adjusted sample.

Two depth layers must be sampled. For example, to capture the soil change in an ESM layer representing approximately 40 cm of soil, the soil can be sampled at 0–32 and 32–48 cm depths. The average sample masses of these two depth layers are determined, and the reference sample mass $M_{\text{SAMPLE}(0-\text{ref})}$ is calculated as the average sample mass of the 0–32 cm depth layers, plus half of the average sample mass of the 32–48 cm depth layer, which

Table 2 Correspondence between sample adjustment method and methods of Gifford & Roderick (2003) and Ellert & Bettany (1995) for single-layer assessments

Base data			By sample adjustment			By Gifford & Roderick (2003) or Ellert & Bettany (1995)				
Depth layer	Soil sample mass	OC conc.	Sample masses used in adjustment	Adjusted sample OC conc.	OC mass in 5050 Mg ha ⁻¹ reference soil mass	Soil mass in increment $M_{\text{SOIL(inc)}}$	OC increment $C_{\text{OC(inc)}}$	Cumulative soil mass to bottom of depth increment	Cumulative OC mass to bottom of depth increment	OC mass in 5050 Mg ha ⁻¹ reference soil mass
	M_{SAMPLE}	$C_{\text{OC(inc)}}$		$C_{\text{OC(inc)}}$						
/ cm	/ g	/ g kg ⁻¹	/ g	/ g kg ⁻¹	/ kg ha ⁻¹	/ Mg ha ⁻¹	/ kg ha ⁻¹	/ Mg ha ⁻¹	/ kg ha ⁻¹	/ kg ha ⁻¹
0–32	558.4	13.1	558.4	11.64	58 808	3845	50 372	3845	50 372	58 808
32–48	292.5	7.0	175.0	—	—	2014	14 099	5859	64 471	—
0–32	567.2	13.0	567.2	11.55	58 329	3906	50 775	3906	50 775	58 329
32–48	315.0	6.6	166.2	—	—	2169	14 316	6075	65 092	—
0–32	579.0	11.7	579.0	10.73	54 197	3987	46 649	3987	46 649	54 197
32–48	303.5	7.1	154.4	—	—	2090	14 839	6077	61 487	—
0–32	603.5	12.0	603.5	11.24	56 757	4156	49 869	4156	49 869	56 757
32–48	340.0	7.7	129.9	—	—	2341	18 028	6497	67 897	—

lies near the midpoint of the 32–48-cm sample depth layer. Soil from the homogenized 32–48 cm depth layer is added to that of the 0–32 cm depth layer until the calculated sample mass is achieved. The reference soil mass represented by the adjusted samples is calculated from a modification of Equation (4):

$$M_{\text{SOIL}(0\text{-ref})} = \frac{M_{\text{SAMPLE}(0\text{-ref})}}{\pi \left(\frac{D}{2}\right)^2 \times N} \times 10\,000, \quad (13)$$

and the OC mass in the reference mass is determined by multiplying the adjusted soil sample C concentration by the reference soil mass from Equation (13). Only a single adjusted sample needs to be analysed.

The sub-soil sample depth layer must be sufficiently large to accommodate adjustment for all soils sampled to the same soil mass, both at the initial sampling and at future sampling times. If the adjustment depth layer is too small (for example, 5 cm), then it is likely that for some samples, the calculated reference sample mass will not fall in the sub-soil depth-layer, and therefore cannot be achieved through sample adjustment. As a general rule, 16–20 cm sub-soil depth layers are sufficient to permit sample adjustments. To achieve an equivalent soil mass that represents, on average, the upper 50 cm of soil, depth layers of 0–40 and 40–60 cm could be sampled.

The sample adjustment method in theory corresponds exactly to the methods described by Gifford & Roderick (2003) and Ellert & Bettany (1995). This is demonstrated in Table 2, which is also used to demonstrate the procedure in general. The sample reference mass (corresponding to an average depth of 40 cm) is calculated as the average masses of the 0–32 cm samples, plus half the average masses from the 32–48 cm sample to be 733.4 g, which corresponds to a reference soil mass of 5050 Mg soil ha⁻¹, as from Equation (13) when four cores taken with a 21.5-mm diameter corer are used. The concentration of the adjusted sample in Table 2 is calculated as the mass-weighted average of the OC concentration of the 0–32 cm sample and the OC concentration

of the sub-soil mass used to adjust the sample to 733.4 g. In practice, it is not necessary to analyse both samples and perform this calculation, but rather analyse only the adjusted sample. If analyses are perfect, sample adjustment will correspond exactly to either of the two-layer methods. In reality, correspondence is not exact because of the imprecision in OC analyses, but does not bias the results towards either method.

Conclusions

Use of the fixed depth equation for quantifying soil properties such as OC results in incorrect assessments of changes or differences in OC stocks when bulk densities differ substantially between treatments or between time periods being compared. Use of this method has led to false conclusions of changes in soil OC stocks, where the reported differences in OC stocks were due to comparisons in unequal soil masses. We argue that this method should be discontinued and that previous results based on the method need to be reassessed. To facilitate reassessment, we have provided an equation to quantify the fixed depth error. Based on that quantification, one can determine if the interpretation of results is substantially affected. Past conclusions may still be valid, provided that bulk density differences were small, or if OC differences between comparisons were so large that bulk density differences would not substantially affect overall conclusions. A shift to reliable assessments based on equivalent soil masses can be further accelerated by changing international protocols such as the European Union and IPCC best practice recommendations.

To the end of facilitating assessments based on ESMs, we have created a spreadsheet that eliminates the laborious calculation process, which is based on a cubic spline curve fit of the cumulative soil mass/soil OC profile.

Acknowledgements

This research was supported by core funding by the Institute for Tropical Agriculture, Ibadan, Nigeria. We would also like

to express our deep appreciation to Ken Giller, Professor of Plant Production Systems at Wageningen University. His personal interest and editorial suggestions were instrumental in bringing this work to fruition.

References

- Ayanaba, A., Tuckwell, S.B. & Jenkinson, D.S. 1976. The effects of clearing and cropping on the organic reserves and biomass of tropical forest soils. *Soil Biology & Biochemistry*, **8**, 519–525.
- Baker, J.M., Ochsner, T.E., Venterea, R.T. & Griffis, T.J. 2007. Tillage and carbon sequestration – What do we really know? *Agriculture, Ecosystems & Environment*, **118**, 1–4.
- Davidson, E.A. & Ackerman, I.L. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry*, **20**, 161–193.
- Deen, W. & Katakai, P.K. 2003. Carbon sequestration in a long-term versus conventional tillage experiment. *Soil & Tillage Research*, **74**, 143–150.
- Ellert, B.H. & Bettany, J.R. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science*, **75**, 529–538.
- Ellert, B.H., Janzen, H.H. & McConkey, B.G. 2001. Measuring and comparing soil carbon storage. In: *Assessment Methods for Soil Carbon* (eds R. Lal, G. Kimble, R. Follet & B. Stewart), pp. 131–146. Lewis Publishers, Boca Raton, FL.
- Ellert, B.H., Janzen, H.H. & Entz, T. 2002. Assessment of a method to measure temporal change in soil carbon storage. *Soil Science Society of America Journal*, **66**, 1687–1695.
- Gifford, R.M. & Roderick, M.L. 2003. Soil carbon stocks and bulk density: spatial or cumulative mass coordinates as a basis of expression? *Global Change Biology*, **9**, 1507–1514.
- IPCC 2003. Chapter 3. LUCF Sector Good Practice Guidance. In: *Good Practice Guidance for Land Use, Land Use Change and Forestry* (eds J. Penman, M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti *et al*). Intergovernmental Panel on Climate Change, Hayama.
- Jenkinson, D.S. 1971. The accumulation of organic matter in soil left uncultivated. *Rothamsted Experimental Station Report for 1970. Part 2*, pp. 113–170. Lawes Agricultural Trust, Harpenden
- Jenkinson, D.S. & Johnston, A.E. 1976. Soil organic matter in a Hoosfield continuous barley experiment. *Rothamsted Experimental Station Report for 1976, Part 2*, pp. 87–107. Lawes Agricultural Trust, Harpenden.
- Murty, D., Kirschbaum, M.U.F., McMurtrie, R.E. & McGilvray, H. 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Global Change Biology*, **8**, 105–123.
- Omonode, R.A., Gal, A., Stott, D.E., Abney, T.S. & Vyn, T.J. 2006. Short-term versus continuous chisel and no-till effects on soil carbon and nitrogen. *Soil Science Society of America Journal*, **70**, 419–425.
- Stolbovoy, V., Montanarella, L., Filippi, N., Jones, A., Gallego, J. & Grassi, G. 2007. *Soil Sampling Protocol to Certify the Changes of Organic Carbon Stock in Mineral Soil of the European Union, Version 2*. Office for Official Publications of the European Communities, Luxembourg.
- Wendt, J.W. 2012. *ESM Sample Spreadsheets.Xlsm* [WWW document]. URL <https://docs.google.com/open?id=0BzxNFzLbFxfjSG9RW1pwQ0FXc0k> [accessed on 26 October 2012].