Equivalent Soil Mass and Mass Coordinate System in Soil Carbon Stock Determination

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Equivalent soil mass (ESM) methods have been increasingly used for assessing soil OC masses in place of "fixed depth" assessments. In fixed depth assessments, soil OC is evaluated in fixed depth increments (e.g., 0-0.1, 0.1-0.2, and 0.2-0.3 m). Ellert and Bettany (1995) pointed out that such assessments are invalid when soil bulk density differences exist between treatments or over monitoring time periods. This is because the soil mass (calculated as the product of the bulk density and depth, and expressed in units of mass per unit area such as Mg m^{-2} or Mg ha^{-1}) will differ when bulk density differs. Comparisons of soil C masses in different soil masses are not valid. For example, for two soils with bulk densities of 1.0 and 1.2 Mg m^{-2} and sampled to 0.10 m, one would be comparing soil C masses in 1000 Mg ha^{-1} in one soil vs. soil C masses in 1200 Mg ha^{-1} in the other soil. This comparison will always result in a relative over-assessment of soil C in the higher bulk density soil, because it contains a greater soil mass. The premise of ESM comparisons is that changes in OC masses that occur over time can be accurately assessed if one compares OC masses in the same (or equivalent) soil masses at all sampling times. Equivalent soil mass (ESM) methods address errors in fixed depth assessments by correcting for bulk density differences at various sampling times, such that all comparisons are made in the same, or equivalent, soil mass.

The publication "Determining soil carbon stock changes: Simple bulk density corrections fail" (Lee et al., 2009) purports to show that using using ESM methods fail in instances when one is comparing soil organic carbon (OC) masses in different interventions such as land systems or tillage treatments, when one has no information regarding the OC masses at an initial time (T0), before interventions were initiated. In such cases, some researchers have used either the maximum ESM or the minimum ESM (the ESM in either the most dense or least dense soil layers, respectively), as the basis for comparisons between interventions. If Lee et al.'s conclusion is correct, it would call into question a considerable body of past research employing ESM methods, when comparisons in OC masses were made between forests, cropland, and pastures, or between till and no-till systems, when no initial OC masses were measured before interventions were initiated. However, the data presented by Lee et al. do not in fact represent valid ESM comparisons. When correctly analyzed, the results indicate that minimum, maximum, and original ESM approaches are all equally valid. This is an important conclusion in itself, in that it validates rather than negates past research results where ESM comparisons were done when no information on initial OC masses was available.

In a thoughtfully designed experiment, Lee et al. (2009) compared soil OC masses at three sampling times: an initial (T0) time, and at two later times (T1 and T2) after two tillage treatments. The time between tillage treatments was short such that one would not anticipate any change in soil OC masses.

They then evaluated OC stock changes in original, maximum, and minimum ESMs. Lee et al.'s publication is difficult to comprehend because the soil masses of the ESM layers to which "minimum", "maximum", and "original" ESMs refer are never shown; rather, they are reported as depth layers (0-0.06, 0.06-0.12, and 0.12-0.18 m), or simply as layers 1, 2, and 3 in their erratum table (Lee and Six, 2011). From the publication, it is difficult to determine whether ESM methods were actually utilized, or correct ESM comparisons actually made.

In a comment on their publication, McBratney and Minasny (2010) suggested that the material coordinate system propsed by Gifford and Roderick (2003), which employs a cumulative soil mass/soil OC approach, would better be applied to the analysis of their data. The cumulative soil mass/OC mass approach is explained in detail by McBratney and Minasny, and is not repeated here for purposes of brevity. Cumulative soil mass/OC mass profiles representing the Lee et al. (2009) field experiment are shown for the 3 soils and sampling times in Figure 1. This approach was rejected by Lee and Six (2011) in response to that comment, on the grounds that its use does not permit one to estimate soil C changes layer by layer.

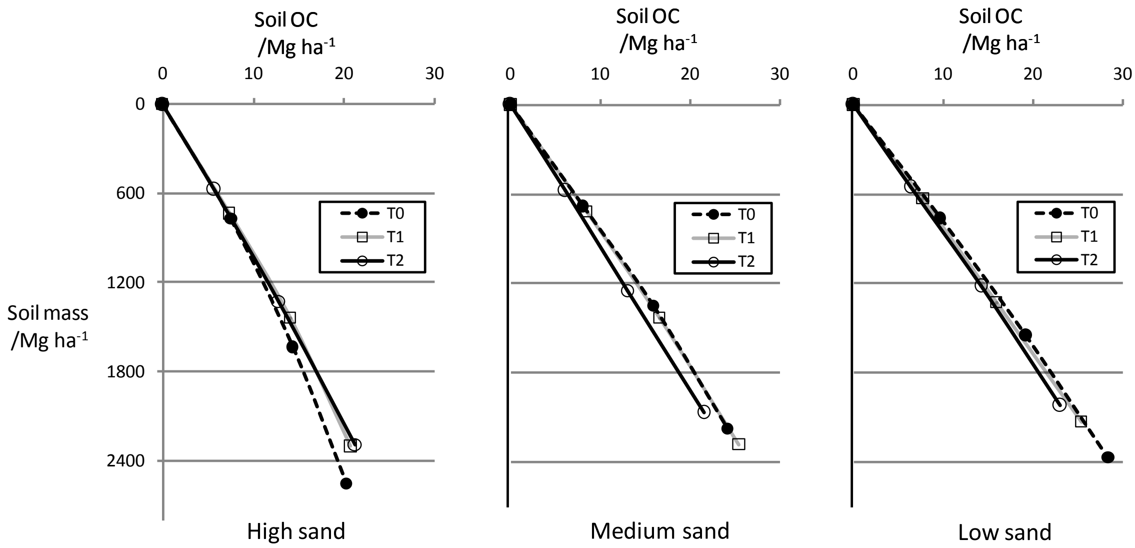

Figure 1. Cumulative soil mass/OC mass profiles from the data in Lee et al. (2009).

However, the Gifford and Roderick method can indeed be applied to assess OC in individual mass layers. Cumulative soil mass layers represent soil mass layers from the soil surface; for example, 0-600, 600-1200, and 1200-1800 Mg ha^{-1}. Soil OC masses in intermediate layers can be calculated by simple subtraction; for example, the OC mass in the 600-1200 Mg ha^{-1} soil mass layer is that in the 0-1200 Mg ha^{-1} soil mass layer minus that in the 0-600 Mg ha^{-1} soil mass layer, and the OC mass in the 1200-1800 Mg ha^{-1} soil mass layer is that in the 0-1800 Mg ha^{-1} soil mass layer minus that in the 0-1200 Mg ha^{-1} soil mass layer. This reflects one application of the Gifford and Roderick method, where all soil masses are equal, which allows comparisons of OC masses in equal soil mass layers. One can also apply the Gifford and Roderick method to soil mass layers that represent “maximum”, “minimum” and “original” cumulative soil masses to calculate OC masses in their respective layers.

This approach was applied to the data in Lee et al. (2009). For the “original” soil mass, the averages of the soil masses in the depth layers at T0 were used as soil reference mass layers. For “maximum” and “minimum” ESM comparisons, since it is not clear precisely what layers were used from the Lee et al. publication, for comparative purposes, ESM layers that best corresponded to the calculated data in the corrected table (Lee and Six, 2011) for the T1 and T2 OC masses were utilized. The results are presented in Table 1. “Original” soil mass is described in this table as “ESM in T0 depth layers”; in terms of the OC masses calculated, this corresponds to what Lee et al. define as “original ESM”. The distinction is important, and is discussed below.

Table 1. Soil OC stocks and changes in OC stocks from data of Lee et al. (2009).

	Equivalent soil mass increment	Equivalent soil mass layer	Soil OC mass				
				Mean		Difference	
			T0	T1	T2	T1-T0	T2-T0
			Mg ha^{-1}				
High sand							
ESM in T0 depth layers	772	0-772	7.50	7.67	7.50	0.17	0.00
	861	772-1633	6.85	7.93	7.82	1.09	0.98
			–	–	–	–	–
Maximum ESM	786	0-786	7.63	7.81	7.64	0.18	0.02
	847	786-1633	6.72	7.80	7.69	1.08	0.97
			–	–	–	–	–
Minimum ESM	575	0-575	5.65	5.79	5.62	0.15	-0.03
	740	575-1315	6.19	7.08	7.06	0.89	0.87
	937	1315-2252	6.55	7.53	8.01	0.97	1.46
To a fixed depth			7.56	7.35	5.66	-0.21	-1.90
			6.80	6.73	7.17	-0.07	0.37
			5.92	6.68	8.39	0.77	2.48
Medium sand							
ESM in T0 depth layers	690	0-690	8.13	8.15	7.25	0.19	-0.88
	669	690-1359	7.82	7.58	6.87	-0.34	-0.94
			–	–	–	–	–
Maximum ESM	719	0-719	8.47	8.48	7.55	0.18	-0.92
	700	719-1419	8.12	7.92	7.20	-0.30	-0.92
			–	–	–	–	–
Minimum ESM	578	0-578	6.81	6.85	6.09	0.19	-0.72
	667	578-1245	7.82	7.61	6.87	-0.27	-0.95
	853	1245-2098	8.42	8.80	8.50	0.46	0.08
To a fixed depth			8.05	8.42	6.09	0.37	-1.96
			7.86	8.12	6.87	0.27	-0.99
			8.24	8.89	8.50	0.64	0.26
Low sand							
ESM in T0 depth layers	764	0-764	9.66	9.25	8.78	-0.41	-0.88
	787	764-1551	9.47	9.24	8.99	-0.24	-0.49
			–	–	–	–	–
Maximum ESM	764	0-764	9.66	9.25	8.78	-0.41	-0.88
	787	764-1551	9.47	9.24	8.99	-0.24	-0.49
			–	–	–	–	
Minimum ESM	541	0-541	6.84	6.59	6.18	-0.25	-0.66
	680	541-1221	8.34	8.00	7.95	-0.34	-0.39
	787	1221-2008	9.13	9.30	8.67	0.17	-0.46
To a fixed depth			8.05	8.42	6.09	0.37	-1.96
			7.86	8.12	6.87	0.27	-0.99
			8.24	8.89	8.50	0.64	0.26

The results show that for any of the 3 soils, the change in soil OC is similar for any ESM method. Thus, all ESM are equally applicable, contrary to Lee et al's conclusions.

A comparison of the results in Table 1 with those of the Lee et al.'s corrected Table 5 (Lee and Six, 2011) highlights the source of the different conclusions. The data in that table have been re-arranged in Table 2 below to correspond with data presentation in Table 1.

Table 2. Addendum data from Lee and Six (2011), with calculated T0 OC masses added.

	Soil OC mass					
	Mean				Difference	
	T0 as T2-(T2-T0)	T0 as T1-(T1-T0)	T1	T2	T1-T0	T2-T0
	----------------------------------Mg ha^{-1}----------------------------------					
High sand						
ESM in T0 depth layers	7.56	7.57	7.66	7.49	0.09	-0.07
	6.80	6.80	7.95	7.85	1.15	1.05
			–	–	–	–
Maximum ESM	7.56	7.57	7.81	7.65	0.24	0.09
	6.80	6.80	7.80	7.69	1.00	0.89
	–	–	–	–	–	–
Minimum ESM	7.56	7.56	5.75	5.66	-1.81	-1.90
	6.80	6.80	7.08	7.06	0.28	0.26
	5.91	5.92	7.52	8.04	1.60	2.13
To a fixed depth	7.56	7.56	7.35	5.66	-0.21	-1.90
	6.80	6.80	6.73	7.17	-0.07	0.37
	5.91	5.91	6.68	8.39	0.77	2.48
Medium sand						
ESM in T0 depth layers	8.06	7.95	8.15	7.18	0.20	-0.88
	7.86	8.09	7.72	6.85	-0.37	-1.01
	–	–	–	–	–	–
Maximum ESM	8.05	7.95	8.75	7.55	0.80	-0.50
	7.86	8.09	8.21	7.20	0.12	-0.66
			–	–	–	–
Minimum ESM	8.05	7.96	6.98	6.09	-0.98	-1.96
	7.86	8.09	7.95	6.87	-0.14	-0.99
	8.24	8.10	8.86	8.50	0.76	0.26
To a fixed depth	8.05	7.95	8.42	6.09	0.47	-1.96
	7.86	8.09	8.12	6.87	0.03	-0.99
	8.24	8.10	8.89	8.50	0.79	0.26
Low sand						
ESM in T0 depth layers	9.68	9.67	9.25	8.79	-0.42	-0.89
	9.46	9.46	9.26	8.98	-0.20	-0.48
	–	–	–	–	–	–
Maximum ESM	9.68	9.67	9.25	8.79	-0.42	-0.89
	9.46	9.46	9.26	8.98	-0.20	-0.48
	–	–	–	–	–	
Minimum ESM	9.68	9.68	6.59	6.17	-3.09	-3.51
	9.46	9.46	8.00	7.97	-1.46	-1.49
	9.19	9.18	9.33	8.65	0.15	-0.54
To a fixed depth	9.68	9.68	7.69	6.31	-1.99	-3.37
	9.46	9.46	8.18	7.83	-1.28	-1.63
	9.19	9.19	9.48	8.82	0.29	-0.37

For “original” OC masses, as well as for T1 and T2 OC masses for the “minimum” and “maximum” ESM methods, soil OC masses closely correspond, differing by less than 1%, with the exception of some of the assessments with the medium sand soil at T1, where differences are up to 4.4% were observed, which is explained below. Since the differences are not in the T1 and T2 OC masses are minor, the differences emerge in the values used at T0.

Lee et al. did not report T0 OC mass values, nor were they reported in the corrected table (Lee and Six, 2011). However, T0 OC masses used by Lee et al. can be calculated as T0 = T1 – (T1-T0), or T0 = T2 – (T2-T0), since T1, T2, T1-T0, and T2-T0 values were reported. The results of that calculation are shown in Table 2 below, using the data from the corrected table (Lee and Six, 2011). The calculations show that T0 OC masses calculated by the two methods do not correspond for the medium sand. The difference appears to be related to a missing replication at T1 in the medium sand; it seems probable that in the amended table, the T0 and T1 OC values were calculated with the elimination of this replication, and is the probable source of the slightly larger differences in T1 in the medium sand soil.

More importantly, however, is what the T0 values used by Lee et al. actually represent: the OC stocks in depth increments at the T0 sampling. Effectively, then, Lee et al. were comparing OC masses in either “minimum” and “maximum” soil masses at T1 and T2 with OC masses in fixed depths at T0. This is not an ESM comparison, because the fixed depths have different soil masses than the “minimum” or “maximum” ESMs. A correct ESM comparison must utilize the same soil masses at all sampling times, whether it be minimum, maximum, or those in fixed depths at T0, which Lee et al. described as “original” soil masses.

Use of the term “original” to describe soil masses in fixed depths at T0 can be misleading. The term “original” has connotations of “in the beginning”; thus, “original” OC masses might be misconstrued as representing in some absolute sense the OC masses at T0, against which all future OC masses must be compared. This is not the case; rather, “original” as used by Lee et al. represents the OC masses in specific soil mass layers at T0; namely, those defined by the soil masses in depth increments at T0. There is no “absolute” OC mass at T0, because the OC mass at T0 varies according to the soil mass layers which one uses as the reference soil masses. For example, for the high sand soil at T0, the OC stocks in the minimum soil mass layers were “originally” 5.65, 6.19, and 6.55 Mg ha^{-1}. These should therefore be used as the basis for comparison when the minimum soil mass method is used, rather than the OC masses in depth layers at T0.

In conclusion, ESM methods or the mass coordinate system to correct for bulk density do not fail; rather, Lee et al. failed to apply ESM corrections to calculate OC masses at T0 in equivalent soil masses. When this is done, all ESM methods are equally applicable.

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