



Review

A critical review of the conventional SOC to SOM conversion factor

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ABSTRACT

Use of a single factor for converting soil organic carbon to soil organic matter is challenged. The basis for this challenge arises from four sources: the original papers published in the nineteenth century, empirical studies published throughout the twentieth century, theoretical considerations of organic matter composition, and a consideration of what led to the popularity and general acceptance of the conventional factor. The conventional factor of 1.724, based on the assumption that soil organic matter contains 58% carbon, applies only to some soils or only to particular components of soil organic matter. Studies published since the end of the nineteenth century have consistently shown that the factor of 1.724 is too low for most soils. In a review of previously published data, the median value for the conversion factor was found to be 1.9 from empirical studies and 2 from more theoretical considerations. A factor of 2, based on the assumption that organic matter is 50% carbon, would in almost all cases be more accurate than the conventional factor of 1.724. A consideration of the possible variation in organic matter composition predicts a range of factor values between 1.4 and 2.5, a range that is narrower than empirical results at least in part because of the interaction between the methods used to estimate organic matter and soil composition. Convenience, authority, and tradition rather than strength of evidence are in large part responsible for the widespread acceptance of the conventional factor.

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1. Introduction

Historically, the conversion factor of 1.724, based on the assumption that organic matter is 58% carbon, has been used for converting measurements of soil organic carbon (OC) into estimates of soil organic matter (OM). This factor, known as the “van Bemmelen factor,” appears in research papers and textbooks, either without citation or with a citation to a previously published paper that simply used the

factor, rather than to the original source. The original source seems to be generally unknown and challenges to its accuracy and precision have been insufficient to remove it from general use.

Recent interest in sequestering carbon in soils underscores the need for a quick, inexpensive, and accurate measurement of soil carbon. Estimating soil carbon from estimates of soil organic matter is a simple and inexpensive procedure but requires the use of a conversion factor. An obvious choice has been the conventional factor of 1.724. Waxman and Stevens (1930), writing in reference to a conversion factor for estimating nitrogenous compounds, state that “[i]t should be emphasized as well that the factor 1.72 for determining the total organic matter, from the carbon content should also be

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considered as merely tentative" (p. 105) and predict that "[t]his factor will probably be modified when considerable information has accumulated concerning the chemical composition of the soil organic matter" (p. 113). Considerable information has accumulated and we now have sufficient cause to reexamine the factor. The purpose of this study is to show that the conventional carbon-to-organic matter conversion factor is too low for universal application and fails to account for the significant variation in the carbon content of soil organic matter, as does any single factor.

2. Establishment of the conventional factor

The first line of evidence against the use of 1.724 comes from a close reading of the earliest papers that initially established the factor (Table 1). These papers were published in German and apparently have not been published in English in their entirety.

The assumption that organic matter is 58% carbon seems to be based on the work of [Sprengel \(1826\)](#) who found "Humussäure" (humus acid) to be 58% carbon, 40% oxygen, and 2% hydrogen ([Sprengel \(1826\)](#) actually reported his results to four significant figures). He isolated Humussäure using a four-step procedure: (1) pre-treatment or "leaching" of the sample (peat) with dilute hydrochloric acid for 24 h; (2) extraction of humus acid from the leached plant material by treating with a dilute aqueous ammonia solution for several days in a "well closed vessel" followed by filtration; (3) addition of hydrochloric acid to the filtrate, which is allowed to stand for several days; (4) filtration of the precipitate and a prolonged rinse with water lasting for several days. Of particular note is that the addition of hydrochloric acid to the ammonium hydroxide extract in step 3 precipitates humic acid. [Berzelius \(Berzelius \(1828\) in Alexander and Byers, 1932, p. 14\)](#) was critical of Sprengel's paper, who according to Alexander and Byers, "on other grounds, considered the work so inaccurate as to be untrustworthy." Such criticism, if aimed at Sprengel's work on humus acid, seems unfounded. The methods he developed nearly 200 years ago, closely resemble the method currently suggested by the International Humic Substance Society for preparation of humic acid (published in [Swift, 1996](#), pp. 1018–1019). As an estimation of the carbon content of humic acid, his results are remarkably accurate. Modern values for humic acid composition range from 51 to 62% carbon ([Schnitzer, 1977; Steelink, 1985; McBride, 1994](#)).

[Schulze \(1849\)](#) also determined that humus is composed of 58% carbon by assuming that soil consists of 25% undecomposed material with a carbon content of 52% and 75% humified material with a carbon content of 60%. He failed to cite any sources and simply declared that "we have a sufficient number of analyses" (p. 286) to support his assumptions. Subsequent investigators such as [Wolff \(1864\)](#), [Loges \(1883\)](#), and [van Bemmelen \(1890\)](#) also relied on the assumption that organic matter is 58% carbon and used the reciprocal factor 1.724 with loss-on-ignition, or 0.471 with dry combustion (the carbon content of carbon dioxide, 27.3%, multiplied by 1.724) to estimate organic matter. [Detmer \(1871\)](#) reported average values of 60% carbon for soils with well humified organic substances and suggested that the

conversion factor should then be 1.667 for such soils rather than 1.724 as used by Wolff. For unknown reasons, history has credited van Bemmelen, but he himself attributed the factor of 1.724 to Wolff ([van Bemmelen 1890](#)) as did [Detmer \(1871\)](#).

3. Challenges to the conventional factor

The second line of evidence against the conventional factor comes from empirical data published over the last 120 years ([Fig. 1](#) and [Table 2](#)). The earliest English-language paper found to date with data that permit the calculation of a conversion factor is by [Warington and Peake \(1880\)](#) working at Rothamsted, England. They observed that organic matter content estimated from loss-on-ignition was considerably higher than that calculated from carbon assuming organic matter is 58% carbon, an observation that leads to a conversion factor considerably higher than 1.724.

Published results early in the twentieth century also suggest that the factor 1.724 was too low. One of the first studies in the United States was done by [Cameron and Breazeale \(1904\)](#) who found an average factor of 2.32 but did not advocate use of the higher factor. [Gortner \(1916\)](#) found a factor of 2 to be appropriate for his data and used it throughout his paper. He did not advocate a new factor and referred instead to the "European factor" of estimating organic matter as percent carbon multiplied by 1.724, "which is decidedly lower than the 1.842 which I found for peats and 1.971 for unchanged vegetable materials" (p. 437n1). By 1932, considerably more evidence had accumulated that the factor of 1.724 was too low. In a review of methods up to that time, [Alexander and Byers \(1932\)](#) criticized previous studies that advocated the conventional factor and strongly challenged the use of any conversion factor. Although [Alexander and Byers \(1932\)](#) claim that data from Mulder reported in [Dana \(1865\)](#) confirmed [Sprengel's \(1826\)](#) finding that humus is 58% carbon, a careful reading of Mulder's procedure reveals that he also actually found the carbon content of humic acid. [Dana \(1865\)](#) describes the process as follows: "Soil was treated by Mulder, first, with boiling alcohol, then with water, then with carbonate of soda, and the acids precipitated as usual, by muriatic acid. These precipitates were with difficulty obtained pure. ... They were then analyzed." (p. 96). The phrase, "as usual" implies that recovery of the acid precipitate of an alkali extract was a common procedure at the time.

Studies continuing into the post-WWII era produced essentially the same results as studies done previous to WWII ([Fig. 1](#)). Three observations

Table 1

Comparison of early studies published in the German scientific literature. All empirical studies used essentially the same methods: extraction of organic matter with a dilute aqueous ammonia solution followed by precipitation with HCl. Carbon was then determined by dry combustion. Organic matter was estimated by mass loss at high temperature.

Conclusion or procedure	Reference
Humussäure is 58% carbon	Sprengel (1826)
Assumed OM is 60% carbon	Schulze (1849)
Assumed OM is 58% carbon; conversion factor is 1.724	Wolff (1864)
Reported OM is 60% carbon; conversion factor is 1.667	Detmer (1871)
Used "factor of Wolff: 1.724"; found OM is 60% carbon	Loges (1883)
Used "factor of Wolff: 1.724"	van Bemmelen (1890)

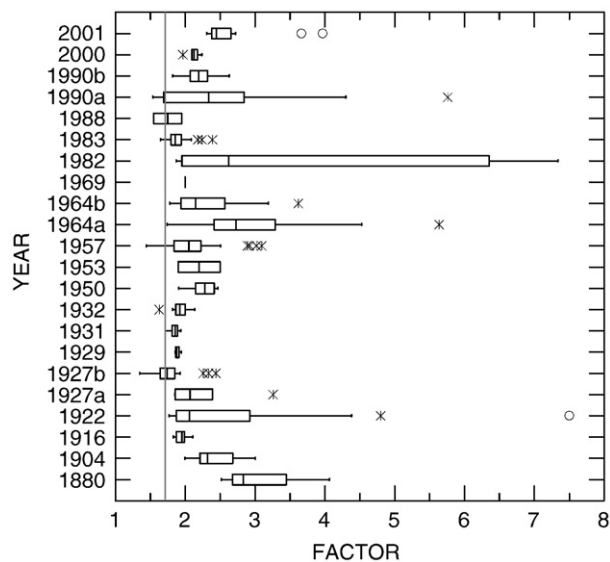


Fig. 1. Year on the vertical axis refers to the year of publication of a study corresponding to the listing in Table 2. The vertical line is drawn at a factor value of approximately 1.724. Factor values above 10 have been removed from the data set (see text) but extreme values identified by the software and marked by \circ and \times still remain.

Table 2

Summary of all studies included in this review. Abbreviations in the first column: US = United States; CA = California; CT = Connecticut; IA = Iowa; MI = Michigan; MN = Minnesota; NE = Nebraska; PA = Pennsylvania; WI = Wisconsin.

Country/ state	General soil description	Factor			Reference
		Low	Average	High	
England	Mineral; agricultural	2.52	3.45	14.1	Warington and Peake (1880)
US	"Typical" agricultural soils	2.00	2.32	3.00	Cameron and Breazeale (1904) ^a
CA, NE, MN	Mineral and organic	1.83	1.96	2.11	Gortner (1916)
US	Surface soils in US	1.77	2.06	7.50	Read and Ridgell (1922)
MN	Forest	1.85	2.07	3.26	Alway and Harmer (1927)
Worldwide	Mineral and organic	1.35	1.74	2.44	Robinson (1927)
Wales	Peat	1.86	1.88	1.95	Robinson et al. (1929) ^b
CT	Forest	1.71	1.85	1.94	Lunt (1931)
US	Mineral	1.63	1.92	2.14	Alexander and Byers (1932)
Columbia	Cleared forest	1.91	2.28	2.47	Barshad and Rojas-Cruz (1950)
Worldwide	Surface soils	1.90	2.20	2.50	Broadbent (1953) ^c
Belgium	Soils "not poor in organic matter"	1.44	2.05	3.10	De Leenheer et al. (1957)
Wales	Mineral and organic	1.74	2.73	5.64	Ball (1964)
England	Forest; wetlands	1.78	2.07	3.62	Howard (1964)
Europe, Burma	Forest; grass; peat	1.97	2	2.50	Ponomareva and Plotnikova (1967)
PA	Organic and mineral soils	1.8	2.0	2.2	Loftus (1966) ^d
PA	Forest; cultivated	1.63	1.8	2.33	Ranney (1969) ^e
Denmark	Forest	1.55	2.63	15.4	Christensen and Malmros (1982) ^f
India	Mineral	1.65	1.86	2.39	Somani and Saxena (1983)
MN, WI, MI	Forest	1.55	1.75	1.95	David (1988)
Australia	Plantation pines	1.82	2.20	2.63	Lowther et al. (1990)
England	Forest; wetlands	1.54	2.34	5.76	Howard and Howard (1990)
IA	Mineral; agricultural	1.97	2.10	2.24	Gale and Cambardella (2000)
Great Plains	Mineral; agricultural	2.31	2.45	3.97	Cambardella et al. (2001)

^a Obtained 42% carbon in organic matter but advocated continued use of 1.724.

^b Found 1.88 but advocated 2.

^c Used data from Read and Ridgell (1922) and two other sources, one unpublished.

^d Reported in Ranney (1969).

^e Found 1.8 but recommended 2.0.

^f The middle value is from their Table 1 data, which are averages.

from Fig. 1 deserve special attention. First is the variability of the conversion factor which ranges from 1.35 to 14.1; second is the tendency of the factor median to cluster around 2; and third is the appearance that the conventional factor of 1.724 actually approaches a lower bound.

Nearly every decade of the twentieth century produced at least one study showing that the factor of 1.724 is too low. One exception is Robinson (1927), who found that the average carbon content of organic matter in the soils he studied was close to 58%, although he acknowledged variability in soils and the considerable evidence that 58% carbon was in many cases too high. He used hydrogen peroxide to determine soil organic matter and acknowledged that the hydrogen peroxide method slightly underestimates the quantity of organic matter. Since underestimation of the organic matter content in a sample increases the apparent ratio of organic carbon to organic matter, his determination of 58% carbon in organic matter may be too high, making his factor estimate of 1.74 too low.

4. A comparison of theoretical estimates with empirical observations

A third line of evidence against the conventional factor comes from theoretical estimates. Theoretical considerations made in the manner

of Schulze (1849) can provide an estimate of the expected range of values that the conversion factor could reasonably take on. As a point of reference, Wiley (1906, p. 360) reported that values of the carbon content of soils range from 40 to 72% (factors of 2.5 and 1.4), presumably based on experimental results but he cites no sources.

An upper limit of the factor can be estimated by considering a soil consisting entirely of the fractions having the lowest OC:OM ratio of about 40% carbon (Table 3). Young soils, for example, with low organic carbon content, have an OC:OM ratio of approximately 40%, similar to that of emergent wetland vegetation (Craft et al., 1991). Soil comprised of organic matter containing 40% carbon would have a conversion factor of 2.5. Establishing a lower boundary on the conversion factor is more problematic. Lipids, primarily fats, waxes, and resins, have the highest carbon content but generally comprise only a small proportion of soil organic matter, although acid peats might contain as much as 20% lignin (Sparks, 1995). Humin, insoluble organic substances often bound tightly to clay, has the next highest carbon content but is difficult to study and estimates of its carbon content are uncertain. Assuming that the carbon content of humin is 70% and that of lipids to be 80%, a soil whose organic matter is comprised of 20% lipids and 80% humin would have a carbon content of 72% and a conversion factor of 1.4. Together, the theoretical limits of 1.4 and 2.5 define exactly the range Wiley (1906) reported.

A middle value of 1.95 for the conversion factor follows from the limits of 1.4 and 2.5 established in the previous paragraph. Considering the accuracy and precision of the data, rounding the average to 2 seems prudent. Several authors have used or suggest using a factor of 2 (see Gortner, 1916; Read and Ridgell, 1922; Robinson et al., 1929; Waxman and Stevens, 1930; De Leenheer et al., 1957; Ponomareva and Plotnikova, 1967; Ranney, 1969; Nelson and Sommers, 1996; Brady and Weil, 1999; Cheng and Kimble, 2001; Mitsch and Gosselink, 2007). Gortner (1916) not only used a factor of 2 with his data but regarded it as an upper bound on the ratio of organic matter to carbon.

The data from the studies summarized in Fig. 1 and Table 2 can be used to build a comprehensive data set to compare with the theoretical value of the conventional conversion factor estimated in the previous paragraph. Making comparisons between studies is difficult because of differences in the methods used to determine carbon, estimate organic matter, and report results. Some studies reported only summaries of the data while some provided the entire

Table 3

Summary of the composition of soil organic matter. Data are based on Schnitzer (1977); Steelink (1985); Stevenson (1994); Sparks (1995). Stevenson (1994) and Sparks (1995) categorize organic matter into various humic and non-humic substances and provide estimates of the carbon content and the proportion of organic matter comprised by each category of humic substances. Carbon contents of non-humic substances were estimated by averaging the atomic mass percentage of carbon from the chemical structures for each class of non-humic compounds given in Stevenson (1994). The figure of 70% carbon for humin is an average from McBride (1994), who reported the carbon content to be above 62%, and that of lipids at 80%, whose carbon content was estimated by the method described above. Some humin fractions appear to be constituents of lipids (Stevenson, 1994).

Component	% of Organic matter	% Carbon content
Humic substances		
Humin	8–50	62–67
Humic acid	10–20	54–59
Fulvic acid	10–40	41–51
Non-humic substances		
Carbohydrates	5–25	40–45
Lipids	2–6 ^a	69–79 ^b
Amino acids	15–45	33–65 ^c

^a May be as high as 20% in acid peat.

^b Median value is 78%. The range represents the 95th percentile range of published values.

^c Median value is 46%. The range represents the 95th percentile range of published values.

data set. Variability of results was of particular interest but not all studies included consistent measures of variability. Reporting only averages decreases the apparent variability of the data. In most cases, however, the range was provided or was obtainable from the data. Because many of the data sets are skewed to high values of the conversion factor, the median was used as the middle value unless only the mean was available. Data analysis was performed using SYSTAT 11 statistical software.

Two extreme factors, 14.12 found in the data from Warington and Peake (1880) and 15.4 found in the data from Christensen and Malmros (1982) were removed from the data set as obvious outliers but are included in Table 2 for completeness. The remaining values are summarized in Table 4. The median value of the factor is 1.97, higher than the conventional value of 1.724 and is in good agreement with the average value of 1.95 obtained from theoretical approximations. The histogram in Fig. 2 shows the modal value of the conversion factor to be 2 even more clearly than does Fig. 1, while again the factor 1.724 lies near the lower bound. Note the difference between the mean and median values as a result of the skewness of the distribution in the direction of high conversion factors. Using the mean would result in a conversion factor of 2.2, 10% larger than 2.0 using the median.

5. Sources of variation

Variability in any estimated factor comes from two sources: the methods used to estimate organic matter and organic carbon, and the natural variability in the composition of soil. Variability contributed by the two sources is not independent. For example, the estimate of organic matter based on the loss-on-ignition method (discussed later) depends on the relative amounts of organic matter and clay in the soil. Estimating the conversion factor ratio OM:OC requires measurements of OC and OM or a measurement of OC plus a conversion factor to estimate OM. The measurement error and natural variation present at each step, and the propagation of error need to be considered.

The accuracy with which any conversion factor is estimated is dependent on the accuracy of the methods used to measure organic carbon and organic matter. Underestimation of OM for example, will inflate OC:OM resulting in a conversion factor that is too low. Overestimation of OM will lower OC:OM resulting in a conversion factor that is too high. Similar problems arise with errors in determining OC. A detailed review of methods is beyond the scope of this paper. Thorough reviews already exist (see for example Nelson and Sommers, 1996; Chatterjee et al., 2009). However, some discussion of methods and procedures is undertaken as it relates to the establishment of an OM:OC conversion factor.

None of the authors of the papers reviewed here specifically claim to have used the Walkley–Black method, which has been a standard method for determination of organic carbon for most of the twentieth century, but instead refer to the more generic term, wet combustion, a term that can be applied to a variety of chromate digestion methods. Walkley–Black is a fast and simple variation that uses $K_2Cr_2O_7$, H_2SO_4 , and H_3PO_4 along with the heat generated by the addition of water to oxidize organic carbon in the sample. Digestion is followed by a back titration to determine the quantity of chromate remaining. The difference between the chromate present in the titrated blank and the

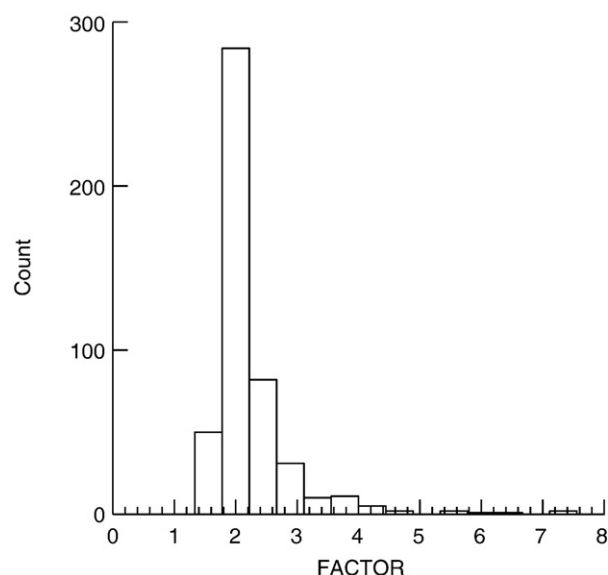


Fig. 2. Histogram of the empirical data set generated from the studies summarized in Fig. 1 and Table 2.

chromate remaining in solution after reaction is assumed to be equivalent to the amount of organic carbon present in the sample. Besides the use of hazardous reagents, perhaps the most serious drawback of Walkley–Black is that final estimation of organic carbon requires a correction factor since oxidation of the organic matter is incomplete and highly variable. Recovery can range from 27 to 100% with 77% being a typical value (Nelson and Sommers, 1996). Correction factors for individual soils, therefore, range from 1.0 to 3.7, with 1.3 being typical. Average correction factors for groups of soils vary from 1.03 to 1.41 but an average value applied to any given individual soil may result in substantial error. Incomplete oxidation of carbon makes wet combustion a poor choice for use on soils with high OM content, those containing more than 5% carbon (Soon and Abboud, 1991; Collins and Kuehl, 2001). These limitations mean that results obtained from Walkley–Black should be considered only an estimate of the amount of easily oxidizable organic carbon in soils (Nelson and Sommers, 1996; Jolivet et al., 1998).

Automated dry combustion (DC) is accurate, precise, and reliable, and has become the standard method for determining soil carbon (Chatterjee et al., 2009). The sample is mixed with a catalyst and heated in a stream of oxygen to approximately 1000 °C. All carbon in the sample is oxidized to CO_2 . The quantity of CO_2 released is measured by infrared absorption spectroscopy and converted to total carbon (TC). Any inorganic carbon present in the sample, such as carbonates, must be measured by a separate procedure and subtracted from TC. Alternatively, inorganic carbon may first be removed by pre-treatment (Kerven et al., 2000). For soils without carbonates, TC equals OC. Dry combustion is expensive and requires that the sample be finely ground, but it directly measures total soil carbon without the need for a correction factor (Grewal et al., 1991; Périé and Ouimet, 2008).

Organic matter is more difficult to measure accurately than organic carbon. Measurements of organic carbon can be used to estimate organic matter through the use of a conversion factor. Carbon content is first measured by a dry or wet combustion method such as Walkley–Black. Use of the Walkley–Black method, however, introduces three sources of error into the estimate of organic matter: measurement error inherent the procedure itself, the correction factor used to account for incomplete digestion of organic material, and the conversion factor used to estimate organic matter from the estimated carbon content. Dry combustion would seem to have a distinct advantage over Walkley–Black since it measures carbon directly but

Table 4
Summary statistics for the data from the empirical data set generated from the studies summarized in Fig. 1 and Table 2.

	Factor
Number of cases	481
Maximum	7.50
Minimum	1.35
Range	6.16
Median	1.97
Mean	2.20

Table 5

Correlation between test methods reported as R^2 . Methods comparisons are as follows: DC-WB = dry combustion to Walkley–Black; DC-LOI = dry combustion to loss-on-ignition; WB-LOI = Walkley–Black to loss-on-ignition. Abella and Zimmer (2007) admit to being unclear as to why their correlations are among the lowest reported in the literature.

Reference	R^2		
	DC-WB	DC-LOI	WB-LOI
Christensen and Malmros (1982)		0.99	
Lowther et al. (1990)	0.98	0.98	
Craft et al. (1991)		0.98	
Grewal et al. (1991)	0.99	0.95	
Soon and Abboud (1991)	0.96	0.97	0.96
Matejovic (1993) (TC)		0.95	
Wang et al. (1996)		0.92	0.89
Wang et al. (1996)		0.91	0.91
Jolivet et al. (1998)	0.99		
Mikhailova et al. (2003)	0.88		
Mikhailova et al. (2003)	0.90		
Zerva and Mencuccini (2005)		0.98	
Abella and Zimmer (2007)		0.69	
Abella and Zimmer (2007)		0.58	
Kamara et al. (2007)	0.98		
Périer and Ouimet (2008)	0.96	0.97	

the two methods correlate well (Table 5). Relatively bias-free results when comparing the two methods may be possible if the proper correction factor is applied with the Walkley–Black method. Another fundamental problem, common to both methods, is to find the correct conversion factor to estimate OM, which requires that the measurement of OM be independent of the measurement of OC.

Loss-on-Ignition (LOI) is a quick and relatively inexpensive method used to estimate OM directly but also seems to generate the most controversy. Some authors recommend its use and others are critical of its use (De Vos et al., 2005). The fundamental principle is simple: the mass lost on heating a dried sample to its ashing temperature is assumed to be organic matter. The accuracy of that assumption depends on the time and temperature of ignition, and on the composition of the sample. The temperature used with LOI must be high enough to completely remove organic matter but low enough to prevent dehydroxylation of clay minerals and oxidation of carbonates. As the amount of organic matter in a sample increases, complete removal of organic matter becomes more difficult, and as the amount of organic matter decreases, dehydroxylation of clays becomes more likely. Generally, if the ignition temperature remains below about 450 °C, adequate removal of organic matter with little dehydroxylation or loss of carbonates would be expected (Nelson and Sommers, 1996). Failure to adequately dry the sample at low temperature before removing the organic matter at high temperature can inflate the estimate of organic matter in the sample since the weight loss associated with removal of hydration water will be assumed to be organic matter.

Correlation between DC, Walkley–Black, and LOI is usually well above 90% (Table 5). Correlation in this context, however, reports only relative reproducibility. A more complete assessment of uncertainty requires a consideration of repeatability and systematic error (Taylor and Kuyatt, 1994). Repeatability of results is not typically reported but a useful way to compare reproducibility and systematic error between any two methods is to use regression analysis. The coefficient of determination, R^2 , is a measure of relative reproducibility while the slope and intercept of the regression line measure systematic error.

When comparing DC and LOI, the slope and intercept take on particularly useful interpretations. When the regression equation is in the form $DC = m(LOI) + b$, where m is the slope and b the intercept, the slope gives the ratio DC:LOI. Making the reasonable assumptions that $DC = OC$ and $LOI = OM$, the slope then gives OC:OM, the inverse of the conversion factor. A slope of 1 would mean that organic matter is composed entirely of carbon. A slope greater than 1 is impossible

since that would require carbon to comprise more than 100% of organic matter. The intercept can be used to study the interaction between sample composition and LOI parameters, an interaction that has been referred to as the “intercept effect” (Grewal et al., 1991). A positive intercept suggests that removal of organic matter is incomplete, resulting in a conversion factor that is too low. A negative intercept suggests dehydroxylation, dehydration, or possibly even removal of carbonates if the ignition temperature is sufficiently high, resulting in a conversion factor that is too high.

Although it is standard procedure to rely on formal measures of significance to decide if the regression line passes through zero, caution is advised. A true non-zero intercept has real meaning and may represent real variation (De Vos et al., 2005). In general, it may be better to include the intercept unless the sample size is very small. Aberrations in the pattern of residuals when using regression through the origin may result in a negative value for R^2 making its interpretation unclear, even meaningless (Neter et al., 1996).

Slopes shown in Table 6 range from 0.41 to 0.73 corresponding to conversion factors ranging from 1.4 to 2.4. These ranges are within those predicted by theoretical approximations. Intercepts range from −9.36 to 3.53. The distribution of intercepts has a skewness of −1.6. The dominance of negative intercepts suggests a tendency towards structural water loss during LOI, resulting in an overestimation of OM: OC and a conversion factor that is too high, and may partially explain the skewness of the distribution in Fig. 2.

Differences in the temperature at which LOI was performed support the hypothesis of water loss. Two studies, Ball (1964) who used 850 °C and 375 °C and Kamara et al. (2007) who used 375 °C and 350 °C, produced larger negative intercepts at the higher temperatures (Table 6). Ball (1964) studied non-calcareous soils so oxidation of carbonates at 850 °C was not an issue. Grewal et al. (1991) and Abella and Zimmer (2007) also found a significant increase in mass loss with increasing LOI temperature. In some cases, including clay content in the regression equation improved R^2 from 6% to 19% (Spain et al., 1982; Grewal et al., 1991; Abella and Zimmer, 2007). Donkin (1991) found that clay becomes significant above 400 °C but that high OM increased the variability of LOI at all temperatures. Organic matter

Table 6

Regression coefficients for the regression of dry combustion on loss-on-ignition. The regression equation is of the form $DC = m(LOI) + b$ where m is the slope and b is the intercept. A 0 intercept means that the regression was forced through the origin. Zerva and Mencuccini (2005) do not breakdown sample sizes by each of the three layers of forest soil studied; their total study comprised 230 samples.

Reference	n	m	b	R^2
Ball (1964) at 375°	65	0.46	−0.40	NR
Ball (1964) at 850°	67	0.48	−1.87	0.98
Christensen and Malmros (1982)	85	0.51	−0.23	0.99
Goldin (1987)	48	0.41	−0.71	0.86
Goldin (1987)	12	0.42	−2.49	0.89
David (1988)	174	0.52	−0.013	0.92
Lowther et al. (1990)	38	0.45	0.015	0.99
Lowther et al. (1990)	38	0.46	0	NR
Grewal et al. (1991)	40	0.60	−1.5	0.76
Soon and Abboud (1991)	28	0.63	−9.36	0.98
Wang et al. (1996)	50	0.73	−1.6	0.92
Wang et al. (1996)	66	0.47	−0.94	0.91
Jolivet et al. (1998)	50	0.61	0.6	0.99
Jolivet et al. (1998)	50	0.62	0	0.99
De Vos et al. (2005)	66	0.53	3.53	0.91
De Vos et al. (2005)	66	0.57	0	0.99
Zerva and Mencuccini (2005)	66	0.51	−0.092	0.99
Zerva and Mencuccini (2005)	230	0.54	0.18	0.99
Zerva and Mencuccini (2005)	230	0.53	−0.7	0.99
Abella and Zimmer (2007)	100	0.43	0.16	0.69
Abella and Zimmer (2007)	100	0.34	0.03	0.58
Kamara et al. (2007) at 350°	–	0.59	−4.32	0.92
Kamara et al. (2007) at 375°	–	0.59	−5.35	0.92
Périer and Ouimet (2008)	122	0.47	0	0.93

content less than 5% may also decrease the reliability of OC predictions from LOI especially without correcting for clay content (De Vos et al., 2005). Conversion factors ranging from 6.2 to 27.4 have been reported in fluvial bed sediments. These extremely high factors were attributed to significant water loss from Fe, Al, and Mn oxide minerals during the LOI procedure (Sutherland, 1998).

Although patterns of structural water loss from heating are dependent on clay mineralogy, water loss for most clay minerals begins to take place at temperatures above 150 °C (Barshad, 1965). Since ignition temperatures used for LOI usually exceed 300 °C, at least some of the weight loss observed during LOI is water loss from clay minerals. Gibbsite and goethite experience a loss of OH⁻ between 150 °C and 370 °C (Barshad, 1965) so when present, they also contribute to the observed weight loss. Furthermore, salts such as gypsum (CaSO₄·2H₂O), epsom salt (MgSO₄·7H₂O), and CaCl₂·6H₂O, lose their hydration water between 100 °C and 200 °C. NaHCO₃ decomposes to NaOH and CO₂ at 270 °C (Schulte and Hopkins, 1996). The loss of water from clay minerals, iron and aluminum (hydr) oxides, and certain salts will increase the apparent OM content estimated by LOI and increase the value of the conversion factor.

Data from Soon and Abboud (1991) further illustrate the relationship (Fig. 3). As clay content increases from 26% to 52%, the difference between OC found by DC and OC predicted by LOI increases to -6%, so at higher clay contents OC, estimated from LOI, overestimates OC in the sample relative to that determined by DC. This overestimate of OC would decrease the value of the conversion factor. As clay content decreases from 26% to 12%, OC estimated from LOI underestimates the quantity of OC present by about 4%, increasing the value of the conversion factor. Underestimation of OC by LOI at clay contents as high as 26% is difficult to explain. The general trend towards positive error with increasing clay content is consistent with a structural water loss hypothesis and supports their inclusion of a clay term in the regression. Including a clay term lowered the *R*² value of the regression of differences from 0.62 to 0.003.

The presence of charcoal in soils can greatly increase their carbon content. Robinson (1927) found 70 to 78% carbon in the organic matter of a soil known to contain charcoal. Fresh charcoal might contain as much as 80% carbon, but the carbon content falls off within about 100 years to the level of the carbon in the surrounding soil matrix, typically about 50%. The effect of charcoal is also dependent on the amount of charcoal present, which has been found to vary from 0 to 400 g/m² (Ohlson et al., 2009).

Walkley–Black gives unreliable results on soils containing significant amounts of charcoal or other forms of elemental carbon (Nelson and Sommers, 1996). Kerven et al. (2000) found that Walkley–Black recovered less than 10% of added charcoal while DC recovered 100%. Elemental carbon is oxidized by LOI even at temperatures as low as 375 °C (Ball, 1964). The variable efficiency of charcoal carbon oxidation and possible overestimation of OC by dry combustion needs further study (Sleutel et al., 2007) but should be considered

whenever soil organic carbon content is of interest since OC or OM can be accurately estimated only in soils substantially free of charcoal or other forms of elemental carbon (Ball, 1964).

Because the surface/subsurface distinction is often made, some observations concerning the relationship between depth and changes in the conversion factor are relevant. Three overall trends are apparent from the data in Table 7. First, surface soils do appear to have a lower factor median and less variability than subsurface soils (column 5) but where organic matter content is given, that relationship is only true in the 1–10% category. Second, the medians for all surface and subsurface soils are 1.9 and 2.2 respectively, exactly what Broadbent (1953) found in his study. Third, the factor decreases consistently with increasing organic matter for surface soils but not for subsurface soils. Despite these inconsistencies, the distinction between surface and subsurface soils may actually reflect differences in organic carbon. Three studies show an apparent relationship between increasing depth, decreasing carbon content, and an increasing conversion factor (see Barshad and Rojas-Cruz, 1950; Howard, 1964; Somani and Saxena, 1983). This trend, in terms of the change in OC:OM with increasing depth, is a relationship that needs further study. It is unclear whether the increase in the conversion factor with increasing depth is an artifact of the test method, in particular with LOI and increasing clay content, or if the change reflects a compositional change in the organic matter with increasing depth. Some studies suggest that the chemical composition of organic matter does change with depth (Jolivet et al., 1998; Périé and Ouimet, 2008).

6. Persistence of the conventional factor

Finally, an argument might be made that the factor 1.724 must have some credibility since it has been used for 150 years. Arguments presented against this position, while being more speculative than the previous lines of evidence, help explain the reason for the widespread adoption and persistence of the conventional factor despite the lack of supporting evidence.

Consider four common reasons for belief: evidence, tradition, authority, and revelation (see Dawkins, 1995). Revelation, based on one or more personal experiences, is not usually subject to falsification and is not typically associated with science so will not be considered. Evidence should be considered the strongest of the four factors and is the basis for all rational scientific thought. It would seem, however, that the evidence against the indiscriminant use of the factor 1.724 has long been ignored.

Table 7

Relation between organic carbon and surface versus subsurface soils. The upper number in each cell is the number of samples; the middle number is the median; the bottom number in parentheses is the range. The "All" in the fifth row and fifth column are not column and row totals but are statistics from the entire data set for each variable category. Because of inconsistencies in the data for each study, not every sample had the organic carbon content available for classification and not every sample that had an organic carbon classification had a surface or subsurface classification. The column labeled "All" gives summary statistics for all surface soils and all subsurface soils included in the study regardless of organic matter content. The rows labeled "All" give summary statistics for all samples with organic carbon contents as given.

	Organic carbon			All
	<1%	1–10%	>10%	
Surface	41	100	125	267
	2.21	1.98	1.86	1.89
	(2.28)	(4.41)	(0.89)	(4.41)
Subsurface	73	39	1	114
	2.09	2.25	1.64	2.21
	(5.83)	(1.99)	(0.00)	(5.88)
All	136	192	146	
	2.24	2.04	1.89	
	(5.83)	(4.41)	(1.16)	

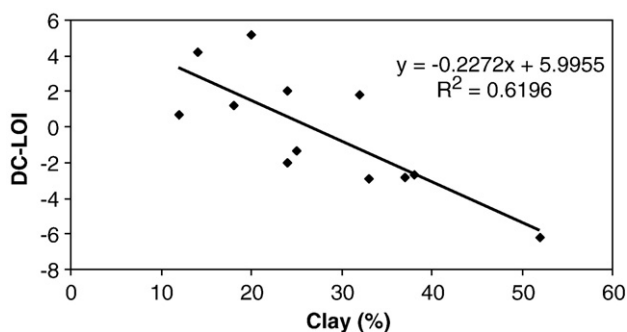


Fig. 3. Regression of the difference between carbon determined by dry combustion and predicted carbon from loss-on-ignition (DC-LOI) against the clay content of each sample. LOI values were estimated from Eq. (1) in Soon and Abboud (1991).

Early adopters may have justified their use of 1.724 through some combination of authority and convenience. A single number that can be applied to any situation is a tantalizing time-saving device, not easily dismissed, especially if that number appears to have come from an authority. The “from authority” argument is explicitly stated by Cameron and Breazeale (1904). A more subtle manifestation is the claim made by Leighty and Shorey (1930) that “the van Bemmelen factor is based on a large volume of analytical work” without specifying what constitutes a “large volume of work” or exactly whose work. They immediately go on to say that “[the van Bemmelen factor] is almost universally recognized as giving an approximation.” They do not state whether they find the approximation accurate or useful but their acknowledgement of the factor as being an approximation does recognize the variable carbon composition of soil organic matter. Assigning a name such as the “van Bemmelen factor” to 1.724 implies a derivation from authority and a lineage of credibility. Finally, the factor is usually given the unwarranted precision of four significant figures. This tradition may go back to Sprengel (1826) who reported his results to four significant figures. This practice may be yet another manifestation of the authority principle.

A fourth possible explanation is tradition, the widespread adoption and perpetuation of the factor 1.724 once it has become established through authority and convenience. It becomes at some point, the “conventional factor,” a number that subsequent generations of scientists are brought up to believe is a fact. It then takes on an aura of infallibility by its continued use. Loges' (1883) procedure for estimating organic matter, which specified multiplying carbon by 1.724, was already used by the German experiment stations at least by the early twentieth century if not earlier (see Wiley, 1906, p. 367). Once in the secondary literature such as textbooks and technical procedures manuals, it is almost impossible to eliminate (Gould, 1983, 1991; Paul, 1987). A recent exception is the popular soil science text, *The Nature and Properties of Soils*. Between the eleventh (Brady and Weil, 1996) and twelfth (Brady and Weil, 1999) editions, Brady and Weil updated the conversion factor from 1.7 to 2, acknowledging that “this value [58% carbon in the organic matter] probably applies only to highly stabilized humus. For most situations, a value of 50% is more accurate” (Brady and Weil, 1999). Given the popularity of their textbook, earlier editions may have helped propagate the factor 1.7. Broadbent (1953) recognized that “[t]he use of the usual conversion factor 1.724, which has become established through long use rather than adequate experimental verification, may lead to an error as large as 50% in estimating subsoil organic matter.” The factor 1.724 has become even more “injurious” than what Darwin calls “false facts” (Darwin, 1998, p. 629), because false facts quickly disappear when confronted with contradictory evidence. The factor 1.724 persists despite substantial contradictory evidence.

7. Conclusion

A preponderance of studies over the last 120 years show that the fundamental assumption upon which the conventional factor is based, that carbon comprises 58% of organic matter, is on average too high. As a result, the conventional conversion factor of 1.724 is too low for most soils. This study found a median value for the conversion factor of 1.9 from all studies and 2 from theoretical considerations. A factor of 2, based on the assumption that organic matter is 50% carbon, would in almost all cases, be more accurate than the conventional factor of 1.724.

The discovery of the lower value of carbon content of organic matter seems to have resulted from a change in the method used to estimate organic matter. The earliest methods that were intended to extract organic matter actually isolated humic acid, which contains approximately 58% carbon. It is of interest to note that Gortner (1916), using either sodium hydroxide or ammonium hydroxide to extract

humus, did not follow the alkali extraction with a hydrochloric acid treatment so did not precipitate humic acid. He found approximately 50% carbon in these alkali-only extracts.

Loss-on-ignition has become a common method for estimating organic matter, which is then converted to an estimate of organic carbon. Ignition at too low or too high a temperature may seriously under- or overestimate the quantity of organic matter resulting in conversion factor estimates that are too low or too high. Loss-on-ignition estimates should be calibrated against the more reliable determination of carbon using dry combustion for each soil type and region studied. Calibration should be done using an intercept model that includes clay and sampling depth.

Although estimates of soil carbon based on converted estimates of organic matter can be useful, if the purpose of a study is to measure soil carbon, then carbon should be determined directly rather than estimated from a measurement of what is assumed to be organic matter, consistent with the stated preference of the National Soil Survey Laboratory (Burt, 1995) and the recommendation of Nelson and Sommers (1996).

Any factor used to convert organic carbon to organic matter is not a universal physical constant. The factor may be influenced by vegetation cover, organic matter composition, depth in profile, amount of organic matter and clay in the soil, and degree of decomposition, all of which might reflect real differences in the carbon content of organic matter. Any empirically derived conversion factor, or method that uses an empirical conversion factor, can only be an estimate. Any single-number conversion factor, universally applied, has the potential for serious error when used to estimate the carbon content of soils. For example, applying the factor 1.724 rather than 2 overestimates the amount of carbon by 15%. The appeal of a single number is powerful, but for most purposes, the carbon content of soils is too variable for a single conversion factor, universally applied and based on questionable assumptions, to provide sufficiently reliable accuracy for reporting the quantity of soil organic carbon.

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