Chapter 20
Comparing Soil C Stocks from Soil Profile Data Using Four Different Methods

Benito R. Bonfatti, Alfred E. Hartemink and Elvio Giasson

Abstract Soil organic carbon (SOC) concentration differs by depth, soils, and distinct land uses. Different methods have been used to calculate SOC stocks, and here, we used data from 10 pedons from Southern Brazil to compare four methods: horizon values with discrete data, exponential function, equal-area exponential function, and equal-area quadratic spline function. SOC stocks were calculated up to 30 cm and 100 cm depth from (i) the original data, (ii) the standardized data based on equal mass, (iii) the standardized data based on equal mass minus coarse fragments (gravels). Results were compared calculating SOC stocks up to 30 and 100 cm depth. Discrete values by horizon produced mean SOC stocks for 30 and 100 cm depth of 6.9 and 14.6 kg/m^2 for original values, 6.5 and 14.1 kg/m^2 for standardized values by mass, and 6.3 and 13.5 kg/m^2 for standardized values by mass minus gravels. Negative exponential functions produced mean values of 6.1 and 14.1 kg/m^2 for original values, 5.6 and 13.3 kg/m^2 for standardized values by equal mass, and 5.4 and 12.9 kg/m^2 for standardized values by equal mass minus gravels. Equal-area exponential function had mean values of 7.1 and 14.5 kg/m^2 for original values, 6.6 and 13.9 kg/m^2 for standardized values by equal mass, and 6.4 and 13.5 kg/m^2 for standardized values by equal mass minus gravels. Equal-area spline produced SOC averages of 6.8 and 14.7 kg/m^2 for original values, 6.3 and 14.2 kg/m^2 for standardized values by equal mass, and 6.1 and 13.7 kg/m^2 for standardized values by equal mass minus gravels. From the comparison, we found that negative exponential functions produced lower SOC stocks than horizons in the

B.R. Bonfatti · E. Giasson
Universidade Federal do Rio Grande do Sul, UFRGS—Faculdade de Agronomia,
Av. Bento Gonçalves, 7712, Porto Alegre, RS 91540-000, Brazil
e-mail: brbonfatti@yahoo.com.br

B.R. Bonfatti · A.E. Hartemink (✉)
Department of Soil Science, FD Hole Soils Lab, University of Wisconsin—Madison,
1525 Observatory Drive, Madison, WI 53706, USA
e-mail: hartemink@wisc.edu

B.R. Bonfatti
CAPES Grand Holder—Process BEX 3095/14-2, CAPES Foundation,
Ministry of Education of Brazil, Brasília, DF 70040-020, Brazil

A.E. Hartemink and B. Minasny (eds.), *Digital Soil Morphometrics*,
Progress in Soil Science, DOI 10.1007/978-3-319-28295-4_20

upper layers and higher stocks than horizons in the lower layers; equal-area exponential produced SOC stocks that are statistically similar to horizon values; equal-area spline function produced values up to 30 cm depth statistically similar to horizon values and statistically different up to 100 cm depth. We can conclude that different methods for calculating SOC stocks by depth produce significantly different results and values derived from equal-area exponential and equal-area splines are more similar to those of the horizons.

Keywords SOC · Spline · Exponential function · Soil equal mass

20.1 Introduction

The levels of soil organic carbon (SOC) and its distribution by depth are related to the climate, vegetation cover, soil type, geomorphology, and agricultural activities. High-precipitation areas commonly with dense vegetation result in the accumulation of soil carbon. The opposite occur in soils of dry areas which, in addition to not having enough moisture, the carbon is bound to calcium and immobile (Schaetzl and Anderson 2005). There is considerable variation in SOC levels across the landscape. Valleys' bottoms may receive erosional sediments from upper areas, forming deep soil profiles with buried A horizons. Agricultural activities largely affect carbon stocks. Tillage and no-tillage practices result in different SOC distribution (Angers and Eriksen-Hamel 2008; Sisti et al. 2004).

There are only few studies that consider carbon up to 100 cm depth (Minasny et al. 2013). Most studies have data up to 30 cm soil depth, which is the standard IPCC depth and relevant to agriculture crops. To assess the amount of carbon below 30 cm it is needed to comprehend the SOC dynamics under different tillage systems (Angers and Eriksen-Hamel 2008; Sisti et al. 2004) or its distribution by depth under different land uses (Guo and Gifford 2002; Jobbágy and Jackson 2000).

Comparison of SOC under different environmental conditions is complicated as the data are often from discrete horizons. Knowledge and interpretation about carbon accumulation is facilitated when data are continuous across the soil. The continuous distribution of properties can give a new insight into diagnostic horizons and may even result in the formation of new classes (Hartemink and Minasny 2014).

Representing SOC by mathematical functions provides continuous values by depth and gives SOC for fixed or ranges of depths. Recent studies have used the equal-area spline function (Adhikari et al. 2014; Malone et al. 2009; Odgers et al. 2012), which models local quadratic polynomials functions (Bishop et al. 1999; Ponce-Hernandez et al. 1986). Other methods have used exponential decay functions (Minasny et al. 2006; Mishra et al. 2009; Zinn et al. 2005), and they assume that carbon concentration decreases exponentially with depth. Studies have also used exponential functions based on horizon data, considering area equivalence similar to equal-area splines (Kempen et al. 2011).

The quantification of SOC stocks includes the variation of bulk density and the content of coarse fragments (e.g., gravel). Miscalculation of SOC stocks occurs when bulk density is altered by compaction or when a reduction in bulk density following tillage is not considered. The SOC stocks under different bulk densities must be corrected by thickness variance (Ellert and Bettany 1995) or standardized by cumulative mass coordinates (Gifford and Roderick 2003). Moreover, when calculating SOC stocks, the amount of coarse fragments should be considered.

This study analyzed four methods for calculating soil carbon stocks up to 30 and 100 cm depth: (a) distribution by horizon, (b) distribution by exponential function, (c) distribution by equal-area exponential function, and (d) distribution by equal-area spline function. The discrete values by horizon use data directly from the database, and the functions use midpoint data from each horizon. The methods were separated into 3 groups: (I) original values, (II) values standardized by equal mass, and (III) values standardized by equal mass minus gravels.

20.2 Materials and Methods

20.2.1 The Soils

We have used the SOC and bulk density data from 10 soil profiles collected in Vale dos Vinhedos (Vineyard Valley) in northeastern Rio Grande do Sul State, Brazil. This area has a mean annual precipitation of 1736 mm and mean annual temperature of 17.2 °C. The climate is classified as Cfb (EMBRAPA 2008). Some of the soils are gravelly (Flores et al. 2012) and dominant soils are Inceptisols, and smaller areas with Ultisols, Mollisols, Entisols, Alfisols, and Oxisols. Most soils are covered by forest or used as vineyards.

The data of 10 profiles (Table 20.1) were extracted from the soil survey report by Flores et al. (2012) and complemented with soil bulk density measurements made in 2014. The bulk density was measured in different soils and land uses (vineyard, forest/planted forest, pasture, arable crops, and fallow). The soils were sampled by soil horizon and SOC was analyzed by Walkley-Black (Flores et al. 2012; Santos et al. 2006).

20.2.2 Methods

In this study, we used four methods for calculating carbon stocks up to 30 and 100 cm depth. The punctual bulk density values were interpolated by smooth splines and the results were calculated using each centimeter. The values were average and assigned to each respective horizon. The horizons' midpoints were used to interpolate the functions. Details of each method are presented below.

Table 20.1 Description of the 10 pedons from the study area in Vale dos Vinhedos in Rio Grande do Sul, Brazil

Pedon	Reference Pedon (Flores et al. 2012)	Horizon	Depth (cm)	SOC (g/kg)	Bulk density[a] (Mg/m^3)	Coarse fragments (%)	Soil class	Land use
1	4	Ap	0–15	19.8	1.15	16	Orthents	Vineyard
		CR	15–35	15.1	1.17	6		
2	5	Ap	0–16	16.7	1.17	0	Udepts	Vineyard
		Bi	16–36	7.4	1.21	0		
		BC	36–50	5.5	1.22	0		
3	27	Ap	0–23	13.8	1.14	1	Udults	Vineyard
		AB	23–55	5.7	1.21	19		
		Bt1	55–74	3.9	1.23	0		
		Bt2	74–120	2.9	1.25	0		
4	28	Ap	0–30	14.7	1.20	0	Humults	Vineyard
		Bt1	30–72	13.8	1.24	1		
		Bt2	72–120/140	8.6	1.17	0		
		C	120/140–200	2.8	1.17	0		
5	53	Ap1	0–30	37.3	0.97	0	Udoxs	Forest
		A2	30–55	26.7	1.06	0		
		Bt1	55–90	14.4	1.18	0		
		Bt2	90–200	6	1.23	0		
6	78	Ap	0–35	25.5	1.03	0	Udepts	Forest
		Bi	35–90	22.6	1.19	0		
		CR	90–150	15	1.28	75		
7	99	Ap	0–28	12.3	1.15	28	Udalfs	Pasture
		Bt	28–61	5.9	1.21	0		
		BC	61–100	4.3	1.25	0		
8	118	Ap	0–39	17.2	1.33	0	Humults	Arable crops
		AB	39–73	12.5	1.37	0		
		Bt1	73–120	10.4	1.28	0		
		Bt2	120–200	6.7	1.28	0		
9	119	Ap	0–24	43.3	1.20	0	Udepts	Fallow
		Bi	24–55	5.2	1.29	23		
		C1	55–85	2.5	1.30	0		
		C2	85–150	2	1.17	0		
10	141	Ap	0–30	21.2	1.09	0	Humults	Planted forest
		BA	30–60	11.8	1.25	0		
		Bt1	60–110	11.1	1.38	0		
		Bt2	110–200	6.2	1.30	0		

[a]Bulk density samples were taken at different depths; values in the table correspond to derivate values for each horizon, from smooth spline functions

Discrete Values by Horizon

In this method, we used the discrete horizon values from the database, without interpolations. Bulk density, carbon content (g/kg), and thickness (up to 30 and 100 cm) from each horizon were multiplied for getting the SOC stocks.

Exponential Function

The exponential function has been used in mapping carbon by depth because of its mathematical ease and apparent similarity to soil profile changes with depth found for most soil properties (Minasny et al. 2006). The negative exponential function can summarize the profile data in three parameters allowing the use of more easy measured or widely available data (Minasny et al. 2006).

The negative exponential function is given as follows:

$$C = C_a \exp(-kz) + C_b \tag{20.1}$$

With conditions C_a, C_b, $k > 0$, where C is the organic carbon content in volume basis (kg/m^3), z is the absolute value of depth from the soil surface, C_a is the difference in carbon content between the surface and the lowest depth, $(C_a + C_b)$ is the carbon content at the soil surface, C_b is the carbon content at the bottom of the profile, and k is the rate of carbon decrease with depth.

To apply the equation, the bulk density values (kg/m^3) were multiplied by SOC concentration (kg C/kg). The calculated SOC (kg/m^3) were used as input values to the function, which parameter k was fitted by nonlinear least squares.

Equal-Area Exponential Function

The equal-area exponential functions have similarities with the equal-area smoothing spline where for each horizon the area fitted to the left of the fitted curve is equal to the area to the right, so the function represents the average value for a horizon. It does not always guarantee mass conservation as in equal-area splines, but it has better mass-conserving properties than a decay exponential function fitted to the midpoints of the soil horizons (Kempen et al. 2011).

For this approach, first the components C_a and k were fitted, minimizing the sum of squared differences between the observed and the predicted SOC stocks for each horizon, by the model:

$$0 = \sum_{i=1}^{n} \left[\left(\frac{C_a}{k} \right) \left[\exp\left(-kz^*_{Li}\right) - \exp\left(-kz^*_{Ui}\right) \right] - C_{li} \right]^2 \tag{20.2}$$

where z^*_{Li} is the depth of the lower boundary of soil horizon i in a soil profile, n is the number of soil horizon, z^*_{Ui} is the depth of the upper boundary soil horizon i, and C_{li} is the observed SOC stock of horizon i.

The exponential function was defined with the fitted C_a and k values, by the equation:

$$C = C_a \exp(-kz) \tag{20.3}$$

The equation needs at least three points to be solved. For soil profile 1 that has only two horizons, the deepest horizon was divided into two parts and the midpoint of each part was taken.

Equal-Area Spline Function

The equal-area spline function produces a continuous function showing the SOC distribution by depth and attempts to negate the damping effects of using discrete data from horizons (Bishop et al. 1999; Ponce-Hernandez et al. 1986). The key characteristics described by Bishop et al. (1999) are as follows:

1. It consists of a series of local quadratic polynomials with the "knots" or positions of joins being located at horizon boundaries.
2. For each horizon, the area to the left of the fitted spline curve above the horizon average (*X*) is equal to the area to the right of the fitted spline curve below the horizon average (*Y*), thus ensuring the mean value of the horizon is maintained.

Malone et al. (2009) used the equal-area smoothing spline, which is a generalization of the quadratic spline model of Bishop et al. (1999). First, the spline functions produce continuous data, then the values are again combined in different depth intervals, by averages.

In the spline method, summarily, $f(x)$ represents a spline depth function and can be solved by minimizing the following:

$$\frac{1}{n}\sum_{i=1}^{n}\left(y_i-\overline{f_i}\right)^2+\lambda\int_{x_0}^{x_n}[f'(x)]^2\mathrm{d}x, \tag{20.4}$$

$$\text{where} \quad y_i=\overline{f_i}+e_i \tag{20.5}$$

The first term of Eq. (20.4) represents the fit to the data, and the second, the roughness of spline function. The parameter λ controls the trade-off between the fit and the roughness penalty; n is the number of layers in a soil profile; depth is denoted by x. The y_i represents the measurement of bulk sample from layer i, and $\overline{f_i}$ is the mean value of $f(x)$ over each layer. The errors e_i in Eq. (20.5) are assumed independent, with mean 0 and common variance σ^2 (Bishop et al. 1999). The function $f(x)$ and its first derivative $f'(x)$ are both continuous and $f'(x)$ is square integrable.

In our study, the spline functions were solved similarly to the method described in Malone et al. (2009) and using $\lambda = 1$. Spline functions were calculated for SOC content (g/kg), bulk density (g/cm^3), and coarse fragments (%), for each of the 10 soil profiles.

20.2.3 Correcting for Mass and Coarse Fragments

SOC stocks were calculated for each method until 30 and 100 cm depth. Then, the values were combined in three different groups. The first groups had the original calculated values. The second group had the values standardized by equal mass, and in the third group the values were standardized by mass minus coarse fragments (gravel).

Standardization by mass was used to make comparisons possible among soils with different bulk densities. We used the method described by Gifford and Roderick (2003) with a cumulative mass coordinates approach. Cumulative soil mass (kg/m^2) was calculated by multiplying the soil bulk density and thickness of each horizon (or 1 cm when using continuous functions). Similarly, it was used to determine cumulative SOC stocks. The soil mass under forest was chosen as a reference. Hence, cumulative mass of the two profiles under forest (profiles 5 and 6) was averaged and the value was used in the following equation for correcting SOC stocks applied to each horizon or 1 cm:

$$c_s(t) = c_s(z_a) + \frac{c_s(z_b) - c_s(z_a)}{m_s(z_b) - m_s(z_a)}(m_s(t) - m_s(z_a)) \tag{20.6}$$

where $c_s(t)$ is the value of cumulative SOC stocks corrected by mass; $c_s(z_a)$ and $m_s(z_a)$ are the values of cumulative SOC stocks and mass, respectively, from the lower boundary of the horizon above it; $c_s(z_b)$ and $m_s(z_b)$ are the cumulative SOC stocks and mass of the lower boundary of the current horizon (or centimeter); $m_s(t)$ is the cumulative soil mass from the lower depth of the reference horizon. For the continuous functions, the values were determined by each centimeter, instead of horizons.

The third group of SOC calculations used the cumulative SOC stocks corrected by coarse fragments (gravels and stones) to standardize by mass using the procedure described above.

20.2.4 Statistical Analysis

Two statistical ways were used to compare the total SOC stocks up to 30 and 100 cm depth, considering the four different methods: (a) assigned by horizon, (b) negative exponential function, (c) equal-area exponential function, and (d) equal-area spline function, and divided into 3 groups: (1) original values, (2) values standardized by mass, and (3) values standardized by mass minus gravels (coarse fragments).

The first analysis compared different methods within the same group using repeated measure ANOVA as the samples are dependent. For paired comparisons, the post hoc Bonferroni test and multiple dependent t-test for paired samples were used. The second analysis compared the same method in different groups using the post hoc Bonferroni test for paired comparisons.

20.3 Results and Discussion

The different methods used to interpolate carbon with depth showed distinct curve (Fig. 20.1). Results differ significantly depending on how the function fits to the SOC variation.

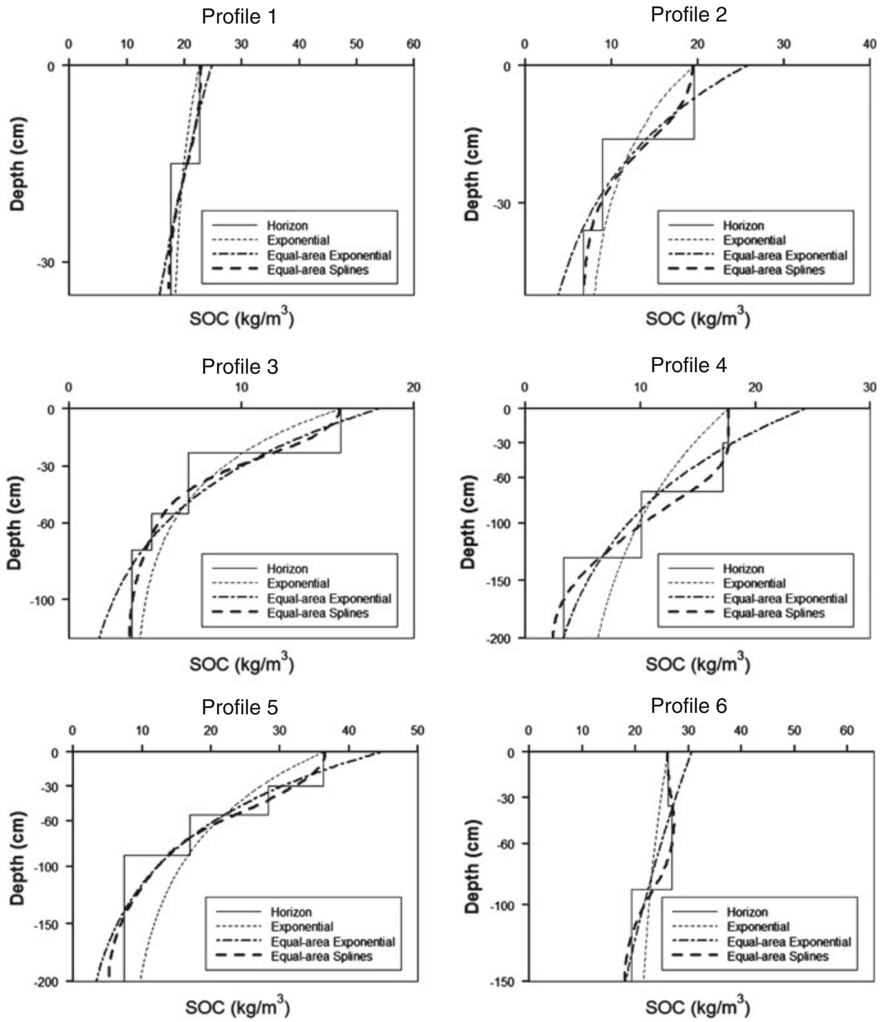

Fig. 20.1 SOC concentration (kg/m^3) by four different methods

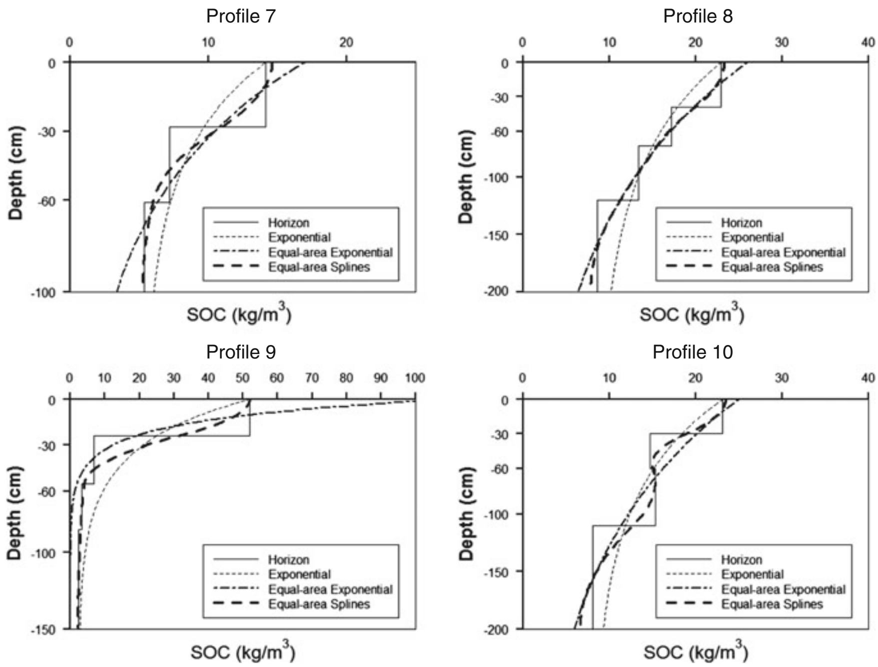

Fig. 20.1 (continued)

20.3.1 The 4 Methods

Discrete Values by Horizon

This method used information directly from SOC analysis by horizon. The graphs assume the aspect of “stairs” (Fig. 20.1) which make it difficult to view the smoothness of carbon variation by depth.

The averages of SOC stocks up to 30 and 100 cm depth were, respectively, 6.9 and 14.6 kg/m^2 for original values, 6.5 and 14.1 kg/m^2 for standardized values by mass, and 6.3 and 13.5 kg/m^2 for standardized values by mass minus coarse fragments.

Exponential Function

The exponential function shows a continuous exponential decrease of carbon with depth. The equation is less complex than equal-area exponential or spline method but the curve adjusting is more limited. It initializes at 0 cm depth interpolating with values of mid-horizon. The curves show lower values than horizons for upper depths and higher for lower depths (Fig. 20.1) producing a lower average of total SOC stocks (Fig. 20.3).

This approach produced the lowest SOC stocks up to 30 cm depth or 100 cm depth. The averages of SOC stocks up to 30 and 100 cm depth were, respectively, 6.1 and 14.1 kg/m^2 for original values, 5.6 and 13.3 kg/m^2 for standardized values by mass, and 5.4 and 12.9 kg/m^2 for standardized values by mass minus coarse fragments.

Equal-Area Exponential Function

The equal-area exponential function showed SOC stocks very similar to stocks calculated by horizons up to 30 cm and up to 100 cm. Starting points of the curves have values higher than SOC values of top horizons. In some soils, as in profile 9, the initial values look exaggerated. For other profiles considering continuous SOC variation with depth, the initial values seem more reasonable.

This approach produced the highest SOC stocks up to 30 cm. The averages of SOC stocks up to 30 and 100 cm depth were, respectively, 7.1 and 14.5 kg/m^2 for original values, 6.6 and 13.9 kg/m^2 for standardized values by mass, and 6.4 and 13.5 kg/m^2 for standardized values by mass minus coarse fragments.

Equal-Area Spline Function

The equal quadratic splines show that curves fit well to discrete distribution (Fig. 20.1). The curves start at or very close to surface with the SOC value from the top horizon. This approach produced the highest SOC stocks up to 100 cm depth. The averages of SOC stocks up to 30 cm and 100 cm depth were, respectively, 6.8 and 14.7 kg/m^2 for original values, 6.3 and 14.2 kg/m^2 for standardized values by mass, and 6.1 and 13.7 kg/m^2 for standardized values by mass minus coarse fragments.

20.3.2 Correction by Mass and Coarse Fragments

The values of SOC stocks were corrected by mass (Fig. 20.2) and for coarse fragments. The 30 and 100 cm depths were marked to facilitate comparisons. Horizontal lines show total SOC stocks up to 30 and 100 cm depth for the reference soil mass. There is a difference between original values and standardized values by mass. Observing the points stressing the values up to 30 and 100 cm depth, the SOC stocks have lower values when using standardized mass.

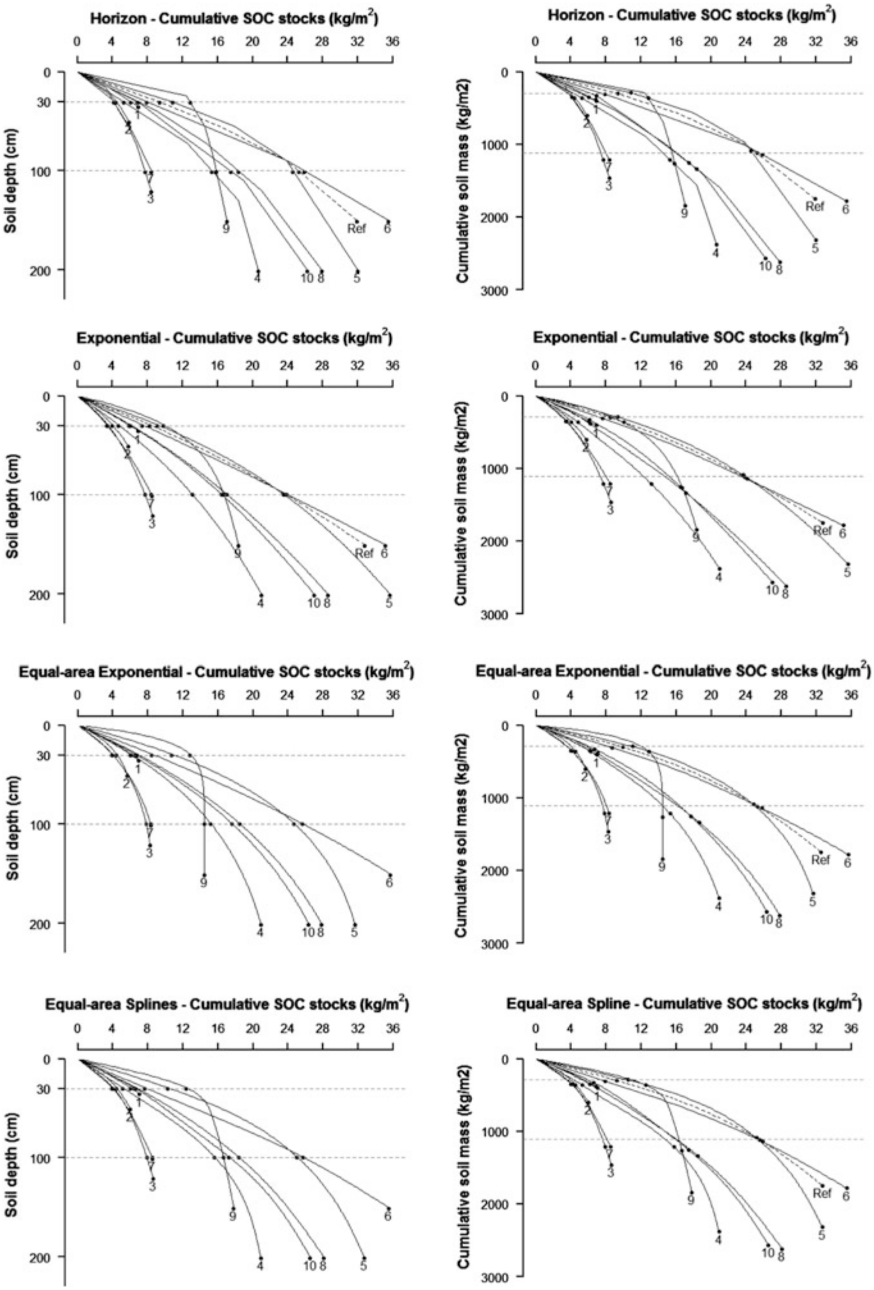

Fig. 20.2 SOC stocks standardized by cumulative mass for 10 soil profiles. The reference line (Ref) is the average of profiles 5 and 6 (under forest) used for SOC stocks comparisons by same accumulate mass. *Horizontal dashed lines* show the cumulative soil mass for 100 and 30 cm of the reference depth. The points indicate the SOC stocks on the 30, 100 cm and depth of each profile

20.3.3 Statistical Analysis

The average total SOC stock is different for each method and group. The highest average total SOC stock up to 30 cm depth, 7.1 kg/m^2, was found using original values interpolated by equal-area exponential function. The lowest average SOC stock up to 30 cm depth, 5.4 kg/m^2, was calculated using standardized values by mass minus gravels and the exponential function. The highest average total SOC stock up to 100 cm depth, 14.7 kg/m^2, was found using original values interpolated by equal-area spline function. The lowest average SOC stock up to 100 cm depth, 12.9 kg/m^2, was calculated using standardized values by mass minus gravels and the exponential function. This considerable difference between different methods and standardization results in significantly different quantification of SOC stocks.

The first analysis compared the four different methods within the same group. In the group with original values, the repeated measured ANOVA with multiple *t*-test showed similarity between the horizon values and the equal-area exponential and spline functions, until 30 cm (Fig. 20.3). When considering the depth up to 100 cm,

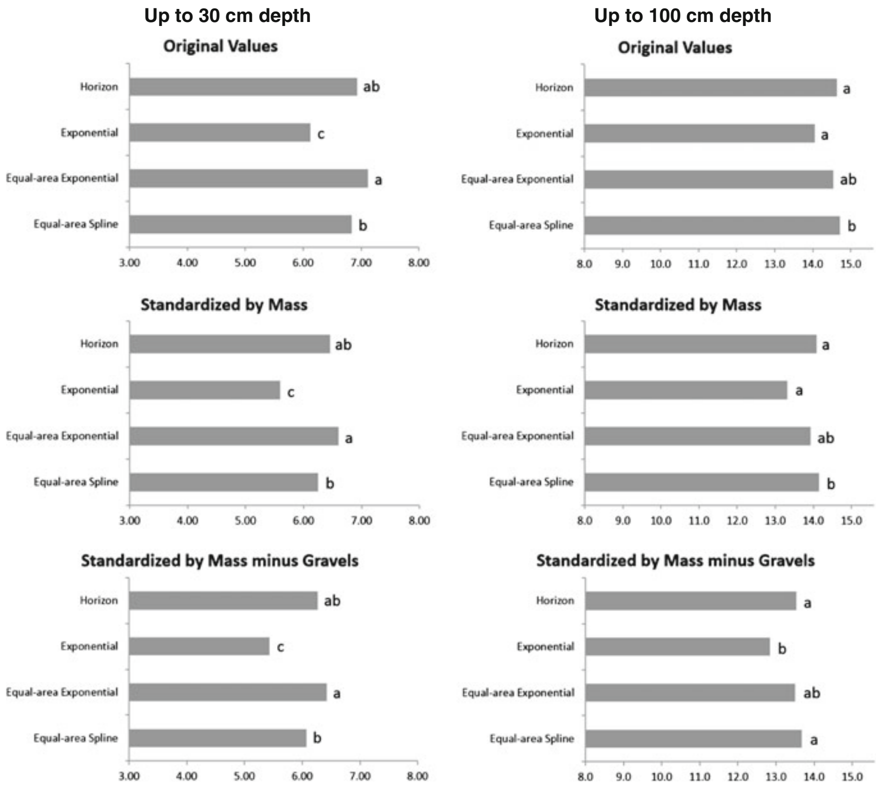

Fig. 20.3 Average SOC stocks (kg/m^2) of 10 soil profiles and statistical comparison between four different methods combined in three groups. Multiple dependent *t*-test for paired samples was used for statistical analysis

equal-area exponential function and discrete values by horizon yield similar results. However, the equal-area spline function is not similar to horizon values as in depth up to 30 cm. The equal-area spline curve, for some profiles, was cut on 100 cm depth, sectioning the interpolation next to half horizon. This considers only the initial part of the fitted curve at respective horizon and the values were not balanced by the final part. As the initial part has higher values than the final, a higher average was found. This difference was reduced when the values were standardized by mass and corrected by gravels.

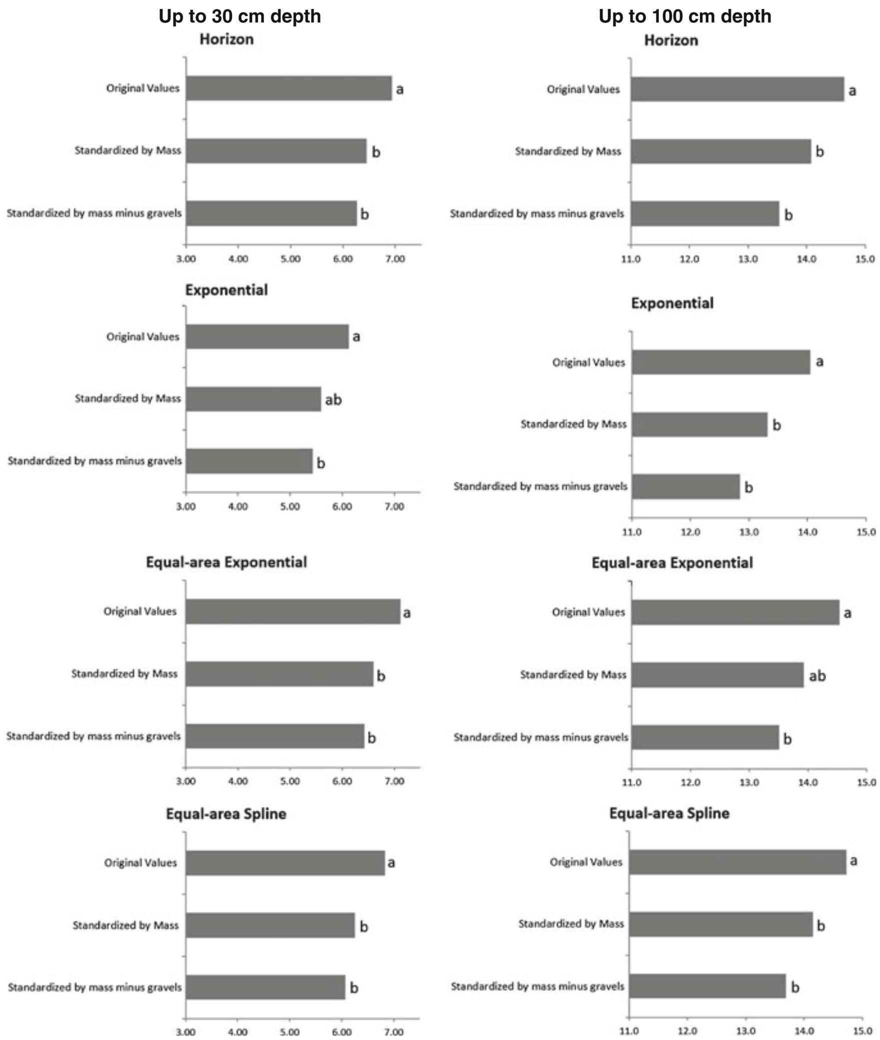

Fig. 20.4 Average SOC stocks (kg/m^2) of 10 soil profiles for each method by different groups. Repeated measure ANOVA with post hoc Bonferroni correction was used for statistical analysis

The results found in values standardized by mass and standardized by mass minus gravels were similar.

The second analysis comparing the same methods in different groups showed that the values standardized by mass and mass minus gravels are statistically similar (Fig. 20.4). When both are compared to the original values, the results differ.

The analysis is complementary and confirms that original data produced significantly different results than standardized data. Different functions can produce different results, independently of the standardization.

The characteristic of each function needs to be considered during the choice of the function and interpretation of the results. When using discrete values, the continuous carbon variation on the profiles is not considered. Negative exponential function tends to produce lower values than horizons in upper layers and higher values at greater depths and lower SOC stocks of the profile. Equal-area exponential and equal-area splines produce SOC stocks similar to horizon values. Differences may appear when the function is not considering the initial and the final balance part of the curve and this generally increases the values.

20.4 Conclusions

From this analysis, the following can be concluded:

- Different functions for calculating SOC by depth produce significantly different results.
- The highest average total SOC stock up to 30 cm depth, 7.1 kg/m^2, was found in the original values interpolated by equal-area exponential function. The lowest average SOC stock up to 30 cm depth, 5.4 kg/m^2, was calculated using standardized values by mass minus gravels and the exponential function.
- The highest average total SOC stock up to 100 cm depth, 14.7 kg/m^2, was found in original values interpolated by equal-area spline function. The lowest average SOC stock up to 100 cm depth, 12.9 kg/m^2, was calculated using standardized values by mass minus gravels and the exponential function.
- Equal-area exponential and equal-area splines produce SOC stocks similar to horizon values, primarily when considering the initial and final parts of the fitted curve by each horizon.
- Values standardized by mass and mass minus gravels yield significantly different results compared to original values.

References

Adhikari K, Hartemink AE, Minasny B, Bou Kheir R, Greve MB, Greve MH (2014) Digital mapping of soil organic carbon contents and stocks in Denmark. PLoS ONE 9:e105519. doi:10.1371/journal.pone.0105519

Angers DA, Eriksen-Hamel NS (2008) Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci Soc Am J 72:1370–1374
Bishop TFA, McBratney AB, Laslett GM (1999) Modelling soil attribute depth functions with equal-area quadratic smoothing splines. Geoderma 91:27–45
Ellert BH, Bettany JR (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can J Soil Sci 75:529–538. doi:10.4141/cjss95-075
EMBRAPA (2008) Normal Climatológica: Estação Agroclimática da Embrapa Uva e Vinho, Bento Gonçalves, RS. Período de 1961 a 1990. http://www.cnpuv.embrapa.br/
Flores CA, Pötter RO, Sarmento EC, Weber EJ, Hasenack H (2012) Os Solos do Vale dos Vinhedos. EMBRAPA, Brasília, DF, Brazil
Gifford RM, Roderick ML (2003) Soil carbon stocks and bulk density: spatial or cumulative mass coordinates as a basis of expression? Glob Change Biol 9:1507–1514
Guo LB, Gifford RM (2002) Soil carbon stocks and land use change: a meta analysis. Glob Change Biol 8:345–360. doi:10.1046/j.1354-1013.2002.00486.x
Hartemink AE, Minasny B (2014) Towards digital soil morphometrics. Geoderma 230–231:305–317. doi:10.1016/j.geoderma.2014.03.008
Jobbágy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol Appl 10:423–436
Kempen B, Brus DJ, Stoorvogel JJ (2011) Three-dimensional mapping of soil organic matter content using soil type–specific depth functions. Geoderma 162:107–123. doi:10.1016/j.geoderma.2011.01.010
Malone BP, McBratney AB, Minasny B, Laslett GM (2009) Mapping continuous depth functions of soil carbon storage and available water capacity. Geoderma 154:138–152. doi:10.1016/j.geoderma.2009.10.007
Minasny B, McBratney AB, Mendonça-Santos ML, Odeh IOA, Guyon B (2006) Prediction and digital mapping of soil carbon storage in the Lower Namoi Valley. Aust J Soil Res 44:233. doi:10.1071/SR05136
Minasny B, McBratney AB, Malone BP, Wheeler I (2013) Digital Mapp Soil Carbon 118:1–47. doi:10.1016/b978-0-12-405942-9.00001-3
Mishra U, Lal R, Slater B, Calhoun F, Liu D, Van Meirvenne M (2009) Predicting soil organic carbon stock using profile depth distribution functions and ordinary kriging. Soil Sci Soc Am J 73:614. doi:10.2136/sssaj2007.0410
Odgers NP, Libohova Z, Thompson JA (2012) Equal-area spline functions applied to a legacy soil database to create weighted-means maps of soil organic carbon at a continental scale. Geoderma 189–190:153–163. doi:10.1016/j.geoderma.2012.05.026
Ponce-Hernandez R, Marriott FHC, Beckett PHT (1986) An improved method for reconstructing a soil profile from analyses of a small number of samples. J Soil Sci 37:455–467
Santos HG, Jacomine PK, dos Anjos LHC, de Oliveira VA, de Oliveira JB, Coelho MR, Lumbreras JF, Cunha TJF (2006) Sistema Brasileiro de Classificação de Solos, 2nd edn. Embrapa Solos, Rio de Janeiro
Schaetzl RJ, Anderson S (2005) Soils genesis and geomorphology. Cambridge University Press, Cambridge
Sisti CPJ, dos Santos HP, Kohhann R, Alves BJR, Urquiaga S, Boddey RM (2004) Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Tillage Res 76:39–58. doi:10.1016/j.still.2003.08.007
Zinn YL, Lal R, Resck DVS (2005) Texture and organic carbon relations described by a profile pedotransfer function for Brazilian Cerrado soils. Geoderma 127:168–173. doi:10.1016/j.geoderma.2005.02.010