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Assessing fixed depth carbon stocks in soils with varying horizon depths and thicknesses, sampled by horizon

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Abstract

Soil surveys for improving carbon (C) stock estimates frequently involve soil sampling by pre-determined regular depth-intervals, in order to enable more convenient computation of soil organic carbon (SOC) stocks. As a result, soil horizons are often neglected in these surveys, although they represent distinct components of the soil profile. When soil-horizon depths and thicknesses vary considerably within the same site, soil sampling by horizon with accompanying depth measurements may be more suitable. The main objective in this study was to investigate the potential differences in current SOC stocks in different afforested mineral soils, with varying horizon depths and thicknesses, and that were sampled by soil horizon, by using the trapezoidal SOC stock computing approach, and comparing it to the spline approach. An adaptation of the trapezoidal rule computation approach, enabling relatively simple crude estimations of the fixed depth-interval SOC stocks from horizon data, was developed. Estimations of SOC stocks for 18 sites located on three different afforested mineral soils (Gleys, Podzols and Cambisols, aged $\geq$ 20 years) were done for 0–30 cm, 30–60 cm and 0–60 cm fixed depth-intervals, excluding surface organic layers. The results indicate that the trapezoidal approach is likely to provide cruder estimates of SOC stocks than the spline approach, although no statistically significant differences were observed between the fixed depth-interval SOC stocks (for 0–30 cm and 30–60 cm) when computed by the two methods. Both methods showed a significant effect of horizon and soil group on SOC stocks. The soil below the 30 cm depth was estimated to store over 22% of the total SOC stocks to 60 cm depth. Gleys showed significantly greater mineral SOC stocks than Podzols, with differences mainly evident in the upper 30 cm, which was observed regardless of the computing methodology used (trapezoidal or spline). The adapted trapezoidal rule computing approach is hoped to facilitate the use of soil-horizon sampling in studies on SOC stocks.

Keywords: Soil organic carbon stocks, soil horizon, soil depth, forest mineral soil, trapezoidal computing approach

1. Introduction

Forest soil surveys which include C stock monitoring are becoming increasingly important due to greenhouse gas emissions reduction targets at national and international level, as well as assessing the role of forest soils in mitigating such emissions. The soil represents the largest terrestrial organic carbon (C) pool, globally estimated at $1115 \cdot 10^9$–$2200 \cdot 10^9$ tC (Batjes, 1996). The total world soil organic carbon (SOC) stock of the upper 30 cm soil depth is estimated at $684 \cdot 10^9$–$724 \cdot 10^9$ tC, and for the upper 100 cm at $1462 \cdot 10^9$–$1548 \cdot 10^9$ tC (Batjes, 2014). In particular, forest soil represents an important terrestrial organic C stock. The estimated soil C stock up to 100 cm depth for worlds forests is c. $383 \pm 30 \cdot 10^9$ tC (Pan et al., 2011). According to Jobbágy and Jackson (2000), the global SOC storage of different temperate forests for 0–100 cm depth can be estimated in the range $73 \cdot 10^9$–$122 \cdot 10^9$ tC. Soil surveys, which aim to improve the estimates of soil C stocks, frequently involve soil sampling to 30 cm depth or even less, and with soil sampling often performed by pre-determined regular soil-depth intervals (Baritz et al., 2010; Cools and De Vos, 2010; UNECE, 2006).

Shallow-depth sampling is often used in soil studies due to difficulties and costs associated with soil sampling at greater depths, as well as due to expectations that deeper soil horizons are more stable and less likely to change over the time although not all studies support this (Harrison et al., 2011). Soil sampling at shallow depths can result in an underestimation of C present in the soil profile (Harrison et al., 2011). Although deeper subsoil horizons are known to have relatively low C content they should still be accounted for in the C-cycle (Rumpel and Kögel-Knabner, 2010). Also, soil sampling is often performed by pre-determined regular soil-depth intervals - e.g. at 10 cm depth-intervals, from a soil profile, for forest soils (Stolbovoy et al., 2005; UNECE, 2010). The advantage of such pre-determined regular depth sampling is that it can enable relatively simple computation of a variable of interest, such as SOC stocks to a specific depth (Stolbovoy et al., 2005). This can be done by e.g. soil-depth normalisation (Freier et al., 2010), or by summing the calculated C stocks of the pre-determined regular depth-intervals (Lee et al., 2009). As a result of soil sampling by regular depth-intervals, soil horizons are often neglected in SOC stock surveys, even though they represent distinct components of the soil profile.

In order to increase the accuracy of SOC stock estimations, and clarify the effects of pedogenic processes on the storage of SOC, Wiesmeier et al. (2012) recommend that SOC inventories should have the soil analysis completed by horizon instead of by fixed depth increments. Where the soil-horizon depths and thicknesses vary considerably within the same site, errors in C stock estimations may be generated if the differences in horizon thickness are not taken into account. These errors could be potentially omitted by e.g. excavating more soil pits at different locations within the same site, but this would require more labour-intensive procedures, and would consequently increase the cost of sampling and its duration. Field methods often need to be adapted in order to reduce the costs and to be feasible within limited project resources. Furthermore, soil pit excavation can also be especially challenging for forest soils due to potentially remote locations, rocky, difficult and steep terrain, the presence of coarse roots, and use of manual methods because of other constraints.

In cases when soil-horizon depths and thicknesses can vary within the same site, and when excavation of more soil pits is not an option, sampling by horizon with horizon-boundary depth measurements may be a more suitable approach (Premrov et al., 2014). However, such sampling may require more demanding computation procedures: e.g. due to differences in thicknesses among sampled horizons at different sampling points, separate computations of C stocks for the chosen fixed depth-interval are required, taking into account the horizon thicknesses from sampled points, separately for each site.

The approach taken in this study was to develop an adaptation of a trapezoidal rule computation by Lord and Shepherd (1993) that would allow relatively simple estimation of fixed depth-interval SOC stocks for soils with varying horizons and depths, and to compare it with the more complex spline computation method based on the equal-area quadratic smoothing spline modelling explained by Bishop et al. (1999). Area-based SOC stocks were to be estimated by adapting the computation approaches in a way that would enable the use of the soil-horizon thicknesses and horizon volume-based C stocks (mass C per volume of soil), and would at the same time also account for varying number of samples obtained for each horizon. The main objective of this work was to investigate the differences in current SOC stocks in different mineral soils with varying horizon depths and thicknesses that were sampled by horizon, by using the adapted trapezoidal SOC stock computing approach, and comparing it with the more complex spline approach. Specific aims were to investigate the potential differences in SOC stock by soil group (in three Irish afforested mineral soils: Gleys, Podzols and Cambisols), by horizon, and by soil depth (0–30 cm, 30–60 cm and 0–60 cm fixed depth-intervals excluding surface organic layers).

2 Materials and methods

2.1 Field sites and sample specifications

Eighteen afforested sites were sampled between March 2014 and March 2015 across the Republic of Ireland (Fig. 1a) as a part of the larger CForRep project (CForRep, 2013; https://www.ucd.ie/cforrep/), with sites being selected from Ireland's National Forest Inventory database (National Forest Inventory, 2012), after pre-screening the database for afforested sites located on selected mineral soils, and aged $\geq$ 20 years (Premrov et al., 2015). The CForRep project used the general Irish soil classification, where the sites were classified into Podzols and peaty Podzols (Po and peaty Po), Brown Podzolics (BP), Acid Brown Earths (ABE), calcareous Brown Earths (BE) and Gleys (G) (Black et al., 2014; Gardiner and Radford, 1980). The sites were classified individually (on site), and were further re-grouped into the three main soil groups: Gleys, Cambisols and Podzols. Po, peaty Po and BP were grouped as Podzols, ABE were assigned to Cambisols (Reidy et al., 2014), there were no sites with BE in this study, while classification of Gleys remained unchanged. Gleys included sites with Stagnosol and Gleysol soils according to the World Reference Base for Soils (WRB) classification (IUSS Working Group WRB, 2015), or Surface Water Gley and Typical Groundwater Gley, respectively, according to the Irish soil subgroup classification (Reidy et al., 2014). Site locations are presented in Fig. 1a. Six sites were sampled in each soil group giving in total of 18 sampled sites (each site included sampling from a soil pit for bulk density measurements, as well as auger sampling from up to nine points on a 3 x 3 grid; further details are explained in section 2.2). The woodland tree species were mainly determined on site but were later classified into three major woodland-type categories of coniferous, broadleaf and mixed. Mineral-soil horizon designation was also done on-site according to the FAO (2006) guidelines for master horizons, but the specific horizons were later grouped into five major categories [A, E, B, B2 and BC, where B2 refers to the second, often more water-saturated B horizon (e.g. Bg horizon), found in Gleys].

2.2 Sampling methods

Each site was positioned with a hand GPS (Geographic Positioning System) instrument, and the slope (in degrees) was measured with a clinometer at the central point. Soil sampling was performed at nine points (on a 3 x 3 grid over 20 x 20 m; Fig. 1b), up to 60 cm depth, by horizon. Organic forest-floor and peat horizons were also sampled under the CForRep project, but were not included in this study on mineral soil horizons.

Soil samples for bulk-density measurements were collected from each horizon separately for each site, from a soil pit located in the centre of the sampling grid (Fig. 1b, 1c). Bulk-density sampling was performed either with 100 cm^3 coring rings, or by the excavation method (i.e. excavation of soil material and replacement by sand, adapted from ISO (1998)) where the volume of excavated (replaced) material was determined on-site using fine sand 300–600 µm in size. For bulk-density ring-sampling, a hammering-head for sample rings (Eijkelkamp, The Netherlands) was used to avoid compression. Where possible, the bulk-density sampling was done from the centre of each horizon, from up to three sides of the soil pit (Fig. 1 c). Exceptionally, the two Gley sites in this study had missing bulk-density samples for a single soil horizon; measurements obtained from the most-similar horizon from the same site (of the same soil-horizon category) were used as replacements (i.e. a missing value for a Bg horizon that was under water-table was replaced with the Bg horizon sampled at that same site, but above the water-table; at another site a missing value for Bg(a) horizon was replaced with Bg horizon sampled at that site; details are provided in Fig. 4). Percentage coarse material was estimated on-site, from the soil pit, according to the FAO (2006) guidelines for soil description.

Horizon samples for SOC analysis were taken with an Edelman auger (Eijkelkamp, The Netherlands), accompanied by the horizon depth measurements (depths to upper and lower boundary). Sampling was performed from up to nine sampling points (each arbitrarily located within one cell of the 3 x 3 sampling grid, Fig. 1b). The entire thickness of each soil horizon was sampled at each sampling point, and the samples from each horizon were bulked together into one composite soil sample by horizon, separately for each site. In order to minimize potential cross-contamination between horizons, the individual sampling by horizon from each sampling point was done by first placing each separate augered soil material onto a clean tray. This was done with a special care not to disturb the sequence of the augered material. The material on the tray was then carefully separated into individual soil horizons. All collected soil samples were transported in cool-boxes and stored in a cold-room at 4°C until further laboratory-processing and analysis. A total of 510 soil samples were collected from the eighteen afforested sites: 126 samples for bulk-density determination and 384 soil samples from the sampling grids (Fig. 1). Bulking of soil samples from individual sampling points (by horizon, separately for each site) resulted in total 50 composite soil-horizon samples.

2.3 Laboratory methods

Bulk-density soil samples were oven-dried at 105°C for > 16 hours, in order to obtain their dry weights (adapted from ISO, 1998). Coarse material (> 2 mm) was separated from fine-earth material (< 2 mm) by dry-sieving, followed by re-drying of coarse material at 105°C for > 16 hours, in order to obtain its dry weight. Volume of coarse material was measured by water-displacement (by submerging the coarse material into a graduated cylinder filled with water). Processing of composite soil samples involved: bulking of individual horizon soil samples, separately for each site (to form a composite sample, in the minority of cases where this was not already done on-site); separation of live biomass; hand-crushing of soil-clods; mixing; and preliminary drying at 40°C. Dry soil was packed and stored at ambient room conditions, to be used for further processing and laboratory analyses. Laboratory sub-sampling was done carefully by hand-mixing and -quartering in several steps (adapted from ISO, 2006). The air-moisture content was determined by drying 5 g of sample (fine-earth < 2mm obtained by sieving) at 105°C for > 16 hours until dry (adapted from ISO, 1993). Composite soil samples were tested for pH on 2.5 mL fine-earth: 12.5 ml distilled water soil-suspension (adapted from ISO, 1995; NSAI, 2011), which showed pH < 6.5. Therefore, it was assumed that the soil from the eighteen sites used in this study did not contain carbonates (ISO, 1995), and the samples were not treated for carbonate-removal. Elemental C analysis on composite soil sub-samples was performed on a CE440 Elemental CHN Analyser (Exeter Analytical Inc.), after first homogenising the material by fine milling using Mixer Mill MM200 (Retsch GmbH) and/or Planetary Mono Mill Pulverisette 6 (Fritsch GmbH).

2.4 Computational methods

The SOC stocks are expressed as volume-based SOC densities, in units of mass of C per volume of soil, and area-based SOC densities, in units of mass of C per area of soil for the specific fixed soil depth-interval. Average horizon thicknesses, including average horizon starting- , ending- and horizon mid-depths were calculated separately for each site from the measurements obtained from the 3 × 3 sampling grid at the site (in continuation the average thickness was named as thickness, and the average mid-depth as mid-depth).The fixed soil depth-intervals were named as follows: “shallow” (0–30 cm); “deep” (30–60 cm), and “total depth” (0–60 cm).

2.4.1 Estimating volume-based organic carbon densities for individual horizons

The volume-based SOC density (SOCVD) of an individual soil horizon was calculated using the SOC content (dry mass-based C percentage) measured from the composite horizon sample, the corresponding horizon bulk-density of fine-earth fraction taken from the soil pit [g soil/cm^3], and the volume-based percent of stones (coarse fraction, also estimated from soil pit), as follows:

$$\mathrm{SOCVD} = \%C/100 \times \rho_f \times \mathrm{CCF}$$

or

$$\mathrm{SOCVD} = \%C/100 \times (m_{tot} - m_{coarse}) / (V_{tot} - V_{coarse}) \times \mathrm{CCF} \qquad (1),$$

where SOCVD is the volume-based SOC density of the horizon [gC/cm^3]; $\%C$ is the C content in the fine earth (< 2 mm) from the composite horizon sample obtained as a dry mass-based percentage C content for oven-dry soil at 105ºC (UNECE, 2006; ISO, 1995); 1/100 is the conversion factor for converting percentage C to gC/g soil; ρ_f is a soil bulk-density of fine-earth material < 2 mm [g soil/cm^3] [calculated as $(m_{tot} - m_{coarse}) / (V_{tot} - V_{coarse})$]; m_{tot} [g] is the total dry-mass (at 105°C) of the whole bulk density sample; m_{coarse} [g] is the dry-mass (at 105°C) of coarse fraction (>2mm) obtained after sieving the material from the bulk density sample; V_{tot} [cm^3] is the volume of the whole bulk density sample (e.g. 100 cm^3 if sampled by core-ring); V_{coarse} [cm^3] is the volume of the coarse fraction (> 2 mm) obtained by displacement after sieving the material from bulk density samples; CCF is the coarse fraction correction factor, calculated as ((100 - %stones)/100) (Baritz et al., 2010; Kessler et al., 2012), where %stones represent the volume-based percentage of coarse material estimated from the soil pit.

2.4.2 Estimating soil organic carbon stocks for fixed depth-intervals using an adapted trapezoidal rule approach

Area-based soil organic carbon stocks (SOCS, tC/ha) for fixed depth-intervals were first estimated with a so-called trapezoidal rule computing approach, adapted from Lord and Shepherd (1993), who used it for calculating soil-solution nitrate leaching losses. The trapezoidal rule was adapted using SOCVD [Eq. 1] expressed as the mass of C per volume of soil [gC/cm^3], and the corresponding horizon thicknesses [cm], with the inclusion of the probability weights (IDRE UCLA, 2016) for each soil horizon, as follows:

$$SOCS_{a\text{-part I}} = 0.5 \times (SOCVD_{a0} + SOCVD_a) \times n_a/n \times L_a/2 \times 100 \quad (2a),$$

$$SOCS_{a\text{-part II}} = 0.5 \times (SOCVD_a + SOCVD_{b0}) \times n_a/n \times L_a/2 \times 100 \quad (2b).$$

where 'a' and 'b' subscripts refer to two adjacent horizons; $SOCS_{a\text{-part I}}$ is carbon stock computed from horizon start to its mid-depth or $L_a/2$ (Fig. 2a); and $SOCS_{a\text{-part II}}$ is stock computed from horizon mid-depth to its end (or the start of the next horizon; Fig. 2a); L_a is thickness of 'a' horizon [cm]; $SOCVD_{a0}$ value [gC/cm^3] refers volume-based soil organic carbon density at the starting depth of 'a' horizon, and $SOCVD_{b0}$ at the starting depth of next 'b' horizon; $SOCVD_a$ refers to carbon density at horizon mid-depth (obtained from composite 'a' horizon sample); n_a/n is the probability weight for horizon/layer 'a' where n_a represents the number of points where the soil horizon/sample 'a' was present out of total number of sampled/augered points n (i.e. n is 9 if all of the points from 3×3 grid were augered; similarly, the probability weight n_b/n applies for next horizon 'b' when computing the carbon stocks for next b-horizon, etc.); 100 is the conversion factor for converting the SOCS units [from gC/cm^2 to tC/ha].

This adaptation of trapezoidal rule formulae was applied because the horizons were often absent at some sampling locations and present at some other locations at the same site, resulting in varying number of samples obtained for each composite horizon sample that was accounted for in the computation of SOCS by applying the corresponding probability weights (IDRE UCLA, 2016).

SOCS of whole 'a' horizon was computed by summing $SOCS_{a\text{-part I}}$ and $SOCS_{a\text{-part II}}$:

$$SOCS_a = SOCS_{a\text{-part I}} + SOCS_{a\text{-part II}} \quad (3),$$

where $SOCS_a$ is soil organic carbon stock [tC/ha] of whole thickness of 'a' horizon (L_a; Fig. 2). The estimated SOCS for the total fixed depth-intervals ("shallow", "deep" and "total") were next calculated by summing the SOCS of individual horizons, as follows:

$$SOCS = \sum SOCS_i \quad (4),$$

where $SOCS_i$ refers to carbon stocks of individual horizons (i.e. $SOCS_a$, $SOCS_b$, etc. Eq.3) computed from their thicknesses (Eqs. 2a and 2b) between: 0–30 cm depth for “shallow”; 30–60 cm depth for “deep”, and 0–60 cm depth for “total” fixed depth-interval (Fig. 2a). In case if the horizon was cut at the 30 cm depth, $SOCS_i$ of the corresponding horizon-section was included in Eq. 4 in order to compute the SOCS of “shallow” and “deep” fixed depth-intervals (Fig. 2a).

Fig. 2b represents a computing scenario that accounts for organic layers/horizons (not included in this study): organic layers are often thinner than mineral soil horizons and are assumed to have relatively constant SOCS throughout their thickness (e.g. area-based stock values obtained from frame sampling).

In order to calculate the SOCS of fixed depth-intervals, the SOCVD values at 30 cm and the individual horizon starting- and ending- SOCVD values had to be estimated first, for each site, using linear interpolation (Fig. 2a.) The “starting SOCVD” value of the first mineral horizon at zero depth was estimated by applying linear regression to *c.* first three horizon SOCVD points (if available) as presented in Fig. 2a, calculated using INTERCEPT Microsoft Excel function. The linear regression was chosen in order to simplify the estimation approach. Although this may result in potential error in the estimation of C-stocks, it was considered that non-linear model application (such as power or logarithmic regression) could also result in estimation errors of the “starting” SOCVD values. This issue may be potentially avoided in case if the “starting” SOCVD values would be known (measured): e.g. by sampling the first few centimetres of the top mineral horizon. A “zero” SOCVD value (Fig. 2a), was assumed for the “ending” SOCVD at the final sampling depth, as the sampling often ceased before reaching the required fixed depth. This assumption was based on an expectation that sampling stopped due to high stone/rock content. It should be noted that this assumption can result in the potential underestimation of C stocks for the last horizon and the “deep” soil depth-interval, which needs to be considered when interpreting results, especially if the sampling stopped due to other reasons than the high stone/rock content.

2.4.3 Estimating soil organic carbon stocks for fixed depth-intervals using a spline approach

The second approach for estimating area-based soil organic carbon stocks (SOCS, tC/ha) for fixed depth-intervals in this study was an already known spline approach, which is based on the equal-area quadratic smoothing spline modelling, explained by Bishop et al. (1999). Splines were fitted to the data with the help of the “mpspline” function from package “GSIF” (Hengl, 2016) in R (R Core Team, 2015), using average horizon starting and ending depth values for each site, and the corresponding SOCVD values from the individiual horizon composite samples (Eq. 1). The parameter lambda (λ) for the “mpsline” function was set to 0.1 as in De Vos et al. (2015). The output obtained was the modelled spline in the form of SOCVD values at 1cm depth-intervals. In order to be able to compare the spline computing approach (dashed curve in Fig. 3) with the trapezodial approach (“trapezodial” line in Fig. 3), each spline was next split into separate horizons (or horizon-sections up to 30 and 60 cm fixed depth-intervals). The SOCSs were computed for each horizon/horizon-section after applying the horizon sampling probablility weights (as explained in section 2.4.2), and summed up to fixed depth-intervals (30 cm and 60 cm depth) according to Eq. 4. SOCSs were computed with approximate integration using 1 cm intervals. The spline-modelled SOCVD value at 1 cm depth was assigned as the “starting SOCVD” value at zero depth (Fig. 3), and in case if the sampling ceased before reaching the required fixed depth, the “zero” SOCVD value was assigned to the “ending” SOCVD (as in section 2.4.2).

2.5 Statistical analysis methods

Statistical analysis was performed in R 3.2.3 (R Core Team, 2015) and selected R-packages. Detailed description is provided in sections below.

2.5.1 Statistical analysis of volume-based soil organic carbon densities

The differences in horizon SOCVD results [gC/cm^3] were assessed by applying linear mixed effects (LME) models followed by analysis of variance (ANOVA) (Fox and Weisberg, 2011). ANOVA Type III [Wald χ^2 test], was chosen due to unbalanced horizon data-design (King, 2016). The LME models were fitted via maximum likelihood (ML) (Pinheiro et al., 2016) to the natural logarithm (ln) transformed SOCVD values (ln transformation was used in order to achieve normality and homoscedasticity of the data). Non-weighted and weighed LME models were used, where the fixed weighing was done using the measured number of soil bulk-density samples in order to specify that the residual variance for each horizon SOCVD value was inversely proportional to the number of sampled bulk-density samples per horizon at each site (Bolker, 2015). The "relative" SOCVD standard deviations (computed by standard deviation error-propagation (Caldwell et al., 2016), used in Fig. 4), were not used for LME weighing because they lacked the uncertainty of the SOC component, due to absence of SOC standard deviations from composite soil samples. A random effect was assigned to the site, and fixed effects to the mid-depth, slope [measured in degrees and converted to radians], soil group [Podzols (P), Cambisols (C) and Gleys (G)], and woodland-type [Coniferous, Broadleaf and Mixed]. Variables slope, woodland-type and mid-depth (main effects and interactions) were later excluded from the analysis due to non-significance, and the testing for the potential spatial non-independence of sampled sites was done on the final LME model. Different spatial correlation structures were included and evaluated using the Akaike's Information Criterion (AIC). For this, a small random noise (of 0.5 m) was assigned to the measured GPS coordinates (due to coordinates repetition for data measured at the same site), which were first transformed to Universal Transverse Mercator (UTM) coordinates (Bivand et al., 2015). The differences in SOCVD between different soil groups and horizons were further assessed using least-squares (LS) means ("lsmeans") pairwise comparison t-tests derived from LME with results averaged over the horizon/soil group using weights proportional to their frequencies in the data-set (Lenth, 2016)).

2.5.2 Statistical analysis of soil organic carbon stocks

The correlations between the area-based SOCSs [tC/ha], slope (in radians) and maximum depth of the soil depth-interval (30 cm for "shallow" and 60 cm for "deep") were first evaluated with the Pearson's correlation coefficient matrix (Harrell et al., 2015). The SOCS results were next assessed by applying the LME models, followed by ANOVA Type II [Wald χ^2 test] (Fox and Weisberg, 2011). LME was fitted via ML (Pinheiro et al., 2016) to the square-root SOCS transformed results. The square-root transformation $(SOCS)^{0.5}$ was used in order to achieve normality and homoscedasticity of the data. Analysis was first performed on combined "shallow" and "deep" depth-interval data. A random effect was assigned to the site, and the fixed effects to the soil group, depth-interval, slope, and woodland-type. The differences between "shallow" and "deep" depth-interval SOCSs were assessed after excluding variable woodland-type (due to non-significance). Testing for spatial auto-correlation of SOCS results was done using Moran's I statistics (Paradis et al., 2004), and by inclusion of different spatial correlation structures (as explained in 2.5.1). The differences in the SOCS results between three different soil groups were further assessed separately for "shallow", "deep" and "total depth" data, by applying the models separately to each data-set. Differences between depth-interval and soil group SOCSs were assessed by applying LS means ("lsmeans") pairwise comparison t-tests derived from LME models (Lenth, 2016).

2.5.3 Statistical comparison of trapezoidal- and spline- computed soil organic carbon stocks

The SOCS results obtained from trapezoidal and spline computing methods were compared using Welch two sample t-test (performed on transformed $(SOCS)^{0.5}$, separately for "shallow" and "deep" depth-intervals). In addition, the results were further assessed for separate depth-intervals, as well as for separate soil groups of “shallow” and “deep” depth-intervals, by obtaining 95 % bootstrap confidence intervals of $(\mathrm{SOCS})^{0.5}$ means, based on the approach explained in De Vos et al. (2015), which assumes statistically significant differences if confidence intervals do not overlap. However, due to limited number of sites the bootstrap confidence intervals were not used as an independent statistical testing in this study, but they were used merely for checking the findings in conjunction with the earlier statistical t-test. Calculations were performed with the help of function “boot” (with 5000 bootstrap replications) from R package “boot”, using the “boot.ci” function set to type “bca” for the adjusted bootstrap percentile interval (Canty and Ripley, 2016; Davison and Hinkley, 1997).

3 Results and discussion

3.1 Horizon volume-based soil organic carbon densities

Gleys had the greatest average horizon SOCVD: the average SOCVD was 0.029 gC/cm^3 for Gleys, 0.027 gC/cm^3 for Cambisols, and 0.017 gC/cm^3 for Podzols (Table 1). A decrease in SOC density was observed from the top A horizons (0.047 gC/cm^3), followed by E and B (0.019 gC/cm^3 for E and 0.018 gC/cm^3 for B), to B2 and BC horizons (0.011 gC/cm^3 for B2 and 0.014 gC/cm^3 for BC; Fig. 4, Table 1). The mid-depth for A horizons ranged from 3.8–13.8 cm, followed by E (6.6–26.5 cm), B (12.8–45.2 cm), B2 (29.5–51.4 cm), and BC horizons (41.9–54.8 cm). In general, weighted LME models appeared to explain the data better than the non-weighted model (lower AIC). Spatial auto-correlation was not detected, which may be a consequence of a relatively small number of sites (eighteen sites) used in this study. Significant effect on SOCVD results was observed for both horizon and soil group, but not for mid-depth. The interaction mid-depth – horizon was also found to be not significant ($p > 0.1$, ANOVA Type III Wald χ^2 test). However, in case of absence of the horizon variable, the mid-depth did show a significant effect on SOCVD results. Horizon appeared to explain the data better than mid-depth, which may be due to variations in horizon depths and thicknesses between different locations, and limited number of sites.

The results showed statistically significant difference in horizon SOVCD between Gleys and Podzols (Table 1), but not between the Cambisols and Gleys, or between Cambisols and Podzols. In Ireland Gleys are classified as poorly-drained mineral soils (Radford and Short, 2013), typically located in low-lying wet areas (Fay et al., 2007). If excluding peaty soils, Podzols, on the other hand, are well-drained soils typically located on hill-land areas (Radford and Short, 2013).

There was a strong effect of horizon ($p < 0.0001$, Table 1) on SOCVD, where A-horizons (that had highest SOCVD) significantly differed from almost all other horizons. Nevertheless, some other horizons, that were generally considered not to be in direct neighbouring sequence to each-other (within the soil profile), also showed differences in SOCVD (Table 1). Considering that Gleys showed the greatest SOCVD in this study, and that they can be rich in clay, future investigations of the clay-associated organic substances and their potential relation to other factors, such as soil type, soil-physical properties, texture, and management (Leinweber et al., 1993) are recommended, in order to obtain further insights into the effect of horizons on SOC storage from this study.

3.2 Soil organic stocks of fixed depth-intervals

The relationships between the area-based SOCSs results, slope and the maximum depth of soil depth-interval (i.e. 30 cm and 60 cm depth) that were assessed using Pearson's correlation coefficient matrix, showed a significant negative correlation between SOCS values and depth (with decrease in SOCS at greater depth), as expected, but no significant correlation between SOCS and the slope. This result was observed for both SOCSs obtained via trapezoidal and spline approach. A significant effect of slope that was only occasionally derived from LME models fitted to separate soil depth-interval data (Table 2b and 2c) turned to be non significant after excluding a single value for "deep" SOCS with the highest measured slope of *c.* 0.37 radians (the remaining sites all had slope < 0.21 radians). This indicates that the present study may not have sufficient data for SOCS at higher slopes in order to investigate the effect of slope on soil C storage. The geo-statistical analysis on LME also showed no spatial auto-correlation, most likely due to limited number of sites; this was further confirmed by Moran's I statistics.

SOC content is generally known to decrease with soil depth. In agreement with this, the "shallow" mean SOCSs observed in this study were significantly greater ($p < 0.0001$) than the "deep" ones (Table 2a). This was observed for both SOCSs obtained using trapezoidal and spline computing approaches. The soil below 30 cm depth could store over 22% of the "total depth" SOCSs (Fig. 5a, 5b). These findings appear to be in general agreement with the total SOC content estimations based on the global soil database by Batjes (1996), who estimated the total of SOC content of the upper 100 cm mineral soil depth-interval at 39-70%, and the SOC content of the upper 30 cm at 58 - 81%. Nevertheless, the results from this study should not be generalised, considering the limited number of sites (eighteen) that has been used, and the maximum total sampling depth of only up to 60 cm.

The mean "shallow" and "total depth" SOCSs were greatest in Gleys followed by Cambisols and Podzols (Fig. 5), whereas the mean "deep" SOCS values of the three soil groups were relatively close to each other, with the greatest SOCS observed in Cambisols and Gleys, followed by Podzols (Fig. 5). The statistical analysis performed on separate soil depth-interval data (separately for "shallow", "deep" and "total depth") showed significant effect of soil group on the "shallow" and on the "total depth" SOCSs ($p < 0.05$, Table 2b, 2c). However, soil group had a less significant or non-significant effect on the "deep" SOCSs (Table 2b, 2c). Gleys had significantly greater SOCSs than Podzols for both "shallow" (G vs. P: $p < 0.05$; Table 2b, 2c) and "total depth" depth-intervals (G vs. P: $p < 0.05$; Table 2b, 2c); whereas the "deep" SOCS results showed no significant differences among the three soil groups (Table 2b, 2c; results derived from LME with inclusion of slope). No significant differences were observed in SOCSs (of any depth-intervals) between the Cambisols and Gleys, and Cambisols and Podzols. These findings appear to be in agreement with the results from statistical analysis performed on SOCVD (section 3.2), and were observed regardless of which computing approach was used (trapezoidal or spline). The above results indicate that differences in SOCSs between soil groups are diminishing at greater ("deep") soil depth-interval, which is in agreement with a study by Wiesmeier et al. (2015), who also found no significant differences between different soil classes for deeper soil horizons (C horizons). Furthermore, Wiesmeier et al. (2015) also observed (among others) significantly higher SOC stocks for Gleysols compared to Podzols.

Despite the fact that this study used relatively approximate estimation of "starting" and "ending" SOCVD values (Fig. 2a) that are required for the computation of fixed depth-interval SOCSs, the results were found to be generally in agreement with the relatively broad range of soil C stocks reported in some examples of studies on mineral forest soils. Some examples are: - a study on Irish forested sites to 30 cm depth by Wellock et al. (2011) [66.7–148.8 tC/ha for Podzols, 38.4–136.6 tC/ha for Cambisols, and 86.6–164.3 tC/ha for Gleys]; - European forest soil study to 20 cm depth by Baritz et al. (2010) [with values for temperate-oceanic to suboceanic climate zones estimated from published figures of *c.* 53 tC/ha for Podzols, *c.* 55 tC/ha for Cambisols and *c.* 65 tC/ha for Gleysols]; - a study by Batjes (2014) with estimated C stocks for up to 50 cm depth based on the global soil database [173 tC/ha for Podzols, 69 tC/ha for Cambisols and 97 tC/ha for Gleysols].

The total depth-interval (0 up to 60 cm) SOC stocks from all eighteen sites in this study were estimated at 122.7 tC/ha (arithmetic mean) if using trapezoidal approach, and *c.* 125.4 tC/ha if using spline approach. These estimates appear to be lower than SOC stocks for e.g. Belgium forests to 1 m depth [*c.* 153 tC/ha (Lettens et al., 2005)], but greater than the average stocks for forest soils in Bavaria, Germany to about 93 cm depth or parent material [*c.* 98 tC/ha (Wiesmeier et al., 2012)]. Nevertheless, the sampling depth of only 60 cm (or less) used in this study can still be considered as relatively shallow, and therefore, it can be expected that certain soils in this study could potentially have some additional carbon stored at greater depths. For example, an ICP Forests-based study (including most of the European forests) by De Vos et al. (2015) estimated SOC stocks up to 1 m depth at 182 tC/ha for Gelysol, and 121 tC/ha for Podzols (bootstrapped mean), with both being greater than SOC stocks to 60 cm depth estimated for Gleys and Podzols from this study (Table 2b, 2c).

3.3 Comparison of trapezoidal and spline computing approaches for estimating soil organic carbon stocks of fixed depth-intervals

The results showed that the trapezoidal approach is likely to provide more crude estimates of SOC stocks than the spline approach: it estimated the overall "shallow" SOCSs for *c.* 4.1 tC/ha less than the spline approach, and the overall "deep" SOCSs for *c.* 1.3 tC/ha more than the spline approach (Table 2b, 2c). This is not surprising, considering that the trapezoidal approach is assuming a simple linear relationship between horizon SOCVD values in the soil profile (Fig. 2a) Nevertheless, the trapezoidal approach has an advantage of being relatively simple (i.e. it can be implemented in Excel) and computationally less demanding. No statistically significant differences were observed between the fixed depth-interval SOCSs computed by the two methods: trapezoidal vs. spline $p > 0.5$, Welch two sample t-test on "shallow" and "deep" data. This was further confirmed by overlapping of the 95 % bootstrap confidence intervals of $(SOCS)^{0.5}$ means from both computing methods. The overlapping of confidence intervals occurred in case of the "shallow" and deep" depth-interval SOCSs, as well as in case of SOCSs of separate soil groups of "shallow", and "deep" depth-intervals. This comparison needs to be interpreted with caution due to limited number of sites used for bootstrapping in this study. Nevertheless, SOCS results obtained from the two computing methods, trapezoidal and spline, showed the similar significant differences between depth-intervals and soil groups (Table 2b, 2c), which indicate that the trapezoidal SOC stock computing approach (despite being cruder) may be suitable when investigating the differences between different SOCSs.

4 Conclusions

This study on organic carbon (C) in soils, with varying horizon depths and thicknesses, demonstrates that sampling by horizon with accompanying depth measurements can enable computational estimations of soil organic carbon (SOC) stocks for fixed soil depth-intervals. The development and application of a simple trapezoidal rule computing approach (adapted from Lord and Shepherd (1993)) is hoped to facilitate the use of soil-horizon sampling in studies on SOC stocks. The comparison of the presented trapezoidal SOC stock computing approach with the more complex spline approach (Bishop et al. 1999) showed that both computational methods can enable estimates of fixed depth-interval SOC stocks to be computed from measurements of mineral soil horizons sampled by auger boring, for the three Irish mineral afforested soils (Gleys, Podzols and Cambisols), aged ≥ 20 years. The study showed that horizon and soil group had a significant effect on SOC stocks. The soil below the 30 cm depth was estimated to store over *c.* 22% of the total upper 60 cm SOC stocks. This result should not be generalised considering that it is based on limited number of sites (eighteen sites) used in this study; nevertheless, it confirms the importance of including the deeper soil horizons in the soil C-cycle. Although the trapezoidal approach is thought to be much more crude than the spline computing approach (and likely to be more suitable for more crude SOC stock estimations), no statistically significant differences were observed between the fixed depth-interval SOCSs for "shallow" and deep" data computed by the two methods. Gleys were shown to have significantly greater mineral SOC stocks than Podzols, with differences mainly evident in the upper 30 cm soil depth, which was observed regardless of computing methodology used (trapezoidal or spline).

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Highlights

- ► An approach for estimating fixed depth SOC stocks from horizon data is presented.
- ► Trapezoidal approach is likely to provide cruder estimates than spline method.
- ► Horizon and soil group had a significant effect on SOC stocks in both methods.
- ► SOC stock differences by soil group were mainly evident in the upper 30 cm.
- ► Demonstrated approach aims to facilitate horizon sampling use in SOC stock studies.

Tables & Table Captions

Table 1 Mean SOCVD and horizon mid-depth along with soil group (a) and horizon (b) comparisons using pairwise t-test derived from LME applied to ln-transformed SOCVD [significant variables and contrasts are highlighted in bold]

(a)

ANOVA Type III, Wald χ^2 test[c] [e]	p-value	Soil group[a]	Mean |ln(SOCVD)| ± SD	Back-transformed mean SOCVD [gC/cm^3]	Arithmetic mean SOCVD ± SD[b] [gC/cm^3]	n	LS means pairwise comparison[d] Comparing soil groups	t-ratio$_{df17}$[e]	p-value
Soil group$_{df2}$	**< 0.05**	P	|4.360| ± 0.840	0.013	0.017 ± 0.014	17	C vs. G.	-0.90	> 0.65
Horizon $_{df4}$	**< 0.0001**	C	|3.824| ± 0.686	0.022	0.027 ± 0.016	16	C vs. P	1.91	> 0.17
		G	|3.915| ± 0.930	0.020	0.029 ± 0.025	17	G vs. P	2.70	**< 0.04**

(b)

Horizon	Mean mid-depth ± SD[a] [cm]	Mean |ln(SOCVD)| ± SD	Back-transformed mean SOCVD [gC/cm^3]	Arithmetic mean SOCVD ± SD[b] [gC/cm^3]	n	Comparing horizons	p-value [t-statistics $_{df26}$[e]]
A	9 ± 2.2	|3.125| ± 0.363	0.044	0.047 ± 0.019	13	A vs. B, A vs. B2, A vs. BC	**< 0.0001**
E	14 ± 8.5	|4.291| ± 0.941	0.014	0.019 ± 0.019	5		
B	31 ± 7.8	|4.166| ± 0.538	0.016	0.018 ± 0.008	20	B vs. B2;	**< 0.05**
B2	44 ± 7.9	|4.727| ± 0.736	0.009	0.011 ± 0.007	6	A vs. E; B vs. E, BC; B2 vs. E; BC vs. E, B2	> 0.05
BC	49 ± 5.4	|4.638| ± 0.978	0.009	0.014 ± 0.016	6		

NOTE: [a] P - Podzols, C - Cambisols, G - Gleys; [b] SD standard deviation without inclusion of error propagation; [c] derived from non-weighted/weighted LME applied to ln(SOCVD), with inclusion of fixed effects (soil group, horizon) and random effect (site); the applied LME was also used for testing the potential presence of SAC; [d] results (derived from LME) are averaged over the horizon/soil group using weights proportional to their frequencies in the data-set, and with the Tukey method p-value adjustment; [e] df - degrees of freedom.

Table 2 Mean SOCSs for fixed depth-intervals and different soil groups along with comparisons between different main effects, derived from LME models applied to square-root transformed SOCSs (calculated by adapted trapezoidal- and spline- approach): (a) analysis on combined "shallow" and "deep" depth-interval data; (b) analysis on separate fixed depth-interval data computed by adapted trapezoidal approach; (c) analysis on separate fixed depth-interval data computed by spline approach [significant variables and contrasts are highlighted in bold]

(a) Combined "shallow" and "deep" data

ANOVA Type II, Wald χ^2 test^a (Tr & Sp)^c Main effect^f	p-value	Depth-interval^c	Mean (SOCS)$^{0.5}$ ± SD	Back-transformed mean SOCS [tC/ha]	Arithmetic mean SOCS ± SD^e [tC/ha]	n	LS means pairwise comparison^g Dp vs. Sh	t-ratio $_{df17}^{f}$	p-value
Depth-interval $_{df1}$	**< 0.0001**	Sh (Tr)	9.150 ± 2.781	83.7	91.0 ± 50.46	18	Tr	-7.33	**<0.0001**
		Dp (Tr)	5.342 ± 1.824	28.5	31.7 ± 20.29	18			
Soil group $_{df2}$	**< 0.005**	Sh (Sp)	9.342 ± 2.871	87.3	95.1 ± 53.64	18	Sp	-7.18	**<0.0001**
		Dp (Sp)	5.205 ± 1.867	27.1	30.4 ± 20.29	18			

(b) Separate fixed depth-interval data computed with adapted trapezoidal approach

ANOVA Type II, Wald χ^2 test^b Main effect^f	p-value	Soil group^d	Mean (SOCS)$^{0.5}$ ± SD	Back-transformed mean SOCS [tC/ha]	Arithmetic mean SOCS ± SD^e [tC/ha]	n	LS means pairwise comparison^g Comparing	t-ratio $_{df14}^{f}$	p- value
"Shallow" [0–30 cm] depth-interval									
Soil group $_{df2}$	**<0.005**	P	7.130 ± 2.397	50.8	55.6 ± 29.92	6	C vs. G	-0.87	0.668
Slope $_{df1}$	>0.05	C	10.004 ± 1.456	100.1	101.8 ± 30.08	6	C vs. P	2.08	0.130
		G	10.317 ± 3.320	106.4	115.6 ± 66.99	6	G vs. P	2.74	**0.040**
"Deep" [30–60 cm] depth-interval									
Soil group $_{df2}$	**0.044**^{h}	P	4.394 ± 1.505	19.3	21.2 ± 13.93	6	C vs. G	-0.72	0.758
Slope $_{df1}$	**<0.05**^{i}	C	5.864 ± 1.966	34.4	37.6 ± 25.64	6	C vs. P	1.54	0.310
	>0.05^{h,i}	G	5.766 ± 1.886	33.28	36.2 ± 18.68	6	G vs. P	2.10	0.125
"Total depth" [0–60 cm] depth-interval									
Soil group $_{df2}$	**<0.05**	P	8.503 ± 2.329	72.3	76.8 ± 35.93	6	C vs. G	-0.93	0.633
Slope $_{df1}$	**<0.05**^{i}	C	11.661 ± 2.040	136.0	139.4 ± 48.24	6	C vs. P	2.13	0.119
	>0.05^i	G	11.848 ± 3.710	140.4	151.8 ± 82.19	6	G vs. P	2.84	**0.033**

(c) Separate fixed depth-interval data computed with spline approach

ANOVA Type II, Wald χ^2 test^b Main effect^f	p-value	Soil group^d	Mean (SOCS)$^{0.5}$ ± SD	Back-transformed mean SOCS [tC/ha]	Arithmetic mean SOCS ± SD^e [tC/ha]	n	LS means pairwise comparison^g Comparing	t-ratio $_{df14}^{f}$	p- value
"Shallow" [0–30 cm] depth-interval									
Soil group $_{df2}$	**<0.005**	P	7.248 ± 2.426	52.5	57.4 ± 31.30	6	C vs. G	-1.13	0.514
Slope $_{df1}$	>0.05	C	10.025 ± 1.403	100.5	102.1 ± 28.98	6	C vs. P	1.97	0.157
		G	10.755 ± 3.457	115.7	125.6 ± 71.31	6	G vs. P	2.89	**0.030**
"Deep" [30–60 cm] depth-interval									
Soil group $_{df2}$	>0.05	P	4.514 ± 1.740	20.4	22.9 ± 17.24	6	C vs. G	-1.01	0.580
Slope $_{df1}$	>0.5	C	5.395 ± 1.963	29.1	32.3 ± 24.04	6	C vs. P	0.86	0.672
		G	5.704 ± 2.015	32.5	35.9 ± 20.41	6	G vs. P	1.79	0.210
"Total depth" [0–60 cm] depth-interval									
Soil group $_{df2}$	**<0.05**	P	8.674 ± 2.474	75.2	80.3 ± 41.0 8	6	C vs. G	-1.25	0.445
Slope $_{df1}$	**<0.05**^{i}	C	11.462 ± 1.921	131.4	134.5 ± 44.92	6	C vs. P	1.84	0.193
	>0.05^i	G	12.224 ± 3.813	142.4	161.5 ± 86.17	6	G vs. P	2.90	**0.029**

NOTE: [a] derived from LME applied to (SOCS)$^{0.5}$ [slope was significant on combined data, if all data were included]; [b] derived from LME applied to (SOCS)$^{0.5}$; [c] Sh - "shallow", Dp - "deep", Tr - adapted trapezoidal computing approach; Sp - spline computing approach; [d] P - Podzols, C - Cambisols, G - Gleys. [e] SD standard deviation without inclusion of error propagation; [f] df - degrees of freedom; [g] results derived from model are averaged over the levels of soil/depth, with the Tukey method p-value adjustment (for soil); [h] close to 'border significant'; [i] significant if including all deep SOCS data, but non-significant if excluding one value for deep SOCS at the highest measured slope (the exclusion of the value appeared not to change the outcome of post-hoc soil group contrast-significance/non-significance).

Figure Captions

Figure 1 Schematic presentation of site locations and soil sampling approach (a) site locations - not to scale; (b) composite soil sampling (per horizon) by arbitrary-choosing the sampling point within each sampling grid cell; (c) bulk-density soil sampling from a central soil pit

Note: (a) schematic illustration of the country-border was created with the help of R 3.2.3 (R Core Team, 2015) and R packages “maptools” (Bivand and Lewin-Koh, 2015) and “mapdata” (Becker et al., 2016); (c) presented is one side of soil pit (at central grid-location V), sampling included up to three-sides of soil pit

Figure 2 Schematic presentation of the adapted trapezoidal rule calculation approach for estimating soil organic carbon stocks (SOCS) in units of mass C per area for required soil horizons and fixed depth-intervals [fictive example]: (a) simplified C stock estimation approach for mineral soil horizons (labelled with a, b, c, etc.), including crude linear regression estimation of the “starting” SOCVD at zero depth (used in this study); (b) scenario that accounts for organic layers/horizons (not included in this study)

Figure 3 Schematic presentation of the modelled spline (dashed curve, obtained from the spline approach) fitted to the horizon volume based soil organic carbon density (SOCVD) data with accompanying average horizon starting- and ending-depths, and the “trapezoidal” line (obtained from adapted trapezoidal approach) for estimating soil organic carbon stocks (SOCS) for fixed depth-intervals [fictive example]

Figure 4 Horizon volume-based soil organic carbon density (SOCVD) and corresponding horizon average mid-depth for Irish afforested Podzols, Cambisols and Gleys

Figure 5 Mean soil organic carbon stocks (SOCSs) of fixed depth-intervals for Irish afforested Podzols, Cambisols and Gleys (six sites per soil group): (a) computed by trapezoidal approach, (b) computed by spline approach

Figures

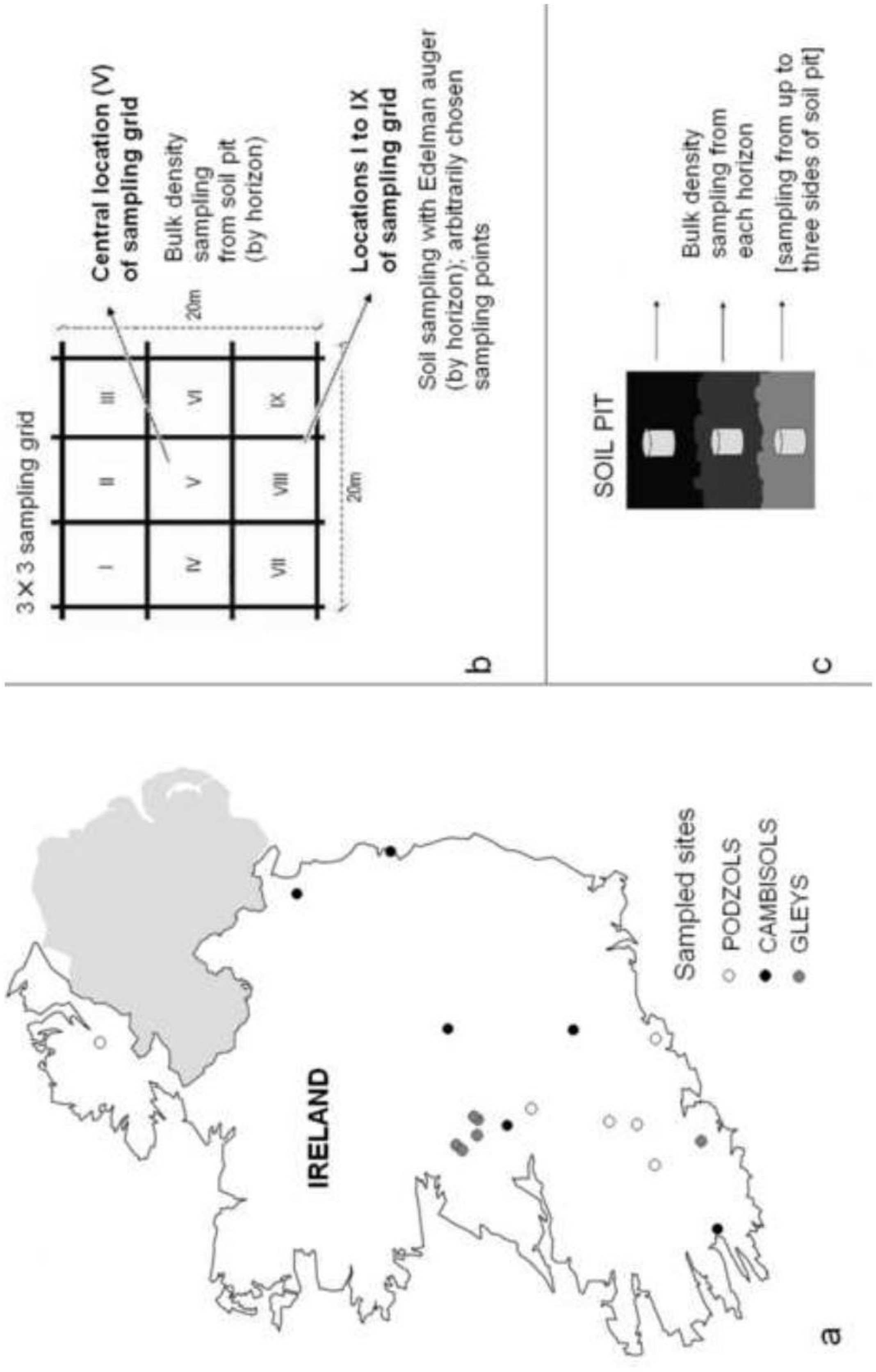


Figure 1

Figure 2

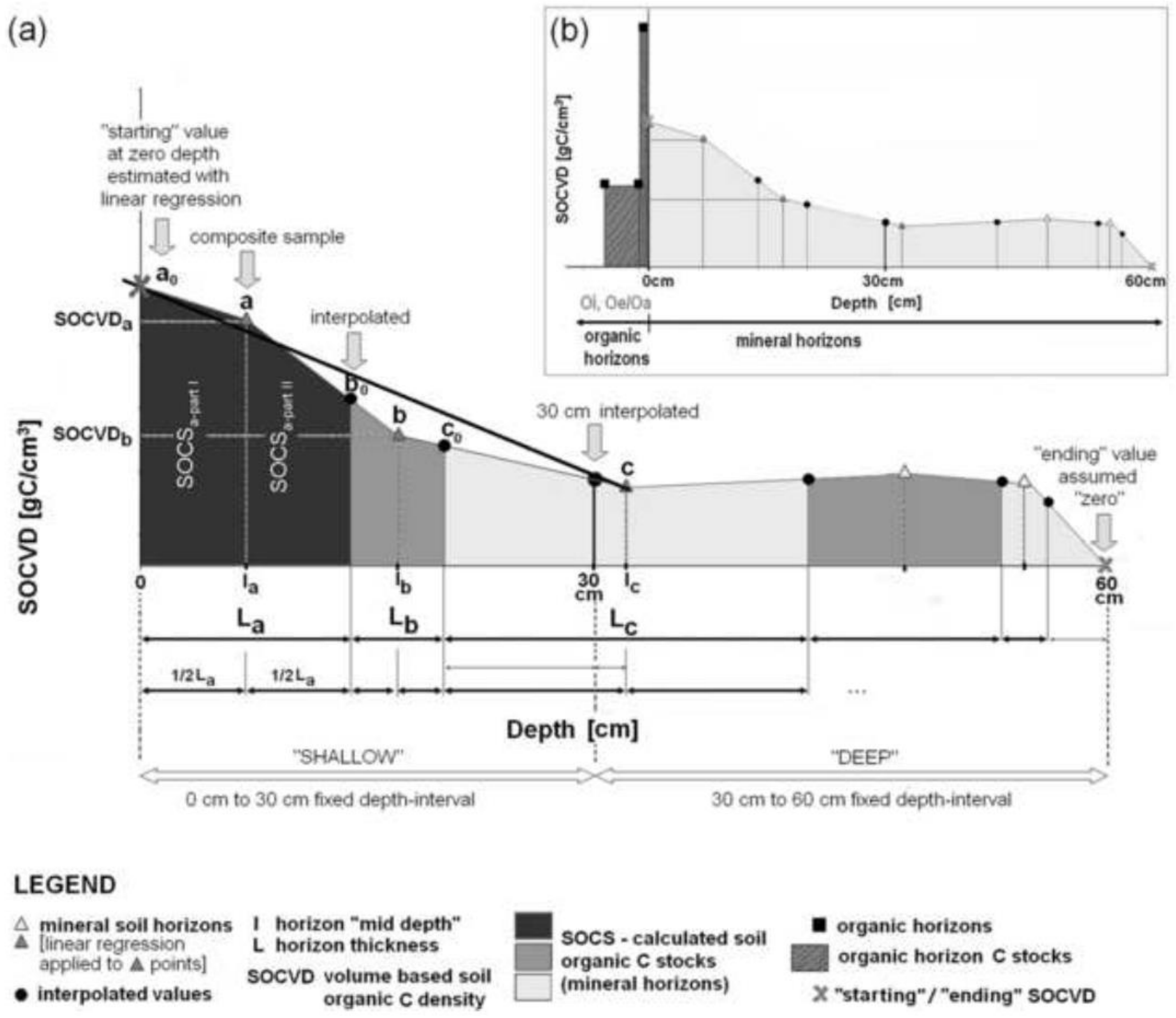

(a)
"starting" value at zero depth estimated with linear regression
composite sample
a_0
a
interpolated
b_0
b
c_0
30 cm interpolated
c
"ending" value assumed "zero"
$SOCVD_a$
$SOCVD_b$
SOCVD [gC/cm³]
$SOCS_{a\text{-part I}}$
$SOCS_{a\text{-part II}}$
0
l_a
l_b
30 cm
l_c
60 cm
L_a
L_b
L_c
1/2L_a
1/2L_a
...
Depth [cm]
"SHALLOW"
"DEEP"
0 cm to 30 cm fixed depth-interval
30 cm to 60 cm fixed depth-interval
(b)
SOCVD [gC/cm³]
0cm
30cm
60cm
Oi, Oe/Oa
Depth [cm]
organic horizons
mineral horizons
LEGEND
△ ▲ mineral soil horizons [linear regression applied to ▲ points]
● interpolated values
l horizon "mid depth"
L horizon thickness
SOCVD volume based soil organic C density
SOCS - calculated soil organic C stocks (mineral horizons)
■ organic horizons
▨ organic horizon C stocks
✕ "starting" / "ending" SOCVD

Figure 3

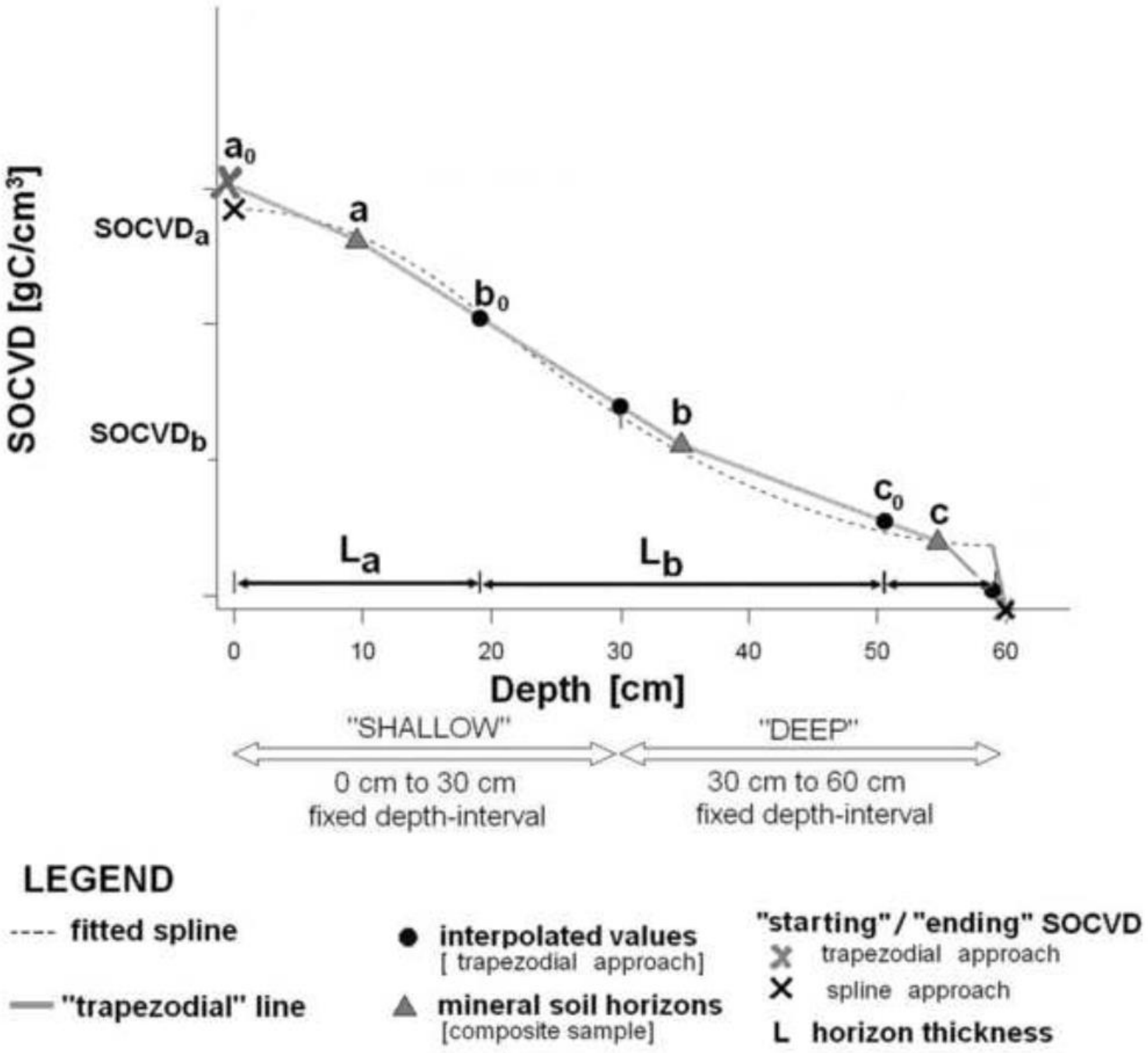
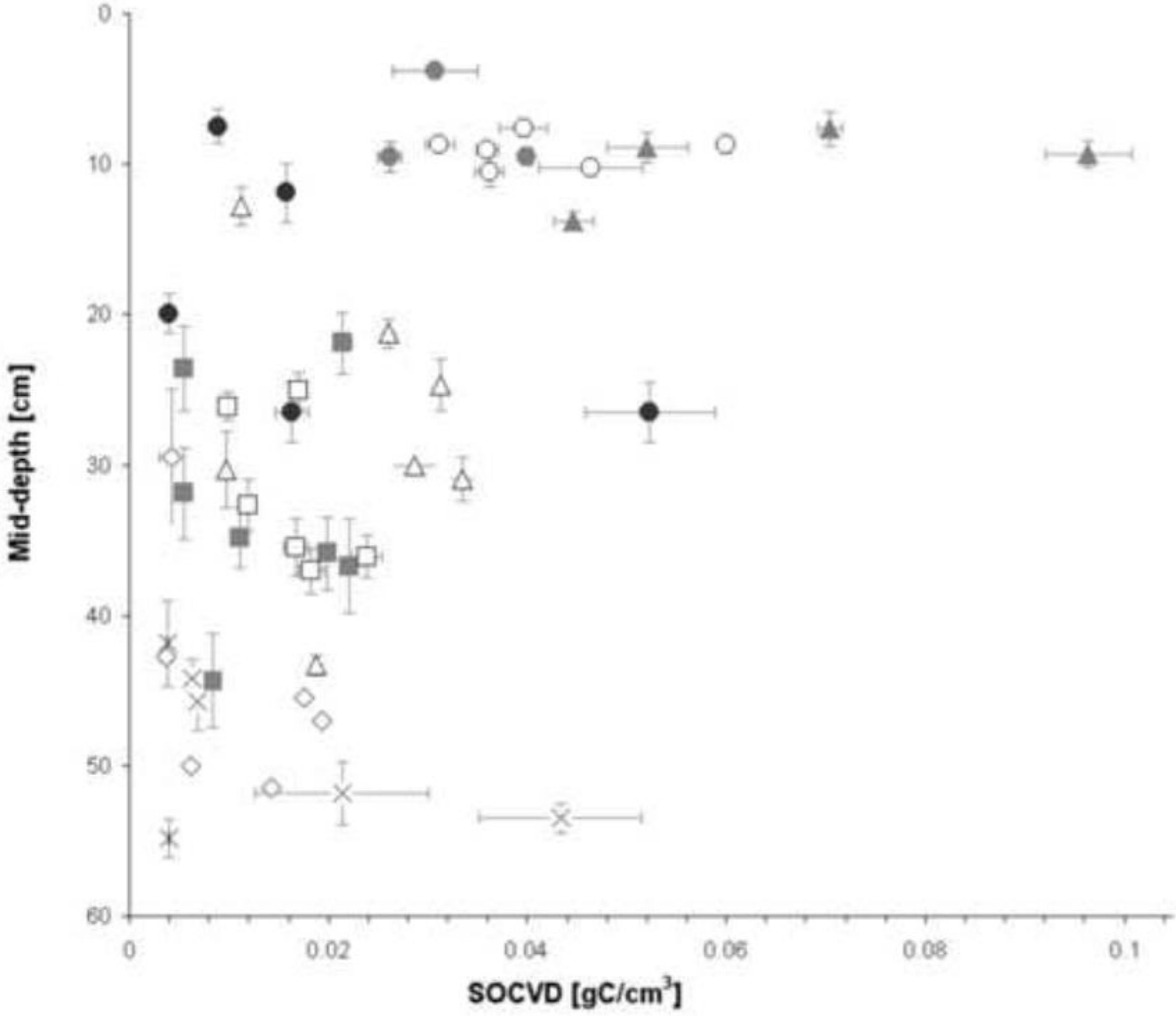

SOCVD [gC/cm³]
SOCVDa
SOCVDb
a0
a
b0
b
c0
c
La
Lb
0
10
20
30
40
50
60
Depth [cm]
"SHALLOW"
0 cm to 30 cm
fixed depth-interval
"DEEP"
30 cm to 60 cm
fixed depth-interval
LEGEND
fitted spline
"trapezodial" line
interpolated values
[trapezodial approach]
mineral soil horizons
[composite sample]
"starting" / "ending" SOCVD
trapezodial approach
spline approach
L horizon thickness

Figure 4



NOTE

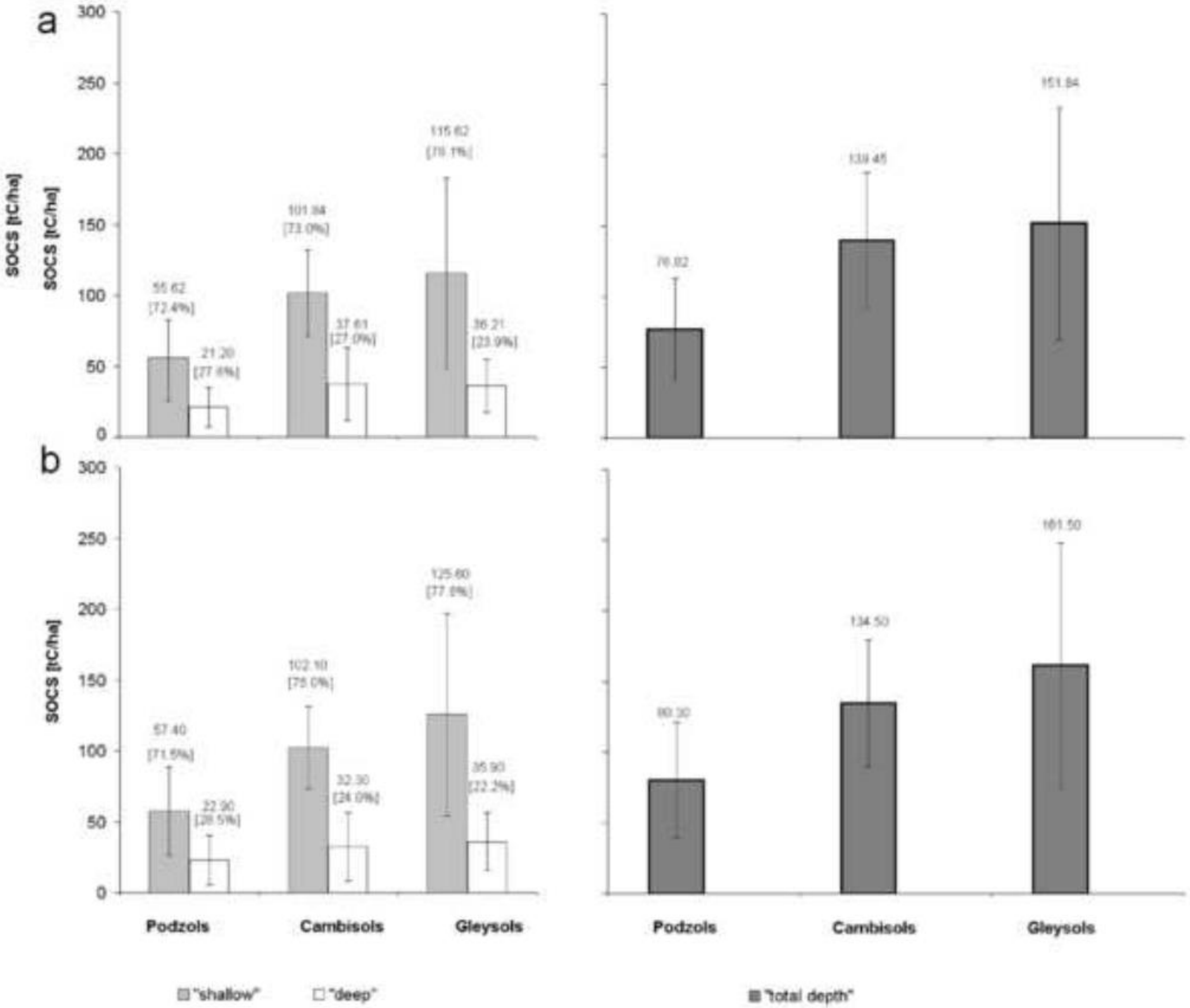
- horizontal error bars - "relative" standard error obtained from bulk-density sample replication (SOCVD value represents one composite sample);

- vertical error bars - standard error of soil-horizon average "mid-depth"

- B-horizons labelled with no. 2 refer to the soil-horizons of B-category found below the first B soil-horizons in the soil-profile of Gleysols;

- * two sites had missing bulk-densities for a single soil-horizon (measurements were taken from the next similar soil-horizon at the same site of the same soil-horizon category).

Figure 5



NOTE: Error bars represent standard deviation (without inclusion of error propagation from individual sampling points of 3×3 grid and bulk-densities); values on top are the mean SOCSs, values in brackets (below) represent the percentage SOCS for "shallow" and "deep" depth-interval (out of the "total depth").