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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 ≥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.

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

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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 ≥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 × 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 × 3 grid over 20 × 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, c). 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. 1c). 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 × 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