Catena 133 (2015) 420–431

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Towards sound comparisons of soil carbon stocks: A proposal based on the cumulative coordinates approach

Pere Rovira [a,*], Teresa Sauras [b], Josefa Salgado [c], Agustín Merino [d]

[a] CEMFOR, CTFC, Carretera de Sant Llorenç de Morunys, km 2, 25280 Solsona, Spain
[b] Dept Plant Biology, Faculty of Biology, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain
[c] Dept Applied Physics, Escola Politécnica Superior, Universidade de Santiago de Compostela, 27002 Lugo, Spain
[d] Unit of Sustainable Forest Management, Universidade de Santiago de Compostela, 27002 Lugo, Spain

ARTICLE INFO

Article history:
Received 5 December 2014
Received in revised form 22 April 2015
Accepted 20 May 2015
Available online 25 June 2015

Keywords:
Soil organic matter
Carbon budget
Carbon cycle
Equivalent soil mass
Carbon sequestration

ABSTRACT

The study of changes in soil organic carbon (SOC) stocks as a result of land use or climate change requires sound criteria to compare SOC stocks in different plots. Just comparing SOC stored down to a standard depth (often, 30 cm) is prone to errors, owing to the changes in soil bulk density due to shifts in SOC content or the soil compaction due to heavy machinery. To solve this problem several approaches have been suggested. Jenkinson proposed in 1971 the concept of 'equivalent soil depth', the depth to which a soil should be sampled to reach a certain amount of fine mineral earth. Here we present a procedure which combines that concept with the modern cumulative coordinates approach (CCA). Our method involves sampling soils down to a given depth (30 cm) with a volumetric core sampler which maintains the profile structure, and divide the obtained core in depth layers (0–5, 5–15 and 15–30 cm). Each layer is studied separately for its stone and gravel content, fine earth (<2 mm) and coarse organic fragments. From these data we calculate the cumulative (with depth) amounts of fine earth (<2 mm), soil organic carbon (SOC), and fine mineral earth (FME), i.e. the fine earth corrected for organic matter. Then, SOC and FME are plotted together and fitted to a double-exponential equation, to obtain the amount of SOC (kg m^{-2}) accumulated in the uppermost *Y* kg m^{-2} of FME. As an example, we apply this approach to the comparison of SOC stocks in four plots differing in land use (crop, old forest, and recent pine stands), and also as to their stoniness and bulk density. Essentially, instead of comparing SOC stocks on a depth basis — amount of C stored in the uppermost *Y* cm of soil, for instance 30 cm — we propose to compare SOC stocks on a fine mineral earth basis — amount of C stored by the uppermost *Y* kg m^{-2} of FME. The value we propose is $Y = 300$ kg m^{-2} of FME. Such an approach automatically corrects for the compression or expansion of soil due to heavy machinery, or the changes in bulk density due to the shifts in SOC content, thus making contrasting plots directly comparable. It is less clear, nevertheless, the usefulness of CCAs to compare SOC stocks in plots strongly differing as to their stoniness.

1. Introduction

The current climate change context has resulted in an increased interest in using soils as a sink for atmospheric CO_2. Today the main subject of research in soil science is how the stock of soil organic carbon (SOC) evolves as a result of changes in climate (increased temperature, decreased precipitation), land use (e.g., afforestation, forest clearing) or land management details (e.g., changes in agricultural practices) (e.g., Malhi et al., 2002; Morris et al., 2010; Lal, 2008; Smith, 2008; Luo and Weng, 2011, among many). In spite of the amount of published information, still relevant uncertainties affect our knowledge of these topics (Díaz-Hernández, 2010).

The estimation of soil OC stock is the result of a calculation of this kind:

$$C_T = \sum_{i=1}^{n} C_i \tag{1}$$

where *n* is the total number of soil horizons, C_T is the total SOC in the profile, and C_i is that of a given soil horizon, which is obtained as follows:

$$C_i = Db_i \times c_i \times 10000 \times (1–V_i) \times T_i \tag{2}$$

Abbreviations: CCA, cumulative coordinates approach; COF, coarse organic fragments, >2 mm; CMF, coarse mineral fragments, >2 mm, i.e. gravel and stones; SOC, soil organic carbon, <2 mm; Db, bulk density of the fine earth; FE, fine earth, <2 mm; FME, fine mineral earth, <2 mm, corrected for (=excluding) organic matter; TMM, total mineral matter, i.e., FME+CMF; Zm, *Zea mays* plot; Pn, *Pinus nigra* plot; Pp, *Pinus pinea* plot; Qf, *Quercus faginea* plot.

* Corresponding author.
E-mail address: pere.rovira@ctfc.cat (P. Rovira).

http://dx.doi.org/10.1016/j.catena.2015.05.020
0341-8162/

where Db_i is the bulk density (g cm^{-3}) of the <2 mm fraction in the i horizon, c_i is the SOC concentration (g C g^{-1}) in the i horizon, V_i is the fraction (0–1) of the total volume of the i horizon occupied by gravel and stones, and T_i is the thickness of the i horizon in cm. The equation gives SOC stock in g C per square meter, but it may be easily modified to give it in kg C m^{-2}, tones per hectare, or the units chosen. The calculation can be restricted to a given depth *d* simply by summing in Eq. (1) only those horizons not deeper than *d*. Eq. (2) may appear in several forms (e.g., Chiti et al., 2012; Howlett et al., 2012), but the underlying concept is always respected. The formula is easy to understand, but its practical application poses problems because, while c_i and T_i are measured routinely in soil surveys, very often neither Db_i nor V_i is really measured. Gravel is quantified when soil samples are sieved to 2 mm for further analyses, but the amount of stones or blocks is often only estimated in the field by visual inspection. As to Db_i, it must be measured by taking undisturbed samples in the field, which is difficult (if done properly) and time-consuming. Often Db is estimated by pedotransfer functions (e.g., Barahona and Santos, 1981; De Vos et al., 2005; Manrique and Jones, 1991; Rodriguez-Murillo, 2001) which usually show a poor fit: errors in estimating Db_i translate immediately to the estimation of its SOC stock.

A result of these uncertainties is that, while obtaining SOC concentration along a soil profile is a trivial matter, estimating SOC stock per unit surface is not. Owing to this difficulty, a universally accepted criterion to compare soil C stocks among a variety of land uses, land use histories and climatic constraints is still lacking after many years of research. The need of such a universal criterion is widely acknowledged (Lal et al., 2000).

Digging a classical soil profile involves a strong disturbance to the plot, and today is barely done in research about SOC stocks, except to obtain supporting additional information (e.g., to have a panoramic view of the soil features, in order to classify the profile according to USDA or WRB taxonomies). Data about SOC stocks is rather achieved by using samplers designed to obtain an undisturbed core, cylindrical or prismatic, down to a stated depth. This approach overcomes many of the above mentioned problems, because quantifying fine earth, stones and gravel in such a volume is easy. It applies well to sampling soils down to 30 cm, which is the reference depth recommended by the IPCC to compare SOC stocks among land uses and vegetation types (IPCC, 1997). This relatively shallow sampling depth has been criticized. Olson and Al.Kaisi (2015) consider imperative to sample soil down to the entire rooting zone or down to a 1–2 m depth when measuring SOC stocks. These depths in most cases could only be attained by means of small-diameter core samplers — unable to account for gravel and stones — of by digging soil profiles, a very destructive sampling method. Such an intensive sampling could be done only in few specific cases, not in large-scale surveys.

The comparison of SOC stocks still faces another problem, which is the question of what do we exactly compare. Soil is not a physically rigid system: along decades, its volume may appreciably change (Fig. 1). Conversion of native vegetation to crops result in soil compression due to SOC losses and increased Db. Additional compression must be expected if heavy machinery is used. On the other hand, an expansion of soil volume is also expected due to plowing. Actually studying changes in SOC storage in croplands may be difficult, because crop soils are subjected to relevant temporal changes throughout the year due to soil preparation, cultivation and harvesting. A forest soil developed on abandoned croplands may be not directly comparable to a never cropped forest soil, because some of the crop features (e.g., the plow pan) may persist for decades. A sound comparison of SOC stocks must necessarily rely on a parameter which can be fixed for all plots and all soil cores taken from them: the simple equalization of the sampling depth may result in erroneous conclusions.

This problem is known many years since (e.g., Nye and Greenland, 1964), and there has been attempts to solve it. The approach of Ellert (Ellert and Bethany, 1995; Ellert et al., 2001) is to compare the soils of contrasting plots by taking their genetic horizons as reference. It involves a careful determination of Db in the topsoil, whereas it is assumed that Db suffers little changes below 20 cm. Horizon masses are pooled down to a pre-determined 'equivalent soil mass': the amount of C stored by this equivalent soil mass is the object of the comparison. This approach needs a previous knowledge of the soil profiles, for their genetic horizons are the sampling units: when profiles are poorly

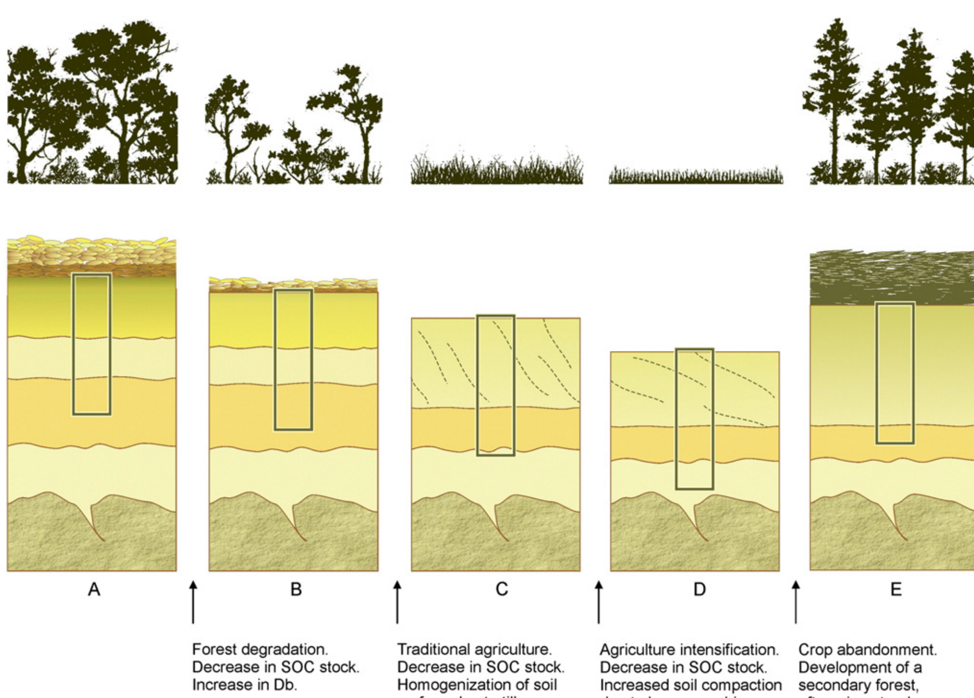

Fig. 1. An example of plot history. Soil evolution comes from a hypothetic original broadleaved forest to a recent secondary pine stand, through stages of forest degradation and conversion to crops. The use of heavy agricultural machinery may result in marked soil compaction. Rectangles show the different 'soils' we would obtain by introducing a core sampler to a previously fixed depth. The several soils would be not directly comparable, nor the obtained total C stocks would really represent the true changes in the C budget of the overall soil system.