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Colluvial soils as a soil organic carbon pool in different soil regions

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ABSTRACT

Subsoil has been recognized as large reservoir of soil organic carbon in recent years. In our study, we investigated deep colluvial soils as a potentially important source of SOC due to high mass redistribution driven by soil erosion. Three agriculture plots from the Chernozem, Luvisol, and Cambisol regions were studied to assess the SOC storage in topsoil (0–25 cm), at 2 m depth (0–200 cm), and over the total soil depth (0–450 cm) as a function of relief. The study is based on 558 borings, and soil profile description and classification to facilitate the colluvial soil delineation. Among these locations, SOC content was measured at 230 sampling points. Prediction of the SOC stock for the plots was based on support vector machine algorithms using digital elevation model derivatives as predictors. Total SOC stock varied among the study plots. The highest relative SOC stock was measured in the Chernozem (CH) plot (144.7 $t \cdot ha^{-1}$), while at the Luvisol (LU) plot, it reached 68.4 $t \cdot ha^{-1}$ and was 73.4 $t \cdot ha^{-1}$ at the Cambisol (CM) plot. The role of colluvial soils regarding their spatial extent and SOC stock differs among the studied plots. Colluvial soils at the CH plot represent an important soil cover both spatially (13%) and by the volume of SOC stock (37%). A moderate importance of colluvial soils is determined for the LU plot (12% of SOC stock), and a low importance for the CM plot (5% of SOC stock). SOC stock contained in topsoil and subsoil differs in each plot. In the Luvisol and Cambisol plots, more than one half of SOC is retained in topsoil (53.4%, 60.3%). In contrast, more than two thirds of the SOC stock (73.1%) occurs in subsoil in the Chernozem plot. Moreover, 19.0% of the total SOC stock occurs at depths below 2 m. This finding indicates the importance of the incorporation of deep colluvial soil horizons in SOC stock estimations.

1. Introduction

The organic carbon stock in soils represents one of the largest terrestrial reservoirs of this substance (Chaopricha and Marín-Spiotta, 2014). Processes driving SOC flow in dynamic landscapes have been widely studied during the last two decades (Doetterl et al., 2012b; Polyakov and Lal, 2004; Van Oost et al., 2007). Some of the works have demonstrated that the SOC redistribution during erosion transport and the consequent terrestrial sedimentation play an important role in the global carbon cycle, and in the spatial variability of various physical and chemical soil features (Berhe and Kleber, 2013). Furthermore, soil erosion and deposition processes have significant implications for SOC persistence in the terrestrial biosphere (Berhe and Kleber, 2013; Van Hemelryck et al., 2010). Most of the understanding of the processes related to SOC storage and release is limited to the topsoil (0–30 cm) (Chabbi et al., 2009; Chaopricha and Marín-Spiotta, 2014). The dynamics and amount of SOC stored in deep soil horizons were not well understood and quantified for a long time. In recent years, subsoil and even deep and buried soil horizons have been recognized as large reservoirs of carbon that are responsive to climatic-environmental processes (Chaopricha and Marín-Spiotta, 2014; Paul et al., 2006). The sensitivity of the subsoil carbon pool to land use changes was unknown until recently (Don et al., 2007). Studies from different environments show a dynamic response of deep SOC pools to land cover management (Devine et al., 2011; Harrison et al., 2011). Recent investigations of subsoil SOC have focused mainly on its chemical composition, persistence (Chabbi et al., 2009; Rumpel et al., 2004), bioturbation or burial, and its vertical transport through preferential flow-paths (Chaopricha and Marín-Spiotta, 2014; Wilkinson et al., 2009). Most of the studies assessing the spatial distribution of SOC stock in the landscape limit their computations to the topsoil, the upper 50 cm (Cambule et al., 2014; López-Fando and Pardo, 2011; Schwanghart and Jarmer, 2011; Simbahan et al., 2006), or the upper 100 cm (De Gryze et al., 2008; Don et al., 2007; Fang et al., 2012; Han et al., 2010; Khalil et al., 2013). Only a few studies have assessed the SOC stocks in deeper soil horizons, namely those situated in Chernozem regions, where deep A horizons are common (Kalinina et al., 2011; Liu et al., 2011; Vasques et al., 2010; Xi et al., 2011).

Deep SOC is often present in specific parts of the landscape where colluvial soils are formed. Colluvial soils form on concave slopes because

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of sedimentation of eroded topsoil material on agricultural land. Their soil profiles are characterized by the presence of a deep humus horizon (or less frequently of a horizon formed by slope sediment with varying SOC content) resulting from sedimentation of eroded topsoil from overlying soils in the landscape. The process of colluvial soil formation is a direct consequence of soil loss by water and tillage erosion conditioned by its position in the landscape. SOC storage in such deep colluvial humus-rich soils has not yet been studied (Zádorová et al., 2011b). Profile development and the thickness of colluvial soil depend on various factors, mainly on soil conditions and properties, the parent material, the source of colluvial material (rich in organic matter or SOC depleted), terrain character and land management (Zádorová et al., 2013). Colluvium several metres thick and rich in organic matter commonly occurs in loess regions and develops from humus-rich soils, mainly Chernozems (Poreba et al., 2011; Zádorová et al., 2011b, 2013; Zglobicki, 2013) and Luvisols (Fuchs et al., 2010; Kadereit et al., 2010; Lang and Hönscheidt, 1999; Rodzik et al., 2014). Shallower colluvial soils with a stratified profile have been reported from areas formed by Luvisol and Cambisols in the Czech Republic (Zádorová et al., 2014).

Techniques for SOC stock estimation can be divided into two groups (Cambule et al., 2014; Mishra et al., 2010): the traditional way of point SOC density measurement in a layer, and multiplying by the layer area. Recently, a landscape modelling approach analysing the spatial variability of SOC stocks with respect to variations in environmental co-variables has been applied in various studies at a local and regional scales (Cambule et al., 2014; Doetterl et al., 2012a; Simbahan et al., 2006). Environmental characteristics, such as terrain, geology, soil type, and land use and management are important variables when assessing and quantifying processes of soil erosion and deposition, and their impact on spatial variability of soil properties (e.g., De Gryze et al., 2008; Florinsky et al., 2002; McBratney et al., 2003). Predictors used as explanatory variables in SOC stock quantification most often comprise land use type, soil and parent material type, climatic factor (precipitation), terrain attributes, or soil reflectance (Cambule et al., 2014; Hancock et al., 2010; Van Oost et al., 2012). Each of the factors influences the soil mass redistribution at different scales. Terrain attributes can be considered as the main ruling factor at a plot scale, namely in tilled plots with homogenous parent material. Because of the lack of information on the relationship between terrain and deep humus-rich sediments, our study aims to:

(i) assess and quantify the role of colluvial soils in SOC storage in three different soil regions; and

(ii) estimate the potential use of topography as an explanatory factor in SOC stock modelling.

Our study is based on the following hypotheses: 1) quantitative terrain modelling can be applied for the SOC prediction and the colluvial soil delineation and 2) the proportion of SOC retained in colluvial soils will vary in different soil regions.

2. Regional setting

Three study plots, which represent the most extensive agricultural land soil units in the Czech Republic, were chosen. Their locations are depicted in Fig. 1. Plots that are similar in terms of terrain, land management and climatic conditions (rain erosivity) were selected to assess the influence of soil development and characteristics on soil mass redistribution. All of the plots are situated on arable land with analogous land management (long-term tillage, no conservation practices), plough depth (25 cm) and crop rotation (5–6 course rotation based on the Norfolk system). Plots were chosen with the aim of covering typical colluvial terrain positions (toe-slopes and side valleys). They are characterized by dissected relief and include the following set of terrain units: side valley, toe-slope, plateau and back-slope. Climatic conditions differ among the plots by annual precipitation rates and temperatures, but belong to the same region in terms of rainfall erosivity factor (Janeček, 2012). Soils at all of the three plots have identical texture classes (silt loam). Each of the plots has homogenous geology and climatic conditions. Soil cover heterogeneity within the plot is according to erosion processes. The resulting erosion catena consists of unchanged autochthon soils, eroded soils in the steep parts of the landscape, and colluvial soils formed by sediment material in the lower parts of the plots (Fig. 2). Plot 1 (CH plot) is situated in the SE of the Czech Republic (48.967°N, 16.882°E). The area is covered by a Pleistocene loess layer with variable thickness (Chlupáč et al., 2002). Climate is characterized by a mean annual precipitation of 542 mm and a mean annual temperature of 8.4 °C. The research was carried out on an agricultural parcel (6 ha) that comprises a complex slope system with different terrain units: a plateau (slope 0–0.5°), a steep middle part (up to 19°) formed by a back-slope and a side valley, and a toe-slope. The mean slope of the plot is 7°. The side valley represents a major line of concentrated runoff emptying into a colluvial fan at the toe-slope. The back-slope is interrupted by a road that separates it from the floodplain. Plateau areas with no erosion are covered by Calcic Chernozem. Chernozems with a truncated mollic horizon cover areas with increasing slope (2–8°). Regosols (ploughed exposed loess material) cover the steepest parts of the slopes. Colluvial Chernozems and colluvial soils with deep A horizons are formed in concave parts of the landscape (Zádorová et al., 2011b). Colluvial soils with a 100–250 cm thick A horizon rich in organic matter have developed in the side valley, whereas the deepest colluvial profiles are formed by a mixture of loess and humus-rich material in the top 300 cm, and humus-rich material at 300–400 cm depth was found in the toe-slope.

Plot 2 (LU plot), which is represented by Luvisols, is situated in Central Bohemia (50.457°N, 14.509°E). The parent material is Pleistocene loess (Chlupáč et al., 2002). The mean annual precipitation is 588 mm and the mean annual temperature is 8.2 °C. The study plot (15 ha) is characterized by two perpendicular side valleys (north–south and east–west) connected in the south-west part of the plot. Adjacent slopes reach up to 17°. Large flat upper parts (0–0.5°) occur in the south, north-east and north-west sections of the plot. The mean slope of the plot is 5°. Haplic Luvisol is the dominant soil unit at the study plot. Regosols and Calcisols are formed in the steepest parts of the plot. Accumulated forms of Luvisol and colluvial soils with a maximum thickness of 100 cm have formed in the depositional areas of the landscape (Zádorová et al., 2014). A stagnic colour pattern at the bottom of the soil profile develops in the lowest part of the plot.

Plot 3 (CM plot; 33 ha) represents a Cambisol region (49.616°N, 14.367°E). The parent material is formed from Paleozoic contact metamorphic greywacke and siltstone (Chlupáč et al., 2002). The climate is cooler (7.1 °C), with higher annual precipitation (659 mm) than in the other two regions. The study plot is represented by a slope system with two side valleys divided by a distinct elevation. The plot has a marked north-south slope, with a maximal gradient of 20°. The flat parts (0–2°) are situated in the south part of the plot adjacent to a road. The mean slope of the plot is 7°. Cambisols cover both the flat parts and the lower and middle slopes. Leptic Cambisols and Leptosols are found on the steepest slopes. Colluvial soils with maximum depths of 100 cm form at the base of the accumulation positions. As in the LU plot, stagnic properties developed in the CM plot in the soils occurring at the confluence of the two side valleys.

Detailed information on terrain, climatic and soil characteristics of the three plots are shown in supplementary materials.

3. Methods

3.1. Terrain sampling and soil analyses

Soil sampling was conducted within two campaigns. The CH and CM study plots were sampled (Fig. 1) on an optimized network of borings and deep cores, projected using the conditioned Latin hypercube sampling (cLHS) approach (with terrain attributes as feature space