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Vertical bulk density distribution in C-horizons from marley till as indicator for erosion history in a hummocky post-glacial soil landscape

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ABSTRACT

For a quantitative understanding of water and element balances of intensively cropped hummocky post-glacial soil landscapes, effects of erosion and colluviation on pedologic structure, and mechanical and hydraulic soil properties should be considered. The C-horizon consisting of glacial till as the parent material can be close to the surface and become part of the plant root zone at exposed locations where topsoil was removed by tillage erosion. Soil bulk density, as one parameter for hydraulic pedotransfer functions, may be characteristic also for the depth location of soil horizons. We propose bulk density as a proxy for the spatially distributed vertical distances between the C-horizon and the soil surface in such landscapes. We analyse the relation between bulk density and depth location for the C-horizon in Luvisol and Regosol soils of various stages of profile reduction by erosion. Within the same diagnostic soil horizon, the bulk density data increased with depth; however, within the C-horizon, the bulk density remained similar or showed a small tendency to decrease with depth. Highest bulk densities of more than 1.8 g cm^{-3} (soil <2 mm) were found in the uppermost C-horizon of the Haplic Regosol. With a model of bulk density based on sand and organic matter contents as well as soil depth, bulk density values of these C-horizons were adapted. The factor of the regression function was increased as a result of calibration by a constant of 0.3 g cm^{-3}. The calibrated model was then used to reconstruct a hypothetical vertical profile of the bulk density for the heavily eroded Haplic Regosol indicating a soil loss of at least 1 m. The bulk density modelling for estimating the vertical position of soil horizons in the original (non-eroded) soil profile could possibly be used for the estimation the topsoil removal rate by erosion for soil types at a certain landscape position. The erosion history may thus be estimated by reconstructing standard bulk density profiles developed in locations where the topsoil removal rate was relatively fast as compared to the soil development processes and the bulk density not in equilibrium with the overburden load.

1. Introduction

Soil bulk density is a basic physical property (Nemes et al., 2010) for determining the porosity and for estimates of permeability. Furthermore, the bulk density is crucial for balancing element stocks or carbon pools (e.g., Throop et al., 2012). Bulk density has often been related to the particle size fraction <2 mm because most other analyses such as texture and soil chemical properties exclude the coarser stone and gravel fractions (Heuscher et al., 2005).

The bulk density of in situ developed mineral soils, except for compaction effects, is assumed to increase with soil depth (Nemes et al., 2010). Thus the dry bulk density of soils in the hummocky formerly glaciated landscapes is highest in the C-horizons that are formed by the glacial till as parent material. These landscapes can strongly be affected by tillage erosion (e.g., Van Oost et al., 2003), which in addition to wind and water erosion, characteristically shapes the morphological appearance of the surface of these landscapes (e.g., Sommer et al., 2008; Gerke et al., 2010). The spatial patterns of more-or-less eroded and colluviated soil types (i.e., Haplic Luvisols and Haplic Regosols) can easily be observed, for instance, directly after soil cultivation when lighter colours on the soil surface indicate the eroded spots and brownish and darker colours the colluvic positions.

The soil types form a 3D continuum of with all transitional Luvisol and Regosol types distributed in the landscape (Sommer, 2006; Sommer et al., 2008). Due to the erosion by tillage and water, the uppermost C-horizons of relatively un-weathered glacial till can be found from practically zero distance below the plough layer to about 1.5 m; or even deeper if the soil was covered by colluvium (e.g., Deumlich et al., 2010). For Stagnic Luvisol, the bulk density of the glacial till was reported to be around a value of 1.8 g cm^{-3}

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(Horn, 2004). Other values were ranging between 1.76 and 1.95 g cm^{-3} for soil depths below 70 cm for Stagnic Luvisols and Stagnic calcaric Regosols (Lennartz et al., 1999; Wichtmann et al., 1998; Gerke and Köhne, 2004).

Soil landscape patterns can have important impact on catchment and hillslope hydrology (e.g., Ticehurst et al., 2007). This is especially true for the hummocky soil landscape, where the topsoil horizons have been removed by tillage and water erosion (e.g., Deumlich et al., 2010). Here, the shallower the till (i.e., Haplic Regosols), the more it impacts on the root zone hydrological processes and the relatively dense C-horizons can play an important role in soil water storage, movement, and water uptake by plant roots. Below the root zone, the relatively compact till mainly acts as a low permeable drainage barrier that can determine the bottom boundary for soil hydrological modelling (e.g., Gerke and Köhne, 2004). If the till is located within the root zone; however, its properties need to be included as part of the flow domain. In pedotransfer approaches, relatively high bulk densities and strength of functional subsoil Bt and C-horizons (i.e., a grouping of pedological horizons in those with similar properties according to Webb, 2003) could be related to a low porosity and hydraulic conductivity.

The high densities of till partly result from the specific textural mixture that allows smaller particles to enter the pores between larger ones (e.g., Koltermann and Gorelick, 1995). The pressure of the ice overburden could additionally force pore water out of the till (e.g., in drumlin landforms, Miller et al., 1993). These authors indicate that high bulk density in parent material was an inherent property attributable to geogenic rather than pedogenic forces, leading to slowly permeable soil horizons and shallow rooting zones. However, the mechanical and hydraulic properties of glacial till-derived soil layers under conditions of reduced overburden loads are relatively unknown. Of course, also the subsoil compaction by agricultural machinery (e.g., Batey, 2009) can strongly affect soil hydraulic properties (Alaoui et al., 2011). Changes in the soil bulk density had a major effect on the water retention curve (Assouline, 2006). Thus, the soil bulk density may be used as a proxy of both mechanical and hydraulic properties. Density has frequently been used in pedotransfer functions as one parameter for predicting the soil hydraulic properties from texture and other basic soil data (e.g., Nimmo et al., 2007). In addition to texture and organic matter content, bulk or particle density, respectively, was used as one of the several parameters to improve hydraulic pedotransfer function (Walczak et al., 2006). Similarly, bulk and particle density were used to estimate the packing state for predicting the soil water retention curve (Mohammadi and Vanclooster, 2011).

Several multiple regression equations and other empirical functions have been proposed to predict bulk density of arable soils (e.g., Heuscher et al., 2005; Nimmo et al., 2007; Nasta et al., 2009) or for fluviatile sediments (Avnimelech et al., 2001). Keller and Hakansson (2010) proposed to estimate a reference bulk density depending on texture and organic matter content for analysing relative soil compactness; in their analysis reference bulk density was weakly related to particle density for mineral soils. Various bulk density models have recently been tested (Martin et al., 2009). The adapted Adams–Stewart model for bulk density prediction splits the effects of mineral and organic particles on bulk density and includes a depth function (Tranter et al., 2007). The model was applied and calibrated as density pedotransfer function for soils from a European database (Hollis et al., 2012).

In contrast to the importance of the underlying till for soil hydraulic analyses in the formerly glaciated hummocky soil landscapes, the physical properties have not been intensively studied. Investigations of soil hydraulic properties often end at the bottom of the B-horizon (e.g., Dörner and Horn, 2006). Also most of the above mentioned approaches did not consider the C-horizons.

The objective of this study was to compare the till density as function of distance to the surface as a measure of erosion intensity. In addition, we will discuss whether the density depth relation could be used for explaining erosive topsoil removal history. After applying a bulk density model to the C-horizon, the results will be compared with bulk density data of the parent material obtained from profiles representing soil landscape positions of an arable field site. In an accompanying study (Rieckh et al., in this issue), the bulk density information of the hummocky soil landscape are used for interpreting porosities and hydraulic properties.

2. Materials and methods

Soils for this study were from the experimental field site CarboZALF-D of the Leibniz-Centre for Agricultural Landscape Research (ZALF) e.V. Müncheberg (http://www.zalf.de). The field is located northwest of the town of Prenzlau in Northeast Germany (53°23′N, 13°47′E) in a glacially shaped intensively cultivated agricultural landscape. Average annual rainfall of 489 mm and mean annual air temperature of 8.6 °C (from 1991 to 2010) were recorded at the nearby Experimental Field Station Dedelow of the ZALF. Soils in this hummocky landscape were derived from weichselian glacial till. Soil types according to FAO classification (WRB, 2006) range from typical Haplic Luvisol (haLV) to Haplic Regosol (haRG) at exposed top and colluvic Regosols (coRG) in foot-slope positions among others (e.g., Deumlich et al., 2010; Gerke et al., 2010). The fully developed LV soil profiles with Ap–E–Bt–C-horizons are mainly found in relatively level plateau positions (Fig. 1); weakly eroded Luvisols (eLV) with Ap–Bt–C-horizons are on gentle slopes, while the strongly eroded haRG with Ap–C-horizons are on steeper slopes mainly in the upper landscape position.

Soil cores were sampled in June 2009 from four LV, four eLV, and two RG soil pits that were about 2 m deep. The 100 cm^3 cores (i.e., 5.05 cm diameter and 5 cm height) were taken horizontally distributed over the whole diagnostic horizon and the distance between the soil surface and the centre of each core was determined. Core cylinder arrangement at RG profile 7w is shown as an example (Fig. 2). The cores were placed such that 5 replicates per diagnostic horizon could be extracted. At selected pits, additional 20–30 cores (100 cm^3) were sampled from each of the diagnostic horizons.

After extraction, the soil cores were immediately stored in plastic bags. In the lab, the fresh mass was determined; the gravimetric moisture content (i.e., after drying at 105 °C for 24 h) was determined on an aliquot where stones were excluded. Stones were separated by dry sieving and their mass and volume fraction

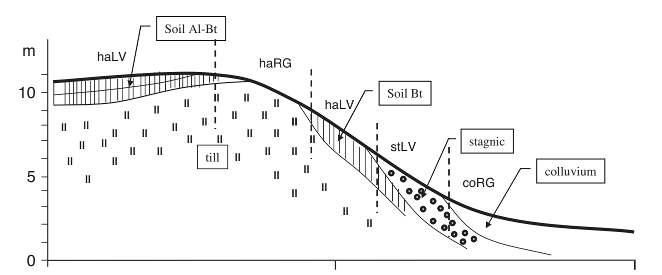

Fig. 1. Sketch of a vertical cross-section through the hummocky soil landscape with location of characteristic soil profiles of Haplic Luvisol (haLV), Haplic Regosol (haRG), eroded Haplic Luvisol (eLV), and colluvic Regosol (coRG), indicating varying distances to the underlying till.
Adapted from Deumlich et al. (2010).