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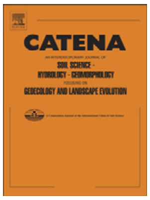

# Carbon dynamics in topsoil and subsoil along a cultivated toposequence

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## ABSTRACT

Topography-induced spatial heterogeneity influences soil organic carbon (SOC) stocks and microbial degradation (respiration) both in topsoil and subsoil compartments. However, the interaction between topographic position and soil horizons has rarely been assessed. This study aimed to investigate SOC dynamics in topsoil (5 cm) and subsoil horizons (40 and 80 cm) at shoulderslope and footslope positions in a toposequence in a Danish winter wheat field. In addition, SOC was quantified for 20-cm depth intervals to 100 cm depths. Over a 1 year period, gas samples for carbon dioxide ($CO_2$) and oxygen ($O_2$) analyses were collected from seven different soil depths (5 to 80 cm) at the shoulder- and footslope positions. Soil surface $CO_2$ fluxes were measured over a shorter period (January to June 2012). Soil samples from 5 and 40 cm depths were incubated at 5 to 34 °C to determine the temperature sensitivity ($Q_{10}$) of soil respiration. Results showed that SOC stocks to a soil depth of 1 m were larger at footslope (202 Mg C $ha^{-1}$) compared to shoulderslope (44 Mg C $ha^{-1}$) positions. Mean annual soil $CO_2$ concentrations were higher at footslope positions, and increased with depth at both shoulder- and footslope positions. Temperature sensitivity of C turnover was similar in topsoil at shoulderslope ($Q_{10} = 2.5$) and footslope ($Q_{10} = 2.6$) positions; in subsoil (40 cm), however, $Q_{10}$ was lower at shoulderslope ($Q_{10} = 2.0$) than footslope ($Q_{10} = 3.2$) positions. Further, shoulderslope subsoil had less non-complexed organic C than footslope subsoil, suggesting that the shoulderslope subsoil was not C saturated and had higher potential for C stabilization. Despite the dissimilar subsoil characteristics at shoulder- and footslope positions, soil surface $CO_2$ effluxes were similar, suggesting low contribution of subsoil C to short-term surface $CO_2$ fluxes at footslope positions.

## 1. Introduction

Globally, soils store an estimated stock of 2344 Pg organic carbon (C) and therefore represent a significant potential source of carbon dioxide ($CO_2$) emissions (Stockmann et al., 2013). Both the accumulation and turnover of soil organic carbon (SOC) are influenced by several factors, including climate, topography, soil type, and land use, causing large spatial variability of SOC stocks at the regional and field scales (Allen et al., 2010; Wiesmeier et al., 2013a). In cultivated landscapes with rolling topography, lateral and vertical gradients in SOC stocks are further enhanced by soil redistribution in the form of tillage and water erosion that redistribute SOC to lower landscape positions of soil toposequences (Quine and Van Oost, 2007). Only in recent years has the importance of tillage for massive soil movement from convex to concave landscape positions been recognized (Van Oost et al., 2005). However, linkages between the resulting redistribution of SOC and its turnover have largely been ignored in assessing the state and fate of SOC stocks in arable soils (Avilés-Hernández et al., 2009; Berhe et al., 2008). This highlights the need for studying the patterns and complexity of SOC dynamics in a landscape context and specifically along toposequences. The quality of the deposited SOC at footslope positions may differ from the native SOC due to erosion-induced breakdown of soil aggregates and the exposure of (physically) protected SOC during transport from the shoulderslope to footslope positions. Thus, Berhe et al. (2007) argue that since labile SOC is more easily decomposed during transport, the SOC deposited at footslope positions is less labile.

In arable systems, topsoil can be operationally defined as the plough layer (soil above 30 cm depth) whereas the subsoil is soil below 30 cm depth. Due to its importance for crop production, topsoil has been the main focus in most studies of SOC dynamics (e.g. Awiti et al., 2008). However, a significant amount of topsoil SOC may be transported vertically to the subsoil either as (i) suspended colloids, (ii) dissolved organic C, or (iii) particulate fractions repositioned by bioturbation (Bruun et al., 2007; Rumpel and Kögel-Knabner, 2011). This downward transport may account for as much as 30–50% of the total movement of organic matter from topsoil (Jenkinson and Coleman, 2008). Despite generally lower SOC concentrations and microbial activity in subsoil horizons compared to topsoil horizons, the large and greatly varying depth of subsoil horizons may be associated with high amounts of SOC and increased variability of $CO_2$ produced (Syswerda et al., 2011). Therefore,

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to validly estimate stocks and flows of current and future SOC, the mechanisms regulating SOC dynamics in subsoil should be taken into account, including possible effects of global warming on SOC turnover (Portner et al., 2010).

Few studies have addressed the interaction between topographic position and soil horizons on SOC stocks and turnover in arable fields (Doetterl et al., 2012; Van Oost et al., 2005; VandenBygaart et al., 2012; Wiesmeier et al., 2013b). In this study we aimed at investigating (i) the variability of SOC stocks and turnover and (ii) the sensitivity of SOC turnover to temperature in topsoil and subsoil horizons at the shoulderslope and footslope positions along a cultivated toposequence. Due to mainly tillage-induced soil and SOC transport, we expected to demonstrate higher SOC stocks at footslope compared to shoulderslope positions. Effects of differences between SOC at the two slope positions were studied with respect to physical state of SOC, i.e. level of complexation and age, temperature sensitivity of SOC turnover, and in situ levels of soil $CO_2$ concentrations and emissions.

## 2. Materials and methods

### 2.1. Field site and pedology

The study was conducted with soils from shoulderslope and footslope positions along a 25-m long catena in a 7.1 ha winter wheat (*Triticum aestivum* L.) field in western Denmark (56° 22.5′ N, 09° 33.6′ E). Mean annual rainfall at the site is 704 mm and the mean annual air temperature is 7.3 °C. We first collected soil samples from four slopes in the same field and analyzed them for physical and chemical properties including texture and SOC. Since similar patterns were observed in all four slopes (Chirinda et al., submitted for publication), one slope (16% inclination) was chosen for this study.

The dominant soil texture at the field site was loamy sand and sandy loam developed on glacial till from the Weichselian glaciation. Soil profile descriptions (down to 1 m) were made in June 2012 where shoulderslope and footslope positions were classified according to the World Reference Base for Soil Resources as Stagnic Podzoluvisol and Aric Anthrosol, respectively.

### 2.2. Management history

The selected field had been under continuous agricultural cropping for more than 100 years with crop rotations dominated by spring barley (*Hordeum vulgare* L.), grass (primarily ryegrass, *Lolium perenne* L.), and fodder beet (*Beta vulgaris* L.) before the 1970s and since then by winter wheat, spring barley and winter oilseed rape (*Brassica napus* L.). Straw has generally been removed from the field following harvest. The field has regularly received livestock manure; prior to 1975 predominantly as farmyard manure and thereafter as pig slurry. Typical annual slurry rates have been 20–30 Mg $ha^{-1}$ supplying about 3–4 kg total N per Mg slurry. Mineral N fertilizer has been applied since the 1950s (in the range of 170–210 kg N $ha^{-1}$ $yr^{-1}$). Soil pH has been maintained between 6.5 and 7.5 by intermittent liming. The field has been mouldboard-ploughed typically once every year to a nominal depth of 20–25 cm from the mid-1950s to 2008, after which reduced tillage was introduced, working the soil to a depth of ca. 8 cm with a tine bar cultivator. Winter wheat was grown in both 2011 and 2012, when this study was conducted.

### 2.3. Soil sampling and characterization

On 20 June 2012, at both the shoulderslope and footslope positions, soils from five sampling points (150 cm apart on a contour transect) were collected down to 1 m depth using an auger. Soil from similar slope positions (shoulderslope or footslope) and depth intervals (0–20, 20–40, 40–60, 60–80, 80–100 cm) were pooled and mixed (to homogenize the soil) prior to being subsampled and pulverized for total C analysis (LECO dry combustion system, LECO Corporation, St Joseph, MI, USA). Separate analyses (Santi et al., 2006) showed no detectable calcium carbonates in the soil samples; therefore total C was equivalent to SOC.

Also on 20 June 2012, two 1-$m^2$ pits, one at the shoulderslope and one at the footslope position, were dug (using a spade) to a depth of 80 cm; the pits were at a central position on each of the soil sampling contour transects. From each of the pits, 20 intact 100 $cm^3$ cores (about 6-cm diameter and 3.5 cm high) were taken at 5, 40 and 80 cm soil depths. Ten cores (from 5 and 40 cm depth) were reserved for a temperature incubation experiment, whereas five cores from each depth were characterized for bulk density by a procedure accounting for the stone content through sieving and excluding coarse fraction (>2 mm) as suggested by Robertson and Paul (2000). Five other cores from each soil depth were pooled and mixed into a composite sample prior to being characterized for soil texture (Gee and Bauder, 1986) and SOC content as described above. Soil C stocks at 20-cm depth intervals from the 0–100 cm soil profiles were calculated on a dry weight basis using SOC concentration in the 20-cm segments and the closest corresponding bulk density determined at 5, 40 and 80 cm depth (Syswerda et al., 2011).

The amounts of complexed organic carbon (COC) and non-complexed organic carbon (NCOC) were estimated using the equations described by Dexter et al. (2008) and tested also for Danish soils (Schjønning et al., 2012):

$$COC = \begin{cases} SOC; & if \;\; SOC < clay/10 \\ & else; clay/10 \end{cases} \tag{1}$$

$$NCOC = \begin{cases} SOC - COC & if \;\; SOC - COC > 0 \\ & else; NCOC = 0 \end{cases} \tag{2}$$

where SOC and clay, respectively, represent the amount of soil organic C (g $kg^{-1}$) and clay (g $kg^{-1}$) in the soil sample. The composite samples from 5 and 40 cm depth were characterized also for apparent age of SOC in topsoil (5 cm depth) and subsoil (40 cm depth) by radiocarbon dating. Measurements were done with the organic fraction that remained after sieving air-dried soil to < 180 μm, to remove any roots or macrofossils, and acid washing with hot hydrochloric acid to remove carbonates (Soreide et al., 2006). Soil carbon dating was done at Beta Analytic Limited (London, UK) using accelerator mass spectrometry (AMS) to determine the $^{14}C$ content, and thus the apparent age, of bulk soil (Rethemeyer et al., 2004).

### 2.4. In situ soil gas concentrations, moisture and temperature

Three stainless steel needles (inner diameter, 1 mm; outer diameter, 1.5 mm) were installed to depths of 5, 10, 20 and 30 cm depths in each of four replicate blocks (ca. 1.5 m apart) at both the shoulderslope and footslope positions (i.e., a total of 96 needles). The blocks were interspaced between the five soil sampling points at the contour transects. Every second week from 14 June 2011 to 16 June 2012 ($n = 27$), gas samples were collected from each soil depth using syringes connected to the needles that had dual 0.7-mm diameter side port openings at 1 cm distance from the tip (Petersen et al., 2011). Each needle had an upper part of ca. 1.5 cm extending from the ground and was connected to a syringe that was kept closed during periods between the sampling campaigns. Gas samples were also collected from 40, 50 and 80 cm depths using three custom-made stainless steel tubes that were placed in each block, ca. 30 cm from the needles (i.e., one rod per depth and block). The steel tubes (outer diameter, 10 mm) were installed at a 45-degree angle and were equipped with tips that had chambers (~1-$cm^3$ volume) that were slatted with two 1-mm holes (10 mm from the tip) connected to aboveground sampling ports through 1 mm (inner diameter) spaghetti PVC tubings (Chirinda et al.,