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Implication of erosion on the assessment of decomposition and humification of soil organic carbon after land use change in tropical agricultural systems

V. Häring [a,*], H. Fischer [a], G. Cadisch [b], K. Stahr [a]

[a] Institute of Soil Science and Land Evaluation, University of Hohenheim, Emil-Wolff-Str. 27, 70593 Stuttgart, Germany
[b] Institute of Plant Production and Agroecology in the Tropics and Subtropics, University of Hohenheim, Garbenstr. 13, 70593 Stuttgart, Germany

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ABSTRACT

Soil organic carbon decline after land use change from forest to maize usually leads to soil degradation and elevated CO_2 emissions. However, limited knowledge is available on the interactions between rates of SOC change and soil erosion and how SOC dynamics vary with soil depth and clay contents. The ^{13}C isotope based CIDE approach (Carbon Input, Decomposition and Erosion) was developed to determine SOC dynamics on erosion prone slopes. The aims of the present study were: (1) to test the applicability of the CIDE approach to determine rates of decomposition and SOC input under particular considerations of concurrent erosion events on three soil types (Alisol, Luvisol, Vertisol), (2) to adapt the CIDE approach to deeper soil layers (10–20 and 20–30 cm) and (3) to determine the variation of decomposition and SOC input with soil depth and soil texture. SOC dynamics were determined for bulk soil and physically separated SOC fractions along three chronosequences after land use change from forest to maize (up to 21 years). Consideration of the effects of soil erosion on SOC dynamics by the CIDE approach yielded a higher total SOC loss (6–32%), a lower decomposition (13–40%) and a lower SOC input (14–31%) relative to the values derived from a commonly applied ^{13}C isotope based mass balance approach. Comparison of decomposition between depth layers revealed that tillage accelerated decomposition in the plough layer (0–10 cm), accounting for 3–34% of total decomposition. With increasing clay contents SOC input and mass of sand sized stable aggregates increased. In addition, decomposition increased with increasing clay contents, too, being attributed to decomposition of labile SOC which was attached to clay particles in the sand sized stable aggregate fraction. In conclusion, this study suggests that *in situ* SOC dynamics on erosion prone slopes are commonly misrepresented by erosion unadjusted approaches leading to an overestimation of SOC input and underestimation of SOC loss.

1. Introduction

Soil degradation and climate change are two global challenges, which are directly linked to each other by soil organic carbon (SOC) dynamics, vegetation productivity and land use change. On a global scale, soils contain about twice the amount of C in the atmosphere and three times of the amount in vegetation (IPCC et al., 2000). Land use change from forest to annual crops mostly results in net CO_2 emissions from soils which are caused by accelerated decomposition of SOC and reduced organic inputs and account for 20–40% of initial SOC stocks (Murty et al., 2002). Thus, soils are a large but labile sink for CO_2 (Smith, 2008). In addition to decomposition, soil erosion is a second major SOC loss pathway on steep slopes, with eroded C being deposited downslope or entering waterways. Regarding the global carbon cycle it remains subject to discussion if soil erosion leads to a net C sink via SOC deposition (Van Oost et al., 2012) or if erosion promotes decomposition (Polyakov and Lal, 2008). Both SOC loss pathways lead to soil degradation on site by deteriorating soil fertility parameters such as cation exchange capacity, field capacity and aggregate stability (Lal, 2001).

Chronosequences (Jolivet et al., 2003; Lemenih et al., 2005; Gottschalk et al., 2010) or paired site studies (Solomon et al., 2002) are widely used methods to determine SOC dynamics. For land use changes involving a change in the photosynthetic pathway, such as the change from forest (mostly C3 plants) to maize (C4 plant) in the present study, the stable carbon isotopic composition ($^{13}C/^{12}C$) of the SOC can be used to differentiate between forest derived and maize derived SOC (Balesdent et al., 1987; Cadisch et al., 1996). A ^{13}C isotope

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[*] Corresponding author. Tel.: +49 711 45922125; fax: +49 711 45923117.
E-mail addresses: volker.haering@uni-hohenheim.de, volker.haering@googlemail.com (V. Häring).

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based mass balance approach is usually used to calculate SOC change as the difference between initial SOC stocks and SOC stocks derived from e.g. maize or forest after a certain time. In flat terrain SOC change is largely explained by decomposition and SOC input. However, on steep slopes, which are predominant in many mountainous areas around the world, the effects of soil erosion on SOC dynamics have to be considered. With the common ^{13}C isotope based approach two challenges lead to a misrepresentation of SOC dynamics when calculating SOC loss or SOC input as difference in SOC stocks between a non-eroded reference and an eroded cultivated site (Häring et al., 2013): (1) It is not known whether the SOC change between the two sites is caused by SOC loss and SOC input or by soil profile truncation due to soil erosion. (2) The SOC lost by erosion before sampling is not considered, because a fixed sampling depth (e.g. 0–10 cm) at an eroded site does not correspond to the same depth at a non-eroded reference site but to the fixed depth plus the eroded soil depth. Therefore, alternative approaches are needed, such as the CIDE (Carbon Input, Decomposition and soil Erosion) approach recently developed by Häring et al., (2013). In contrast to the usual isotope based mass balance equation, the CIDE approach considers (1) SOC contained in the topsoil which was removed before sampling the present topsoil and (2) erosion induced exposition of the subsoil with different contents of SOC, δ^{13}C values or other parameters compared to the topsoil. Worldwide, only a few studies exist where the combined effect of SOC loss by soil erosion, decomposition and SOC input was determined. For example, Gottschalk et al. (2010) determined SOC dynamics considering SOC loss by soil erosion, but they did not consider the truncation of the soil profile by soil erosion. On gently sloped fields (6%) Diels et al. (2004) found that SOC loss by soil erosion was negligible compared to decomposition. More recently, Sanderman and Chappell (2012) highlighted the misrepresentation of SOC dynamics on erosion prone slopes. They provided an approach to characterize SOC dynamics on erosion prone slopes, but they did not use δ^{13}C as input parameter and so the calculated SOC loss is a net value and decomposition and SOC input can only be estimated. This study aims to fill this gap.

The CIDE approach was developed for the plough layer. For determination of SOC dynamics in deeper soil layers the concept of the CIDE approach needs to be extended. The effect of soil depth on decomposition is discussed controversially: Some studies argue that decomposition decreases with soil depth because the substrate quantity and quality decrease (Lomander et al., 1998), tillage does not reach that deep (Balesdent et al., 1990; Pierce et al., 1994; Conant et al., 2007) and priming effects don't occur (Kuzyakov, 2002). More recently Salomé et al. (2010) argued that decomposition depends on soil depth, when calculated as absolute amount but depends not on soil depth when calculated per unit carbon. Extension of the CIDE approach to deeper soil layers allows quantifying whether or not soil depth affects decomposition and SOC input in the research area.

Among the processes affecting decomposition, tillage is the only one which is restricted to the plough layer (0–10 cm in the present research area). Thus, comparison of the relative decomposition in the plough layer with that in the two underlying no-till layers (10–20 and 20–30 cm) over time has the potential to estimate tillage induced decomposition in the plough layer. Whereas most other studies determined the tillage impact on decomposition by comparison of spatially separated tilled with no-till fields (Balesdent et al., 1990; Pierce et al., 1994; Conant et al., 2007), the present study tested whether differences of relative decomposition between soil layers can be used to determine tillage induced decomposition.

Further, clay content is a major controlling factor of the stability of SOC by the formation of organo-mineral complexes and physical protection of SOC in the interior of aggregates (Parton et al., 1987; Six et al., 2002). It was hypothesized that bulk soil decomposition rates decrease and bulk soil humification rates increase with increasing clay contents (Zech et al., 1997; Six et al., 2002). Bulk SOC can be regarded as a continuum of SOC pools, which contribute to total decomposition and humification with varying rates. Physical fractionation based on particle size and density is a useful technique to highlight the effect of texture on decomposition and humification rates in SOC pools (von Lützow et al., 2007). It was hypothesized that with decreasing particle size rates of humification and decomposition within the pools decrease and mass of the pools increase (Christensen, 2001; Jolivet et al., 2003).

Thus, the aims of the present study were: (1) to test the applicability of the CIDE approach to determine the rates of decomposition of forest derived SOC and net input of maize derived SOC under particular considerations of concurrent erosion events, (2) to adapt the CIDE approach to deeper soil layers (10–20 and 20–30 cm), and (3) to determine the variation of decomposition and SOC input with soil depth and clay contents. SOC dynamics were determined for bulk soil and physically separated SOC fractions along three chronosequences (up to 21 years) after land use change from forest to maize.

2. Materials and methods

2.1. Study area and site characteristics

The study area was located in the Yen Chau district in NW Vietnam (Fig. 1). Chronosequence sites were selected on three soil types which varied in clay contents (material between 0 and 2 μm in percent of the fine earth fraction at 0–10 cm depth): Cutanic Alisol (Chromic) (57.4–67.9% clay), Cutanic Luvisol (52.6–58.3% clay) and Haplic Vertisol (Chromic) (39.3–54.8% clay; unpublished data; WRB, 2007). The altitude of the sites on the adjacent Luvisol and Alisol was between 920 and 1040 m asl. All sites had a straight profile and horizontal curvature. Inclination ranged from 40 to 66%. The Vertisol sites were between 510 and 540 m asl. Climate was monsoonal showing a rainy season from April to September and dry season from October to March. Annual rainfall was 1259 mm (years 2000–2006, Yen Chau climate station). Average annual temperature varied due to the altitudinal differences between 24.0 °C on Vertisol sites and 20.1 °C (years 2010–2011, Ban Dan climate station) on Luvisol and Alisol sites. Natural vegetation was tropical monsoonal primary forest. Beginning in 1989, forest was removed progressively for subsequent continuous cultivation of maize as monocrop. Land use history was reconstructed by interviews with farmers. In some fields, farmers deforested primary forest not at once but stepwise a few meters every year in uphill direction (Fig. 1). The borders of the deforested areas of each year were reconstructed together with the farmers in their fields. Fields were tilled by buffalo after the first rainfalls in April. After that, maize was sown and fertilizer was applied. Harvest took place in September or October. Harvest residues and weed were burnt during each dry season. During the time from burning until the maize plants developed the first leaves, soils were bare and prone to severe soil erosion.

2.2. Sampling and analysis

Each chronosequence comprised one reference site under primary forest and several cultivated sites (7 on Alisol, 8 on Luvisol and 4 on Vertisol), which were deforested up to 21 years before sampling (Table 1, Fig. 1). SOC contents and stable carbon isotopes were analyzed for five field replicates at 0–10, 10–20 and 20–30 cm soil depth from each site, taken parallel to the contour at 2 m intervals. Bulk density was determined for each site and depth increment by taking three undisturbed soil samples in 200 cm^3 steel cylinders. SOC content and carbon isotopic composition of