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Soil formation and its implications for stabilization of soil organic matter in the riparian zone

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ABSTRACT

Riparian woodlands consist of different landscape units characterized by different hydroecomorphological site conditions that are reflected in the distribution of soils and tree species. These conditions are determined by flooding frequency and duration, distance to river channels, elevation and water flow velocity. The influence of these environmental drivers on the stabilization of soil organic matter (SOM) has as yet not been investigated. Hence, the aim of our study is to link soil formation and its drivers with stabilizing processes of SOM in riparian floodplain forests. We investigated soils and sediments at two sites in the ash–maple–elm–oak alluvial forest zone (AMEO sites) and two sites in the willow-poplar alluvial forest zone (WiP sites) within the riparian zone of the Danube near Vienna (Austria). Sediments and soils were characterized based on texture, contents of organic carbon (OC), nitrogen, Fe oxides, and soil pH. Density fractionation was used to separate OC fractions in terms of stabilization process and resulting organic matter (OM) turnover time: the free light fraction (fast turnover), the light fraction occluded in aggregates (intermediate turnover) and the heavy fraction of OM associated tightly to mineral surfaces (slow turnover).

At both sites, soil and sediment properties reflect the hydroecomorphological site conditions for formation of the landscape units in the riparian zone: Soils at AMEO sites develop during constant deposition of fine-textured sediment while water flow velocity is low. Progressing soil development causes a continuous decrease in OC content with increasing soil depth, mainly from fractions with fast and intermediate turnover. As a consequence the heavy fraction clearly dominates with around 90% of OC. Temporally variable flooding conditions with occurring turbulences found at WiP sites result in a discontinuous change of soil properties with increasing soil depth. Former topsoil horizons buried by huge amounts of sediments seem to keep the OC fractionation typical for topsoil horizons with extraordinarily high amounts of light fraction OM (free and occluded) representing 20–40% of total OC. The presented results confirm that sedimentation and soil formation are simultaneous processes at AMEO sites. At WiP sites both processes seem uncoupled with alternate phases of sedimentation and soil formation. Thus, the frequent burial of topsoil material formed at WiP sites seems to enable the conservation of unstable organic matter fractions at this part of active floodplains.

1. Introduction

Soil formation in the riparian zone is determined by the delivery and erosion of sediments as well as alternating redox conditions in periodically inundated soils (Naiman and Décamps, 1997; Bai et al., 2005; Rinklebe et al., 2007). It is widely acknowledged that mineral floodplain soils contain huge stocks of organic carbon (OC) (Batjes, 1996; Zehetner et al., 2009; Cierjacks et al., 2010; Ricker et al., 2013) for two reasons (Rinklebe et al., 2001): (1) sediment entering the floodplain may contain significant amounts of allochthonous organic matter (OM) from terrestrial and riverine sources (Pinay et al., 1992; Cabezas and Comín, 2010), and (2) floodplain ecosystems are often characterized by high net primary production (Tockner and Stanford, 2002), which provides the soil with large amounts of autochthonous OM. The resulting amount of OC stocks underline the significance of floodplain soils in the regional and global carbon cycle, and the need to understand the dynamics of soil organic matter (SOM) in these ecosystems (Mitra et al., 2005; Rieger et al., 2014).

Accretion and stocks of OC seem to respond to different drivers in riparian forests as input of OC is related to sediment quantity whereas long-term OC stocks rely on stabilization processes (Rieger et al., 2014). Consequently, the OM dynamics in floodplain soils are not only a matter of the input of OM but also stabilization of SOM against mineralization (Bernoux et al., 2006; Bernal and Mitsch, 2008). However, few

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publications (e.g. Zehetner et al., 2009) consider stabilization processes of SOM in riparian ecosystems. Quantification of processes of *SOM stabilization* in different landscape units formed by differences in *hydroecomorphological drivers* of soil formation are yet not existent.

1.1. Hydroecomorphological drivers

According to Naiman and Décamps (1997) riparian zones are the most diverse and dynamic biophysical habitats on earth. A complex interplay of flooding, geomorphology and vegetation leads to various landscape units with specific characteristics in the riparian zone (Harris, 1987; Clerici et al., 2011; Gurnel, 2014). Following a conceptual model introduced by Piégay and Schumm (2003) the river hydrosystem can be divided into three main spatial gradients (lateral, vertical and longitudinal). In this model, the main drivers for differences along the gradients are water flow velocity, sediment load and inundation time and frequency (Bendix and Hupp, 2000; Busse and Gunkel, 2001; Busse and Gunkel, 2002; Bornette et al., 2008, Du Laing et al., 2009). Along these gradients, sediment changes with regard to quality and yield (Asselman and Middelkoop, 1995; He and Walling, 1998; Lindbo and Richardson, 2001). Areas close to the main river channel and low altitude above sea and mean water level receive high amounts of coarse sediments due to increased water flow velocity during flooding. This implies the formation of sandy soils with a high number of distinguishable soil horizons caused by different sedimentation events (Cierjacks et al., 2011). High frequency of flooding (Rinklebe et al., 2007) may further induce the formation of redoximorphic features in these soils. In areas with higher elevation distant to the main river channel, decreased water flow velocity during flooding results in the sedimentation of fine material and in the formation of loamy soils.

Furthermore, tree species composition of alluvial forests show pronounced differences among these landscape units, which are results of diverging demands of tree species on sediment and soil quality and plant-specific sensitivity against inundation (Rieger et al., 2013). Hence, tree species distribution may be used as an indicator to identify different landscape units (Wisskirchen, 1995; Cierjacks et al., 2010; Suchenwirth et al., 2012): tree species with high tolerance against inundation and wood with a low specific density and high flexibility such as *Salix* spp. and *Populus* spp. form the willow-poplar zone (WiP zone) that prevails along the main river channel and side branches at low-lying sites. In contrast, species that are more sensitive against inundation and have a higher wood density (*Acer* spp., *Fraxinus excelsior*, *Ulmus* spp., *Quercus robur*) grow more distant to the main channel or side branches at high-lying sites and form the ash–maple–elm–oak zone (AMEO zone).

These differences in sources and quality of autochthonous OM, soil forming factors and sediment or soil properties along the lateral and vertical gradient are known to influence OM dynamics in riparian forests (Rinklebe et al., 2001; Cierjacks et al., 2011; Rieger et al., 2013, 2014). However, it remains an open question how such differences are also related to stabilization processes of SOM.

1.2. Stabilization of SOM

In general, stabilization of SOM is governed by three different mechanisms: chemical stabilization by adsorption of SOM to mineral surfaces, spatial inaccessibility of SOM against mineralizing microorganisms by occlusion into soil aggregates, encapsulation within a macromolecule matrix or hydrophobic environments and preservation due to chemical recalcitrance of SOM or its compounds (Christensen, 1996; Sollins et al., 1996; Knicker and Hatcher, 1997; von Lützow et al., 2006 ; Jastrow et al., 2007). Recent findings indicate that stabilization of SOM is a result of physicochemical and biological conditions in the surrounding (micro and macro) environment which reduce the probability of SOM decomposition (Schmidt et al., 2011). In particular, the pivotal role of soil structure and aggregation for SOM stabilization is underlined through previous results on the relevance of physical SOM stabilization due to spatial inaccessibility (Sollins et al., 1996). There is also scientific evidence that similar processes may be found in young soils in the riparian zone (Guenat et al., 1999; Bullinger-Weber et al., 2007).

Several pools of SOM with different levels of resistance against mineralization can be determined using various fractionation approaches based upon physical or chemical properties of SOM (von Lützow et al., 2007). One of these approaches is density fractionation of SOM, which is suitable to differentiate particulate OM (POM) with low density and soil constituents with higher densities such as soil minerals with OM associated to their surfaces (Golchin et al., 1994; Gregorich and Beare, 2008). The light fraction is present in soil in two states (Christensen, 1992) and can be attributed to either the fast turnover pool if it is not or only loosely attached to other soil constituents (Baisden et al., 2002; Poirier et al., 2005; John et al., 2005) or the intermediate pool with a wide range of turnover rates if it is occluded in soil aggregates (Jastrow et al., 2007; von Lützow et al., 2007). The OM stabilized on mineral surfaces contributes mainly to the slow turnover pool of SOM.

1.3. Aims and hypotheses

Mechanistic links between the formation of soils in different landscape units within riparian floodplains and the development of the different pools of organic matter are hardly considered. Thus, the overall aim of our study is to quantify processes of SOM stabilization in different landscape units in the context of environmental drivers of soil formation in the riparian zone of the Danube. Yet, by combining both our knowledge on floodplain soil formation and stabilization of SOM, hypotheses on the distribution of SOM in different pools in riparian zones can be deduced with aggregate formation representing one of the most important links between soil formation and SOM stabilization (Guenat et al., 1999; Bullinger-Weber et al., 2007). In particular, we assessed the following hypotheses: (1) Sediment delivered to the floodplain consists of unstructured parent material and flocs of particles that are formed in-situ during the transport in the river (Nicholas and Walling, 1996; Droppo, 2001). Soil-borne aggregates derived from eroded topsoil undergo disaggregation during transport in the river (Woodward and Walling, 2007; Grangeon et al., 2014). As a result of this separation of formerly occluded POM, OM in sediments is mainly present as free POM and OM associated to mineral surfaces. (2) Soil structure formation is among the most relevant soil forming processes in floodplains (Guenat et al., 1999; Bullinger-Weber et al., 2007). Accordingly, an increasing amount of OM is stabilized in soil aggregates with increasing soil age (Jastrow, 1996). It is known that aggregates built of coarse material are less stable than aggregates consisting of fine material (Kaiser et al., 2012). Consequently, aggregation and OM stabilization by occlusion is of lower relevance in coarse soils at WiP sites compared to fine soils at AMEO sites. (3) Stabilization of OM on mineral surfaces most likely depends on the available surface area, which is negatively correlated with particle size. Consequently, there will be a higher amount of OM stabilized on mineral surfaces in fine soils in the AMEO forest zone compared to coarse soils in the WiP forest zone. (4) The continuous delivery of sediments implies that subsoil material has undergone longer time of soil development compared to topsoil material at the same site (Lair et al., 2009a). The activity of meso- and macro-fauna is decreased in subsoil compared with material in topsoil (Fontaine et al., 2007). In combination with a lack of delivery of fresh POM to subsoil, we hypothesize that the amount of OM in free or occluded states decreases with increasing soil depth. The content of OM associated to mineral surfaces is only slightly affected by progressing soil development and does not decrease with increasing soil depth because of the long turnover time of OC in this fraction.

Our study is based on the characterization of soils at four riparian sites with natural inundation regimes in two main alluvial forest types distinguished by indicator tree species: two sites at low elevation close to the main river channel (WiP sites), and another two sites