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The interplay of sedimentation and carbon accretion in riparian forests

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ABSTRACT

Sediment trapping and organic carbon (OC) accretion in soil are crucial ecosystem services of floodplain forests. However, interactions between the two processes have scarcely been analyzed at the ecosystem level. This study aimed at quantifying OC accretion parameters (CAP, including sedimentation rate, OC concentration, OC accretion) over roughly the last 50 years on both sides of a dike in a Danubian floodplain forest in Austria. Additionally, we determined soil OC stocks (0–100 cm in depth) and modeled both CAP and OC stocks in relation to environmental parameters. Overall, mean sedimentation rate and OC accretion of the riparian forest were 0.8 cm y^{-1} and 3.3 t OC ha^{-1} y^{-1} and significantly higher in flooded riparian forest (FRF; 1.0 cm y^{-1} and 4.1 t OC ha^{-1} y^{-1}) than in diked riparian forest (DRF; 0.3 cm y^{-1} and 1.5 t OC ha^{-1} y^{-1}). In contrast, mean OC concentration (0.05 t OC m^{-3}) and OC stocks (238 t OC ha^{-1}) were significantly higher in the DRF than in FRF (0.05 vs. 0.04 t OC m^{-3} and 286 vs. 201 t OC ha^{-1}). Modeling revealed tree species, fluctuation of groundwater table, and the distance to the river as valuable indicators for OC accretion rate. The OC concentration and distance to the river were positively and sedimentation negatively correlated with OC stock. The dike was consistently ruled out as a significant predictor variable. Consequently, differences among FRF and DRF seem to be related rather to longer term processes during the last centuries than directly to the dike. Our findings highlight the relevance of sediment quality (i.e., OC concentration) for building up long-term soil OC stocks, whereas sediment quantity is the main driver of recent OC accretion rates.

1. Introduction

Wetlands fulfill various ecosystem services (Mitra et al., 2005) of which sediment trapping and organic carbon (OC) sequestration have been repeatedly highlighted (Phillips, 1989; Cavalcanti and Lockaby, 2005; Samaritani et al., 2011). Although wetlands cover only about 5–8% of the Earth's land area (Mitsch et al., 2012), they account for 20–30% of the total C stored in the Earth's upper surface layer (Bridgham et al., 2006; Mitsch et al., 2012). In contrast to an array of northern peatlands (Gorham, 1991; Turunen et al., 2002; Bridgham et al., 2008) and tropical coastal wetlands (Chmura et al., 2003; Suratman, 2008; Howe et al., 2009; Mitsch et al., 2012), OC dynamics of periodically flooded temperate riparian forests are understudied (but see Cierjacks et al., 2010, 2011; Mitsch et al., 2012). Soils and aboveground biomass comprise together more than 90% of the overall OC stocks in temperate forests, while other OC pools such as fine roots and woody debris are less relevant (Cierjacks et al., 2010; Rieger et al., 2013). In soil, sedimentation of organic matter and on-site OC input from highly productive riparian forests are expected to be the main drivers of OC accretion. However, the dynamic processes of sedimentation and their links to the riparian OC cycle are not well understood.

In many river systems, dike constructions and other human interventions have substantially changed the flow regime — and presumably sedimentation processes and carbon storage capacity (Phillips, 2003; Reid and Dunne, 2003; Howe et al., 2009). This may explain why sedimentation regimes have mostly been studied in small rivers where water discharges average 11.7 up to 250 m^3 s^{-1} (Asselman and Middelkoop, 1995; Heimann and Roell, 2000; Cabezas and Comín, 2010) or watersheds smaller than 4000 km^2 (Walling and He, 1998; Craft and Casey, 2000; Noe and Hupp, 2005, 2009; Samaritani et al., 2011), where natural sedimentation processes are likely to persist. In contrast, sedimentation rates and related OC accretion have been considered less frequently in major floodplains, such as for the Rhine and Meuse (Asselman and Middelkoop, 1995), Garonne (Steiger and Gurnell, 2002), and the Ebro rivers (Cabezas and Comín, 2010). Many existing studies provide a quantification of sedimentation (e.g., Asselman and Middelkoop, 1995; Heimann and Roell, 2000; Hupp and

Abbreviations: BRT, boosted regression trees; DRF, diked riparian forest; FRF, flooded riparian forest; OC, organic carbon; TRF, total riparian forest.

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Bornette, 2003; Noe and Hupp, 2009) or OC concentrations (Asselman and Middelkoop, 1995; Steiger and Gurnell, 2002; Hupp et al., 2008; Samaritani et al., 2011) but focused on isolated aspects such as spatial gradients (i.e., Pizzuto, 1987; Walling and He, 1997, 1998; Petts et al., 2000; Hupp et al., 2008), the trophic state of a river (McTammany et al., 2003), or the particle size distribution of sediments (Walling and He, 1998; Petts et al., 2000; Steiger and Gurnell, 2002). Important ecosystem services such as carbon sequestration in soil have not been taken into account comprehensively. Furthermore, the results of these studies are based on single flooding events that preclude general conclusions on the long-term sedimentation regime. The mechanisms of sedimentation and OC accretion at the ecosystem level in riparian forests have not been disentangled thus far. To overcome these limitations, we aimed to quantify and model each aspect of recent OC accretion. Moreover, OC stock in the upper soil (0–1 m) was analyzed to test if recent OC accretion translates to long-term carbon storage in soil. Organic carbon accretion is a function of sediment increment per year (sedimentation rate) and the OC concentration of the deposited allochthonous and/or autochthonous material along with soil development (Zehetner et al., 2009). We therefore refer henceforth to these three parameters, i.e., carbon accretion, sedimentation rate, and OC concentration, as carbon accretion parameters (CAP).

We determined CAP by applying dendrogeomorphical methods (Hupp and Bazemore, 1993; Hupp and Bornette, 2003) in a riparian forest of a large European river in the Donau-Auen National Park, Austria. Dendrogeomorphical methods link tree age from increment cores to the depth of burial of the stem base since the germination of the studied tree. This approach ensures that sedimentation processes can be assessed over longer periods of time (i.e., tree age) as opposed to short-term measurements using artificial grass mats, (fire) clay and feldspar pads, or markers (e.g., Asselman and Middelkoop, 1995; Steiger and Gurnell, 2002; Noe and Hupp, 2005, 2009; Olde Venterink et al., 2006; Hupp et al., 2008). An additional survey of long-term, presumably stabilized, OC stocks (0–100 cm) allows us to consider the potential link between CAP and OC stocks at the ecosystem level.

In particular, we aimed (i) to quantify mean CAP since germination of the tree and OC stock of the top meter of soil in total riparian forest (TRF), and in the same area divided into flooded (FRF) and diked riparian forest (DRF); (ii) to analyze which environmental parameters (spatial gradients, hydrology, forest stand structure, sedimentation, and dike presence) influence CAP and soil OC stock, and (iii) to assess if OC accretion during approximately the last 50 years translates to long-term OC stocks in the top meter of soil in the study area.

2. Methods and materials

2.1. Study area

The study area is adjacent to the Danube River which at 2875 km is the second largest in Europe (BMU, 2003) and part of one of the largest near-natural riparian systems remaining in central Europe, the Donau-Auen National Park in Austria (Fig. 1). About 65% (6045 ha) of the total park area is covered by forests with the remainder in open grasslands and waterways. The Danube River water level fluctuates within a range of up to 7 m as a response to meltwater and precipitation in the upstream watershed (Drescher and Fraissl, 2006). River embankments have been fixed using riprap, and since the end of the nineteenth century, the Marchfeld dike has divided the area into a section where surface flooding occurs ca. every 5 years (C. Baumgartner, Donau-Auen National Park, Austria, personal communication, 2012) and a section that is protected from flooding by the dike. Data were collected from both river banks of the section between the villages of Schönau (48°8′ N., 16°36′ E., river kilometer 1910) and near Hainburg (48°1′ N., 16°88′ E., river kilometer 1889), including areas of both flooded and diked floodplain forests (Fig. 1). Soils are fluvisols (calcaric, eutric) and gleysols (haplic, calcaric) (Sali-Bazze, 1981; Cierjacks et al., 2010). The nearest climate station (Schwechat, 48°7′ N., 16°34′ E.; 184 m asl) reports an annual mean temperature of 9.8 °C and a mean annual precipitation of 533 mm (1948–2008; Zentralanstalt für Meteorologie und Geodynamik, 2002). The area is part of the upper reaches with a fast flow regime (rhithral character) and was classified as the furcation type and order 9 (Wimmer and Moog, 1994). The main channel is ca. 350 m wide, has a mean annual discharge of 1950 $m^3\ s^{-1}$, and a slope of 0.045%. The velocity of the surface water ranges from 1.9 to 2.2 $m\ s^{-1}$ (Tockner et al., 1998).

2.2. Study design

To cover a wide range of environmental gradients in space and time, the study area was stratified into three lateral zones (flooded riparian

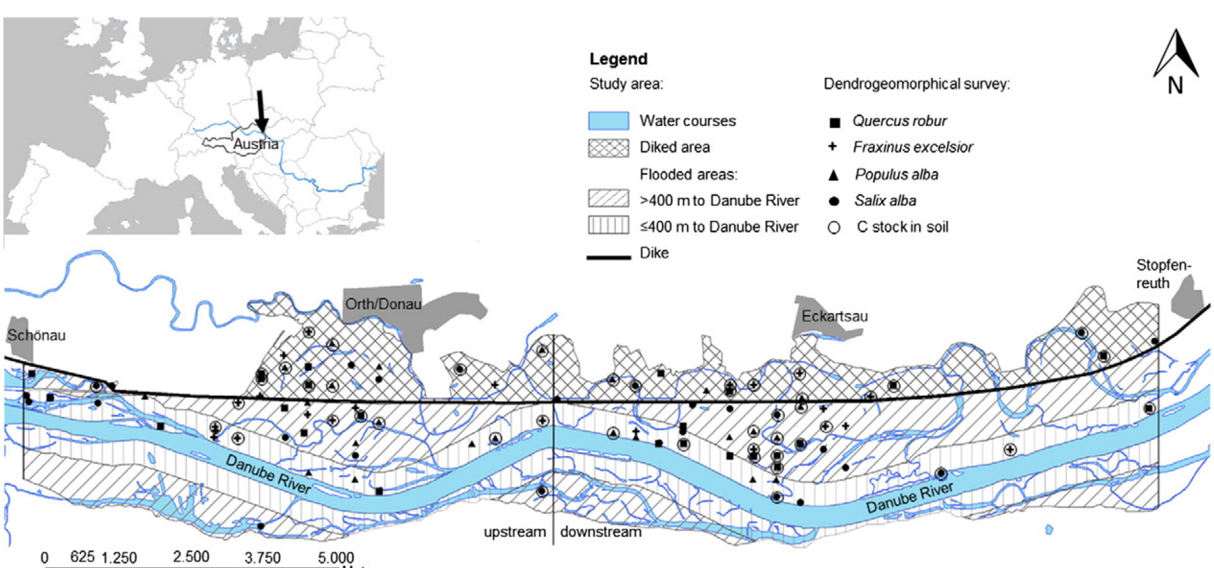

Fig. 1. Study area within the Donau-Auen National Park and study design (tree symbols refer to individually sampled trees).