Carbon storage and soil organic matter stabilisation in near-natural, restored and embanked Swiss floodplains ☆

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ABSTRACT

Over recent decades, the number of floodplain restoration projects has increased worldwide. In Switzerland, several projects have been implemented to maintain or recreate ecological functions of floodplains. Despite this, little is known about the potential of floodplain soils to release and/or accumulate carbon. In alluvial soils, carbon storage is strongly influenced by fluvial dynamics, and therefore a better understanding of carbon fluxes and stocks in such settings is clearly needed.

To evaluate the impact of river restoration on carbon storage in alluvial soils, we aimed to quantify and explain carbon storage and soil organic matter (SOM) stabilisation in the uppermost soil humic layer. Three floodplains were investigated showing each of them different levels of human disturbance: a near-natural section along the Rhine River, and both restored and embanked sections along the Thur River and Emme River. Carbon storage was determined by total organic carbon (TOC) stocks. SOM stabilisation was evaluated by considering the TOC content in different granulometric fractions (1000–2000 μm, 500–1000 μm, and 250–500 μm) and the macro-aggregate formation, i.e. the abundance of water-stable aggregates (WSA) and the mean weight diameter of macro-aggregates (MWD).

Our results show that the carbon storage and SOM stabilisation parameters were all related to soil properties such as clay, silt and total iron contents of the upper humic layer. Within each floodplain, carbon storage and SOM stabilisation parameters differed according to soil profile groups, thus reflecting a soil gradient evolution from bare alluvium soils to more stabilised soils and a hydric functioning (soils with hydromorphic features). In addition, river restoration showed various impacts on carbon storage and SOM stabilisation parameters depending on the floodplains, with a significant difference between embanked and restored sections for the Emme floodplain and no difference for the Thur floodplain.

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1. Introduction

Wetlands play an important role in the global carbon cycle (Mitra et al., 2005), but their carbon source and sink functions are complex. While most studies on carbon budget have focused on peatlands, non-peat wetlands, such as near-natural riverine floodplains and restored riverine floodplains, have scarcely been considered (Cierjacks et al., 2011). Compared to other wetland soils, alluvial soils are much more variable in space and time, resulting from a succession of sedimentation/erosion processes combined with an *in situ* soil formation between flood events

(Gerrard, 1987), thus leading to a gradient of soil evolution from bare soils to well-developed soils under forests.

Focusing on humic layers, i.e. soil layers containing high proportions of soil organic matter (SOM), sedimentation/erosion events lead to i) the inheritance of organic matter brought by sedimentation (Bechtold and Naiman, 2009), and/or ii) the erosion of humic layers (Hoffmann et al., 2009), and/or iii) the burying of humic layers under new sediments (Blazejewski et al., 2009; Cierjacks et al., 2010). SOM accumulation also depends on *in situ* soil pedogenesis between floods, as well as the elevation from the riverbed, especially along a primary forest succession from pioneer tree species to old-growth uneven-aged forest (Van Cleve et al., 1993). Similarly, Zehetner et al. (2009) showed that SOM accumulation depends on soil age, with the highest rates to be found within 50 to 100 years of soil formation. Focusing more specifically on soil organic carbon, the major component of soil organic matter, its storage in alluvial soils may vary as a function of several variables. For instance, the frequency of flooding (Bernal and Mitsch, 2008) and the concomitant deposition of carbon-rich sediments usually lead to an increase in soil organic

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carbon stocks (Cierjacks et al., 2011; Wohl et al., 2012), either in the humic layer or in the underlying organic matter layers enriched within the profile (Blazejewski et al., 2009; Cierjacks et al., 2010) thus preserving autochthonous organic material (Zehetner et al., 2009). Moreover, vegetation directly influences soil carbon accumulation and consequently soil development by aboveground and belowground inputs (Giese et al., 2000) leading to high spatial heterogeneity in terms of vertical and horizontal SOM distribution (Blazejewski et al., 2009; Drouin et al., 2011). Soil properties, such as profile development, texture, moisture and water table also greatly affect carbon storage (Mitra et al., 2005; Steiger et al., 2001). Carbon content is hence significantly and positively correlated with the clay content in alluvial deposits (Bai et al., 2005; Cabezas and Comin, 2010). For a given hydrological regime, a causal relationship may exist between organic carbon concentrations and average soil moisture (Barton et al., 2000). Organic carbon dynamics in alluvial soils may also be modified by human disturbance mainly due to changes of natural flood dynamics (river diversion, dam; Tockner and Stanford, 2002) and/ or changes in vegetation composition (tree cutting, plantation, exotic plant invasion; Gerber et al., 2007). River restoration also causes soil disturbances such as the removal of organic-rich topsoil or the use of heavy machinery (Bruland and Richardson, 2005; Unghire et al., 2011).

Another aspect of SOM poorly understood is its stabilisation in soils which consists of several mechanisms, namely 1) physical protection, 2) physicochemical stabilisation, by binding SOM and mineral particles (i.e. clay and silt) leading to occlusion of organic matter into micro- and macro-aggregates, and 3) biochemical stabilisation (Six et al., 2002). Largely studied in agricultural soils, the formation of macro-aggregates (larger than 250 μm) is usually considered as the aggregation product of micro-aggregates (>53–250 μm), silt–clay sized aggregates and particular organic matter. Depending on aggregate size, von Lützow et al. (2007) suggested that the time-scale of SOM stabilisation varies from 1–10 years for macro-aggregates larger than 250 μm to 10–100 years for micro-aggregates (20–250 μm). Focusing on alluvial soils, SOM stabilisation has been usually evaluated by the distribution of organic carbon content in particle-size fractions, the latter being assumed to have a different role in SOM turnover and then in assessing the state of floodplain restoration (Wigginton et al., 2000). These authors ensured that it may be sufficient to analyse SOM content in conjunction with aggregate size distributions to monitor the long-term trajectory of restoration efforts. In addition, the macro-aggregate characteristics, i.e. the water stable aggregate abundance (WSA) and the mean weight diameter of macro-aggregates (MWD) are also widely used to evaluate SOM stabilisation in alluvial soils (Bullinger-Weber et al., 2007; Guenat et al., 1999; Onweremadu et al., 2010).

In a context of floodplain restoration, little is still known about the impact of river restoration on soil properties, and especially on carbon storage and SOM stabilisation despite a considerable increase in the number of floodplain restoration projects during the last decade (Palmer and Bernhardt, 2006; Palmer et al., 2005). Only some research has highlighted the necessity to include carbon storage in the framework of river restoration (Ballantine and Schneider, 2009; Cabezas and Comin, 2010; Cierjacks et al., 2010).

As a consequence, the aim of our research was to quantify and explain carbon storage and soil organic matter stabilisation in the uppermost humic layer in terms of soil properties, soil profile groups (related to soil morphology), and three levels of human influence (near-natural, restored and embanked). Three floodplains were investigated: the Rhine floodplain is considered as a near-natural one, while the Thur and the Emme floodplains are both composed of one restored section and one embanked one. We hypothesized that: 1. Carbon stocks and SOM stabilisation parameters are related to soil properties, especially soil texture; 2. Carbon stocks and SOM stabilisation parameters differ among profile groups (defined by morphological criteria) within each floodplain; 3. Carbon stocks and SOM stabilisation parameters vary between embanked and restored sections within the Emme and Thur floodplains.

2. Material and methods

2.1. Floodplain descriptions

We investigated three Swiss floodplain areas differing in the levels of human disturbance. Their main characteristics are given in Table 1. The Rhine floodplain (Canton of Graubünden — GR) located along the Rhine River is a site of Swiss national importance and is considered as a near-natural floodplain due to its vegetation composition (Gallandat et al., 1993) and the absence of embankments in the surroundings.

The floodplain along the Emme River (canton of Bern — BE) is the first restoration project by river widening conducted in Switzerland. This floodplain had been embanked until 1991, after which a section was widened in 1991/92 and 1998/99. The restoration consisted of the mechanical removal of the embankments along a 530 m long section and the river was widened by 30 m. Two sections were studied, a restored section and an adjacent embanked section.

The floodplain along the Thur River (canton of Thurgau — TG) is currently the biggest widening river restoration project in Switzerland. Restoration of the site was conducted in two steps: first, following a major flood in 1995, the embankments were partly destroyed thus allowing river bank erosion. Secondly, in 2002, the river bed was widened by the mechanical removal of the embankments along a 1.5 km section from 50 to 110 m in width, and the banks were stabilised by plantations of willow (*Salix viminalis*; Pasquale et al., 2011). For both the Emme and the Thur floodplains, we chose two sections, one restored and one embanked, this latter being located upstream in order to have the state of the floodplain prior to river widening.

2.2. Preliminary soil survey

A preliminary soil survey was performed using an auger boring in order to evaluate the variability of soil morphologies in the floodplains (Fournier et al., 2013). Along transects perpendicular to the river flow, a total of 104, 260 and 125 borings were performed in the Rhine floodplain (3 transects), the Emme floodplain (10 transects) and the Thur floodplain (6 transects). The following morphological descriptors were taken into account to describe each boring: total soil depth from top surface to gravel limit, number of layers, number of humic layers, corresponding to soil layers containing high proportions of soil organic carbon (related to a brown colour), and number of textural layers (i.e. layers that differ according to their particle-size distribution) found in the profile. Additionally, the main texture of soil layers as well as presence of hydromorphic features, coarse elements (particle size >2 mm) and roots in the uppermost humic layer were noticed. Then, based on these morphological descriptors, clustering analyses (by Ward's method) were performed in order to get a hierarchical classification of soil morphologies for each floodplain. Resulting from these hierarchical classifications, different soil clusters were then obtained in each floodplain, six for the Rhine floodplain (GR 1 to GR 6), eight for the Emme floodplain (BE 1 to BE 8) and six for the Thur floodplain (TG 1 to TG 6). Details of these different soil clusters are given in Appendix A.

2.3. Soil profile sampling

A soil profile sampling campaign (final study) was performed in spring 2010. At each floodplain, we described and sampled three representative soil profiles (from 0 to 30 cm) for each soil cluster resulting from hierarchical classification. These three soil profiles of each cluster are named "soil profile groups". In the field, the thickness of the uppermost humic layer (in cm) was measured. On the whole soil profile, total depth from top surface to pebble limit (Total Depth in cm) was measured and the presence or absence of hydromorphic features was indicated (Hydro, composed by 3 classes: 0 = no hydromorphic features, 1 = redoxic marks, 2 = reductic marks). Moreover, an alluvial index (Alluvial Index) reflecting alluvial dynamics (Bullinger-Weber and