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Discussions

Spatio-temporal heterogeneity of riparian soil morphology in a restored floodplain

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Abstract

Floodplains have been intensively altered in industrialized countries, but are now increasingly being restored and it is therefore important to assess the effect of these restoration projects on the aquatic and terrestrial components of ecosystems. Soils are a functionally crucial component of terrestrial ecosystems but are generally overlooked in floodplain restoration assessment.

We studied the spatio-temporal heterogeneity of soil morphology in a restored (riverbed widening) river reach along River Thur (Switzerland) using three criteria (soil diversity, dynamism and typicality) and their associated indicators. We hypothesized that these criteria would correctly discriminate the post-restoration changes in soil morphology within the study site, and that these changes correspond to patterns of vascular plant diversity.

Soil diversity and dynamism increased five years after the restoration, but typical soils of braided rivers were still missing. Soil typicality and dynamism correlated to vegetation changes. These results suggest a limited success of the project in agreement with evaluations carried out at the same site using other, more resource demanding methods (e.g. soil fauna, fish, ecosystem functioning).

Soil morphology provides structural and functional information on floodplain ecosystems and allows predicting broad changes in plant diversity. The spatio-temporal heterogeneity of soil morphology represents a cost-efficient ecological indicator that could easily be integrated into rapid assessment protocols of floodplain and river restoration projects.

1 Introduction

Floodplains fulfil ecological, economic and social functions such as biodiversity reservoirs, supply of natural resources, and flood regulation (Malmqvist and Rundle, 2002) and are increasingly appreciated for their aesthetic value and for recreational uses

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(Nassauer et al., 2001). However, floodplains are also one of the most threatened ecosystems worldwide (Malmqvist and Rundle, 2002; Tockner and Stanford, 2002).

In the last decades, the primary goal of floodplain management has shifted from controlling rivers to restoring their biodiversity, ecological quality and related functions and services (Malmqvist and Rundle, 2002; Tockner and Stanford, 2002). As a result, the number of river restoration projects aiming at increasing ecosystem goods and services such as protection against flood, biodiversity and drinking water is strongly increasing worldwide (Nakamura et al., 2006, 2009; Palmer and Bernhardt, 2006; Palmer et al., 2005; Wohl et al., 2005). Assessing the outcome of these projects is essential for adaptive management, evaluation of project efficiency, optimization of future programs, and gaining public acceptance (Woolsey et al., 2007). However, restoration projects often lack post-restoration monitoring using standardized evaluation methods (with well-defined criteria and indicators), which would increase their cost-efficiency (Palmer et al., 2007; Sudduth et al., 2007; Bernhardt et al., 2005, 2007). This lack of monitoring is mainly due to lack of funding beyond the practical restoration project. Rapid yet informative, cost-effective monitoring tools are extremely precious; existing methods consider hydrology, physical and biological structures, and the landscape context (Rohde et al., 2004), but only include general elements with respect to soils.

Soils play a central role in critical ecosystem processes (e.g. decomposition, water filtering), and are among the main drivers of community assembly (Gobat, 2010; Wardle, 2002). For example, soil conditions strongly determine vegetation dynamics (Caylor et al., 2005) and plant productivity and diversity (Naiman et al., 2005). In turn, the vegetation influences soil properties such as organic matter content (Quideau et al., 2001). Through their morphology, soils also provide information on ecosystem structure, and record past and present fluvial dynamics (Gerrard, 1992; Daniels, 2003; Bullinger-Weber and Gobat, 2006). This information may be especially useful when a site has been ditched, drained, and stripped of its vegetation (Cole and Kentula, 2011). Soil morphology is influenced by different factors that are related to important

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processes occurring in floodplain ecosystems such as erosion/sedimentation, flood dynamics, soil biota activity or pedogenesis.

Soils are simpler to monitor than vegetation and hydrology. In contrast to biological surveys that are dependent on species' developmental stages (e.g. vernal species, or adult stages) or population fluctuations (e.g. seasonal migration, and effects of exceptional climatic event), soil morphology can be assessed in any season and in a single field campaign. However, in order to use soils in monitoring programs it is necessary to understand how they change over time (Cole and Kentula, 2011). To date, most research on the impact of river restoration on floodplain soil have focused on processes such as organic matter accumulation and decomposition (Sifneos et al., 2010; Stein et al., 2009; Bush, 2008), litter decomposition (Ballantine and Schneider, 2009), or denitrification (Orr et al., 2007; Sutton-Grier et al., 2010). There is thus a need to integrate soil physical, chemical and biological factors and processes (Heneghan et al., 2008) and soil temporal dynamics (Ballantine and Schneider, 2009) into the planning and assessment of river restoration projects.

Here we explore the possible use of riparian soil morphology as indicators of floodplain dynamics by studying the spatio-temporal heterogeneity of soil morphology in a restored river reach along River Thur (Switzerland). Our main aim was to assess the post-restoration changes in soil morphology as well as the variations of the main aspects of soil morphology along the river lateral gradient. We considered three criteria (and associated indicators) designed to cover these main aspects: (1) soil diversity, (2) soil dynamism, and (3) soil typicality. We hypothesised that these three criteria would reflect changes in vascular plant diversity and vegetation type.

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2 Methods

2.1 Study site

The Thur River restoration is among the biggest river widening projects in Switzerland to date and includes post-restoration monitoring and evaluations of several stretches (Schneider, 2011). We selected a study site along the Thur River near "Schäffäuli". The site lies at 365 m a.s.l. Annual precipitation is about 1000 $mm\,yr^{-1}$ and the average annual temperature is 7.9 °C. Restoration of the site was conducted in two steps. Following a major flood in 1995, the bed protection structures were removed. In 2002, the riverbed was widened along a 1.5 km stretch from 50 to 110 m by embankments removal and the new bank stabilized by planting willows (*Salix viminalis*). The project aimed to improve flood protection, to maintain drinkable water resources and to enhance the ecological quality of the river.

We distinguished three well-differentiated situations within the study site based on field observations (topography and vegetation), available information on the site restoration, river maps and illustrations from the early 19th century, historical data on Swiss lowland braided rivers (Moor, 1958; Imboden, 1976; Gallandat et al., 1993; Baer, 1976; Roulier, 1998), and the literature on braided river soils (AFES, 2008; Guenat et al., 2003; IUSS Working Group, 2006). The first situation corresponds to *open habitats* with poorly developed soils closest to the river. Restoration had the highest impact on this zone. Further from the river lays an *alluvial forest* growing on deeper soils. This forest was present before restoration and restoration had only a limited impact on this area. Finally, we used an un-restored section of the same site located directly upstream from the restored one as a *control* that was not, or only marginally, impacted by the restoration. We expected the criteria and indicators of soil morphology presented below to show clear differences among these three areas, revealing how the restoration affected the functioning of this riparian zone.

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2.2 Data acquisition

Soil surveys were carried out in summer 2007 along five transects corresponding to topographical surveys over time, each starting at the main river bed and ending about 65 m further where no more floodplain soils were encountered. Three transects were selected in the restored area with a sampling point every 1.5 m in the most variable part (up to a distance of about 15 m from the river) and then every 3 m resulting in a total of 73 sampling points. Two transects were selected within the control area with a sampling point every 3 m resulting in 22 sampling points. The precise location, elevation and distance to the river of each sampling point were recorded.

Soils were surveyed by describing the morphology of profiles and horizons from auger borings (1.2 m length). Different variables were used to describe soil profiles and topsoils. Profile characterization was based on: profile depth (cm); number of sandy, loamy, clay, or humic horizons; total number of horizons, volumetric percentage of coarse elements (%); presence, type (reduction or oxidation), and intensity of hydromorphic features; depth of the first horizon with hydromorphic features (cm). Topsoil descriptions were based on: horizon thickness (cm); texture; root density; soil structure type; volumetric proportion of coarse elements and organic matter (%); presence, type (reduction or oxidation) and intensity of hydromorphic features; macroscopic plant remains; biological activity features.

2.3 Soil characteristics and typology

In order to describe changes in soil profiles and topsoils, we constructed site-specific typologies (Table 1). Two typologies (profile and topsoil) were generated using the complete linkage algorithm which preserves small clusters of observations (Everitt et al., 2001) and thus prevents groups composed by few points (i.e. rare soil types) to be included in larger groups. Clusters validity was evaluated using silhouette width – a distance-based method that assesses the quality of each cluster – (Rousseeuw, 1987). Positive values indicate correct classifications and negative un-correct ones respectively. The calculations of the indicators were based on the resulting soil groups. To facilitate comparisons among studies, we indicated the correspondence between our classification of soil profiles and two standard soil taxonomy references (AFES, 2008; IUSS Working Group WRB, 2006).

2.4 Soil criteria and indicators

For each criterion and indicator derived from the soil typologies we defined the range of possible values, an application domain (soil profiles and/or horizons), and the rationale for its use (Table 2).

2.4.1 Soil diversity

Tools for measuring pedodiversity increasingly attract the attention of soil scientists (Toomanian and Esfandiarpoor, 2010; Saldaña and Ibáñez, 2004, 2007; Ibáñez et al., 1998; Ibánez et al., 1995). Information on richness, diversity and evenness of soil types may be useful for evaluating restoration projects, especially given the mosaic of soils that can be observed in floodplains. Soil morphology spatio-temporal heterogeneity was first estimated by comparing pedodiversity indices, among the forest, the open area closed to the river (restored), and the control managed pasture (non-restored) to characterize the distributions of profile and topsoil groups. We used five measures of alpha diversity according to Hill (1973): richness (N0), Shannon and Simpson diversity (N1 and N2) and evenness (N1/N0 and N2/N0, respectively). We used soil types as surrogate of species for the calculations of these metrics.

2.4.2 Soil dynamism

Soil dynamism is defined here as the successions through time of sedimentation and/or erosion processes related to the fluvial regime. In natural floodplains, the fluvial dynamic creates through floods and in situ pedogenesis between flood events a mosaic

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of soil morphologies. Therefore, efficient river restoration should lead to recreating or maintaining such a mosaic of soils.

Practically, we plotted the total number of horizons per meter (Hm) against distance to river to get a 2-D picture of the erosion/sedimentation processes along the lateral gradient. The soil dynamism criterion was assessed by comparing the resulting patterns (1) along the river lateral gradient and (2) between the restored (open habitats + floodplain forest) and control areas.

Elevation deltas (i.e. the surface elevation variation of a given point measured through time) were calculated using cross-section topographical surveys. Negative and positive deltas are due respectively to net erosion and deposition processes. Cross sections data covering a period ranging from 1996 to 2002 (before restoration) and from 2002 to 2007 (after restoration) were used to assess elevation variations through time and flood events. Seven classes of distance to the river (10 m sections) were used to characterize the lateral gradient. Average elevation deltas before and after the restoration and their associated standard deviations were first calculated for each distance class. Finally, two five-year floods (HQ5) showing similar discharges before and after the restoration were selected based on hydrological surveys of the local authorities (Canton Thurgau) and on the available cross-section data. The elevation values just before and after each of these two floods were used to characterize the erosion/sedimentation patterns for each distance class.

2.4.3 Soil typicality criterion

Typical floodplain soils are mainly characterised by their limited evolution and the impact of water saturation on their morphology and functioning. They all show varying frequency and duration of waterlogging. An efficient restoration should allow the complete range of typical floodplain soils to develop at a site. This potential range of soils depends on the fluvial dynamic and is therefore context-specific. For example, hydromorphic features and clay-rich soils generally increase in frequency in lower river reaches.

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We compared the frequency of soil groups among the different areas of the site both for the entire profiles and for the topsoil horizons.

2.5 Vegetation survey

Vegetation surveys were conducted seven times between April 2008 and 2009 using the Braun-Blanquet method (1964) in 41 plots (4 m radius circles) distributed throughout the restored and reference areas. Among these plots, 26 were selected for their spatial correspondence with the soil survey, 22 in the restored area and 4 in the control. The different sampling sessions were pooled together in order to have a site X species matrix representing an entire year.

We calculated vascular plant species biodiversity for the three areas (open habitats + floodplain forest) using the same set of metrics as for pedodiversity. We then assessed whether the changes in soil morphology observed in Fig. 1 corresponded to vegetation types and, thus, whether soil morphology was a good predictor of successional patterns of vegetation.

3 Results

3.1 Soil typology

The cluster analysis revealed eight groups of profiles (silhouette width = 0.42) and seven groups of topsoils (average silhouette width = 0.44). Most soils could be classified as Fluvisols and to a lesser extent Stagnosols or Gleysols, according to the WRB classification, or FLUVIOSOL, REDOXISOL or REDUCTISOL according to the AFES classification. The average of each variable within each group are given in Table 1.

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3.2 Soil diversity

Profile and topsoil diversity and richness were highest in the open habitats of the restored area and lowest in the floodplain forest (Table 3). The control area had intermediate values. More soil groups (both topsoil and profile) were present and soil variability was higher close to the river. Evenness of soil groups differed between soil profiles and topsoils. Evenness of profile groups was maximal in the forest and minimal close to the river, while the evenness of horizon groups was maximal in the non-restored pasture (control) and minimal in the forest.

3.3 Soil dynamism

Soil dynamism as assessed by the variation of the total number of horizons per meter (Hm) along transects differed significantly between the restored and control areas (Kruskal–Wallis Rank Sum Tests, $p = 0.003$ and $p < 0.001$, for Hm values and standard deviation respectively) and between the open and forest habitats in the restored section. The pattern was flat in the control area (Fig. 1). Indeed, the control area was only rarely influenced by fluvial dynamics and as a result, soils were well developed and homogenous all along the lateral gradient. By contrast, in the restored area (Fig. 1), the pattern was highly variable. Five different sectors could be distinguished along the river-upland gradient. Between 0 and 5 m, Hm was null. Erosion processes were dominant and soil development could not occur. Between 5 and 20 m, Hm values increased slightly. Sedimentation could occur with some accumulations of organic matter. Between 20 and 35 m, Hm values showed a high variation. Erosion, sedimentation, and soil development (i.e. accumulation of organic matter, soil layer differentiation, in situ pedogenesis) alternated. Between 35 and 50 m, Hm values were more stable. Erosion decreased and soil development increased. Further, Hm values stabilized at about two horizons per meter.

The average sedimentation and erosion rates were higher between 1996 and 2002 than for the period after restoration (Fig. 2). Indeed, the average negative elevation

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delta before the restoration was −0.54 m and only −0.21 m after. The same trend was found for the average positive delta (before = 0.22 m and after = 0.16 m).

The effect of a similar five-year flood differed significantly before and after the restoration (Fig. 3; Kruskal–Wallis Rank Sum Test $p = 0.002$), and between the control and restored (i.e. open habitats + forest) areas after the restoration ($p = 0.02$). Along the river lateral gradient, the patterns were conspicuously different before and after the restoration. Before the restoration, erosion forces concentrated on the first thirty meters from the river. Further away, erosion forces were weaker and sedimentation started to occur. After restoration, the pattern was more regular. Sedimentation processes were dominant, but erosion occurred marginally.

3.4 Soil typicality

Soil group abundances were compared among the open habitats, the alluvial forest and the control for the entire profiles and topsoil horizons (Table 4). In the open habitats, restoration led to the creation of thin and coarse soils (profile types 4 and 5, Table 1) that correspond to the initial stages of soil development under high fluvial dynamism.

The transition between (1) the open and forest areas (profile groups 2 and 3) and (2) the more stable forest and control pasture (profile group 1) was marked by the presence of soil with low coarse material content which are little impacted by erosion and sedimentation processes, and moderately influenced by water table fluctuations. Such soils are not typical of active floodplains along natural braided rivers, but are rather an indication of human activity (i.e. embanking and associated reworking of soil and sediments). A single profile was characterized by the presence of a reduced horizon (profile type 8), indicating quasi-permanent waterlogging, a situation typically encountered along the lateral branches of braided rivers where water discharge is low.

Observed patterns in topsoil groups confirmed those of profile groups (Table 4): Humified organic matter deeply incorporated to the soil was characteristic of the forest and pasture areas (topsoil type 1), whereas organic matter was mainly composed by coarse residues in the open restored area (topsoil types 4 and 7). Topsoils with coarse

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material lacking organic matter occurred close to the river (topsoil types 2 and 3). Topsoils showing hydromorphic features (group 7) remained marginal since they accounted for 3 % of the investigated topsoils.

3.5 Vegetation

In total, 100 species were identified at the Thur River site. These species were organized into five well-differentiated vegetation successional stages along the lateral gradient: (1) the closest to the river, no vegetation or only isolated plants, (2) patches of pioneer vegetation and, (3) a thicket dominated by *Phalaris arundinacea*, (4) willow bushes dominated by *Salix viminalis*, (5) a deciduous forest dominated by *Fraxinus excelsior* far from the river. The control (un-restored) area was a managed pasture dominated by *Arrhenatherum elatius*. It was thus not meaningful to include it in the succession and compare it with the other habitats. We rather focused on the succession of plant communities along the river lateral gradient.

Plant species diversity and evenness were higher in the forest whereas the open habitats and forest had similar values of species diversity. The increase in plant species evenness paralleled the one in soil evenness, but this was not the case for richness and diversity. Vegetation successional stages corresponded to those in soil dynamism. The notable exception was the *Phalaris* thickets vs. willow bushes where differences in vegetation did not match those observed in soil. This is most likely due to the fact that the willow bushes were planted during the restoration and are not part of the natural succession.

Vegetation was expected to respond to the composition of profile groups. As expected, the typicality criterion was successful in predicting the broad vegetation types within the site (Fig. 5). Pioneer vegetation appeared with the first stages of soil development (profile 5) whereas when soils were too poorly developed (profile 4) no vegetation was present. Vegetation colonization in the most dynamic part of the gradient (profile 4) was associated to organic matter accumulation (topsoil 4). Data from topsoils, such as organic matter content and origin, are therefore complementary to those provided from profile morphology. Alluvial forests (*Fraxinion)* mainly occurred on stable, moist soils (profiles 2 and 7). Potential surfaces of suitable hydromorphic soils for the typical vegetation of braided river lateral branches such as *Typha minima* and *Inula Helvetica*, for which reintroduction plans exist in Switzerland (Keel and Flöss, 2004; Flöss and Keel, 2004), were only limited in our study area (i.e. only one sampling point for profile type 8).

4 Discussion

The restoration of River Thur globally increased soil diversity, and improved dynamism and typicality. It changed the fluvial dynamics leading to changes in soil morphology (e.g. intensity of erosion/sedimentation processes; coarse material and organic matter content) and soil functioning (e.g. loss of hydromorphy). The most striking changes occurred within the first 30 m from the river. Post-restoration fluvial dynamics created diverse and dynamic patterns of soils close to the river. Habitats located further away from the river were less frequently exposed to floods and therefore less influenced by the restored fluvial dynamic. However, restoration had not yet succeeded in creating significant surfaces of hydromorphic soils typical of braided river lateral branches (AFES, 2008; Guenat et al., 2003; IUSS Working Group, 2006).

Given the known importance of soil type in determining vascular plant communities (Gobat, 2010), we hypothesized that a relatively simple study of soil morphology would provide an indirect source of information on the potential vegetation and plant diversity of a site. This was not the case for diversity and richness most likely due to the influence of factors such as soil chemistry, water and nutrient availability, surface, connectivity, biotic interactions and species reservoir. However changes in the evenness of soil groups, and in soil dynamism and typicality paralleled those observed for vegetation, in agreement with our hypotheses. Indeed, the Hm index reflected the number of vegetation successional stages. Soils typical of floodplain lateral channels were strongly under-represented and the vegetation associated with such conditions was

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not yet able to colonize the site. The dynamism and typicality of soil morphology as described here can thus allow predicting major changes in potential vegetation – and other organisms responding either directly to changes in soil type or to the changes in vegetation – resulting from restoration project. The increased diversity of soil types and the dramatic changes of dynamism suggest a positive impact of restoration, but the lack of typical hydromorphic soils could have been improved by integrating soil morphology in early project planning. Thus, five years after river widening, the indicators of soil morphology suggest that this restoration project was a partial success in restoring soil habitat and vegetation.

Previous evaluations of the same site, but based on different methods, criteria and indicators, reached similar conclusions. Woolsey et al. (2007) found that fish assemblage structure and composition were similar in embanked and restored reaches and concluded that the restoration of River Thur failed to meet the objectives 'near natural abundance and diversity of fauna. Weber et al. (2009) showed that hydro-physical habitat diversity had been improved by the widening but that the current geomorphological complexity was still considerably impaired in the restored reach in comparison with historical near-natural shoreline. Rohde et al. (2004) used GIS methods based on landscape indexes and vegetation and concluded that the widening improved the degree of vegetation naturalness but in a limited way as compared to other restoration projects. Although the methods used were fundamentally different, the results we obtained using soil morphology were in agreement with these other evaluations. The indicators we used also allowed investigating complementary aspects of floodplain restoration: the diversity criterion proved to be complementary to vegetation surveys, the dynamism criterion discriminated precisely the zones that were differently impacted by the fluvial dynamic and the typicality criterion allowed characterizing the changes among these zones.

In the context of river restoration, indicators should be easily measured, be sensitive to stresses on the system, demonstrate predictable responses to stresses and be integrative (Palmer et al., 2005). Our results show that soil morphology criterion and

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indicators fit these requirements. Soils may respond slowly to perturbations such as riverbed widening but in our case, clear changes in soil morphology were already observed five years after restoration. Furthermore, soil indicators provide two different and complementary levels of information (i.e. soil units/profile, topsoil). Nevertheless, the time between the restoration and the integration of the changes into soil morphology depends on the fluvial regime. Successive floods (including HQ5, HQ10, or HQ20) have to occur to potentially modify the soil morphology. Erosional and depositional processes should be frequent, ideally corresponding to the "medium-energy non cohesive floodplains" river category of Nanson and Croke (1992) with braided, meandering and anastomosing channels.

We studied the relatively short-term effects of floodplain restoration. According to Ballantine and Schneider (2009) as soil development is a relatively slow process, which only appears to accelerate later in the successional recovery sequence, the role of different soil successional phases in determining long-term trajectories of ecosystem development should be considered in restoration design, research, and monitoring. It would therefore be useful to assess the longer-term trends of soil development at the study site and other comparable restored floodplains.

5 Conclusions

Our results show that soil morphology responded fast and clearly to river restoration and that typicality and dynamism correlated to vegetation changes. Analysis of soil morphology has the potential to improve the quality and accuracy of rapid assessment protocols (Sifneos et al., 2010; Stein et al., 2009).

Despite the known importance of soils in terrestrial ecology, soil morphology has been under-used for the assessment of floodplain restoration success. The number of river restoration projects is increasing rapidly but there is still no general agreement on evaluation methods. The analysis of soil morphology offers many advantages (ease of

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use, quick and cost-effective) that make it a promising approach for the river restoration evaluator's tool kit.

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Table 1a. Description of eight soil groups and number of "individuals" (n) resulting from a cluster analysis based on a simplified set of variables for profiles (1a), and five groups of topsoil horizons (1b). Soil taxonomy is based on AFES (2008) and correspondences to the FAO World reference base for soil resources (IUSS Working Group, 2006) are given. Depth is the mean depth of a particular group of profiles (cm). Texture is based on the US texture triangle (Saxton et al., 1986). For the profiles, texture is described using the total number of loam, sandy loam and sandy horizons within each group of profile, and the average number of horizons per profile. The volumetric percentage of coarse material (blocks, pebbles and gravels) of the coarsest horizon within the profile is indicated under coarse material. Proportion of blocks, pebbles and gravels are given for each group in percentage of total volume. Topsoil thickness (1b) is given in cm. Hydromorphic features represent the average depth (in cm) at which hydromorphic features were first observed. The intensity of the hydromorphic features is given using a semi-quantitative scale (absence, weak, moderate, and high). The organic matter OM content (null, low, medium, and high) and type (no, humified, and coarse residuals) are given.

	Taxonomy			Number of Horizons					Hydromorphy	
Soil profile	AFES, 2008	WRB, 2006	Depth [cm]	Loam	Sandy loam	Sand	Average per profile	Coarse material [%]	Hydromorphic features	Intensity of hydromorphy
Group 1 (11)	REDOXISOLS fluviques carbonatés	Gleyic Fluvisols Calcaric	111	7	47	0	2–4	0.3	15	Moderate
Group 2 (25)	FLUVIOSOLS typiques carbonatés	Fluvisols Calcaric	95	0	91	2	1–4	1.2	No	No
Group 3 (2)	FLUVIOSOLS typiques redoxiques carbonatés	Fluvisols Calcaric with redoximorphic features	120	1	10	0	3	6.5	50	Weak to moderate
Group 4 (32)	FLUVIOSOLS bruts carbonatés	Regosols Calcaric	0.8	0	1	31	0	87	No	No
Group 5 (22)	FLUVIOSOLS bruts carbonatés	Regosols Calcaric	20	0	42	5	1–2	45	No	No
Group 6 (9)	FLUVIOSOLS typiques redoxiques carbonatés	Fluvisols Calcaric with redoximorphic features	69	0	36	2	3	5.6	25	weak
Group 7 (8)	FLUVIOSOLS typiques redoxiques carbonatés	Fluvisols Calcaric with redoximorphic features	104	0	33	0	2	1.1	50	Weak to moderate
Group 8 (1)	REDUCTISOLS fulviques carbonatés	Gleysols Calcaric	30	0	2	0	1	7	15	High

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Table 1b.

Topsoil layer	Thickness [cm]	Organic matter content	Organic matter type	Texture (US triangle)	Blocks [%]	Pebbles [%]	Gravel [%]	Hydromorphic features
Group 1 (27)	8	low-medium	humified	Sandy loam	0	0	0	absent
Group 2 (21)	0	null	no	Sand	0.6	68	29	absent
Group 3 (10)	0	null	no	Sand	0.9	33	55	absent
Group 4 (36)	9	medium-low	coarse residuals	Sandy loam	0	0	5	absent
Group 5 (13)	9.5	medium-low	coarse residuals + humified	Sandy loam	0	0	1	absent
Group 6 (1)	5	medium	humified	Sandy loam	0	0	0	heterogenous iron distribution
Group 7 (2)	15	medium	coarse residuals	Loamy sand	0	0	1	related to roots, spots

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Table 2. Criteria and indicators of the soil morphology method for floodplain restoration success assessment.

Criterion	Indicators	Range	Application domain	Reference	Rationale
Diversity	Shannon index	0−> *n*	Soil profile Topsoil	Hill (1973)	Indicator of soil/topsoil habitat diversity
	Richness	0−> *n* max	Soil profile Topsoil		Indicator of soil/topsoil habitat diversity
Typicality	Frequency of typical soil profile groups	Expressed in %	Soil profile	AFES (2008)	Indicator of soil typical of natural floodplains
	Frequency of typical topsoil groups	Idem	Topsoil	AFES (2008)	Indicator of recent changes characteristic of natural floodplains
Dynamism	Total number of horizons per meter (Hm)	0−> *n*	Soil profile	Bullinger-Weber et al. (2007)	Indicator of morphological changes due to fluvial dynamics
	Elevation variation through time (Δ)	−*n*−> *n*	Topography		Indicator of rate of erosion/sedimentation

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Table 3. Soil diversity and richness calculated at the Thur site.

		N0	N1	N2	E1	E2	J
Profile	Open habitats	7	4.28	3.47	0.61	0.50	0.75
	Forest	2	1.97	1.95	0.97	0.97	0.98
	Pasture	4	2.95	2.60	0.74	0.65	0.78
Topsoil	Open habitats	6	4.50	3.78	0.75	0.63	0.84
	Forest	4	2.59	2.03	0.65	0.51	0.69
	Pasture	3	2.61	2.33	0.87	0.78	0.87

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Table 4. Relative abundance (%) of profile and topsoil groups for the restored and reference areas.

	Soil profile							
	group 1	group 2	group 3	group 4	group 5	group 6	group 7	group 8
Open habitats	1.3	11.8	–	42.1	28.9	10.5	3.9	1.3
Forest	–	58.3	–	–	–	–	41.7	–
Pasture	45.5	40.9	9.1	–	–	4.5	–	–

	Topsoil layer						
	group 1	group 2	group 3	group 4	group 5	group 6	group 7
Open habitats	7.9	27.6	13.2	39.5	9.2	–	2.6
Forest	58.3	–	–	8.3	25.0	8.3	–
Pasture	63.6	–	–	22.7	13.6	–	–

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Table 5. Averages of plant species biodiversity metrics for the open and forest habitats of the River Thur site.

	N0	N1	N2	E1	E2	J
Open habitats	17.88	4.39	2.87	0.25	0.17	0.48
Forest	16.71	6.75	4.88	0.41	0.30	0.67

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

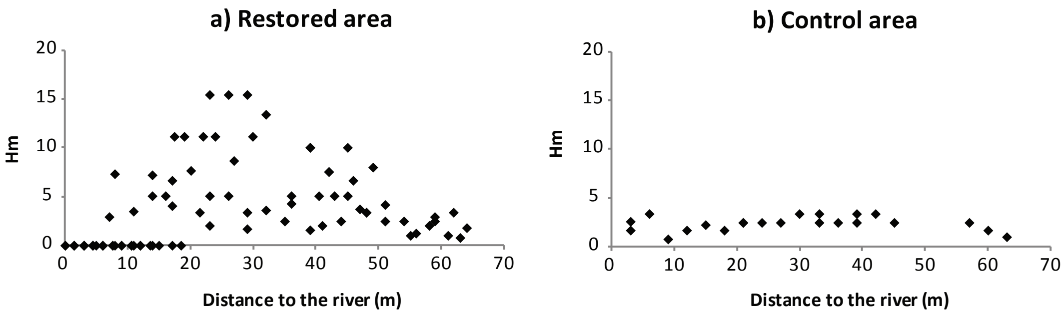

Fig. 1. Number of horizons per meter (Hm) versus lateral distance to the river (m) for the restored **(a)** and the reference areas **(b)**.

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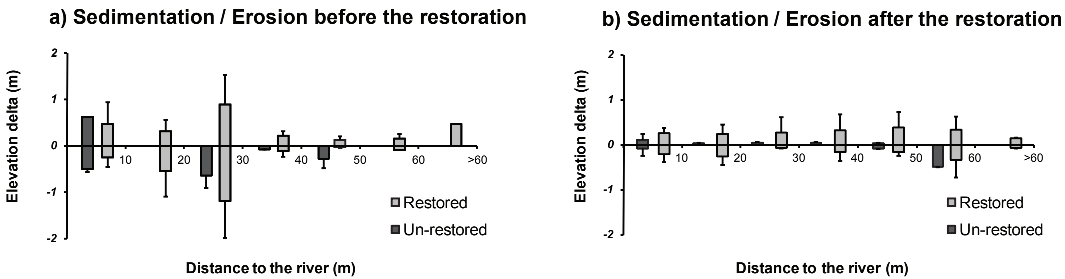

Fig. 2. Average elevation deltas (m) and their associated standard deviations before (**a**: period ranging from 1996 to 2002) and after the restoration (**b**: period ranging from 2002 to 2007) in the restored and in the reference (un-restored) areas. Calculations are based on cross sections data for seven classes of distance to the river (10 m sections). Positive deltas (+) correspond to sedimentation process and negative deltas (–) to erosion process.

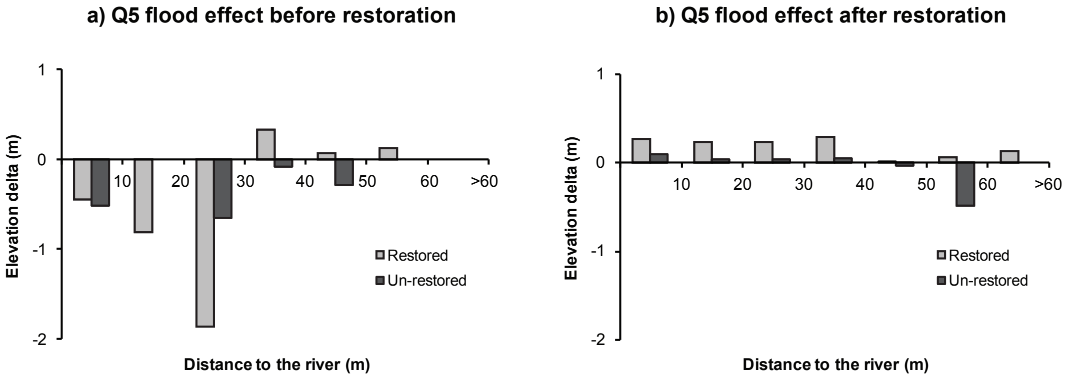

Fig. 3. Effects of a single flood with a similar discharge (Q5, five-year flood) on elevation deltas (m) in the restored and in the reference area before **(a)** and after restoration **(b)**. Calculations are based on cross sections data for seven classes of distance to the river (10 m sections). Positive deltas (+) correspond to sedimentation process and negative deltas (–) to erosion process.

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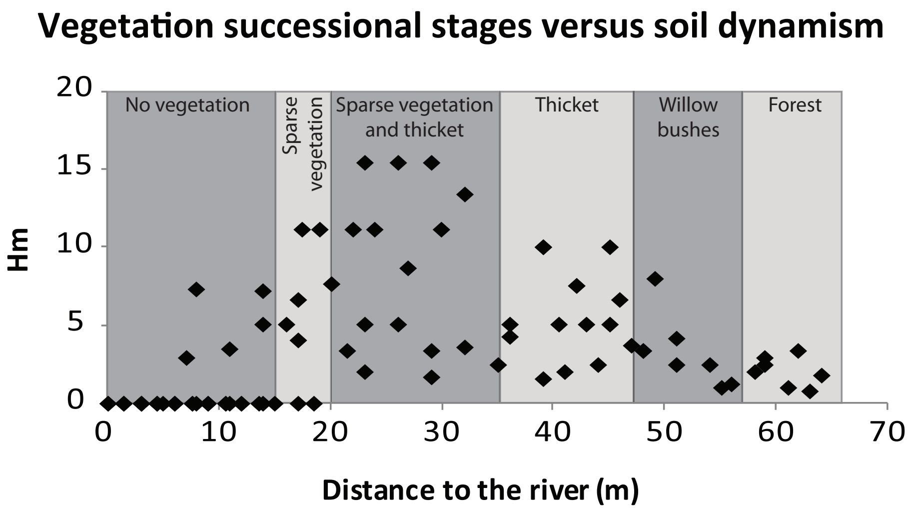

Fig. 4. Vegetation successional stages versus soil dynamism (Hm) in the restored area (0–65 m from the river).

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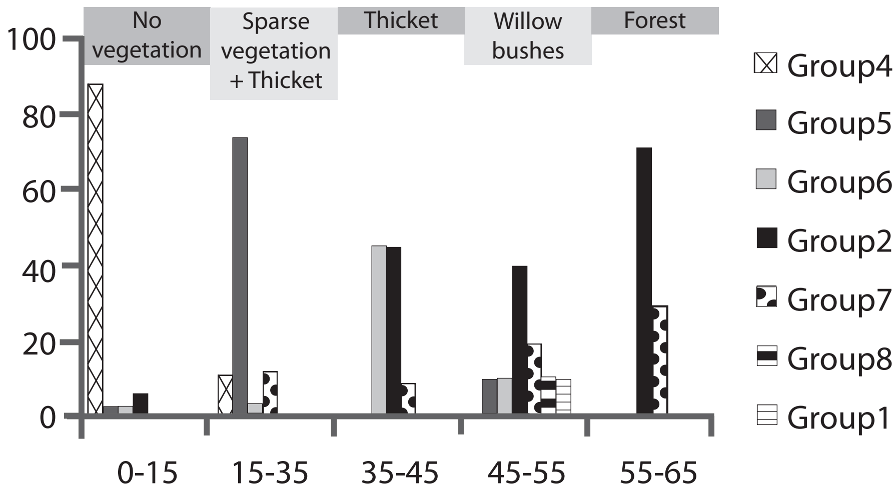

Fig. 5. Vegetation successional stages versus frequency of soil profile groups in the restored area. Soil groups are given according to their succession along the river lateral gradient. Soil profile group 3 was only observed in the control area.

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