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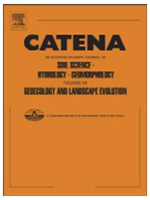

Organic matter processing and soil evolution in a braided river system

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ABSTRACT

Traditionally, braided river research has considered flow, sediment transport processes and, recently, vegetation dynamics in relation to river morphodynamics. However, if considering the development of woody vegetated patches over a time scale of decades, we must consider the extent to which soil forming processes, particularly related to soil organic matter, impact the alluvial geomorphic-vegetation system. Here we quantify the soil organic matter processing (humification) that occurs on young alluvial landforms. We sampled different geomorphic units, ranging from the active river channel to established river terraces in a wandering/braided river system. For each geomorphic unit, soil pits were used to sample sediment/soil layers that were analysed in terms of grain size (<2 mm) and organic matter quantity and quality (Rock-Eval method). A principal components analysis was used to identify patterns in the dataset. Results suggest that during the succession from bare river gravels to a terrace soil, there is a transition from small amounts of external organic matter supply provided by sedimentation processes (e.g. organic matter transported in suspension and deposited on bars), to large amounts of autogenic *in situ* organic matter production due to plant colonisation. This appears to change the time scale and pathways of alluvial succession (bio-geomorphic succession). However, this process is complicated by: the ongoing possibility of local sedimentation, which can serve to isolate surface layers via aggradation from the exogenic supply; and erosion which tends to create fresh deposits upon which organic matter processing must re-start. The result is a complex pattern of organic matter states as well as a general lack of any clear chronosequence within the active river corridor. This state reflects the continual battle between deposition events that can isolate organic matter from the surface, erosion events that can destroy accumulating organic matter and the early ecosystem processes necessary to assist the co-evolution of soil and vegetation. A key question emerges over the extent to which the fresh organic matter deposited in the active zone is capable of significantly transforming the local geochemical environment sufficiently to accelerate soil development.

1. Introduction

Geomorphologically active systems, such as braided rivers, exhibit a complex mosaic of fluvial habitats (Tockner et al., 2010) including bare sediment surfaces, islands within the active zone at various vegetation succession stages, and established river terraces with floodplain forest and well-developed soils. Thus, the river landscape comprises a range of ages with reworked zones, and ages at the sub yearly timescale, to much more stable zones, potentially many decades old.

Recent research has established that the transition from a bare sediment surface to a vegetated patch results in important changes in fluvial processes. Vegetation can be seen as a type of ecosystem engineer, critically involved in this transition during fluvial landform formation (Corenblit et al., 2011, 2014; Gurnell, 2014; Gurnell et al., 2012; Jones et al., 1994; Osterkamp and Hupp, 2010) by: (i) stabilising sedimentary deposits through rooting (Crouzy and Perona, 2012; Perona et al., 2012); and (ii) enhancing fine sediment deposition due to above ground biomass induced energy losses that lead to surface aggradation (Gurnell and Petts, 2002). Both plant-facilitated processes allow habitat development within the most active zones of the floodplain by improving local edaphic conditions (moisture and nutrient retention, reduced susceptibility to erosion) so allowing the progress of succession – from pioneer island species to stable terrace hardwood species (e.g. Francis, 2007; Francis et al., 2009; Gurnell et al., 2001; Moggridge and Gurnell, 2009). Nevertheless, if the deposition rate is too high, vegetation may get buried, leading to an optimal aggradation range for successional processes (Gurnell and Petts, 2002). Conversely, if the erosion rate is too high, the entire vegetated patch may be removed and its materials redeposit elsewhere, where it may again facilitate plant development (large woody debris, e.g. Francis, 2007; Francis et al., 2008).

These processes have been recently conceptualised into a biogeomorphological life cycle model for *Populus nigra*, deemed to be valid for *Salicaceae* pioneer vegetation in general (Corenblit et al., 2014). The main phases of the life cycle identified are: (i) in the

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geomorphological phase, seedlings are dispersed by floods and germinate on suitable bar surfaces; (ii) in the following pioneer phase, seedlings are challenged by water stress, erosion and deposition processes. During these first two phases, *P. nigra* is completely exposed to the physical riverine processes without relevant feedbacks to river morphology; (iii) in the third phase, interaction between plants and their physical environment is highest, the biogeomorphological phase. Young trees take on an engineering role by fixing sediments and trapping fine sediments. Symbiosis with endomycorrhizal fungi improves their access to the soil nutrient pool and groundwater (Harner et al., 2011). Finally, (iv) during the last or ecological phase, the vegetated patch becomes relatively independent from the river and is able, via autogenic ecosystem processes, to auto-sustain its own resource demands. Rare shallow overland deposition or lateral erosion processes are the main riverine processes affecting this phase (Corenblit et al., 2014).

The latter two stages imply timescales of the order of years to decades. At these longer timescales soil, as an emergent property of the developing ecosystem, must also be considered as an element of the braided river system (Bätz et al., 2014a). In stable systems, such as river terraces of meandering systems, pedogenesis has been extensively studied (Cierjacks et al., 2010, 2011; Gerrard, 1987). However, this is much less the case in more dynamic alluvial environments, such as braided rivers, and hence the question arises: are soil forming processes passive process that react to stabilizing geomorphic conditions, or are they actively involved in controlling the rate of biogeomorphic succession (*sensu* Corenblit et al., 2009)? In other words, is pedogenesis able to change the rate of biogeomorphic succession?

Because the later stages of Corenblit et al.'s (2014) model imply the presence of soil, a second question follows: to what extent is pedogenesis involved in the first two of Corenblit et al.'s (2014) stages? For instance, flood pulses, that lead to deposition, may provide water but also exogenously produced energy rich organic matter (plant debris but also pedogenically transformed material), that is easily decomposed and humified into plant available forms by the sediment/soil micro-flora and fauna (Cabezas and Comín, 2010; Francis, 2007; Gregory et al., 1991; Langhans et al., 2012; Naegeli, 1997; Pusch et al., 1998; Tabacchi et al., 2000). This depositional process might significantly enhance the nutrient pool of the nutrient-poor, young mineral sediments, and so accelerate initial ecosystem processes including soil forming processes (Doering et al., 2011; Guenat et al., 1999; Guex et al., 2003; Langhans et al., 2012). However, either massive deposition, leading to burial, or erosion events which lead to local loss of pedogenically transformed organic matter, may potentially hamper fluvial planform development. These interactions with the biogeomorphic component, can lead to a multitude of pathways and trajectories of alluvial soil formation, so that it is better to talk about soil evolution (Johnson, 1985; Schaetzl and Anderson, 2005).

Yet, we know surprisingly little about initial soil development on active surfaces of braided river deposits and its interaction with biogeomorphological processes (Bätz et al., 2014a).

Addressing the question of initial soil evolution requires a multi-angled approach (Bernasconi and Biglink Project Members, 2008). In this paper we focus upon the question of organic matter processing (humification), which is considered an important part of young ecosystems. Initial soil evolution is a result of these processes and we can consider how soil horizons reflect and record organic matter processing of the developing fluvial landform (biogeomorphic succession), through its transition from a barren sediment surface to a vegetated soil covered patch. As explained above, organic matter may profoundly transform the local abiotic environment, increasing the nutrient pool, ameliorating water and nutrient retention through soil aggregate and soil structure formation, but also through production of humic acids, which may enhance weathering rates (Bätz et al., 2014a).

A Swiss braided river system, the Allondon River (Canton Geneva Switzerland), has been analysed for this study. We use a chronosequence (space for time substitution) approach, ranging from young surfaces close to the active zone of the river, to older stable floodplain terraces. On each area along the chronosequences, soil properties, mainly in terms of grain size and organic matter quality, were analysed. Principal components analysis is used to generalise the data obtained and to develop a model for organic matter processing in braided rivers soils. Moreover, we try to identify the time scales for soil formation and its link to biogeomorphic succession.

2. Material and methods

2.1. Study site

The gravel bed Allondon River is located to the west of Geneva (Switzerland). A large part of the catchment is located in the calcareous French Jura Mountains. A number of small (karstic) torrents flow from the Jura and combine into a single river at the French/Swiss border. From this point, a 3 km long reach of wandering/braided floodplain is formed before its confluence with the Rhône River. The catchment area above the study reach is about 120 km^2 (FOEN, 2013). This reach, incised by about 60 m into fluvioglacial sediments, overlays the Swiss Molassic basin. Fluvioglacial sediments were deposited during the last glacial cycle (the Würm and Riss glaciations), and their origin typical of the Rhône basin geology (CJB, 1990; Coutterand, 2010).

Erosion into these fluvioglacial sediments (valley side slopes) is thought to lead to slope failures, exacerbated during localised saturation during storm events and river lateral undercutting processes. These are thought to be the main source of sediments in the braided reach. There are terraces of fluvial origin within the reach and the river has a potentially wide range of surface ages, ranging from active sites with a high turnover, to mature floodplain terraces, which are much older (Beechie et al., 2006). Following the biogeomorphic succession model proposed by Corenblit et al. (2009), there is evidence of rapid vegetation colonisation on exposed sediments of engineering species (*Salix elaeagnos, Salix purpurea*) and progressive plant facilitated stabilisation of some braid bar deposits which eventually lead to more stable fluvial landforms such as alluvial terraces (*Alnus glutinosa, Corylus avellana, Quercus robur, Fraxinus excelsior and Carpinus betulum*). However, terraces covered by dry grasslands can also be found (CJB, 1990). Moreover, there is clear evidence of both contemporary and historical soil development (e.g. buried soils).

The hydrology is pluvio-nival, having two maximum flood probabilities: (i) during spring due to snowmelt and especially rain on snow in the Jura Mountains; and (ii) during autumn, when heavy and prolonged rainfalls occur. The catchment hydrology responds quickly, causing rapid hydrograph rise and high magnitude flood peaks, with return periods of 45 m^3/s (2 years), 66 m^3/s (5 years), 81 m^3/s (10 years), and 123 m^3/s (50 years). Baseflow conditions are between 0.5 and 7.5 m^3/s (FOEN, 2013; Fourneaux, 1998). The river flow is also closely coupled to groundwater. There is clear evidence of surface flow loss to groundwater in the upper part of the reach and the return flow of calcareous groundwater to the main river in the lower part (e.g. Fourneaux, 1998; Hottinger, 1998).

Land use in the catchment is mostly forest, prairies and pasture (70%), and agriculture (15%). Nevertheless, both industry and the CERN research centre use the water of the Allondon River and, despite extensive wastewater treatment, several polluting events impacted the river ecology between 1970 and 1990 (DIM, 2010). Generally, there is little river management within the 3 km reach considered in this study and most of the interventions (e.g. spur dykes) were removed in 2000 during a revitalisation and renaturalisation programme. The spur dykes did not significantly hamper braiding processes of the sections studied, which are still very active. However, whilst still in a braided/wandering state, there is evidence that the study reach is evolving from a 90 m wide bar braided system (1957) to a c. 40 m narrower river with vegetated islands. These changes may be caused by land use changes of the alluvial terraces (pasture to forest) and changes in the hydrological and sediment regime. Nowadays, the river corridor is recognised both nationally (eg. Federal Inventory of Alluvial sites of National Importance) and internationally as a protected site (DIM, 2010).