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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 braided river system. For each geomorphic unit, soil pits were used to sample sediment/soil layers that were analysed in terms of grain size (<2mm) and organic matter quantity and quality (RockEval 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.

Highlights:

- Grain size and organic matter characteristics are key pedo-biogeomorphic variables;
- Geomorphic processes can potentially add valuable resources to the young ecosystem;
- Thus, geomorphic processes can hamper but also facilitate alluvial soil evolution;
- Initial alluvial soils experience a transition from exogenic towards endogenic matter input.

Keywords: Alluvial soils; Braided river; Rock-Eval; Organic matter; River terraces; Biogeomorphic succession

# 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., 2014, 2011; 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 nigar*, deemed to be valid for *Salicaceae* pioneer vegetation in general (Corenbilt *et al.*, 2013). The main phases of the life cycle identified are: (i) in the 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., 2011, 2010; 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 reacts 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 Corenbilt et al.'s (2013) model imply the presence of soil, a second question follows: to what extent is pedogenesis involved in the first two of Corenbilt et al.'s (2013) 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 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 the 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 3km long reach of 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 (eds.), 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 (eds.), 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 90m 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 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).

Figure 1 about here

## 2.2 Identification of sample sites

By means of an analysis of a series of historical aerial images, a Digital Elevation Model of 1m resolution (DEM; SITG, 2012; SWISSTOPO, 2012), Electrical Resistivity Analysis (ERT) and field observations (vegetation type and microtopography), four chronosequences covering a large range of ages has been defined. The historical aerial images and the DEM where used to reconstruct recent geomorphological development and to trace fluvial landform boundaries. Additional field observations have been integrated to validate the remote sensing data. Moreover, ERT data with 0.5m electrode spacing, following the method proposed by Laigre et al. (2013), have been used to visualise belowground soil/sedimentary structures along each chronosequence (see also Bätz et al. (2014b) for an example). Within each mapped landform a representative site, in terms of microtopography, vegetation type and soil/sediment thickness/structure has been chosen for detailed soil analysis.

The chronosequence with the sample numbers 11 to 16 includes an active zone and three terraces (Figure 1). The increasing altitude is an indication of increasing age of the surface. Sites 12 (1.3m elevation above the river), 11 (2.5m) and 13 (3.7m) are already visible in the oldest aerial image (1957 Figure 1), consequently, only a minimum age can be assigned of about 60 years for the lowest terrace (12).

Site 16 (1.1m) is part of a large mid-bar in 1999 (Figure 1) and experienced fast vegetation colonisation, potentially due to (fast resprouting) large woody debris. Due to its island character, we expect this landform to interact (engineering action) with the floods (geomorphological processes). Site 14 (0.4m) and 15 (0.3m) are the youngest sites on this chronosequence. In 2001 they appear to part of the main channel system. From 2005 both sites are exposed, but different rates of vegetation colonisation can be observed.

The chronosequence with the samples 31 to 34, 21 and 22, cover medium to long time spans. 21 appears to be an old terrace at 2.2m from the river bed and is already visible in the oldest aerial image (1957 in Figure 1). In the aerial image of 1980, sites 22 (0.8m) and 31 (0.75m) are part of the main channel, while sites 34 (1.15m) and 33 (1.31m) recently experienced an avulsion process and are in the former outer and inner meander respectively. The island or cut-off terrace that has formed in this period has been almost completely eroded during an avulsion between 1980-1996. The same event created the base for the development of sites 31 (0.75m) and 32 (0.88m), which in 1996 show already vegetation colonisation of the avulsion channel with 32 being in the former inner and 31 in the former outer meander.

The shorter chronosequence of samples 41 to 43 cover mid to short time spans. In 1996 (Figure 1) site 41 appears as a barren surface whilst 42 shows already a pioneer vegetation cover. Based on the elevations above the river, which are respectively 1.1m for 41 and 1.59m for 42, and the avulsion pattern observed earlier for the sites 31-32, we might think of site 41 being part of former main channel and 42 being a former point bar. Site 43 (0.98m) has experienced a series of revegetation processes, but erosion processes reset the local system in 2006.

The chronosequence 51 to 55 covers young time spans of a decade. These sites have been continuously exposed to geomorphological disturbance and revegetation processes (Figure 1). However, site 5.3 (1.77m) is the oldest site on this chronosequence. In 2001 it is part of the main channel, but subsequent lateral erosion exposed the site (2005 – Figure 1). Vegetation colonisation appears to be slow on this site. The lateral erosion observed between 2001-2005 is also the starting point for the development for sites 55 (1.23m) and 54 (1.43) as part of the point bar system. In 2006 both sites became isolated from the main channel by avulsion processes. Only larger floods have impacted these two during recent years. Site 51 (0.86m) is still part of the main channel system in 2009, while site 52 (1.45m) appears to be a mid-bar as part of a riffle system. Between 2009-2011 site 51 became exposed due to avulsion.

### 2.3 Soil sampling strategy

In each of the six areas, a soil pit was dug at a representative location to a minimum depth of 50cm (P1 through P6). For each pit, soil/sedimentary layers were identified and described using standard soil description methods. The following parameters were recorded in the field: layer depth (H-layer), layer thickness, root density (nr./dm$^2$) and volume of soil stones (% > 2mm). Further data, such as the distance of each soil pit from the main river along the most likely line of connection, were acquired using a differential global positioning system (dGPS). For each layer in each profile, a sample was taken for laboratory analyses in terms of grain size distribution (<2mm) and organic matter quality, as explained in the next section. 116 soil/sediment samples were obtained in total.

## 2.4 Laboratory analysis

Each of the soil/sediment samples was analysed using laser diffraction to determine the grain size distribution (Malvern Mastersizer 2000) and by pyrolysis to determine organic matter quality and pools (Rock-Eval 6).

For the grain size distribution, 1g of <2mm sieved material of the bulk sample was used to remove organic matter with a $H_2O_2$ solution (first at 15% then at 35% concentration), making sure that the pH did not drop below 3. Before performing particle size analysis, samples were dispersed in a calgon solution (sodium hexametaphosphate) for one night. Measurement outputs were grouped into 5 classes of apparent diameters: clay (0.01-4µm), silt (4-63µm), fine sand (63-250µm), medium sand (250-500µm), and coarse sand (500-1000µm).

In order to analyse the organic matter quality, the Rock-Eval method was followed (Disnar et al., 2003; Lafargue et al., 1998; Sebag et al., 2006). Here, only a short summary of the main principles and methodological steps is given (for details see Disnar et al., 2003 and Sebag et al., 2006). The analysis needs little pre-treatment of the samples: untreated bulk raw samples were sieved at <2mm and then grinded (with an agate mortar) to powder.

The principle of the Rock-Eval method lies in the fact that the quality of organic matter components is closely related to their thermal stability. Thus, in a first step, samples are slowly heated to 650°C in an inert atmosphere ($N_2$) – the pyrolysis step. Organic matter components gradually undergo cracking while hydrocarbon, CO and $CO_2$ emissions are continuously measured. Hydrocarbon emissions can then be plotted versus temperature (labelled as the S2 curve) and, using signal deconvolution, different proportions of organic matter pools can be identified: labile fresh litter (A1), stable litter components such as cellulose and lignin (A2), humified litter (namely humic and fulvic acids; A3), stable humus components such as humins (A4) and resistant humus components/geopolymers such as black carbon and charcoal (A5). Note, that these data are expressed as proportions (pools) of the fraction of Total Organic Carbon (TOC).

The temperature at which most hydrocarbons are liberated (TpS2) is determined using the S2 curve. TpS2 refers to the predominant organic matter pool in the sample. Following Sebag et al. (2006), two indices are used to describe the relationships between the five different organic matter pools :

$$I = \log\left(\frac{A1 + A2}{A3}\right) \qquad [1]$$

"*I*" stands for immature and this I index represents the amount of fresh organic matter. Another index, "R" defined as:

$$R = \log\left(\frac{A3 + A4 + A5}{100}\right) \qquad [2]$$

represents the thermo-resistant or more humified stable/resistant organic matter components (R stands for thermo-resistant).

In a second step, the residue of the pyrolysis is heated from 450°C to 750°C in an oxygen enriched environment, allowing combustion of resistant organic matter. Again, CO and $CO_2$ emissions are measured continuously.

From the combined pyrolysis and oxidation steps, fractions of soil organic (%TOC) and mineral carbon (%MINC), a Hydrogen Index (HI) and an Oxygen Index (OI) can be obtained. The higher the HI, the less organic matter is transformed (fresh litter). The OI expresses the oxidation rate of organic matter and thus the humified and more resistant organic matter pools.

## 2.5 Statistical analysis

The field and laboratory data are highly inter-correlated. Thus, they were analysed using a principal component analysis (PCA; Matlab R2012b). A total of 22 variables were available for the 116 samples. The five grain sizes and the five organic matter pool variables, expressed as proportions, were first transformed by a centred log ratio function into a new metric system to avoid problems of co-linearity and the closed data effect. In a second step, all variables were standardized assuming a Gaussian distribution of the data set. The PCA was performed using eigenvectors and eigenvalues of the correlation matrix. The Pearson correlation coefficients between principal components and variables were calculated by multiplying eigenvectors by the square root of their associated eigenvalue. We set the level of significance ($p$=0.005) for the correlation of the variables with the principal components at r>0.2540 based on 100 degrees of freedom. However, we also consider correlations r> 0.8 to be strongly correlated with the related component. For the interpretation, we included all the components explaining more than 5% of the total variance.

# 3. Results

Figure 1 shows the analysed profiles and their position in the floodplain. The related data are summarised in Annexes A and B, while some examples of the analysed profiles are given in Figure 2. Based on the USS Working Group WRB (2006), the old terrace soils (11, 13, 21, 21) can be considered as mollic fluvisol skeletic, because they have a think, organic matter enriched topsoil. The very young sites (14, 43, 51, 52) can be defined as leptosol skeletic. Most mid aged soil profiles would best fit the name fluvisol skeletic (15, 31, 32, 33, 34, 41, 42, 53, 54). However, profile 16 would be a classical fluvisol and profile 55 also shows stagnic properties.

The vegetation of the terraces (11, 12, 13, 21) is dominated by *Corylus avellana, Quercus robur and Fraxinus excelsior*. Location 16 is dominated by *Alnus glutinosa* and some *Robinia pseudoacacia* stands, while site 22 is dominated by a *Populus alba* stand. Most of the very young stands (14, 43, 51) do not show significant vegetation cover – only a few sporadic grass stalks. Site 53 is covered by dry grass land. Sites 14, 52, 54, 55, 41, 32, 31, 33, 42, 34, are dominated by *Salix elaeagnos and/or Salix purpurea* with increasing ages (14 young and 34 the oldest stand).

Figure 1 and Figure 2 about here

Grain size distributions (<2mm) and organic matter quality and quantity, but also data related to the position in the landscape (see Annexes A and B) have been used as input variables for the principal component analysis (PCA). Some samples have low Total Organic Carbon values (TOC<0.02%; Annex B) and thus, this absolute value should be considered with caution (Disnar et al., 2003; Sebag et al., 2006). Nevertheless, these data are coherent with the conceptual model described below and, as such, were not excluded from the analysis: they simply indicate samples with exceptionally low organic matter content.

Table 1 and Figure 3 about here

The first four Principal Components (PC) explain 72.7% of the total variance (Table 1). From the fifth PC on, explained total variance drops below 5% and so these PCs are not considered further. The first PC explains 40.5% of the data variability (Table 1; Figure 3A). It correlates positively with the proportions of clay, silt and fine sands, TOC, with the proportions of more stable biopolymers and humified litter (A2 and A3), the root density and to a lesser extent with the HI. It correlates negatively with the fractions of coarse sands, the mineral carbon content (MINC), the OI, the resistant humus components (A5) and to a lower degree with the proportion of medium sand and the percentage of stones in the layer (%stones). Thus, the first PC appears to be representing the level of pedogenesis in the system with higher levels of pedogenesis associated with higher scores on this PC. Evidence for this is related to the higher quantities of organic matter and related humification processes, as shown by the presence of several organic matter decomposition stages (A2, A3 and to a lesser extent A4) a key process in early pedogenesis.

The second PC explains less variance, 17.2% as compared with PC1 (Table 1; Figure 3A). It is mainly associated with stable humus components (A4%) the R-index and it is negatively associated with fresh organic matter input (A1%; I-Index), but also to a lesser extent with TOC and HI. Thus, PC2 appears to be a measure of the fraction of fresh organic matter (negative values) versus stable organic components (positive values): high values of PC2 describe a lack of fresh organic matter input and where organic matter processing has transformed the available fresher pools towards more stable ones (R-Index). It is surprising that the fresh and resistant organic matter qualities (PC2) are, to a certain extent, independent from pedogenesis (PC1). This might be due to the fact that there are two main sources for organic matter: fluvial input, and endogenic vegetation production (e.g. Langhans et al., 2012; Naegeli, 1997; Pinay et al., 1992; Steiger and Gurnell, 2003)

PC3 explains 8.1% (Table 1; Figure 3B) of the variance and is mainly correlated with layers that have high values of clay and silt. A negative correlation exists with the medium sand content. We suggest that this PC represents the sedimentary processes the layers are or have been exposed to. With positive values for environments with rather silt and clay rich deposits (e.g. shallow overland deposits on terraces, or plant-colonised old avulsion channels) and negative values for sites exposed to more powerful events.

The PC4, explains 6.9% of the total variance (Table 1) and correlates positively with distance and elevation from the river. PC4 can be interpreted as representing the chronosequence, with the older terrace profiles being higher and more distant from the actual channel. However, it is interesting to note that this component actually explains very little of the total variance. We attribute this to the morphodynamics of the active channel, e.g. avulsion processes, which prevent simple substitution of time by space and create a complex mosaic of states of organic matter within the active zone. Depending on flood magnitude and position in the landscape, landforms can have different amounts and qualities of sedimentary inputs (Cabezas and Comín, 2010;

Steiger and Gurnell, 2003). It is only when a part of the active zone is stable for sufficient time that the effect of time becomes dominant.

Figure 3C plots the sample sites onto the first two PCs for each of the 3 analysed zones. This plot spreads the samples based mainly on the organic matter quantity and quality. Organic matter enriched topsoil layers (Ah layers) of the older terraces (notably 13, 12, 11, 22) are grouped into the lower right corner of the plot. However, also some younger and fluvially exposed sites (54, 55) are found in this area of the plot. They are characterized by high values on PC1, that is they tend to have higher proportions of clay, silt and fine sands, TOC, higher proportions of the A2 and A3 organic matter compounds and lower mineral content and a lower thermo-resistant organic matter fraction (A5). They are also characterised by low values on PC2 that is they typically have a high fraction of fresh organic matter (A1% and I-Index). We argue that these samples are typical of the upper horizons of soils where pedogenesis processes tied to organic matter processing are very active, with high in situ organic matter production, which explains the relatively lower fraction of stable organic matter compounds.

Samples in the upper and lower left side of the plots shown in Figure 3C, tend to be the subsurface layers (C horizons) of these older terrace soils (13, 12, 11, 22) but also the C horizons of younger profiles (53, 54, 55, 14), with low values of PC1, that is where TOC is low, with a high fraction of resistant organic components (OI and A5). These samples distribute along the entire range of PC2, indicating that subsurface layers are very variable in terms of fresh (negative PC2) versus stable humus components (positive PC2). Whilst these sites may be beneath surface layers where pedogenesis and in situ organic matter production is occurring, the young nature of these alluvial soils means that their C horizons can still be clearly distinguished as relatively inert. However, some M samples mix within this group. These are sandy deposits mixed with some exogenous pedogenically altered organic matter. Due to sediment transport processes only the most stable pools can be found in these layers, because they are attached to finer grains (e.g. Asselman and Middelkoop, 1995; Pinay et al., 1995; Steiger and Gurnell, 2003). However, because of the low TOC content on the right side of the plot, the fractions of the different organic matter pools need to be considered with caution.

Samples in the higher right corner of the plots shown in Figure 3C have high values on PC1 and PC2: organic matter humification is active but, because of a lack or scarcity of fresh organic matter input (A1), the organic matter pool tends to be biased towards the mature and resistant components. The lack of fresh organic matter input and organic matter humification has transformed the available labile matter (first A1 then A2) to more stable compounds. Samples in this area of the plot include very young (2-5 years old) A horizons (51(Ai), 14(Ai)) and some Ah horizons of profiles that are still impacted by shallow depositional events (41, 15, 22), mostly composed by humified litter and stable humus components in combination with fine sands. Nevertheless, most sites are related to the buried surface horizons (Ahb) and organic matter enriched sandy deposits (M). The first (Ahb) have been progressively decoupled from fresh organic matter input via burial, while the second (M) have been deposited together with large quantities of stable humus components.

Summarising, sites close to positive values of PC2 can arrive through three fundamentally different processes: (1) a stable surface deposit where pedogenesis has formed an initial organic matter enriched topsoil after a period of stability with good fresh organic matter input (transition from sediments into a soil); (2) a buried soil horizon and (3) deposits of upstream eroded organic matter enriched sands, with its fresh organic matter supply being cut off and the accumulated organic matter becoming progressively more resistant. Thus, even though the soil horizons show similar properties in this zone, their evolution may be very different. Indeed, the accumulation of stable humus compounds in Ahb layers is due to recessive pedogenic processes, which lead to degradation of the organic matter (Johnson, 1985; Schaetzl and Anderson, 2005). On the other hand, the initial accumulation of stable humus compounds in layer Ai is due to progressive pedogenesis, in which the sparse vegetation cover and/or fluvial litter input provides easily and fast transformable organic matter (Gregory et al., 1991; Langhans et al., 2012; Sebag et al., 2006).

When plotting the samples on PC1 versus PC3 (Figure 3D) the entire range of sedimentary composition gets clear and can almost be read like a classical grain size triangle. The organic matter enriched topsoils, which are placed on the positive axe of PC1, show high variability in clay to medium sand content (PC2), but with initial A horizons (55Ai, 51(Ai), 42 Ai(M), 14(Ai)C1, 16Ai) mainly placed in the upper right part of the plot (high fine sand content). The buried soil horizons (Ahb) distribute, as the Ah on the entire right part of the plot. Most of the M horizons, as being organic matter enriched sandy deposits, concentrate in the fine to medium sand range.

The plot PC1/PC4 of the samples (not shown here) show the distribution of sedimentary and /or soil layers along the chronosequence, with samples being older on the positive axis of PC4. The plot is not shown here because it simply reflects the chosen sampling strategy along the chronosequences.

# 4. Discussion

## Pedo-geomorphic interactions of the Allondon River

The shape of figure 3C need special mention: as PC1 is defined as an axis of pedogenesis, as we move from the higher middle of the point cloud towards higher organic matter contents (from the left to the right), there is simultaneously an increase in amount of fresh organic matter supply (negative values of PC2) because of the establishment of vegetation with higher biomass productivity  (eg. Van Breemen and Finzi, 1998). This is supported by the correlation with the root density. It also suggests higher organic matter humification rates indicated by the presence of all the organic matter humification steps (A1-A2-A3). However, the same change in organic matter supply can be observed if moving towards negative values on PC1. Although, this increase in fresh organic matter supply is characterised by no increase in TOC and related humification steps (pools A2 and A3). Samples located in the lower right corner (14 and 22) tend to be geomorphic stable but still influenced by the fluctuating ground water (elevation from river is respectively 0.9m and 1.2m). Possible sources are, in the case of the terrace soils, illuviation products from the upper Ah horizons, while for younger sites dissolved organic matter from the fast infiltrating (gravelly material) river flow and related processes of the hyporheic zone may be a potential source.

It is interesting to notice that there is no clear correlation of topsoil maturity, thus moving from the top of the point cloud of Figure 3C towards the lower right corner, and landform age observed form the historical aerial images. We can find young sites with about one decade of development (54), mid aged (15-30 years) sites (22, 32, 33) and old terrace soils (13, 11, 21) in the same area of the plot. In connection with the low degree of explained variance of PC4, representing the chronosequence, this indicates that there is no clear impact of time on young alluvial soils. Local and reach scale geomorphological setting in conjunction with different flood magnitudes, create a complex pattern of geomorphological impact (Steiger and Gurnell, 2003), thus directing local soil evolution trajectory (Johnson, 1985; Schaetzl and Anderson, 2005).

The shape of Figure 3D does not show a clear pattern. However we can notice the affinity of fine sand, silt and clay for higher TOC as observed in other studies (e.g. Cabezas et al., 2010; Pinay et al., 1995). Moreover, the old terrace topsoil appears to have higher contents of fines (higher right corner), while younger sites are rather composed of medium to fine sands (lower right corner), indicating the kind of depositional processes each site is/has been exposed to. The C horizons, located in the left part of the plot (Figure 3D) are generally high in coarse sands, but show a wide range of silt/clay versus medium sand content. It is interesting to notice that there is a trend: section 2-3 and 4-5 have higher contents of silt and clay if compared to the C layers of section 1.

Based on the above interpretation, we can conceptualise braided river soil evolution (Figure 4). Pedogenesis starts from a large range of deposits in terms of grain size and organic matter quantity and quality (top of the PC1/PC2 plot – Figure 3C). If conditions are favourable (vegetation establishment, water and nutrient supply from low magnitude depositions events) a soil starts to form (towards the lower right corner of the PC1/PC2 plot – Figure 3C) and eventually form a mature terrace soil (Figure 4). However, young deposits can also get buried before pedogenic alteration occurred due to high magnitude events (taking a position in the left corner of the point cloud). Burial or erosion and re-deposition of pedogenically altered material can also occur whilst following the pedogenic trajectory, indicated by the presence of Ahb (buried surface horizons) and M (organic matter enriched sandy deposits) horizons in the right lower to mid right part of Figure 3C. Burial leads to the ageing of the organic matter pools of the ancient surface (Ahb) (e.g. Schaetzl and Anderson, 2005). The rates of ageing, thus following positive PC2 (A4 and R-Index), diminish in relation to the availability of unstable organic matter compounds and because of the missing fresh organic matter input. The thick organic matter enriched sandy deposits (M) may also contain rather stable compounds, because they tend to be attached to sand particles (e.g. Asselman and Middelkoop, 1995; Pinay et al., 1995; Steiger and Gurnell, 2003).

The geomorphic activity in this area of the plot suggests that there are close interactions between geomorphic processes and braided alluvial soil evolution. Especially during early stages of braided alluvial pedogenesis these appear critical. Major geomorphological events might reset the system, through either deposition or erosion. However, weaker deposition events may supply organic matter enriched fine sediments (Cabezas and Comín, 2010; Langhans et al., 2012; Pinay et al., 1992; Steiger and Gurnell, 2003) forming cumulic soils (Daniels, 2003; Jacobson et al., 2005), and act as an exogenic organic matter source that can accelerate initial ecosystem processes (Bätz et al., 2014a). This processes can potentially be facilitated by the engineering action of vegetation, thus during the biogeomorphic phase proposed in the biogeomorphic succession model of Corenblit et al. (2009).

Bätz et al., (2014b) reconstructed the geomorphological, soil evolutionary and vegetation successional development of a section which includes profile 15 of this study. High temporal frequency historical images were used to infer past geomorphological changes. These were combined with a 2D grain size distribution model (Electrical Resistivity Analysis - ERT) of the entire section and soil profile 15 of this study to deduce soil maturity and distribution. The analysed section is characterised by two distinguished areas. A first low altitude zone with shrubby willow stands and a soil covered surface (Ah/M/C profile); this site can be attributed to the biogeomorphic phase proposed in the biogeomorphic succession model of Corenblit et al. (2009). A second higher elevated gravel/cobble barren surface with only a few grass stalks with no soil. The historical images show that the barren higher located area formed about 10 years before sampling. The lower located soil covered area was been created 8 years before sampling and experienced sand aggradation over the entire period due to the rapid colonisation of river engineering species. If the deposit is not too thick it can be integrated into the soil (Daniels, 2003; Jacobson et al., 2005), then the organic matter component of the deposit may act as an exogenic input. The close interaction between geomorphological processes (fine sediment and resources supply such as organic matter), vegetation development (trapping and fixing sediments with its biomass but also producing fresh litter) and soil processes (nutrient transformation and storage) has led to the rapid development of a more productive local ecosystem. Conversely the older site, which was cut-off from the river supply early, experienced a slow development (Bätz et al., 2014b). This close interaction between these three components during fluvial landform formation has been defined as a coevolutive process (Bätz et al., 2014a; Corenblit et al., 2014, 2009). The time scale of coevolution of the two zones changes due to different rates and forms of interaction between geomorphic processes (deposit quality - Asselman and Middelkoop, 1995; Langhans et al., 2012; Pinay et al., 1995, 1992; Steiger et al., 2001; Steiger and Gurnell, 2003), vegetation colonisation (Corenblit et al., 2011, 2009; Gurnell, 2014; Gurnell et al., 2012) and soil evolution (Bätz et al., 2014a, 2014b; Langhans et al., 2012; Mardhiah et al., 2014).

Similar observations can be made in the point distribution of Figure 3C. Samples 54Ah and 55Ai, with an approximate age of 10 years, estimated by a series of historical images, show similar properties (OM quality/ quantity and grain size) as mature terraces soils (13Ah, 11Ah, 21Ah, >50 years), thus indicating the changes in speed of the biogeomorphic succession due to pedo-biogeomorphic feedbacks. Thus, sedimentation processes appear to either constrain or contribute to initial soil development by facilitating the accumulation of an organic matter stock before isolation from the river flux (shown by the intensity triangles in Figure 4). Initial deposits are commonly very low in organic matter content (Figure 3 – annexe A). Fluvial fresh input of exogenic organic matter may then be a main source. The young deposits in Figure 3, are exposed to (weak) fluvial sedimentary processes. The associated organic matter deposition ages quickly because of the limited fresh input and the relatively high biological activity of alluvial environments (Bullinger-Weber et al., 2007; Guenat et al., 1999; Langhans et al., 2012; Pusch et al., 1998). The more stable litter compounds, such as lignin (A2), accumulate in the topsoil with time (Doering et al., 2011; Langhans et al., 2012) because transformed more slowly into more stable compounds such as humic and fulvic acids and humins (A3+A4) - higher right part of Figure 3C. Moreover, the deposited material, as the M horizon shows, has a high fraction of more stable and resistant humus components (A4 and A5). However, when plants establish and the biomass production increases, the organic matter transformation chain is established and organic matter pools arrange in the order A2-A3-A4 (Annex B), as the position of mature terrace soils in the lower right part of Figure 3C suggests.

Plant colonisation, is particularly dependent on ambient and geomorphic conditions (Cierjacks et al., 2011; Francis, 2007; Gurnell et al., 2012; Hupp and Rinaldi, 2007). These might be favourable from the beginning (e.g. access to water in a gravelly environment) but can also develop within a few decades (e.g. water retention through fine sand or silt deposition), changing the timing in the shift of main fresh organic matter input (exogenic to endogenic as indicated by the intensity triangles in Figure 4). This means that there are locations in which soil evolution can be fast (high exogenic and endogenic input) and others which develop relatively slowly (low exogenic and endogenic input), thus changing the time scale and pathway of landform coevolution processes in gravelly braided river systems.

## Comparison with other river systems and future research challenges

Clearly a major question arises from this research: even though the amounts of total organic matter are relatively low in the most recent deposits (Annexe B) as compared with those sites where in situ production can occur (Cierjacks et al., 2011), are these sufficient to enhance the rate of initial soil-forming processes? Tabacchi et al. (2000) noted that the riparian corridor may be seen as a recycling zone of exogenous inputs coming from the entire upland catchment. They argue that there will be a dependence of fluvial habitats on such organic matter supplies, with supply closely related to geomorphological riverine processes. Cierjacks et al. (2011) found that the difference in organic matter quantity and quality found in alluvial soils of the Danube River (Austria) are related to flooding history. Floods can import significant amounts of particulate OM (Hein et al., 2003). Based on sediment trap analysis of meandering rivers Garonne (France) and Severn (UK), Steiger et al. (2001) and Steiger and Gurnell (2003), found a strong relationship between the quantity of deposit fine grain sizes (silt/clay) and quantity of TOC and organic nitrogen. Only phosphorous showed a dependence on the quantity of deposition, regardless of its grain size distribution. This research also emphasises the importance of the geomorphological setting and flood magnitude in defining the spatial distribution of deposits and related quality (grain size, and the elements NPC) confirming findings of Pinay et al. (1995, 1992). Low magnitude events in constrained meandering river reaches, show deposition peaks on landforms closely located to the main channel (e.g. point bars). As flood magnitude increases, the deposition peak shifts towards higher located and distal fluvial landforms (e.g. side channels, higher benches). However, less constrained and more geomorphologically complex river reaches will have a less clear shift in the sedimentation peak (Steiger et al., 2001; Steiger and Gurnell, 2003).

Cabezas et al. (2010) and Cabezas and Comín (2010) analysed the spatial pattern of deposition in terms of OM quantity/quality and grain size for different landforms of the meandering Ebro River (Spain). Similar to this research historical aerial images were used to estimate landform age and to deduce hydrological connectivity. Moreover, sediment traps were used to quantify fluvial deposits. Results indicated that on old sites, endogenic OM production dominates, while on younger sites river depositional events were the main source of OM. Their results also show that the exogenic input is also dependent on the position in the fluvial landscape, with higher values for fluvially exposed sites (point bars compared to side channels), and from the channel-floodplain morphology.  However, in their research, time since formation was well- correlated with net carbon accumulation (Cabezas et al., 2010; Cabezas and Comín, 2010). This might be related to the higher geomorphological activity of braided river (e.g. avulsion).

Bechtold and Naiman (2009) developed a modelling approach, which combines the CENTURY model for predicting changes in the soil organic matter pools with a simple fluvial deposition model and a forest growth/production model. The model was tested for the meandering Queens River (Washington – USA). Results confirmed that fluvial OM, but also the deposition of fines, are especially important during the first decades of fluvial landform development, because they influence moisture retention and nutrient regime. These results are deemed to be less clear in higher energy systems (Bechtold and Naiman, 2009).

Similar observations have been made by Doering et al. (2011) and Langhans et al. (2012) for the braided Tagliamento River (Italy). Riparian forest and especially vegetated islands have a high productivity. Pre-processed fresh organic matter can then be exported from these sites by wind and fluvial processes and deposited on less productive sites such as river bars. This influx could provide a high quality resource (Doering et al., 2011; Langhans et al., 2012) to initialise ecosystem processes such as soil forming processes, and notably to enhance local weathering processes and plant nutrient availability due to the decomposition processes. Naegeli (1997) has studied the spatial and temporal variability of particular organic matter in gravel bed river deposits of the Necker River in Switzerland. The spatial and temporal variations of particular organic matter stocks were found to be closely related to river dynamics. This resource reservoir can be activated and transformed by microbial activity (Bridge, 1993; Doering et al., 2011; Gregory et al., 1991; Naegeli, 1997; Pusch et al., 1998; Uehlinger, 2000). Especially, earthworms, bacteria, algae and biofilms can transform such organic matter inputs and make resources available for plants (Bätz et al., 2014a; Bullinger-Weber et al., 2007; Pusch et al., 1998). Even if sediments free of fresh organic matter are considered to be highly reactive (as for those found on glacier forefields for instance; Burga et al., 2010; Mavris et al., 2010), the organic matter found in alluvial deposits will provide an even more accessible resource (Bardgett et al., 2007; Gregory et al., 1991; Guelland et al., 2013), potentially functioning as a start-up for plants and thus the biogeomorphological succession. The mycorrhizal fungi symbiosis that *Salicaceae* can establish may further promote resource up-take from the sediment, soil and groundwater stock (Harner et al., 2011, 2010).

Whilst the dynamics of organic matter in fluvial systems have been addressed, there are fewer studies that investigated the extent to which it is important or, more precisely, the conditions under which it is important. For instance, if the source of exogenous organic matter is the erosion of river banks and/or terraces, then this will require the highest flows. Nevertheless, these are the flows that are also likely to mobilise large amounts of sediments, so diluting the organic matter concentration. The large variations of initial substrate (C and M) of our analysis show the large variability of fluvial inputs in terms of grain size distribution and organic matter quality and quantity. Additionally the amount and frequency of the deposition determines whether or not the active river surface aggrades or is even buried (Bätz et al., 2014a). We know very little about organic matter delivery in braided rivers during flood events and its relationship to sediment delivery rates and thus the balance between the benefits (organic matter delivery) and risks (burial) of deposition. If it can be shown that exogenous organic matter does enhance pedogenesis, even at relatively low concentrations, then we may conclude that geomorphological processes not only disturb negatively the soil-vegetation development (through erosion for instance), but may also facilitate, or even trigger, more rapid plant colonisation in braided rivers. In turn, because of the engineering action of plants (Gurnell, 2014; Gurnell et al., 2012) overall landform development speed and trajectory (biogeomorphic succession *sensu* Corenblit et al. (2014, 2009) might be affected.

A second broad group of unanswered questions relates to the likelihood of erosion and burial, which will equally locally reset the surface organic matter dynamics. Deposition is an interesting process, because it may have a range of competing effects. On the one hand, it may progressively aggrade the landform surface and so isolate it from the active river channel (Daniels, 2003; Jacobson et al., 2005). This may make it more stable, inundated less frequently and, provided water supply and nutrient stock does not become a limiting factor, colonised by plants. It is established that typical early colonisers are able to adapt their root network so as to avoid water logging whilst also follow the falling water table to avoid drying (Glenz et al., 2006; Pasquale et al., 2012). But if the deposition is too great, or it involves grains that are too coarse, this may prevent plant recovery and/or development as well as isolate the ancient topsoil from the potential benefits of exogenous organic matter input. Indeed, Gurnell and Petts (2002) proposed an optimal range of (fine) sediment aggradation and vegetation recruitment types (propagules, resprouting of woody debris) that promote rapid fluvial landform development. Similar for the development of a topsoil in a fluvial setting: only deposition events that are within a certain magnitude, frequency and quality (grain size and organic matter) can be integrated into cumulic topsoil (Bätz et al., 2014a; Daniels, 2003; Steiger and Gurnell, 2003).

In relation to erosion, sites closer to the riverine matter flux, will also be exposed to a certain risk; soil profile 15 (Bätz et al., 2014b), for instance, has now been removed by a later channel migration during a large flood in winter 2013. Whilst such a site may have higher resource availability due to riverine matter fluxes, thus a faster pedo-biogeomorphic evolution, it also bears a higher risk of being eroded and destroyed. Hence, braided rivers morphodynamics can be described as a continuous battle between destructive processes (e.g. powerful floods) and stabilising processes (aggradation, vegetation establishment and soil matter transformation) that coevolve (from a landform development perspective) as fast as possible to prevent damage and/or destruction.

# 5. Conclusion

In this paper, we have considered the relationship between geomorphic processes and organic matter processing (humification) in relation to initial braided alluvial soil evolution. Soils form as an emergent property and are deemed to represent the state of ecosystem organic matter processing. In the field, identified soil and sedimentary layers were sampled and analysed in the laboratory for organic matter quality and quantity (Rock-Eval method) and grain size distribution <2mm. Additionally, variables describing the position of the layers in the fluvial landscape, and the rooting density were added to the dataset. To explore possible relations, a principal components analysis has been performed. Results lead to three main conclusions:

1. the amount and quality of organic matter, as well as grain size distributions, may be key variables in understanding pedo-biogeomorphological feedbacks;
2. results suggest that geomorphological processes may add organic matter and fine grained sediments to the normally inert sedimentary sites and change the rate of fluvial landform development (biogeomorphic succession *sensu* Corenblit et al., 2014, 2009). Research needs to establish the extent to which

this additional resource can facilitate initial fluvial landform ecosystem matter turnover processes and soil formation. The enhanced overall ambient conditions (enhanced nutrient and water availability), potentially promotes vegetation growth/succession and eventually may lead to a river independent and self-sustained fluvial landform (e.g. river terrace).

3. data suggest that, during the coevolution mentioned above, there might be a shift from small amounts of external organic matter supply during fluvial deposition (e.g. bars) to large in situ production due to vegetation colonisation and related biomass production (terraces). The extent to which these two organic matter sources interact, changes biogeomorphic succession time scales and pathways.

Although the data show an impact of organic matter dynamics on fluvial landform development, the spatial and temporal variability of these processes is not yet clear. Our future work will focus on quantifying the impact of initial organic matter supply on the vegetation-soil system and its relation to fluvial geomorphic processes. Moreover, the general validity of the concept should be investigated, by trying to identify these processes in other river systems but also, for instance, in alluvial fans.

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