1 **Linking riparian woody communities and fluviomorphological characteristics in a regulated**

2 **gravel-bed river (Piave River - Northern Italy).**

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17

18    **Abstract**

19

20    Gravel-bed rivers featuring a near dynamic equilibrium state usually display a good correspondence

21    between geomorphological and riparian community gradients, whereas long-term human alterations

22    may disrupt these patterns. The aim of this study was to investigate the distribution of woody

23    riparian vegetation on three geomorphic units - floodplains, bars, islands along the Piave River, a

24    gravel-bed river located in Northern Italy suffering from various degrees of human pressure and

25    disturbances. A total of 214 plots (4×4 m) along three cross-sections in each of two sub-reaches of

26    the river were surveyed in order to identify the different morphological units, dendrological

27    characteristics of standing plants and species composition. Three riparian woody communities, with

28    decreasing woody species richness and tree size, were identified by cluster analysis: *Alnion incanae*

29    (n=58), *Salicion eleagni* (n=52) and *Rhamno-Prunetea* (n=27). The first was significantly

30    associated with floodplains and the others with bars. No community showed a relatively stronger

31    association with islands. Linear mixed models showed that the three geomorphic units significantly

32    differed in mean elevation, fine sediment depth and geomorphic persistence, but not all Tukey

33    contrasts were significant and absolute differences in mean elevation above talweg were quite small

34    (< 25 cm). Moreover, the three woody communities were not always related to corresponding

35    geomorphological gradients, which reflected the river's complex history of channel adjustments.

36    Most notably, mean grain size did not differ between either geomorphic or vegetation units. This

37    study therefore indicates that riparian woody vegetation along altered gravel-bed rivers may differ

38    substantially from that characterising near-equilibrium river systems.

39

40    **Keywords:** riparian vegetation; fluvial island; gravel bed river; incised river; channel morphology;

41    regulated river.

42

**1. Introduction**

The role of riparian vegetation in determining the morphology and the morphodynamics of wide river systems has long been recognized (e.g. Hadley, 1961; Brice, 1964; Zimmermann *et al.*, 1967), as well as the relationships between river morphology and vegetation characteristics (Wharton *et al.*, 1982; Hupp and Osterkamp, 1985; Hupp 1988). The type of riparian vegetation and the size of trees and shrubs play a crucial role in increasing bank strength against erosion through soil reinforcement (Simon and Collison, 2002; Simon and Thomas, 2002; Van de Wiel and Darby, 2007), altering flow velocities (Larsen *et al.*, 2009; Folkard, 2011; Nepf, 2012) and direction (Rominger and Nepf, 2011; Zong and Nepf, 2011), dissipating energy by vortices and turbulences (Tanino and Nepf, 2008), and thus influencing fluvial style and channel pattern (Nanson and Knighton, 1996; Millar, 2000). As reported by McBride *et al.* (2010), the impact of vegetation on the river morphology and morphodynamics acts at different scales, ranging from the bank (Hession *et al.*, 2003; Pollen *et al.*, 2004; Rutherfurd and Grove, 2004; Pizzuto *et al.*, 2010; Pollen-Bankhead and Simon, 2010;), to the floodplain (Griffin and Smith, 2004; Smith, 2004; McBride, 2007), up to the entire fluvial corridor (Millar, 2000; Gurnell *et al.*, 2001; Gurnell, 2014).

The influence and impact of vegetation growing on bars, banks and floodplains on channel morphology has been increasingly verified in the field (e.g. Simon and Collison, 2002; Bertoldi *et al.*, 2011; Perignon *et al.*, 2013), both numerically (Murray and Paola, 2003; Li and Millar, 2011) and experimentally (Coulthard, 2005; Tal and Paola, 2007; Braudrick *et al.*, 2009; Tal and Paola, 2010). These studies have begun to directly show the influence of riparian vegetation in stabilizing banks, increasing mean channel depths, significantly reducing the number of channels per river cross-section, and increasing the ecological value of the riverine area. Remarkably, a recent theoretical meandering-braiding transition criterion (Eaton *et al.*, 2010) incorporated riparian vegetation among the other abiotic factors.

While vegetation can influence river morphodynamics, the type and density of vegetation cover is in turn largely dictated by physical processes controlling river dynamics (Hupp and Osterkamp, 1996), such as water discharge, sediment transport, climate and human activities (McBride *et al.*, 2010; Surian *et al.*, 2014). The pattern of riparian vegetation along gravel bed rivers also depends on morphological settings of the river and bank material composition. The marked spatial variability of density, height, species diversity, age and rates of growth reflects the complexity of bed colonization (McBride *et al.*, 2010), the strong influence of sequences and magnitude of floods, and the feedbacks between morphology, vegetation and hydraulics (Hupp and Osterkamp, 1996). In

fact, the distribution of riparian species within the river corridor is usually related to hydrogeomorphic conditions that shape the physical habitat. This is because the distribution pattern is controlled by the tolerance of a species to specific disturbance regimes (Hupp and Osterkamp, 1996; Tabacchi *et al*. 1998; Bendix and Hupp 2000; Gurnell and Petts 2002). The vegetation successions can be strongly affected by mechanical processes of submersion, erosion and sedimentation during floods (Naiman and Décambs, 1997; Tabacchi *et al*., 1998; Corenblit *et al*., 2007).

In addition, a wide array of human pressures acting at both basin and reach scale can substantially influence the morphodynamics and thus the characteristics, types and distribution of vegetation along the river corridor (Hupp, 1992; Shafroth, 2002). A disturbed reach usually reacts by adjusting its morphological pattern to the varied water and sediment input conditions (Surian and Rinaldi, 2003; Comiti *et al*., 2011). For example, analysing the riparian vegetation distribution and diversity along disturbed rivers of Tuscany (Italy), Hupp and Rinaldi (2007) observed different vegetation types in geomorphic units related to stage of channel evolution, and also lower species richness in river reaches suffering intense channel incision and narrowing.

The assessment of riparian vegetation structures is of crucial importance for evaluating the hydromorphologic conditions of rivers (Kollmann *et al*., 1999; Ward *et al*., 1999; Gurnell, 2014). For instance, in the European Water Framework Directive, the structure of the riparian vegetation is explicitly mentioned as a hydromorphologic parameter required for classifying the ecological status of a river system, with host plant communities designated as priority habitats in Europe's Natura 2000 conservation strategy (European Commission, 2013). However, apart from a few pioneering studies, little evidence on vegetation patterns in altered and rapidly changing river systems is available in the literature. In particular, little is known about vegetation dynamics on islands and bars in gravel-bed rivers (Gurnell *et al*., 2001; Collins and Montgomery, 2002; Gurnell *et al*., 2012; Dufour *et al*., 2015). Vegetation dynamics on islands and bars is considered an effective indicator of functional stability and more general floodplain ecosystem health, which can be strongly affected by human pressure. Indeed, islands in many rivers of the Alps and other European mountainous regions are an endangered attribute of floodplain corridors (Gilvear *et al*., 2008). There is therefore a need to study the interaction between gravel bar geomorphology and vegetation development on a wider spectrum of regulated rivers than those identified in less disturbed river systems (Hupp and Osterkamp, 1996; Tabacchi *et al*., 1998; Bendix and Hupp, 2000; Gurnell and Petts, 2002), with sampling methods capable of delineating cross-section variability in geomorphology and riparian vegetation (Harris, 1988).

Usually, the natural spatial succession of woody communities from the floodplain to the channel conforms to a profile where higher-elevation floodplains belong to developed tree communities, while lower-elevation and more disturbed islands and bars are covered by pioneer shrub communities or only by sparse annual herbaceous plants. For example, the profile that Pedrotti and Gafta (1996) provide for the middle course of the Tagliamento River, one of the most near-natural gravel-bed rivers in Europe (Lippert *et al*., 1995; Müller, 1995; Ward *et al*., 1999), shows that the bars and islands have only patchy communities belonging to pioneer shrubby willow communities. Moreover, Gilvear *et al*. (2008) demonstrated that elevation above talweg and grain size are the most important variables controlling the moisture on in-channel vegetated patches, and hence morphological and sediment diversity are important factors supporting plant species richness and habitat diversity.

Here we use cross-wise transects to assess the distribution of woody riparian vegetation on three geomorphic units in the Piave River, a gravel-bed river located in northern Italy, subjected to various types of human pressures, most importantly gravel extraction and hydropower generation. The main aims of the paper are to investigate, in a disturbed gravel-bed river: i) the riverine vegetation structure along two different sub-reaches; and ii) the relationships between woody vegetation structure and morphological characteristics. We then compare our results with existing studies carried out in less disturbed rivers. We hypothesize that in human-altered rivers, the relationships between morphological/sedimentary structure and woody vegetation characteristics, and the resulting cross-sectional vegetation profiles, are more complex than in near-equilibrium systems.

**2. Study area**

**2.1. The Piave River (Eastern Italian Alps)**

The Piave River is one of the most important and largest rivers in north-eastern Italy (Fig. 1). It flows for 222 km from its source in the Alps at about 2000 m a.s.l.) to the Adriatic Sea. The drainage basin is mainly composed of sedimentary rocks (predominantly limestone and dolomite) and has an area of 3899 km$^2$. Morphologically, the river can be divided into three reaches. An upper reach, confined and with a narrow channel, extends for 62 km from the source to Longarone. A middle reach, where the river is wider and characterized by a transition to multi-thread channel pattern, extends for about 117 km from Longarone to Ponte di Piave. The lower reach, where the

river meanders but has been artificially straightened in places, extends for 43 km to the mouth (Surian, 1999).

The present physiographic setting of the river results mainly from drainage system evolution during the Late glacial and Holocene. Following retreat of the Würmian glacier (15500-16000 years BP), a phase of valley aggradation occurred up to 8000-9000 years BP (Surian, 1996). After that, the river in the Vallone Bellunese began to incise into the deposits, to form a series of terraces (Carton *et al*., 2009).

The upper Piave basin has been inhabited since prehistoric times. Its forest cover reached a minimum probably during the 19th century because of wood harvesting, cropping and farming. During the 1930s-1950s dams were built along its channel network, intercepting sediments from 54% of the basin area. Between the 1960s and 1980s there was intense gravel mining. Natural and artificial reforestation has been taking place since World War I, most effectively after the 1950s. Erosion and torrent control works started in the 1930s, but massively only after the 1970s. In recent times, abandonment of management has led to forest stand aging and expansion in several areas of the basin (Sitzia *et al*., 2012).

The Piave River underwent a strong narrowing tendency during the last century that led the former braided pattern to change to a wandering/single-thread morphology, leaving large areas available for the establishment of riparian forests (Comiti *et al*., 2011).

**2.2. The Piave River study reaches**

The analysis was conducted along two sub-reaches of the middle reach of the Piave River, within the "Vallone Bellunese" (Fig. 2), where the river is quite dynamic, with frequent channel migrations and bar and island modifications (Comiti *et al*., 2011, Picco *et al*., 2014). The river features a complex pattern of vegetation distribution along the analysed reach (Picco *et al*., 2012).

The upper study sub-reach is located near Nogarè (Belluno), at around 360 m a.s.l., while the lower sub-reach is located just downstream of the confluence of the Cicogna Creek (60 km² basin) into the Piave River, at around 316 m a.s.l., near Praloran (Belluno). The upper and lower sub-reaches are called Belluno and Praloran, respectively.

The Belluno sub-reach has a length of around 2 km, a median gradient of around 0.0033 m m$^{-1}$, a maximum active channel width of 550 m and features a predominantly braided morphology. It is characterized by the presence of several islands of different ages and sizes, with a large, complex established island in the middle (Picco *et al*., 2014). There is a groyne built in the 1940s now part of

175 a low terrace on the right bank of this sub-reach, and another more recent structure is located just

176 upstream. The left bank of the sub-reach instead consists of a higher post-glacial terrace.

177 The Praloran sub-reach has a total length of about 1.8 km, a mean gradient of 0.0048 m m$^{-1}$, a

178 maximum active channel width of about 350 m, and a predominantly wandering morphology. This

179 sub-reach has fewer islands than the Belluno one, but there is an extended vegetated bar, covered

180 mainly by annual herbaceous vegetation, in the middle on the right side. The left bank is

181 characterized, for almost its total length, by the same ancient terrace as in the upper study area.

182 There is also a bank protection along the left side of the sub-reach.

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184 **3. Materials and methods**

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186 **3.1 Data collection**

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188 Three cross-sections were selected as being representative of their respective sub-reaches, i.e.

189 featuring all the morphological units within the sub-reach, including islands (Fig. 2). The cross-

190 sections were topographically surveyed in 2010, using a Differential Global Positioning System

191 (DGPS) (average accuracy ± 0.025 m). The surveyed length of the cross-sections ranged from 266

192 to 770 m, as the endpoints were determined by the lateral extent of the floodplain as defined by

193 topographic, soil, and hydrological characteristics.

194 Within the cross-sections, 4×4 m plots spaced 10 m apart were identified along transects. The plots

195 position was surveyed with DGPS. All plots were precisely identified in the field using tapes and a

196 compass in order to establish a squared plot area. The amount of plots per cross-section ranged from

197 19 to 55. Overall, 214 plots were surveyed, 186 of which were on islands, bars or floodplains, and

198 137 of these 186 plots contained at least one woody species. All woody species found on plot areas

199 were recorded and diameter at breast height (DBH) and height of all individuals with DBH > 3 cm

200 were measured. On each plot featuring a developed soil, its depth was determined by digging a

201 small trench down to the gravel layer. On plots featuring coarse sediments (gravel), the grain size

202 distribution of the surface layer was calculated by measuring the b-axes of at least 30 coarse

203 elements. The discrete geomorphic units relative to each plot were classified in the field based on a

204 combination of characteristics such as elevation above talweg, size of bed material and vegetation

205 cover. Main and secondary channels were identified as low-relief areas of the cross-sections

206 featuring an obvious preferential flow path. Bars were identified as higher-relief gravel units

207 exposed at lower flows, either bare or supporting only annual vegetation and a small accumulation

208 of river-transported plants and large wood. Islands were identified as sparse to densely-vegetated
209 areas surrounded by channels or bars. Their surface was large enough to support woody vegetation
210 with a developed canopy. Floodplains were identified as those fluvial landforms at the channel
211 edges with a surface consisting of fine sediments (in this case sand) and vegetation cover. Along the
212 Piave River, channel incision during the late 20th century transformed the pre-incision floodplains
213 (formerly inundated every 1-3 yr) to less frequently flooded low terraces in contrast to the post-
214 glacial high terraces. However, these recent terraces were considered floodplains in this study.

215 In order to establish the persistence of each geomorphic unit, a multi-temporal analysis was
216 performed using aerial photos of the same areas dating to 1960, 1970, 1980, 1991, 1999, 2006, and
217 2010, which were considered year classes from 0 (2006) to 5 (1960). Each plot was then identified
218 on the most recent aerial photo (2010) and the minimum geomorphic persistence of each surface
219 was calculated comparing the vegetation cover in the older photos (Vitti, 2010; Picco *et al*., 2012).

220

221 **3.2 Data analysis**

222

223 Each plot was associated to a dominant morphological unit, and characterized by sediment depth,
224 grain size of coarse sediments, and properties of the vegetation cover. A hierarchical cluster
225 analysis using Ward linkage based on Bray-Curtis dissimilarities was applied to woody species
226 composition data in order to search for homogeneous relevé groups that emphasized overstory trees
227 and shrubs, which were felt to be responsive to geomorphic conditions. To assess the strength of the
228 association between single woody species and the communities we conducted an indicator species
229 analysis with $\alpha=0.05$ (De Cáceres and Legendre, 2009). As a measure of association, we used the
230 Pearson's phi coefficient of association corrected for unequal group sizes (De Cáceres, 2013). The
231 statistical significance of each relationship was verified by a permutation test described in Dufrêne
232 and Legendre (1997) with 999 permutations.

233 To show the distribution patterns of the woody communities along the surveyed transects, we first
234 drew cross-section one-dimensional profiles of the vegetation along the centreline of each transect
235 where we reproduced the most frequent and continuous blocks of vegetation types.

236 Continuous variables were summarized by geomorphic and plant community type in the form of
237 means to enable comparisons among types. Because plots were nested within sub-reaches, the use
238 of a random effects model was necessary to take into account the correlation within plots belonging
239 to the same sub-reach, by assigning a random effect for each plot within each sub-reach. We first
240 applied linear mixed models (LMM), after transformation of the original values, where needed. In

some cases, violations of assumptions, led to choosing generalized linear mixed-effects models (GLMM). The number of woody species was therefore modelled using a Poisson error structure, and a binomial model was applied to fine sediment depth, which was grouped in the presence or absence of fine sediments.

For the stands, the larger the DBH and height, the larger the variation of their residuals was. We therefore allowed for wider residual spread if DBH or height increased, through the command varFixed of the function lme {nlme} in R software (R Core Team, 2013). Akaike's information criterion favoured the second model (Zuur *et al.*, 2009). Multiple comparisons were tested using the Tukey all-pair comparisons between the types.

Finally, we tested the association between morphological and plant community types with Fisher's exact test and plotted the results on a mosaic plot, which displays the standardized residuals of a log-linear model of the counts by the colour and outline of the mosaic tiles (Crawley, 2007).

All analyses were performed by the software R (R Core Team, 2013) using the function hclust of the package 'stats' 3.0.2 (R Core Team, 2013) for the cluster analysis, function multipatt with func = "r.g" of the package 'indicspecies' 1.7.1 for IndVal analysis (Dé Caceres and Legendre, 2009), function lme of the package 'nlme' 3.1-115 for LMM (Pinheiro *et al.*, 2014), function glmer of the package 'lme4' 1.1-5 for GLMM (Bates *et al.*, 2014), function glht of the package 'multcomp' 1.3-2 (Hothorn *et al.*, 2008) for Tukey all-pair comparisons and the function mosaicplot of the package 'graphics' 2.15.3 (R Core Team, 2013) for the mosaic plots.

**4. Results**

**4.1. Vegetation analysis**

The cluster analysis revealed three relevé groups at a height of 8, which corresponded to three woody communities that we called: Alninc (n=58), Acecam (n=27) and Saldap (n=52). Their indicator species are reported in Tab. 1. The Alninc group includes riparian woodlands dominated by grey alder (*Alnus incana*) with other species belonging to the *Alnion incanae*. The Saldap group is associated with violet willow (*Salix daphnoides*) and includes the first pioneers of riparian woodlands belonging to *Salicion eleagno-daphnoidis*. The Acecam group associated species is field maple (*Acer campestre*), and shards many species with the Alninc group. Acecam represents a recent secondary community transitional between the Alninc and Saldap groups, belonging to the *Rhamno-Prunetea*, where pioneer trees and shrubs, both native species like field maple, hazel

(*Corylus avellana*), dogwood (*Cornus sanguinea*) and alien like black locust (*Robinia pseudoacacia*) and butterfly bush (*Buddleja davidii*) dominate, and other tree species are still developing in the understory. This was confirmed by their stand attributes (Fig. 3). In fact, mean diameters (Fig. 3a) and heights (Fig. 3b) were greater in Alninc (10.6 cm and 7.8 m, respectively) if compared both with Acecam and Saldap ($P < 0.001$, Tukey contrasts), while Saldap (4.2 cm and 2.6 m, respectively) and Acecam (3.8 cm and 2.8 m, respectively) did not have significantly different stand attributes. Woody species richness (Fig. 3c) followed the trend: Alninc > Saldap > Acecam ($7.7 > 3.1 > 2.2$) ($P < 0.05$ for all the corresponding Tukey contrasts).

The Alninc and Saldap groups may include the Natura 2000 habitats 91E0 (priority) and 3240, respectively, while the Acecam may belong mostly to the 3240 habitat (see also Lasen *et al.*, 2008). The distributions of trees and shrubs within the cross-sections are depicted in Figure 4, which shows that the spatial distribution of plant communities is quite complex. The Belluno sub-reach is the more complex of the two, with more areas featuring different vegetation patches also between channel and exposed gravel.

**4.2 Morphological units**

The geomorphic classification of the surveyed sections led to the identification of 63 plots on bars, 21 on islands and 53 on floodplains. For each of these morphological units, the height was defined as the elevation above the talweg of the main channel. From the mixed models, floodplain plots resulted as being significantly higher than bars ($P < 0.05$, Tukey contrasts), but with small absolute differences (2.08 vs. 1.83 m). Islands were marginally significantly higher than bars ($P = 0.052$, Tukey contrasts), with an absolute difference of mean values of only around 24 cm. On the other hand, islands and floodplain appeared to lie at similar elevations (Fig. 5a), and featured not significantly different probability of fine sediment occurrence. As expected, bars featured a lower probability of fine sediment occurrence ($P < 0.001$, Tukey contrasts) (Fig. 5b). The three morphological units did not significantly differ in mean grain size (Fig. 5c). Finally, as indicated by the analysis of aerial photos, the geomorphic persistence followed this trend: floodplains > islands > bars ($P < 0.001$ and $P < 0.05$ for Tukey contrasts with bars, and between floodplains and islands, respectively) (Fig. 5d).

**4.3 Relationship between vegetation communities and morphological characteristics**

The mean elevation of Saldap (1.78 m) resulted as being significantly lower than Alninc (2.11 m) (P < 0.01, Tukey contrasts). However, the absolute differences were relatively small. Moreover, Acecam (2.00 m) did not lie at elevations significantly different from Saldap and Alninc (Fig. 6a). Sampling areas with a measurable depth of fine sediments were significantly more frequent in Alninc (91%) than in the other two groups (P < 0.001, Tukey contrasts), while Saldap and Acecam showed similar frequencies (50% and 41%, respectively) (Fig. 6b). Mean grain size (Fig. 6c) was not significantly different among the groups. Alninc was significantly more frequent on longer persistent sites than the other two (P < 0.001, Tukey contrasts), which did not display any significant difference between one another (Fig. 6d).

The mosaic plot (Fig. 7) indicated that Saldap and Acecam were significantly more associated with bars than expected with independence, while Alninc and Saldap were significantly less represented on floodplains. Island units were not univocally associated with any of the three communities.

**5. Discussion**

Previous studies have shown that geomorphological processes provide the framework for vegetation development on gravel bars. For example, Bendix and Hupp (2000) demonstrated that there is a strong relationship between floods, seed transport, bar formation, forest development and riparian species richness. Also, Gilvear *et al*. (2008) observed that morphological and sediment diversity are important factors supporting high species richness and a high range of mosaic habitats. However, the evidence has usually been collected in relatively undisturbed rivers.

In our study, as expected, the presence of a fine sediment layer was related to areas associated with tree species belonging to relatively mature communities (e.g. *Alnus incana*, *Acer pseudoplatanus*, *Quercus robur*). However, no clear relationships were found between topographic elevations or morphological units, and mean grain size of sediments. Because riparian vegetation and large wood accumulations typically interact with flows allowing the deposition of finer sediments (Kollman *et al*. 1999), a higher frequency of fine sediment layers on floodplain and island plots than on bars was expected. The analysis revealed that, in a heavily disturbed gravel-bed river such as the Piave, vegetation communities associated with both highly dynamic (bars) and stable (floodplains) units grow on surfaces with different geomorphic persistence (Fig. 5d) but relatively similar elevations. For instance, Gilvear *et al*. (2008) measured approximately the same elevation above low water stage of around 40 cm, within a single gravel bar in the wandering gravel-bed Tummel River. Overall, the Piave River showed a complex pattern of vegetation distribution along the cross-

sections, with no clear relationship between elevation and plant communities. This contrasts with the typical plant species distribution patterns dependent on specific fluvial landforms and processes that have been identified in less disturbed river systems (Osterkamp and Hupp, 1984; Hupp and Osterkamp, 1996; Tabacchi *et al*., 1998; Bendix and Hupp, 2000; Gurnell and Petts, 2002, Gilvear *et al*., 2008). In particular, the pattern does not conform to the profile presented by Pedrotti and Gafta (1996) for the Tagliamento River, a less disturbed river system, as hypothesized in the introduction. It is thus likely that the typical vegetation-landform association is not respected in the studied river due to its complex history of channel adjustments.

Indeed, a comprehensive study (Comiti *et al*., 2011) using historical maps, aerial photos, repeated topographic measurements and geomorphological surveys revealed that the river underwent a strong narrowing during the 20th century with an associated shift from a dominant braided pattern to a wandering morphology. This change was associated with a moderate to intense bed incision mostly connected to the gravel mining activities (Comiti *et al*., 2011), typical of many Alpine rivers (Comiti, 2012; Campana *et al*., 2014).

Large areas of the former active channel were colonized by riparian forests, both as islands and as marginal woodlands. The end of gravel extraction in the late 1990s seems to have determined a reversal or at least a halt in this evolutionary trend, with evidence of vegetation erosion/channel widening (Comiti *et al*., 2011).

This complex series of planimetric and vertical adjustments, and especially the recent active channel widening and aggrading tendency may help to explain why patches dominated by species belonging to relatively mature communities (e.g. *Alnus incana*, *Acer pseudoplatanus*, *Quercus robur*) lie at elevations similar to areas covered by species belonging to pioneer plant communities (e.g. *Salix eleagnos* and *S. daphnoides*).

Even if vegetation types seem unrelated to strong differences in elevation, the analysis revealed interesting differences in persistence between different morphological units. In fact, even if floodplains, islands and bars lie at relatively similar elevations, floodplains persist for longer. Also, despite the fact that the sand layer is deeper on islands and floodplains, islands are more recent. This is in agreement with the fact that there is a significant difference in plant communities associated with floodplains and bars, while islands are not associated with a distinct plant community, suggesting that floodplains and islands formation and dynamics are fundamentally different. In fact, the present islands in the Piave River are generated by a process of vegetation growth and surface aggradation (building islands) rather than from floodplain dissection, and no woody communities clearly dominate, as the association plots demonstrated (Fig. 7).

373      Building islands result from the progressive development of a vegetation cover and accumulation of
374      fine sediment around sprouting trees lying on bars. In contrast, because floodplain dissection islands
375      are created during major flood events, they usually have a flatter cross-profile, and a relatively even
376      tree age structure and geomorphic persistence (Gurnell *et al.*, 2001). The fact that most of the
377      islands are relatively young could be due to the recent phase of active channel widening, which has
378      occurred over the past 20 years. This permitted both large wood recruitment from bank erosion -
379      necessary for creating the pioneering cores - and the chance for building islands to resist the erosive
380      force of ordinary floods.

381      Parallel to the substantial active channel narrowing and incision, the proportion of the fluvial
382      corridor covered by vegetation at/along the channel banks significantly increased during most of the
383      20th century. These extensive mature riparian areas within the fluvial corridor have beneficial
384      effects on the overall ecological potential of the area, and are in fact sometimes protected, e.g. there
385      is a riparian reserve a few kilometres downstream where a dyke was built to protect several priority
386      Natura 2000 habitats from erosion (Sitzia, 2008). However, these forested areas lie on former active
387      channel portions of the river corridor and their protection could hamper efforts directed at
388      promoting river restoration through channel expansion and aggradation. Furthermore, they could
389      represent significant sources of large wood if eroded and transported downstream during major
390      flood events.

391

### 392      6. Conclusions

393      This study indicates that riparian vegetation along an altered gravel-bed river can differ
394      substantially from undisturbed river systems. In the Piave River a clear cross-sectional transition
395      from older to younger pioneer communities – following a corresponding gradient from higher to
396      lower morphological units – is lacking, most likely reflecting the complex history of human-
397      induced channel adjustments in the river system. This contrasts with the typical trend in near-
398      equilibrium rivers, where elevation above talweg and grain size are the most important variables
399      controlling the moisture for in-channel vegetation patches.

400      However, the conclusions of our study can be based solely on a descriptive comparison with the
401      existing literature on undisturbed rivers, due to the lack of multi-temporal analysis of vegetation
402      dynamics associated to morphological adjustments in the studied river. These limitations call for a
403      better understanding of how vegetation reacts to natural and human impacts in order to increase our
404      ability to predict the response of river systems to flood events, and to assess the effects on river
405      dynamics from different management strategies of riparian vegetation and river restoration

schemes. Moreover, this requirement for an improved understanding is also enhanced by the need to better predict river system and ecological habitat response to environmental change, notably climate, land use alterations and spontaneous forest expansion (Sitzia *et al*., 2010).

Future studies should be conducted along other cross-section profiles on rivers, analysing a gradient of vertical, lateral and longitudinal dimensions of the channel, and a patch hierarchy of different channel types, morphological and vegetation units (van Coller *et al*., 2000) as well as levels of human disturbance. This will further explain the main variation in vegetation pattern as related to fluvial processes and regulating actions, notably climate, landscape pattern alterations and spontaneous forest expansion (Sitzia *et al*., 2010; Sitzia and Trentanovi, 2011).

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**Table captions**

643

644    Table 1: Indicator woody species (α= 0.05, 999 perm.) of three riparian communities identified

645    along three sub-reaches of the Piave River, north-eastern Italy (Alninc: *Alnion incanae*, Acecam:

646    *Rhamno-Prunetea*, Saldap: *Salicion eleagni*). In grey: the combination of relevé groups most

647    strongly related to the species pattern.

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**Figure captions**

Figure 1: The Piave River basin in north-eastern Italy.

Figure 2: Location and aerial photo of the analyzed sub-reaches along the Piave River basin, the cross-sections analysed in the study areas are also shown.

Figure 3: Box-and-whisker plot of stand variables in each of three riparian communities (Alninc: *Alnion incanae*, Acecam: *Rhamno-Prunetea*, Saldap: *Salicion eleagni*) identified along three sub-reaches of the Piave River, north-eastern Italy. Horizontal line: median. Box margins: 25th and 75th percentiles. Outliers are plotted individually. Letters represent the results of Tukey all-pair comparisons. In case they were transformed, the values are back transformed to the original ones.

Figure 4: Cross-sections analysed in the Belluno sub-reach (on the left) and Praloran sub-reach (on the right). The left side of all images corresponds to the left bank.

Figure 5: Box-and-whisker plot of morphological variables in each of three morphological units (ba: bars, fp: floodplain, is: island) identified along three sub-reaches of the Piave River, north-eastern Italy. Horizontal line: median. Box margins: 25th and 75th percentiles. Outliers are plotted individually. Letters represent the results of Tukey all-pair comparisons. In case they were transformed, the values are back transformed to the original ones.

Figure 6: Box-and-whisker plot of morphological variables in each of three riparian communities (Alninc: *Alnion incanae*, Acecam: *Rhamno-Prunetea*, Saldap: *Salicion eleagni*) identified along three sub-reaches of the Piave River, north-eastern Italy. Horizontal line: median. Box margins: 25th and 75th percentiles. Outliers are plotted individually. Letters represent the results of Tukey all-pair comparisons. In case they were transformed, the values are back transformed to the original ones.

Figure 7: Mosaic plot showing departures from expectations of the observed frequencies in a contingency table between proportions of plots in each morphological (Umorf) and vegetation unit (Clus_veg). The figure shows the standardized residuals of a log-linear model of the counts by the colour and outline of the mosaic tiles. Negative residuals are in shades of red with broken outlines,

while positive residuals are in shades of blue with solid outlines. Alninc: *Alnion incanae*, Acecam: *Rhamno-Prunetea*, Saldap: *Salicion eleagni*. Ba: bars, fp: floodplain, is: island.
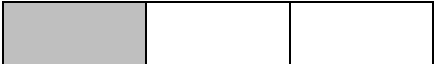
736   Table 1

| Woody plant communities | | | | | |
| Alninc (n=58) | Acecam (n=27) | Saldap (n=52) | Species | IndVal | p-value |
| --- | --- | --- | --- | --- | --- |
| | | | *Alnus incana* | 0.607 | 0.001 |
| | | | *Acer pseudoplatanus* | 0.478 | 0.001 |
| | | | *Frangula alnus* | 0.477 | 0.001 |
| | | | *Fraxinus ornus* | 0.422 | 0.007 |
| | | | *Quercus robur* | 0.406 | 0.009 |
| | | | *Lonicera xylosteum* | 0.397 | 0.001 |
| | | | *Picea abies* | 0.397 | 0.007 |
| | | | *Euonymus europaeus* | 0.324 | 0.018 |
| | | | *Cornus sanguinea* | 0.7 | 0.001 |
| | | | *Robinia pseudoacacia* | 0.517 | 0.001 |
| | | | *Fraxinus excelsior* | 0.471 | 0.001 |
| | | | *Corylus avellana* | 0.447 | 0.002 |
| | | | *Acer campestre* | 0.369 | 0.02 |
| | | | *Buddleja davidii* | 0.438 | 0.007 |
| | | | *Salix daphnoides* | 0.369 | 0.02 |

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