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Geomorphic effects of wood quantity and characteristics in three Italian gravel-bed rivers

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ABSTRACT

In-channel wood is a fundamental component of the riverine system. Its nature, abundance, and distribution as well as the role of wood in trapping sediment have been reported by many authors. However, a lack of knowledge still exists on how the geomorphic effects, quantity, and characteristics of in-channel wood may be altered by different human pressures. For this reason, in-channel wood was surveyed in the Brenta, Piave, and Tagliamento gravel-bed rivers (northeastern Italy), which are altered by different degrees of human pressures. Both single pieces of wood (>0.1 m diameter, and/or >1 m long) and accumulations of large wood were measured on cross sectional transects within the active channels. Overall, 3430 (8.4, 13.9 and 10.7 elements/ha in the Brenta, Piave, and Tagliamento rivers, respectively) of isolated pieces and 591 (9.8, 15.0, and 11.0 wood accumulations/ha in the Brenta, Piave, and Tagliamento rivers, respectively) accumulations were surveyed in the study sites. In the Brenta and Piave rivers, which feature the greater human pressures, logs appear in a worse state of conservation. In the less disturbed Tagliamento River, the logs appear to be smaller and in a better state of conservation with higher capacity for resprouting. In addition, higher geomorphic interactions were found between wood and sediments in the Tagliamento River. Because of its ability to create geomorphic effects, in-channel wood represents an important source of complexity that can increase habitat diversity in river systems. A better knowledge of the role of human disturbances on the characteristics and abundance of large wood in river systems could help in developing better river management and the practical application of river ecology.

1. Introduction

In-channel wood enhances the dynamics of the river network, exerting substantial geomorphic and ecological functions (Harmon et al., 1986; Gregory et al., 2003). Pieces of wood are recruited from basin hillslopes (e.g., windthrow, landslides, debris flows) or may be eroded from the banks, and whilst in the river network they can float downstream (Abbe and Montgomery, 1996, 2003; Braudrick and Grant, 2000). Logs can be trapped, remaining stable in the active channel (Mazzorana et al., 2009) and, in turn, stabilizing some sectors of that channel (Abbe and Montgomery, 2003). If able to capture and trap other floating elements, these logs create wood jams (WJ) of which they can be considered the key elements (e.g., Nakamura and Swanson, 1993; Abbe and Montgomery, 1996). Based on different wood characteristics, Abbe and Montgomery (1996) classified jams as autochthonous, allochthonous, or mixed (depending on the origin of the jammed logs) and identified three different common types of wood accumulations in the Queets River (bar top jam, bar apex jam, and meander jam), suggesting that in large braided rivers the large wood is often retained on top of the gravel bars. Single pieces of wood are mainly located at the channel margin, along the edge of islands and floodplains or along concave banks (Piégay, 2003). In-channel wood may change local sediment transport and budget (Buffington and Montgomery, 1999; Gurnell et al., 2002; Wohl, 2013) and modify the channel form and floodplain structure, creating channel avulsions and enhancing the formation of pioneering islands (Montgomery et al., 1995, 2003; Abbe and Montgomery, 1996; Piégay and Gurnell, 1997; Brooks et al., 2003; O'Connor et al., 2003). Large wood can also exert a considerable ecological function, as it contributes to the creation of habitat diversity, helps the regeneration of various riparian plant species (Naiman et al., 1988), and represents a source of biomass (Francis et al., 2008; Wohl, 2013). Abundance and characteristics of in-channel wood in gravel-bed rivers have been investigated by Piégay et al. (1999) who measured between 16 and 64 m^3 ha^{-1} of large wood storage in the Drôme (France) and by Wyzga and Zawiejska (2005) who reported volumes up to 33 t ha^{-1} in wide braided sections of the Czarny Dunajec River in Poland. As the amount of wood can vary considerably between rivers (Gurnell, 2013), the knowledge of how wood interacts with fluvial processes over time (i.e., wood budgets) and under different environment conditions could be helpful toward improving management strategies. Despite the positive effects, when logs are transported during flood events, they may be an issue for various

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human activities, for example disturbing the normal navigation (Gurnell et al., 2002; Piégay, 2003) or becoming a potential hazard if they accumulate near sensitive structures such as bridges (Comiti et al., 2008; Ruiz-Villanueva et al., 2014), increasing the scours around the piles (Diehl, 1997; Wallerstein, 1998; Kothyari and Ranga Raju, 2001). For these reasons and because in-channel wood tends to increase roughness (Abbe and Montgomery, 1996), the traditional management strategy adopted in the past was to remove it (Abbe and Montgomery, 2003) and to clearcut vegetation from islands and floodplains. During the first half of the twentieth century, almost all Alpine rivers in Europe were affected by human interventions (Tockner et al., 2003), which still persist in some countries (Ollero, 2013). However, recent research has provided evidence of the positive effects that wood exerts in-channel, leading to a change in the traditional management strategies so that introducing wood into the river channels and managing riparian areas to guarantee wood delivery have now become common practices (Gurnell et al., 1995; Abbe et al., 1997; Hildebrand et al., 1997; Reich et al., 2003; Brooks et al., 2006; Kail et al., 2007; Mao et al., 2008a, 2013). Within this context, a proper knowledge of how large wood affects rivers depends on the degree of human pressures on the river system that could enhance the efficiency of in-channel wood management strategies. For this reason, the present study was conducted in three gravel-bed rivers (Brenta, Piave, and Tagliamento, in northeastern Italy) characterized by similar climatic and hydrologic conditions but different levels of human pressures. Field investigations were performed to explore the characteristics, abundance, distribution, and geomorphic effects of in-channel wood on these rivers. This study aims at relating the degree of human pressures on rivers with the nature and abundance of in-channel large wood in order to shed some light on the effects on wood recruitment, transport, and finally the potential for large wood to exert positive geomorphic roles in river channels.

2. Study area

The research was conducted in three gravel-bed rivers located in northeastern Italy (Brenta, Piave, and Tagliamento; hereinafter B, P, and T, respectively). The three rivers are comparable in terms of climate, geological settings, and vegetation but substantially differ in terms of the level of human disturbance at basin and reach scales.

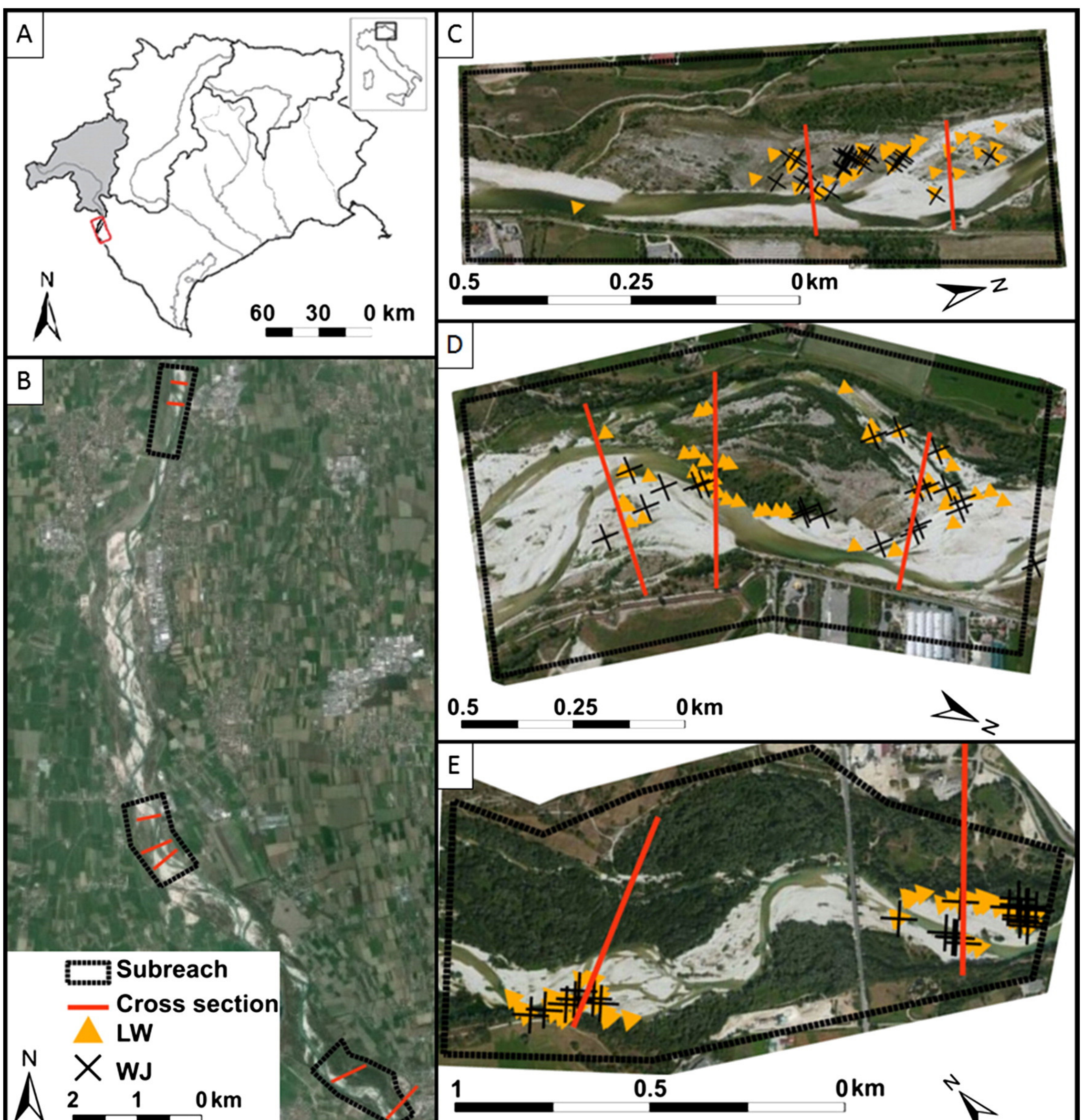

Fig. 1. The catchment of the Brenta River (A), showing the enlargement of the study site (B); planview of Nove (C), Friola (D), and Fontaniva (E) subreaches within the study site.

2.1. Brenta River

The Brenta River basin is located in the eastern Italian Alps (Italy) where the upper part features a typical continental–alpine climate with an annual precipitation of about 1500 mm. The river has a drainage basin of ~1567 km^2. It is 174 km long with an average slope of 0.003 m m^{-1}.

Field surveys were conducted in three subreaches named (from upstream to downstream) after the nearby villages of Nove, Friola, and Fontaniva (Fig. 1). The Nove site is composed of a single straightened channel, and the average width of the active channel is about 300 m with a mean slope (S) and bed sediment grain size (D_{50}) of 0.003 m m^{-1} and 0.037 m, respectively. The Friola subreach features a more complex multithread pattern (~500 m wide, $S = 0.002$ m m^{-1}, $D_{50} = 0.035$ m) with a densely vegetated island. The Fontaniva subreach (~800 m wide, $S = 0.003$ m m^{-1}, $D_{50} = 0.031$ m) features a braided morphology with multiple densely vegetated islands.

2.1.1. Human impacts on Brenta River

Especially during the second half of the twentieth century, intense human interventions such as damming, gravel mining, and torrent control works (see Moretto et al., 2014a) have affected the Brenta River, changing its natural settings (Surian and Cisotto, 2007). Gravel mining has been defined as the most important human action that affected the main channel of the Brenta River, generating a considerable change in sediment fluxes (Surian and Cisotto, 2007). However, in the study reach the slope increased only slightly (0.0033 to 0.0036 m m^{-1}), with channel narrowing being by far the most important river reaction to the reduced supply of sediments from the upper reaches (Surian et al., 2009). At the basin scale, the construction of dams strongly disturbed the Brenta River. The Corlo dam, built in 1954 for hydroelectric power generation and irrigation purposes, reduced sediment and flow discharges downstream (Moretto et al., 2014b). The considerable human pressures on the Brenta basin have impacted the study subreaches, which suffered consistent channel adjustments in response to an alteration of sediment fluxes—the most remarkable being the vertical incision up to 8–9 m and the reduction of 50% of the active channel width (Surian et al., 2009; Moretto et al., 2014b). Especially in the Nove subreach, the river is strongly influenced by artificial embankments and bridges (Moretto et al., 2014b).

2.2. Piave River

The Piave has a basin area of 3899 km^2, and the river is 222 km long with an average slope of 0.004 m m^{-1}. The climate is temperate-humid with average annual precipitation of about 1350 mm.

Surveys of the Piave River were conducted in two subreaches selected in the middle section of the river course where the morphology is dominated by braided and wandering channel patterns. The subreaches are named (from upstream to downstream) Belluno and Praloran (Fig. 2). Belluno subreach is about 2.2 km long and 550 m wide ($S = 0.0033$ m m^{-1}, $D_{50} = 0.045$ m), whereas Praloran is 3.2 km long and 350 m wide ($S = 0.0048$ m m^{-1}, $D_{50} = 0.040$ m).

2.2.1. Human impacts on Piave River

Major dam building, phases of deforestation and reforestation, water diversions, gravel mining, and bank protections have strongly influenced the river (Picco et al., 2012, 2014a). As a result, the river has been exposed to considerable widening and incision phases (up to 2–3 m). Surian et al. (2009) and Comiti et al. (2011) also reported a progressive shift from a dominant braided (multichannel) to a wandering (sensu Desloges and Church, 1989) morphology. However, more

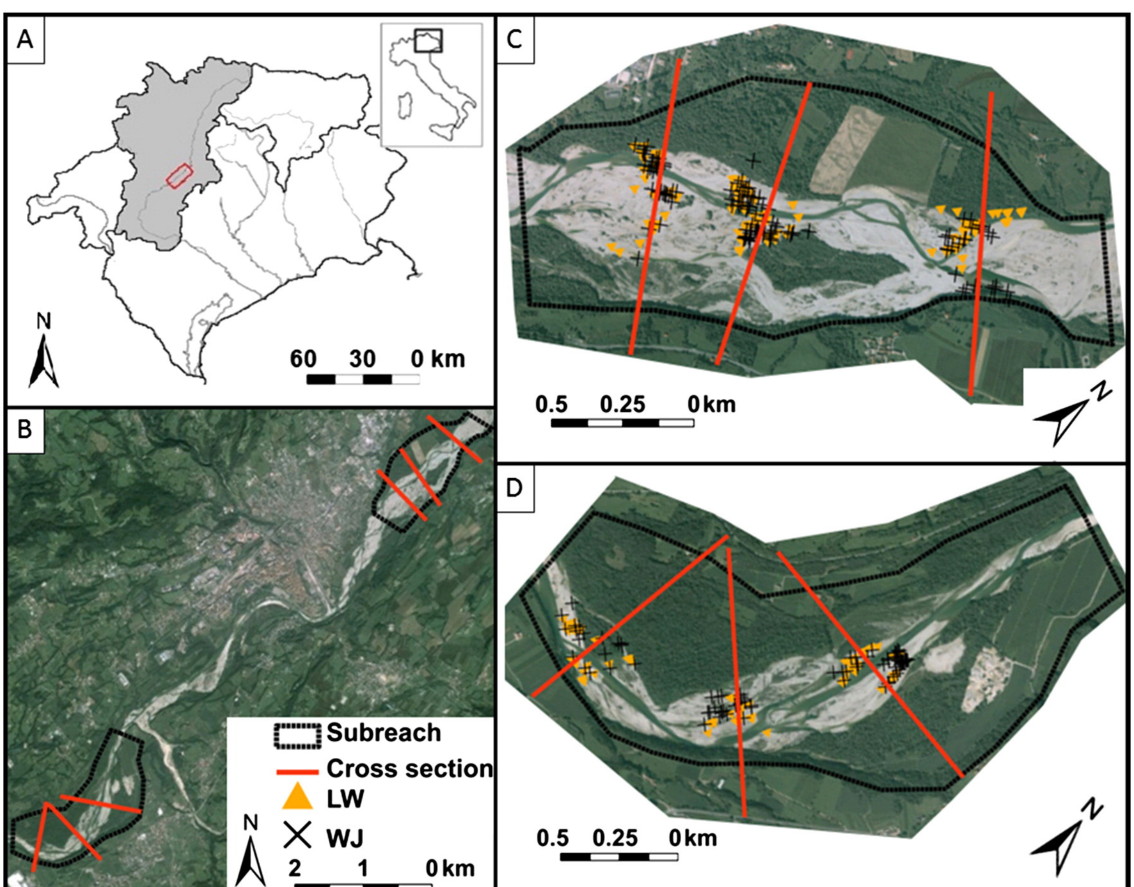

Fig. 2. The catchment of the Piave River (A), showing the enlargement of the study site (B); planview of Belluno (C) and Praloran (D) subreaches within the study site.

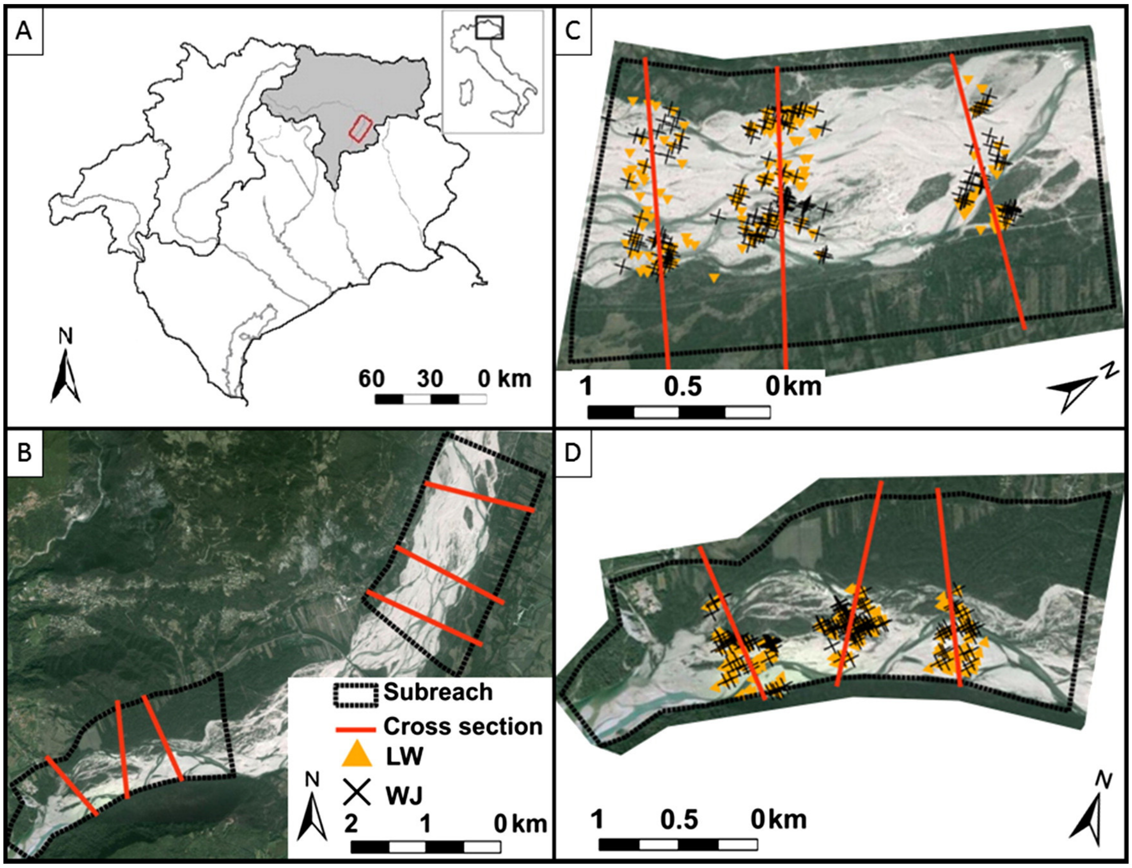

Fig. 3. The catchment of the Tagliamento River (A), showing the enlargement of the study site (B); planview of Cornino (C) and Flagogna (D) subreaches within the study site.

recently this tendency appears to be changing, probably because of the abandonment of gravel mining. Comiti et al. (2011) reported a recent general channel widening with no clear signs of aggradation detected, suggesting that this phase could be defined as a true period of adjustments and not simple morphological changes ascribe to the occurrence of large floods. Changes in sediment supply–generated by the presence of dams, transverse structures, and embankments–can be defined as the key factor for channel adjustments. Instead, gravel mining can increase the bed incision with consequent strong vegetation encroachment that can be removed just during flood events with RI = 10–15 years (Comiti et al., 2011).

2.3. Tagliamento River

The Tagliamento River has a drainage basin of 2871 km^2, a length of 178 km, and a slope varying in the range 0.003–0.005 m m^{-1}. A strong climate gradient (from an alpine to a Mediterranean condition) along the length of the river has an influence on average annual precipitation (from 1000 to 3000 mm), temperature (from 5 to 14 °C), humidity, and consequently vegetation patterns (Tockner et al., 2003). Because of this gradient, the Tagliamento River floodplain is an important biogeographical corridor with a strong longitudinal, lateral, and vertical connectivity; high habitat heterogeneity; a characteristic sequence of geomorphic types; and very high biodiversity (Tockner et al., 2003). Two subreaches, named Cornino and Flagogna (from upstream to downstream) were selected in the Tagliamento River (Fig. 3). The two subreaches have similar flow conditions, longitudinal bed slope (around 0.003 m m^{-1}), and bed sediment grain size (D_{50} = 0.035 m; Bertoldi et al., 2012). The Cornino subreach is around 3 km long and 800 m wide and can be described as a wide bar-braided subreach. The Flagogna subreach is of similar size but features slightly fewer anabranches and a wider main channel because of the larger number and size of established and pioneering islands (Bertoldi et al., 2011).

2.3.1. Human impacts on Tagliamento River

Because of the reduced human impacts compared to other rivers in the region, the Tagliamento is considered one of the few European gravel-bed rivers with high ecomorphological complexity and dynamics (Tockner et al., 2003). As such, several studies have reported its ecological proprieties (Van der Nat et al., 2003), morphodynamics and sediment transport characteristics (Surian et al., 2009; Mao and Surian, 2010; Picco et al., 2013), large wood (Gurnell et al., 2002; Bertoldi, 2012), and riparian vegetation and bar/island dynamics (Gurnell and Petts, 2006; Gurnell et al., 2009; Picco et al., 2014b). The upper reaches

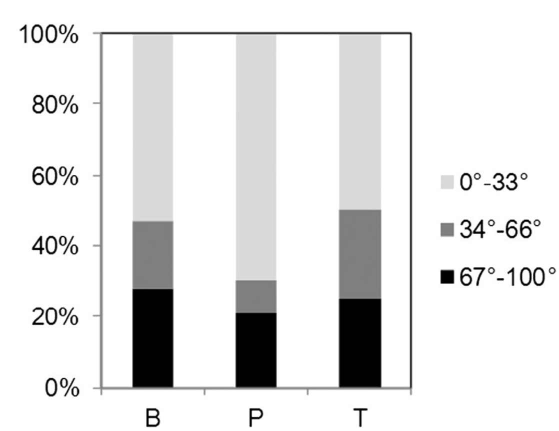

Fig. 4. Orientation of the logs in the Brenta, Piave, and Tagliamento rivers; 0° being parallel to the flow and with the rootwad facing upstream, 100° being parallel to the flow but with the rootwad facing downstream.

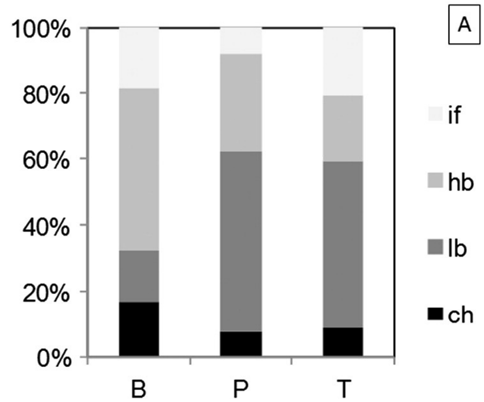

Fig. 5. Percentage of large wood (A) and wood jams (B) distribution in different morphological units on the Brenta, Piave, and Tagliamento rivers (ch: main and secondary channels; lb: low bars; hb: high bars; if: islands and floodplains).

of the river are relatively unimpacted, so the basic river processes such as flooding and sediment erosion/accumulation take place under near natural conditions.

3. Material and methods

3.1. Survey sites

Because of the considerable extension of the selected subreaches, large wood was surveyed on transects around cross sections within the active channel (as previously done, e.g., by Gurnell et al., 2000; Andreoli et al., 2007; Sear et al., 2010). Cross sections were surveyed in June 2010 using a dGPS system, with a maximum vertical error of 0.025 m. All slope changes along the cross sections were measured, with an average point density of 1/3 m of channel width. The following transects were surveyed: two in the Nove subreach of the Brenta River with length and width of ~300 and ~200 m, respectively; three in the Friola subreach ~300 m long and ~400 m wide; two in Fontaniva ~350 m long and ~300 m wide. In the Piave River, three ~400 m long on each subreach with a width that ranges from ~280 to ~350 m. In the Tagliamento River, three on each subreach in the Cornino subreach, those around the cross sections ranged from ~400 to ~600 m long with ~800 m wide, whereas in Flagogna they were ~450 m long and ~600 m wide.

3.2. Large wood and wood jam classification

All pieces of wood >0.1 m in diameter and/or longer than 1 m (see standards proposed by Morris et al., 2010) found within the transect areas along the cross sections were recorded. Single pieces of wood (large wood, hereinafter LW) and accumulations of large wood (wood jams, hereinafter WJ) within the active channel (identified as the area flooded during bankfull events) were recorded. Wood elements were classified as trunks (i.e., lacking branches), shrubs (i.e., with multiple coarse branches), or trees (i.e., featuring nearly-complete branches and rootwad). Wood jams were classified into two main categories, partially based on the Abbe and Montgomery (2003) WJ classification. We considered accumulations as autochthonous when a log recruited locally from the banks jammed further logs transported from upstream reaches or as allochthonous when most of the composing elements appeared to have been trapped in a jam whilst floating. Allochthonous jams include bar-apex jams, flood jams, meander jams, bar top jams, and bank edge jams (sensu Abbe and Montgomery, 2003).

3.3. Assessment of wood characteristics

The length and mid-diameter of each LW element were measured using a tape and a tree caliper, respectively. The measurement precision was estimated to be ~1 cm for diameter and ~5 cm for length. Several ancillary data were recorded during the field surveys, such as type of woody element (shrub, trunk, tree), orientation to flow (parallel, orthogonal, oblique), and recruitment mechanism (bank erosion, natural mortality, transported from upstream reaches). A further field observation for logs regarded their likely residence time as transported logs on the morphological units where they were found and were assessed using proxies such as the presence of complete branches, presence of leaves, and state of decay (intact, porous, decaying) of the wood and bark.

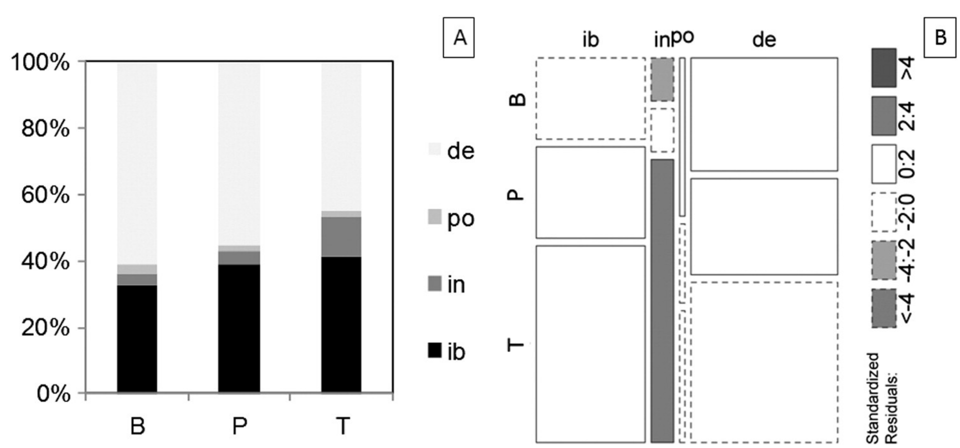

Fig. 6. State of conservation of the logs in the Brenta, Piave, and Tagliamento rivers (A). Deviations from independence of the observed frequencies shown with a mosaic plot (ib: intact with bark; in: intact without bark; po: porous; de: decaying) (B).

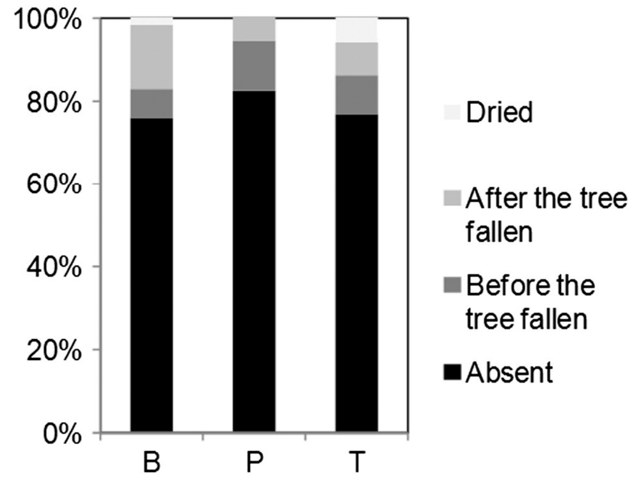

Fig. 7. Presence or absence of leaves on LW. In the case of woody element with leaves, it was analyzed if their origin was before or after the tree had fallen.

3.4. Assessment of wood volume and its geomorphic effects

The volume of logs was calculated by approximating the log to a cylinder. All visible elements composing WJ were measured, and the wood volume of each jam was calculated by summing them up so as not to take into account porosity because of the air between pieces of wood. The wood volume was calculated for each river and related to the area surveyed (i.e., m^3 ha^{-1}) in order to be comparable. The geomorphic effects of LW and WJ were assessed by measuring local sediment volume stored and/or scoured around each isolated and jammed element. These volumes were estimated as a solid wedge from length, depth, and width measured in the field.

3.5. Statistical analysis

We verified departures of observed frequencies from random distribution expectations through the standardized residuals of a log-linear model of the counts, using the function mosaic plot of the package {graphics} of R software (R Core Team, 2013). The resulting mosaic plots display the standardized residuals by the color and outline of the mosaic's tiles. Negative residuals are drawn in shades of gray scale and with broken outlines, whilst positive residuals are drawn in shades of gray scale with solid outlines (Crawley, 2007). Statistical differences in means of quantitative variables among rivers were checked using one-way ANOVA. Relationships between quantitative variables were analyzed through linear regression models using the function lm of the package {stats} of R software (R Core Team, 2013). When needed, variables were log-transformed to assure normality of residuals and variance homoscedasticity.

4. Results

4.1. Wood characteristics

A total of 3430 woody elements were measured in the study sites, 8.4, 13.9, and 10.7 elements/ha in the Brenta, Piave, and Tagliamento rivers, respectively. Trunks were the most common (57, 42, and 55% in B, P, and T, respectively). Trees with complete branches and rootwads were also relatively frequent (32, 31, and 28% in B, P, and T, respectively), whereas relatively fewer isolated rootwads and shrubs were collected. A total of 591 accumulations were surveyed, 9.8, 15.0, and 11.0 WJs/ha in B, P, and T, respectively. Overall, 70% of logs were found jammed, and more than 90% of wood jams were classified as allochthonous, meaning that most of the logs and the key elements had been transported from upstream reaches. More specifically, floated logs represented 80.5, 89.0, and 80.7% of logs in B, P, and T, respectively. A further confirmation that logs had likely been transported was gathered from their orientation with respect to the main flow direction, assessed in degrees ranging from 0 to 100 for logs parallel to the flow and rootwad facing upstream and downstream, respectively (Fig. 4). The range from 34 to 66° corresponds to logs that feature an oblique or transversal orientation. Notably almost 90% of logs were oriented mostly parallel to the main flow direction, suggesting that they had floated downstream (Francis et al., 2008); and the percentage with rootwad facing upstream was about 81, 90, and 71% in the B, P, and T, respectively. On the other hand, logs with oblique or transversal orientation were 19, 10, and 25% in B, P, and T, respectively. The relative organization of single pieces of wood within a WJ was also considered and classified as clogged or parallel, the logs being oriented randomly in the former case and mainly oriented in the same direction in the latter. The degree of porosity of the jams (i.e., the voids between logs) was also classified as wide or narrow, logs being at a distance equal to their length in the former case and less than their diameter in the latter. Jams classified as parallel and narrow tend to dominate on the study sites (66.0, 53.5, and 40.5% in B, P, and T, respectively), followed by jams with texture clogged and narrow (22.2, 38.9, and 43.5% in B, P, and T, respectively).

Almost 40% of all LW and WJ were found on high morphological units (high bars, islands, and floodplains) in the Piave and Tagliamento rivers, and this percentage rose to ~70% in the Brenta River (Fig. 5). In

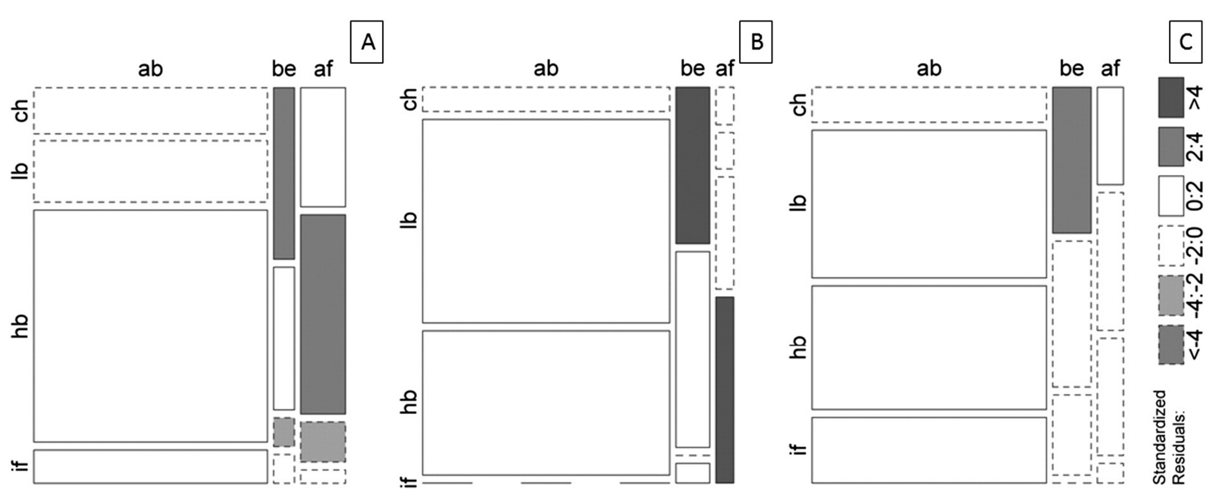

Fig. 8. Deviations from independence of the observed frequencies in resprouting capacity between each river shown with a mosaic plot (A: Brenta, B: Tagliamento, C: Piave). (ch: main and secondary channels; lb: low bars; hb: high bars; if: islands and floodplains; ab: absent; be: before the tree fallen; af: after the tree fallen).

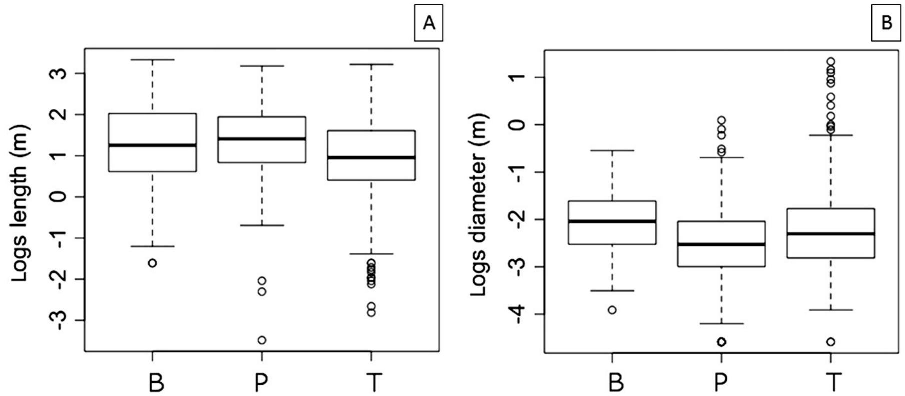

Fig. 9. Log plots of length (B) and diameter (A) of LW surveyed in the Brenta, Piave, and Tagliamento rivers.

the Piave and Tagliamento, more than 50% of wood was found stranded on very dynamic morphological units, such as low bars. Overall, only 10% of logs and jams were surveyed in the main and secondary channels.

Conservation of the logs further reveals that most were either intact with complete bark (i.e., recently recruited) or in an advanced state of decay (i.e., recruited long before the survey). Fig. 6A shows that logs in an advanced state of decay are more frequent in the Brenta (64.0% with decaying or even porous wood) than in the Piave (57.0%) and Tagliamento (46.5%). Fig. 6B indicates that there are significantly more pieces of wood with better state of conservation (i.e., intact with bark) in the Tagliamento River and fewer in the Brenta River than expected in the case of independence.

The presence/absence of bark further supports this observation as approximately half of the trunks were <30% covered by bark, and the other half by complete and fresh bark. In the three rivers, more than 70% of logs had no leaves, especially in the Piave River (up to 83%), suggesting that recruitment and transport had not occurred in the same or previous year as the survey. If only intact logs in a good state of conservation (nearly complete and fresh bark) are considered, Fig. 7 shows that half of them lacked leaves or had leaves on resprouts from the main branches (i.e., logs had likely been recruited the year before the survey). Fig. 8 shows that logs with resprouts are significantly more present in the Brenta River, where more logs were lying in the main and secondary channels if compared with the other two rivers.

4.2. Wood dimensions and abundance

The mean length and diameter of logs were significantly different among the three study rivers ($F_{2,3298} = 70.43$, $p < 0.0001$; $F_{2,3971} = 120.8$, $p < 0.0001$, respectively). The mean lengths were 5.70, 5.09, and 3.71 m for the B, P, and T, respectively (Fig. 9A). The longest log was recorded in the Brenta River and measured 26 m. The mean diameter of logs was 0.15, 0.10, and 0.14 m in the B, P, and T, respectively (Fig. 9B). The greater diameter was 0.96 m and was surveyed in the Tagliamento River. Fig. 10 shows that slightly higher volume of wood/ha were recorded in the Piave (11.46 m^3 ha^{-1}; 3.65 and 7.81 m^3 ha^{-1} for LW and WJ, respectively) than in the Brenta (9.76 m^3 ha^{-1}; 3.20 and 6.56 m^3 ha^{-1} for LW and WJ, respectively) and Tagliamento (7.41 m^3 ha^{-1}; 1.03 and 6.38 m^3 ha^{-1} for LW and WJ, respectively). The percentage of wood volume in the different morphological units varied among the three rivers (Fig. 11). Almost 75% of wood volume in the Brenta River was found in low bars and channels. The departures of the observed frequencies from random distribution expectations (mosaic plots not shown) demonstrate that wood volume of the Brenta is significantly higher than in the Piave and Tagliamento, where it is reduced to 62% and only 38%, respectively. Indeed, in the Tagliamento River more than 60% of wood volume was recorded on high bars, island and floodplain. Despite the fact that fewer LW and WJ were found in the most dynamic morphological units of the Brenta River, these feature high volumes, likely because the dimension of elements were generally higher.

4.3. Geomorphic effects

The overall amount of scour and deposition, scaled to the areal size of the surveyed area is shown in Fig. 12. The volumes of scour and deposition measured in the Brenta River (1.97 and 5.44 m^3 ha^{-1}, respectively) were less than those obtained in the Piave (6.19 and 12.53 m^3 ha^{-1}, respectively) and Tagliamento (6.74 and 11.7 m^3 ha^{-1}, respectively).

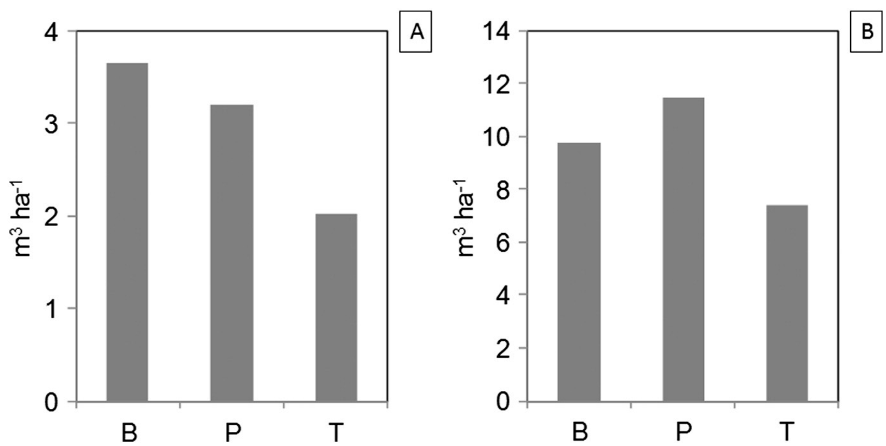

Fig. 10. Amount of single logs (A) and logs plus jams (B) in the Brenta, Piave, and Tagliamento rivers.

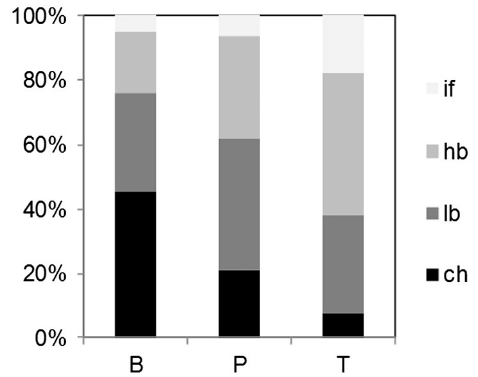

Fig. 11. Percentage of wood volume in different morphological units on the Brenta, Piave, and Tagliamento rivers (ch: main and secondary channels; lb: low bars; hb: high bars; if: islands and floodplains).

Positively and statistically significant relationships were obtained between volume of jammed wood and both scour (adj$R^2 = 0.12$, $F_{1,92} = 14.3$, $p < 0.001$) and deposition (adj$R^2 = 0.16$, $F_{1,212} = 41.43$, $p < 0.0001$) volumes generated by the jams (Fig. 13). Field evidence shows a similar distribution of geomorphic effects around wood in the Brenta and Piave rivers (Fig. 14) where most sediment deposition is associated with jams on high bars, whereas scours around jams are mostly on low bars. In the Tagliamento River, sediment deposition is more concentrated in high bars; and scour of sediments is fairly distributed among low and high bars and is also recognizable around jams found in the secondary channels and pioneering islands.

Furthermore, Fig. 15 shows that the rootwad diameter of in-channel wood is positively related with the volume of sediment scoured (adj$R^2 = 0.285$, $F_{1,34} = 14.95$, $p < 0.01$) and deposited (adj$R^2 = 0.18$, $F_{1,76} = 17.95$, $p < 0.0001$) around isolated logs.

5. Discussion

5.1. Abundance and wood distribution

If a wood density of 500 kg m^{-3} is used for the weight-to-volume conversion, in the Tagliamento River we surveyed 3.7 t ha^{-1}, which is within the range of 1 to 6 t ha^{-1} of wood reported on the gravel bar surfaces by Gurnell et al. (2000)—who used the same wood density. On the other hand, Van der Nat et al. (2003) collected a range of wood volumes that varied from 15 to 70 t ha^{-1} in braided reaches. These different amounts of wood are probably because of the highly dynamic nature of the Tagliamento River and its capacity to recruit wood from islands and floodplains.

In the Piave River, a range of 4 to 9 m^3 ha^{-1} of wood storage was estimated by Pecorari (2008), who reported a higher abundance of logs in

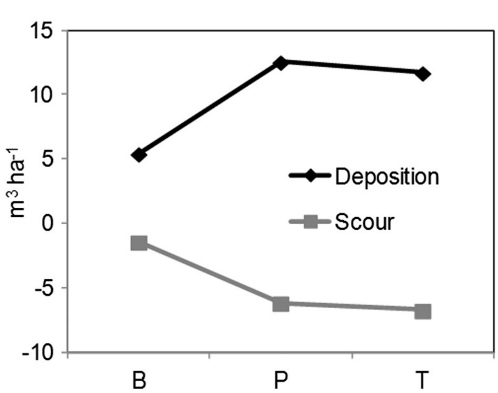

Fig. 12. Geomorphic effects of large wood in the Brenta, Piave, and Tagliamento rivers, measured as the volumetric scour and deposition around single logs and jams.

braided than in wandering subreaches. In the same study area, we detected larger volumes of wood (~11.46 m^3 ha^{-1}), probably for the higher magnitude of discharges reached during the years before the survey, which likely supplied a greater recruitment of wood in-channel. In fact, before the survey conducted by Pecorari (2008), the highest mean daily discharges were 287, 96, and 137 m^3 s^{-1} in 2004, 2005, and 2006, respectively. In our case, the highest mean daily discharges were 423, 619, and 499 m^3 s^{-1} in 2008, 2009, and 2010, respectively. The probably main effects of the 2009 flood that almost reached the bankfull stage (700 m^3 s^{-1}; Comiti et al., 2011) are important to be underlined. Contrary to Pecorari (2008), we found lower volumes in the Belluno braided subreach (3.43 m^3 ha^{-1}; 32% as LW and 67% as WJ), than in the Praloran wandering subreach (8.03 m^3 ha^{-1}; 25% as LW and 75% as WJ). In the Brenta River we recorded less wood/ha in the braided reach (Nove; 0.28 m^3 ha^{-1}) than in the wandering subreaches (Friola and Fontaniva, 1.81 and 3.95 m^3 ha^{-1}, respectively). The fact that Nove subreach appears quite depleted of large wood could be partially attributed to the presence of artificial banks, which reduce the active channel width and increase the water stage, thus diminishing the chances of logs being trapped on bars. In addition, because of the presence of dams and torrent control works in the mountain basin, very little wood (and a small amount of sediments, see Surian and Cisotto, 2007) is likely to reach Nove. Conversely, logs are more likely to be recruited from bank erosion on floodplains and islands located farther downstream, and indeed Friola and Fontaniva contain higher volumes of large wood. Also, Friola and Fontaniva subreaches are much wider than Nove and have denser riparian vegetation, probably because of less human disturbance (Moretto et al., 2014b).

5.2. Geomorphic effects of large wood

Apparently, logs and jams on the Brenta River are less effective in generating local geomorphic effects. Indeed, evidence suggests that in-channel wood exerts a more important geomorphic role in the Piave and Tagliamento than in the Brenta River. As reported elsewhere (e.g., Mao et al., 2008b), a positive relationship exists between wood volume and the volumes of sediment deposition and scour. Notably, the geomorphic effects of logs were identified in all morphological units in the more natural Tagliamento River, whereas in the Brenta and Piave they were more evident in lower morphological units, showing a positive relationship with the rootwad diameter, which was larger than in the Tagliamento River. This is probably in relation to the fact that in the Tagliamento River the frequent and more natural fluctuation of discharges (flow pulses sensu Tockner et al., 2000) are able to move more sediment around single pieces of wood and jams, increasing local scours and depositions, including in higher morphologic units. In particular, the deposition of fine sediment around or behind logs plays an important role, increasing the chance for logs to resprout. In addition, trapped seeds and vegetative tissues can germinate, leading to the development of pioneer islands (Nilsson and Grelsson, 1990; Gurnell and Petts, 2006; Manners and Doyle, 2008), which are more frequent in the Tagliamento River than in the Piave and Brenta, probably due to the greater thickness of sand and fine sediments along bars in the Tagliamento (Sitzia et al., in preparation).

5.3. Wood characteristics and dynamic in the study rivers

Field evidence suggests that, in all three rivers, 90% of the pieces of wood in jams had been transported from upstream reaches. In the Tagliamento River, Van der Nat et al. (2003) observed that at least 30% of deposited wood came from species that grew upstream, and Gurnell et al. (2002) observed that the overwhelming majority of the LW was detected with rootwad facing upstream, which is the typical disposition of LW transported in large rivers (Francis et al., 2008). The condition of the rootwad and the presence of bark and branches can also provide information about the history of single pieces of wood. In

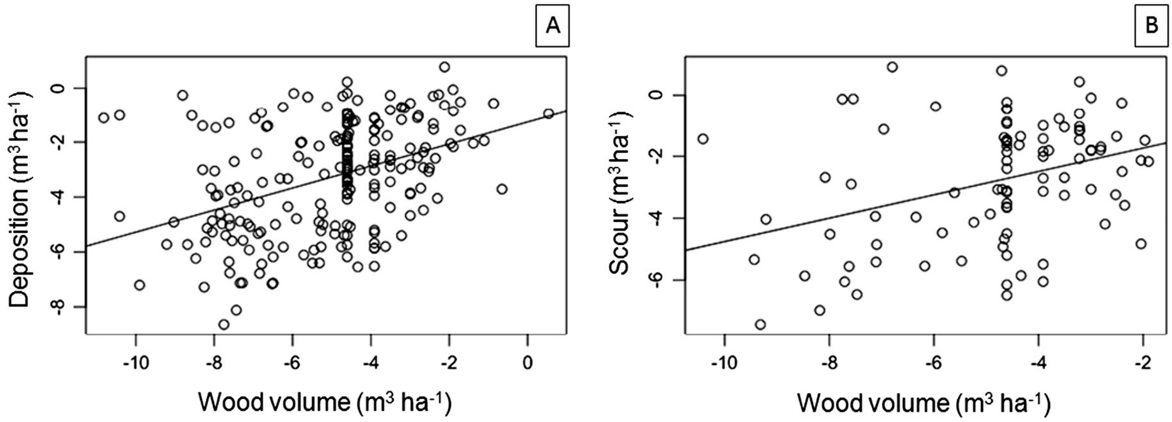

Fig. 13. Log plots of the relationships between the volumetric deposition (A) and scour (B) with the amount of in-channel wood.

fact, wood with fragments of bark, branches, and their roots indicate that the tree was recruited in-channel in its entirety instead of as a fragment from in situ decay (Moulin et al., 2011). Indeed, the time and location of deposited in-channel wood are two important factors controlling whether logs decay or resprout (Francis and Gurnell, 2006; Francis, 2007). Resprouting is usually associated with wood deposited on low bars and river margins (Gurnell, 2013), and the ability of the wood to sprout could be a key factor for vegetation regeneration and island stabilization. Field evidence of stranded trees suggests that in the Tagliamento River the elements closer to the channels lead to a higher presence of fresh leaves.

Along with the effect of LW, magnitude and timing of flood disturbance can exert a fundamental control on the occurrence and persistence of islands (e.g., Mikuś et al., 2012). In the Tagliamento River, Surian et al. (2015) reported relevant bank and vegetation erosion during low-magnitude floods ($1 \leq RI \leq 2$–3 years), even if in other studies (e.g., Bertoldi et al., 2009; Comiti et al., 2011) the importance of high floods in determining channel dynamics and persistence of vegetated islands was stressed.

If the importance of low-magnitude events holds for the Brenta and Piave, the much higher presence of longitudinal protection structures that regulate their flow conditions could exert a further role in reducing LW recruitment and bank erosion from more dynamic morphological units. The greater presence of wood on high bars and islands in the Brenta River (65%) suggests that logs probably were recruited, transported, and deposited during high-magnitude events in the past. These logs appeared more degraded (i.e., decaying and porous) and with less bark and branches, confirming the observation of Gurnell et al. (2002) who reported that the state of conservation and morphology of wood suggest the rate of movement and residence time. The presence of wood elements on higher morphological units in the Brenta River is likely to be ascribed to the relatively scarcer high magnitude floods able to reach the top of bars than in the Tagliamento River (~0.9 and ~1.6 mean annual over bankfull floods estimation for Brenta and Tagliamento, respectively) and the considerable human pressures that led to a higher bed incision of the main channel in the Brenta River than in the Piave (Surian and Cisotto, 2007; Surian et al., 2009; Comiti et al., 2011). Accordingly, Picco et al. (2015) observed that the Piave River has floodplain and islands lying at similar elevations above thalweg. The lower residence time of logs within the same reach in the Tagliamento River is probably attributable to the higher dynamicity of the channel and wood recruitment from islands and floodplains because of much less lateral constraints (artificial banks and rip raps) than in the Piave and Brenta. The presence of wood deposited along the bars in a better state of conservation increases the capacity to resprout, which allows the wood to remain alive. Indeed, the Tagliamento River, having no significant flow controls like the Brenta and Piave, has more natural fluctuating discharges that lead to very dynamic channel migrations (Welber et al., 2012; Picco et al., 2013), increasing the rapid turnover of in-channel vegetation (50% persists for <5–6 years, as observed by Surian et al., 2015). For this reason the Tagliamento River exhibits a high LW recruitment of young and fresh plants with a slightly smaller diameter than in the Brenta and Piave. If compared with the Tagliamento, the larger amount of wood in the Brenta River seems to be because of the number of very big logs (e.g., a tree 11.20 m long, diameter 0.33 m, with canopy diameter of 2 m) in a bad conservation state, stranded on very high bars, thus

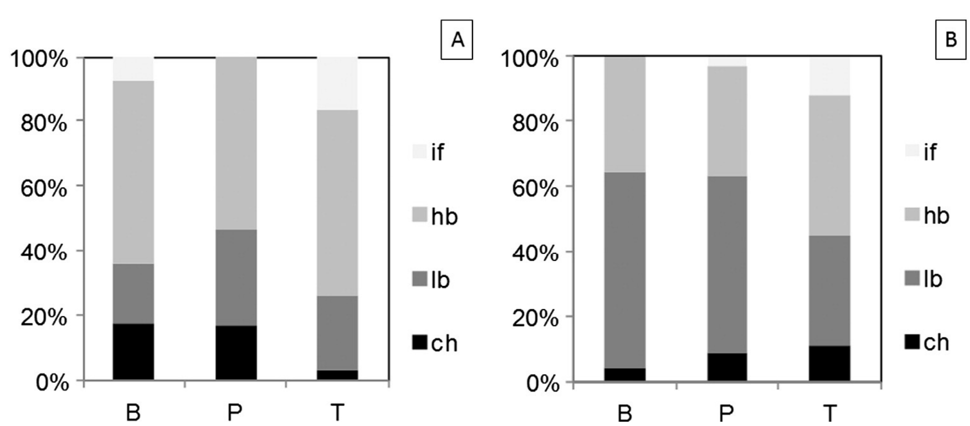

Fig. 14. Percentage of volume deposition (A) and scour (B) around jams in different morphological units on the Brenta, Piave, and Tagliamento rivers. (ch: main and secondary channels; lb: low bars; hb: high bars; if: islands and floodplain).

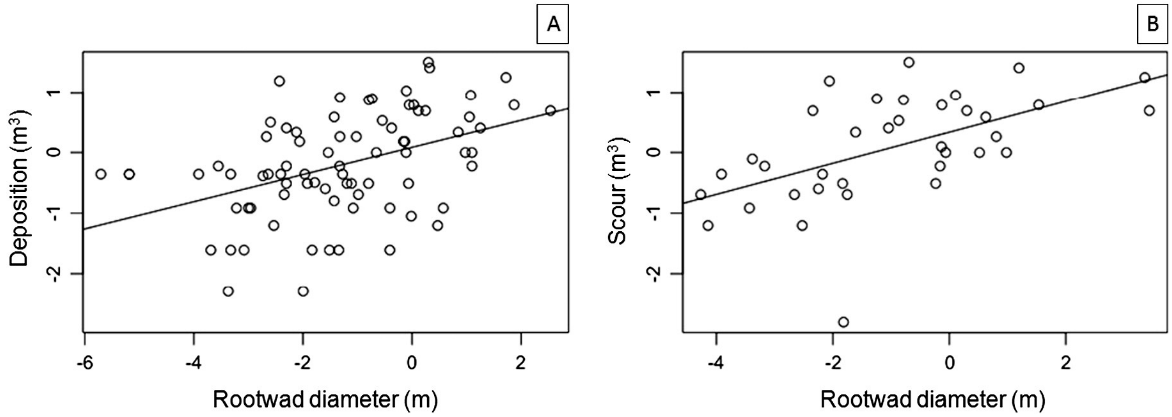

Fig. 15. Log plots of the relationships between volumetric deposition (A) and scour (B) with the rootwad diameter of in-channel wood in the Brenta, Piave, and Tagliamento rivers.

eroded from established islands and floodplains during very high-magnitude/low-recurrence events in the past.

6. Conclusions

This study focuses on the characteristics, quantity, distribution, and geomorphic effects of in-channel wood in three gravel-bed rivers (the Brenta, Piave, and Tagliamento). The geomorphic interactions between wood and sediments are crucial in determining the number of potential habitats for different organisms (Abbe and Montgomery, 1996). Isolated and jammed wood provide a wide variety of habitats, hydraulic refugia, as well as a food source for many organisms. For these reasons, appropriate loads and dynamics of wood should be maintained within the river corridor (Crispin et al., 1993).

This work suggests that the amount of and qualitative information on in-channel wood can provide some insight into the degree of human pressures at basin scale and that further comparative studies could shed more light on how human disturbances can affect large wood in gravel-bed rivers. The future studies should consider improving the analysis of the interactions between wood pieces and accumulation, standing vegetation, and channel dynamics. In addition, the analysis of the abundance and characteristics of buried wood from floodplains and channel bed should be taken into account, given its geomorphological and ecological interest. A better understanding of the many complex feedbacks between in-channel wood and geomorphology is crucial in order to achieve sustainable management of vegetation and large wood in rivers.

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