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Vegetation turnover in a braided river: frequency and effectiveness of floods of different magnitude

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ABSTRACT

This work addresses the temporal dynamics of riparian vegetation in large braided rivers, exploring the relationship between vegetation erosion and flood magnitude. In particular, it investigates the existence of a threshold discharge, or a range of discharges, above which erosion of vegetated patches within the channel occurs. The research was conducted on a 14 km long reach of the Tagliamento River, a braided river in northeastern Italy. Ten sets of aerial photos were used to investigate vegetation dynamics in the period 1954-2011. By using different GIS procedures, three aspects of geomorphic-vegetation dynamics and interactions were addressed: (i) long-term (1954-2011) channel evolution and vegetation dynamics; (ii) the relationship between vegetation erosion/establishment and flow regime and (iii) vegetation turnover, in the period 1986-2011. Results show that vegetation turnover is remarkably rapid in the study reach with 50 % of in-channel vegetation persisting for less than 5-6 years and only 10 % of vegetation persisting for more than 18-19 years. The analysis shows that significant vegetation erosion is determined by relatively frequent floods, i.e. floods with a recurrence interval of *ca.* 1-2.5 years, although some differences exist between subreaches with different densities of vegetation cover. These findings suggest that the erosion of riparian vegetation in braided rivers may be not controlled solely by very large floods, as is the case for lower energy gravel-bed rivers. Besides flow regime, other factors seem to play a significant role for in-channel vegetation cover over long time spans. In particular, erosion of marginal vegetation, which supplies large wood elements to the channel, increased notably over the study period and was an important factor for in-channel vegetation trends.

KEYWORDS: braided river; vegetation dynamics; threshold discharges; channel adjustment; Tagliamento River

Introduction

Over the last three decades there has been a growing interest in the relationship between vegetation and channel processes. Research has focused both on specific processes, such as bank stability (e.g. Pollen and Simon, 2005; Van de Wiel and Darby, 2007; Docker and Hubble, 2008; Pollen-Bankhead and Simon, 2009; Pizzuto *et al.,* 2010) and island formation (e.g. Fetherston *et al.,* 1995; Edwards *et al.,* 1999; Gurnell and Petts, 2006; Francis, 2007), as well as on the overall role of vegetation on channel dynamics and morphology (e.g. Millar, 2000; Gran and Paola, 2001; Murray and Paola, 2003; Perucca *et al.,* 2007; Tal and Paola, 2007; Hicks *et al.*, 2008; Murray *et al.,* 2008; Jansen and Nanson, 2010; Gurnell, 2014). Field observations, along with flume experiments (e.g. Coulthard, 2005; Tal and Paola, 2010), and numerical and analytical modeling (e.g. Murray and Paola, 2003; Perucca *et al.,* 2007; Perona *et al*., 2009; Crosato and Saleh, 2011; Li and Millar, 2011; Nicholas *et al*., 2013), have increased substantially our awareness of vegetation as a key component of the fluvial system.

It is worth recognizing that the role of aquatic and riparian vegetation varies greatly among fluvial systems. A recent conceptual model by Gurnell *et al.* (2012) describes the interaction between vegetation and fluvial morphology as a function of flow energy. The authors highlight the role of different plants (ranging from macrophytes to riparian trees) that can act as “riparian engineers”, controlling channel dynamics in a spectrum of forms and processes. In low energy systems (e.g. Brooks and Brierley, 2002; Gurnell *et al*., 2010), vegetation strongly controls channel morphology, causing the formation of specific fluvial landforms and trapping fine sediments, while in high energy systems the role of vegetation is more limited.

Hydrological processes are crucial for understanding the interplay between vegetation and channel morphodynamics (e.g. Johnson, 2000; Bendix and Hupp, 2000; Camporeale and Ridolfi, 2006; Hicks *et al.*, 2008; Greet *et al.,* 2011; Perona *et al.,* 2012). Several studies have analyzed how different flow regimes affect such interplay, controlling vegetation growth and the colonization of specific riparian species (e.g. Pettit *et al.,* 2001; Nilsson and Svedmark, 2002; Shafroth *et al*., 2002; Lytle and Merritt, 2004; Rood *et al.,* 2005). Other studies have focused on the effects of floods on vegetation dynamics, and have demonstrated the major role that extreme floods play in the evolution of riparian vegetation (Friedman *et al.,* 1996; Corenblit *et al.,* 2010; Mikuś *et al.* 2013).

The main issue addressed by this work is the role of floods of different magnitude on riparian vegetation dynamics. We investigated to what extent frequent low magnitude floods influence vegetation turnover. The research was conducted on the Tagliamento River, a large braided river in northeastern Italy. The Tagliamento River has been a natural laboratory for exploring the geomorphological and ecological processes and interactions of large fluvial systems under slightly-altered conditions over the last 15 years (Ward *et al.,* 1999; Kollmann *et al.,* 1999). Studies conducted on the Tagliamento have been fundamental to explaining island formation in high energy gravel-bed rivers. However, most of the previous work on vegetation has focused on short term dynamics, i.e. periods up to 10-15 years (Gurnell *et al.,* 2000; Karrenberg *et al.,* 2002; Bertoldi *et al.,* 2011; Welber *et al.,* 2012), or were characterized by low spatial and/or temporal resolution (e.g. Zanoni *et al.,* 2008; Henshaw *et al.,* 2013).

The novelty of the present work is the analysis of geomorphic-vegetation dynamics over a long time span (57 years), using high spatial resolution and a temporal resolution that, while not sufficient to capture the changes between all flood events, nonetheless was sufficiently detailed to enable us to investigate the role of the hydrological forcing on vegetation establishment and erosion. In the investigated reach, vegetation uprooting occurs mainly due to lateral migration of anabranches and does not imply vegetation submergence. Because of this, the working hypotheses are: i) the probability of vegetation erosion increases with flood discharge; ii) low magnitude, frequent floods may also cause vegetation erosion; iii) a threshold discharge (or range) for vegetation erosion can be identified. These hypotheses drove the analysis of short-term vegetation dynamics (i.e. 1986-2011). In addition, a longer period (i.e. 1954-2011) was investigated to analyze the relationship between channel adjustment (i.e. evolutionary trajectory of channel morphology) and vegetation dynamics. The hypothesis for the second analysis was that the expansion of marginal vegetation can influence in-channel vegetation dynamics through the delivery of large wood elements which catalyse island formation.

Study area

The Tagliamento River basin has a drainage area of 2580 km^2 and total relief of 2696 m (Figure 1). From its source at 1194 m a.s.l., the river flows first within the eastern Southern Alps and Prealps, then across the Venetian-Friulian plain and finally enters the Adriatic Sea, for a total length of 178 km. Because of high coarse sediment production in the catchment, the Tagliamento River displays a wide braided channel along 90 km of its course.

The study reach is 14 km long, and extends from the Osoppo bridge to the Pinzano gorge (Figure 1A), with a slope varying in the range 0.003 – 0.005 m m^{-1}, and a braided morphology. Within its active channel, the study reach is characterized by patches of riparian shrubs and trees of different size and age. *Populus nigra* is the dominant riparian tree species, although willow species are also abundant (*Salix eleagnos* in particular, but also *S. alba, S. daphnoides, S. purpurea, S. triandra*) (Karrenberg *et al*., 2003). The upper and lower sections of the reach have distinctly characteristics, thus we divided it into two subreaches, for detailed analysis (Figures 1B and 1C). The two subreaches differ in terms of confinement, bedrock depth, and channel configuration. In both subreaches river channel has some degree of confinement, but the upper subreach is less confined and the river flows in a large intermontane alluvial plain (the Osoppo plain). Bedrock depth is about 150 m in the upper subreach from Osoppo to Cornino (Giorgetti *et al*., 1995), whereas in the downstream subreach, between Cornino and Pinzano gorge, the bedrock depth is about 40 m and bedrock outcrops at Cornino. The different setting of the bedrock is determined by the rise of active thrusts of the eastern Southalpine Chain (Poli *et al*., 2009; Zanferrari *et al*., 2013). Furthermore, the westward migration of the Tagliamento River, which took place at the end of the last glacial maximum (ca. 19 ka BP, Monegato *et al*., 2010), established a new path from Cornino to the Pinzano gorge. This different geological setting produces a higher water table in the alluvial aquifer of the downstream subreach, which is also fed by spring water in the southern portion of Campo di Osoppo (Giorgetti and Stefanini, 1989), creating more favorable conditions for vegetation growth (Bertoldi *et al*., 2011). Because of these differences, the upstream subreach is characterized by a wider active channel and a lower vegetation cover (Figures 1B and 1C). According to Gurnell *et al.* (2000) both subreaches can be defined as “bar-braided with occasional islands”, though the downstream subreach displays locally an “island-braided” morphology.

Hydrology

Mean annual precipitation (1961-1990) in the Tagliamento basin is approximately 2000 mm, but there are significant variations within the catchment, ranging from 1500 mm in some small portions of the upper and lower parts up to 3100 mm in some central sub-basins. Daily precipitation can exceed 400 mm. Seasonal maxima in precipitation as well as in river flow occur in fall and spring, whereas minima are observed in winter. The Tagliamento River is characterized by a flashy pluvio-nival flow regime, which results from both alpine and Mediterranean snowmelt and precipitation regimes. At the Pioverno gauging station (basin area of 1880 km^2), the maximum and the mean discharges in the period 1932–1973 were 4050 and 81 $m^3 s^{-1}$, respectively (Surian *et al.*, 2009a). Due to the lack of continuous records at Pioverno during the last years, in this study we referred to the Venzone gauging station which is located a few hundred meters downstream of Pioverno and about 8 km upstream of the study reach (Figure 1). Flow stages have been recorded at Venzone daily for the period January 1988 – December 2001 and supported by observations of peak flood levels, and at 30 min intervals for the period May 2003 - August 2011. For the missing periods at Venzone (i.e. December 1986 – December 1987 and January 2002 – April 2003) daily maximum stages at Villuzza gauging station (located at Pinzano gorge) were used and modified by taking into account the increased drainage area (10%) at Villuzza. Discharge estimation for the Tagliamento River is rather difficult, due to the absence of stable cross-sections and the multi-channel character of the river. We used a stage-discharge relationship developed by Bertoldi *et al.* (2010) for Venzone station, which is located in a relatively narrow cross-section. Changes in the bed topography are expected to have an impact on low discharges only, so we consider this relationship sufficiently accurate for peak flood values. The mean annual flood (equal to 1645 $m^3 s^{-1}$) with a recurrence interval (RI) of 2.33 yr, was estimated using a Gumbel frequency distribution applied to 99 peak annual discharge values recorded for the period 1886-1996. The flow discharge series at Venzone in the period 1986-2011, i.e. the period used to analyze relation between flows and vegetation dynamics, is shown in Figure 2. The highest flood in that period occurred on 31st October 2004, with a peak discharge of 3470 $m^3 s^{-1}$ and an estimated RI of approximately 40 yr.

Methods

Changes in channel morphological features and vegetation cover were analyzed over a time period of 57 years, from 1954 to 2011, using 10 sets of aerial photos (1954, 1970, 1986, 1993, 1997, 1999, 2003, 2005, 2009, 2011; Table I). The average spatial resolution of photos (i.e. pixel size) is 0.88 m, but ranged between 0.11 m and 1.7 m. The analysis was carried out with a GIS software (ArcGIS 10) and the photos were coregistered using maps at 1:5000 scale as a base layer. Ten ground-control points were selected on average for each photo and second-order polynomial transformations were then applied, obtaining maximum root mean square errors (RMSE) of 2-3 m.

The overall analysis was divided into three steps to yield information on (i) long term channel evolution, (ii) vegetation establishment and erosion, and (iii) vegetation turnover (Figure 3). In the first step, photo interpretation was carried out for all the photo sets along the whole fluvial corridor (area of 22.7 km^2) which includes the active channel, the floodplains and the recent terraces formed by channel incision over the last 50-100 years. Six fluvial features were identified within the active channel: flowing channels, non-flowing channels, exposed sediments, low vegetation, medium vegetation, and high vegetation (Table II). Vegetation was classified in these three categories according to height (as inferred from shadows and field observations) and canopy size: herbaceous vegetation and low shrubs/trees (low vegetation, approximately < 1.5 m, tree age <3 - 5 years); high shrubs and trees of low-medium height (medium vegetation, in the range 1.5 m - 10 m, tree age about 3 - 15 years); and tall trees (high vegetation, approximately > 10 m, tree age > 10 - 15 years). The riparian zone (i.e. floodplain and recent terraces) was classified using the three vegetation classes, plus additional features related to human activities such as urban/industrial areas, agricultural areas, mining sites (see Table II for the complete list). Because the main focus of the analysis was on the dynamics of the active channel, features were digitized using different resolutions (i.e. scales for photo interpretation) according to their location in the fluvial corridor. A minimum area of 100 m^2 was adopted for digitizing features in the active channel whilst 1000 m^2 was selected for the riparian zone (Figure 4).

In the second step, the analysis was restricted to the period 1986-2011 and aimed at the relationship between vegetation erosion/establishment and flow regime (Figure 3). Relatively short time spans between subsequent photos were needed in this step, and the minimum, average, and maximum time spans were 1.7, 3.5, and 6.4 years respectively. The analysis was restricted to areas that were within the active channel at some point during the study period, thus some areas of riparian zone included in step 1 were excluded from this analysis (Figure 3).

A simpler classification was used in step 2. The classes referring to the active channel were not modified, but the riparian zone features were simplified to three (Table II). These riparian feature classes included riparian forest (RF), low vegetation (RLV), and riparian unvegetated areas (RUA). Re-classification produced eight new maps with eight feature classes possible per map. Then we proceeded with vector intersection of each pair of subsequent maps (e.g. 1986-1993, 1993-1997, etc.) (Figure 5). The result of intersection between two maps is illustrated by the matrix of Table III which shows that 14 different types of processes (e.g. vegetation erosion, vegetation establishment, lateral erosion, etc.) can be identified from the 8 feature classes (see Table III for details on processes and related codes).

Among the 14 processes identified by map intersections, we focused on vegetation erosion (VE) and vegetation establishment (VES). At this stage, error assessment was needed in order to estimate the threshold for detection of change in vegetation cover. The GIS analysis introduced errors due to georectification, photo interpretation, and digitization (e.g. Mount *et al*., 2003; Hughes *et al*., 2006). As recently stressed by Swanson *et al.* (2011), error estimate is still rarely considered in this type of study, although it may represent a crucial point especially if the magnitude of change is small. Our aim was to define an error threshold that is the smallest area (polygon) that could be considered as a real change in vegetation cover for each pair of photos. After considering analytical approaches, such those used by Mount *et al*. (2003) and Swanson *et al.* (2011), an empirical approach was defined. Though the approach is case specific, required visual interpretation of errors, and was time consuming, it was assessed as being more reliable and accurate than an analytical approach. All the polygons identified by intersection as vegetation erosion were ranked according to their area and then divided into 20 classes with increasing area. Then, a visual analysis was carried out on 10% of the polygons randomly selected from each class. If the majority (i.e. more than 50 %) of those random polygons were inconsistent with expected result (i.e. vegetation erosion) from comparison of subsequent photos, the whole size class was defined as error. The size class with more than 50 % of consistent polygons and with smallest area was used to define a minimum area threshold for change detection. Finally, polygons with areas equal to or larger than the error threshold were considered as ‘real’ sites of vegetation erosion or establishment, while polygons below that threshold were excluded from analysis. The error threshold ranged between 61 m^2 and 190 m^2 and was 104 m^2 on average (Table IV). Using the thresholds for change detection, it was possible to estimate the error for each pair of photos. For instance the error for vegetation erosion ranged between 1.1% (1999-2003 photos) and 16.9 % (2009-2011 photos).

The aim of the third step of the analysis was the investigation of vegetation turnover for the period 1986-2011 (Figure 3). It is worth clarifying that in this work we define the turnover of a vegetated patch as the time span during which that patch was classified as within-channel vegetation. This can be different from the age of trees or shrubs, particularly for vegetation that was originally part of the riparian zone (i.e. dissection islands).

We focused the analysis on areas covered by medium and high vegetation (“CV” in Table II), therefore we used a third classification with one class for all the unvegetated areas (Table II). The following GIS procedure was adopted: (i) vector intersection of each pair of subsequent maps and error estimation (as described above in step 2); (ii) rasterization of the intersection maps, using a cell size of 0.5x0.5 m; (iii) linking of the seven intersection maps to obtain a final raster holding information on vegetation turnover for the whole study period (i.e. 1986-2011). This final raster map shows vegetation turnover in high detail, since it reports, for each cell, the occurrence of medium-tall vegetation (CV). Only small portions of the two sub-reaches were covered by vegetation for the whole study period (Table V).

This procedure resulted in the definition of a minimum and maximum time span that vegetation patches lasted in the channel. Minimum time is the time interval between the aerial photos. When turnover occurred between 1993 and 2009, the maximum time was estimated by adding the time intervals preceding and following turnover to the minimum time. From this we subtracted 1.5 years, which is the estimated length of time that woody vegetation takes to grow to a height of 1.5 m on a gravel bar, and which would place it in the "medium vegetation" class (Figure 6). This estimate was done taking into account vegetation establishment observed (i) in 2003-2005, the shortest period we could analyze, and (ii) on ground-based images taken by a fixed camera with an hourly temporal resolution starting from 2008 (this monitoring system is described in Welber *et al*., 2012). As an example, for a vegetated patch that was present in 1993-2003 (i.e. the patch was vegetated in 1993, 1997, 1999, and 2003, but not in 1986 and in 2005) we estimated a minimum time of 10.3 yr and a maximum time of 16.9 yr (Figure 6).

For the areas covered by vegetation in 1986 or in 2011 (i.e. the limits of our study period) maximum time was estimated by a different approach. The maximum times estimated from the patches whose turnover occurred within 1993-2009 were added randomly to the minimum times. Considering that maximum time for the period 1993-2009 varies between 4.2 and 23.2 years (Figure 6), for each area covered by vegetation in 1986 or in 2011 a time within that range (i.e. 4.2 – 23.2 years) was added to its minimum time. The procedure took into account the frequency of patches with a certain maximum time. For instance, about 44% of the patches in the period 1993-2009 have a maximum time of 8 yr, so this time interval was added randomly to 44% of areas with vegetation in 1986 or in 2011. To test that the overall procedure, and specifically that maximum time was not overestimated with this approach, we compared vegetated area in 1970 and 2011. This comparison confirmed that our estimate of maximum times is reasonable and that no vegetated areas persisted within the channel for more than 41 years, with the exception of the Cornino island which stands on a bedrock outcrop.

Results

Long-term channel evolution and vegetation dynamics (1954-2011)

As shown in Figure 7, remarkable changes occurred within the fluvial corridor between 1954 and 2011. Besides the highly dynamic nature of the active channel, a noticeable change over this period is a substantial decrease in the active channel area (from 14.1 km^2 in 1954 to 9.8 km^2 in 2011) and a concomitant expansion in the marginal vegetated areas. The 10 sets of aerial photos permit a detailed reconstruction of the evolutionary trajectory of active channel area (Figure 8A). As is commonly defined in this type of analysis (e.g. Comiti *et al*., 2011; Ziliani and Surian, 2012), active channel area does not include vegetated areas, except for areas with low vegetation. For the whole study reach, channel area decreased markedly from 1954 to 1993 (- 45 %), then increased in the period to 2003 (+15 %), and finally changed relatively little in the most recent period (2003-2011). The upstream and downstream subreaches show very similar trends, except for the last period (2003-2011) when the upstream reach underwent slight widening (+1 %) while the downstream reach underwent a slight channel narrowing (-3 %) (Figure 8A).

The extent of vegetation (i.e. sum of medium and high vegetation classes) within the active channel was analyzed as the ratio of “vegetation area / active channel area”, rather than in absolute terms (Figure 8B). The vegetation ratio for the whole reach ranged between 0.04 (in 2003) and 0.13 (in 1986), and was 0.08 on average. The temporal trend of this ratio shows that vegetation cover increased in the period 1954-1986, decreased to 2003 and then increased again in recent years (2003-2011). Substantial differences exist between the two subreaches. First, vegetation cover is higher in the downstream subreach, except for the first two photos (i.e. 1954 and 1970). Secondly, the downstream subreach is characterized by a larger variability, with the "vegetation area / active channel area" ratio ranging between 0.04 (in 1954) and 0.21 (in 1986), while in the upstream subreach it ranged only between 0.04 (in 2003 and 2005) and 0.09 (in 1970).

Vegetation erosion, vegetation establishment and relation with flow regime (1986-2011)

Figure 9 illustrates the vegetation erosion and establishment rates for the 7 analyzed time spans, corrected for the identified error thresholds (Table IV). Both vegetation erosion and establishment were calculated as a ratio (percentage) with reference to the vegetated area at the beginning of each time span. Significant vegetation erosion took place in all seven time intervals, though with different magnitudes. For the whole study reach, three sub-periods were characterized by less intense erosion, i.e. annual rates of erosion varying between 3.2 % and 4.9 %, three sub-periods by more intense erosion, i.e. annual erosion rates in the range 10.1 % - 12.5 %, and one period by an intermediate level of erosion (7.4 %). This means that during the period characterized by the most intense erosion (i.e. 1999-2003) approximately 50 % of the vegetation cover was removed in 4 years. However, a significant proportion of vegetation cover was eroded even when rates were relatively low (e.g. 13 % of vegetation cover eroded in 4 years during the period 2005-2009). The two subreaches show similar ratios in the first four sub-periods, but erosion was always more intense in the upstream subreach post 2005 (Figure 9A).

As expected, annual rates of vegetation establishment show a trend opposite to that of vegetation erosion (Figure 9B). This is true for all the sub-periods with the exception of the last one (2009-2011), which is characterized by the maximum establishment rate (12.8%

in the whole reach) and a significant erosion rate (7.4%). Overall, when considering both vegetation erosion and establishment, it is clear that the upstream subreach is more dynamic than the downstream one, as it is experienced higher annual rates of both erosion and establishment in 11 out of the 14 time periods.

Vegetation dynamics were then related to flow regime. The main objective was the identification of a threshold discharge, or a range of discharges, responsible for vegetation erosion. Annual erosion rates were plotted against the corresponding mean annual cumulative discharges for the seven time spans, varying the minimum discharge threshold (Figure 10). Cumulative discharge (also called effective runoff in bedload transport studies) represents a proxy for the total flow energy within a given period over a certain reach. We used different discharge thresholds assuming that if the cumulative discharge includes also (low) flows without effects on vegetation the relation with erosion rates should be less significant. On the other hand, such relationship is anticipated to be strongest when the cumulative discharge is calculated including only flows actually responsible for vegetation erosion. Erosion rates could be analyzed both in terms of absolute rates (e.g. in km^2) or as ratios (i.e. percentage). The first option would be more suitable to represent the force exerted by the river on the vegetated channel boundary within a given period, but it would be meaningful for a comparison among periods only if vegetation cover was relatively constant at the beginning of each period. This was not the case; there were significant differences between periods (Figure 8B). Therefore, we opted for a vegetation erosion rate expressed as a proportion relative to the initial vegetation extent of each time span.

The cumulative discharge-erosion rate plots (Figure 10) show that when a low discharge threshold is used (e.g. Q=315 m^3s^{-1}, RI < 1 yr) the relationship is very weak and not significant, whereas the relationship becomes stronger at higher thresholds. Using the highest threshold (i.e. Q=1785 m^3s^{-1}, RI=2.5 yr), cumulative discharge volume explains a significant amount of the variation in erosion area (R^2=0.79 for the whole reach and 0.66 and 0.78 for the upstream and downstream subreaches, respectively). The relationship is weaker using an intermediate threshold, R^2 is 0.28 and 0.37, respectively, for Q=735 m^3s^{-1} (RI < 1 yr) and Q=1155 m^3s^{-1} (RI=1.2 yr) (Figure 10). For such threshold discharges there is a notable difference between the two subreaches, R^2 being higher in the upstream subreach (i.e. R^2 is 0.47 and 0.53, respectively for Q=735 and Q=1155 m^3s^{-1}) than in the downstream one (i.e. R^2 equals to 0.17 and 0.26 for the same discharge values). As a result, Figure 10 suggests that: (i) frequent flows (i.e. Q=315 m^3s^{-1}, RI < 1 yr) have no or very little effect on vegetation; (ii) floods with RI ≥ 2.5 years have a significant effect on vegetation; and (iii) floods with a RI ~ 1 year (e.g. Q=1155 m^3s^{-1}, RI=1.2 yr) have a significant but lesser impact on vegetation, but which was particularly noticeable in the upstream subreach.

To strengthen the analysis between flow regime and vegetation erosion, we considered the flow regime in the seven periods in terms of the largest flood that occurred and the number of flow events above the 4 selected discharge thresholds (Table VI). The role of relatively frequent floods is particularly evident when observing two periods, 1997-1999 and 2009-2011, which are characterized by high or moderate rates of vegetation erosion and an absence of major floods. During these two periods the largest flood events were relatively mild (i.e. RI=2.4 yr in 1997-1999 and RI=3.1 yr in 2009-2011), but several low magnitude floods occurred, with 6 and 7 floods above Q=735 m^3s^{-1} (RI < 1 yr) in 1997-1999 and 2009-2011, respectively (Table VI). More support for the significant role of frequent floods is given by the 2003-2005 period which had a very large flood (RI=40 yr), but a relatively low mean annual erosion rate (i.e. 4.9%). Only 3 floods above Q=735 m^3s^{-1} took place during this period.

Assessment of vegetation turnover

Figure 11 shows the time distribution of vegetated patches, considering both minimum and maximum times of turnover. Average turnover time ranges from 2 to 9 years and from 2 to 10 years, respectively, in the upstream and in the downstream reaches. Only 10 % of vegetated patches persisted in the channel for more than 12.5-23 years and 14-24 years in the upstream and in the downstream reaches, respectively. Therefore, some differences do exist between the two subreaches, with vegetation slightly more stable in the downstream reach. It is worth pointing out that although a relevant difference does exist between minimum and maximum times (Figure 11), overall the results are considered to be reliable as a large number of vegetated patches were used for calculations.

Focusing on maximum turnover times, it turns out that 50%, 90%, 95%, and 99% of the vegetated patches have, respectively, less than 9-10 years, 23-24 years, 27-32 years, and 35-37 years (Figure 12). These results show that most of the vegetation is relatively young and few vegetation patches persisted in the channel for more than 20-30 years (Figure 13). Specifically only one island (i.e. near Cornino) is older than 40 yr, but this island is not representative of the whole study reach because it has a bedrock substrate.

Discussion

The role of floods of different magnitude in braided river morphology

One of the main questions addressed in this work is the role of floods of differing magnitude on vegetation dynamics. This was addressed by comparing the erosion of vegetation patches for time periods with different flow regimes, specifically periods with large floods (i.e. RI = 30-40 years) compared to those with lower magnitude, more frequent events only (i.e. RI = 2-3 years). Results of our analysis show that significant vegetation erosion occurs during years with relatively frequent, low magnitude floods, i.e. 1≤RI≤ 2-3 years (Figure 9 and Table VI). These findings suggest the need to reevaluate the current perspective on the role of floods on vegetation dynamics because, until now, most studies have emphasized that only relatively large floods (RI > 10-20 years) cause significant vegetation erosion (e.g. Bertoldi *et al.*, 2009; Comiti *et al.*, 2011; Mikus *et al.*, 2013).

In a previous study on the Tagliamento River (Bertoldi *et al.*, 2009), floods with RI ~ 3 yr were argued to represent the threshold for vegetation erosion. This work shows that the threshold is actually lower, inasmuch as floods with RI = 2.5 yr certainly have a significant effect on vegetation, and more frequent floods do have some effects as well (Figure 10). Notably, floods as low as RI ~ 1 yr had a significant impact on vegetation patches in the upper subreach, suggesting that the threshold discharge is lower in this reach which is characterized by a bar-braided pattern with occasional islands. The lower subreach, which features a more island-braided morphology, has a higher threshold for vegetation erosion. This supports the recent conceptual model developed by Corenblit *et al.* (2014), who identified the existence of hysteretic patterns, where established vegetation can resist higher levels of disturbance than plants during the colonization phase. The bio-geomorphological evolution of vegetated islands determines the deposition of fine sediments and the soil reinforcement by root network, with a consequent increased stability.

As for vegetation turnover, our analysis shows that 50 % of in-channel vegetation persisted <5-6 years and only 10 % of vegetation persisted > 18-19 years. Moreover, turnover appears to differ slightly between subreaches, and is marginally shorter in the upstream subreach. These results confirm that turnover is remarkably rapid and even greater than estimates from previous studies on the Tagliamento (Karrenberg *et al*., 2003; Zanoni *et al*., 2008). Also, such turnover appears to be faster than in other braided rivers. For example, Mikus *et al*. (2013) estimated that the average tree age in an island-braided reach of the Czarny Dunajec (Polish Carpathians) is 15-20 years.

The identification of hydrological thresholds for vegetation erosion and a more accurate estimate of turnover enhance our understanding of the role of vegetation in the geomorphology of highly dynamic river systems such as the Tagliamento. Such a role was summarized by Gurnell *et al.* (2012) who analyzed the interplay between vegetation and channel form and processes by comparing fluvial systems with different energy. The overall role of vegetation on channel morphology and dynamics is very high in low energy systems and progressively decreases in higher energy systems. In these latter systems vegetation is still a key ingredient of channel processes and morphology (e.g. Gurnell and Petts, 2006; Bertoldi *et al.*, 2011) but its "engineering" role is more limited, in terms of both spatial and temporal scales, in comparison to lower energy systems. Because vegetation is eroded also by moderate floods, we can argue that the long-term dynamics of vegetation in a braided river as the Tagliamento is not controlled solely by very large floods, unlike other gravel-bed rivers with lower energy, as the River Tech in France (Corneblit *et al.*, 2010) or the Czarny Dunajec in Poland (Mikus *et al.*, 2013). This is in agreement with the conceptual model proposed by Paola (2001) and the related laboratory and field observations (Tal and Paola, 2007; Hicks et al., 2008), which highlighted that the ratio between the vegetation establishment time and the average time between morphologically-relevant floods is key in determining planform morphology in gravel-bed rivers. This ratio is likely > 1 in the Tagliamento because, according to our observations, vegetation establishment (i.e. formation of pioneering islands) takes more than 2-3 years.

In terms of practical implications, our findings imply that flow regulation affecting frequent, low magnitude floods (RI=1-3 yr) can cause significant changes on vegetation dynamics in a braided river. This is not the case for the Tagliamento, but most Alpine rivers are regulated by large reservoirs for hydropower production and frequent floods are often lessened.

The identification of flow thresholds for vegetation erosion can be combined with previous findings regarding the Tagliamento River to obtain an overall conceptual framework for morphodynamics. Figure 14 shows the thresholds, expressed in terms of discharge and RI, for different fluvial processes, i.e. bedload transport in the channels, on low bars and on high bars, in-channel bank erosion, sudden channel shift, and vegetation erosion. Five of these six processes feature a discharge threshold having RI ≤ 1 yr. Only bedload transport on high bars requires floods with a RI > 1 yr. This framework points out two important findings: (i) the morphology of a braided river like the Tagliamento is the product of geomorphic processes operating over a wide range of discharges; and (ii) relatively frequent floods (i.e. RI=1-3 yr) are key drivers of morphodynamics for this river typology.

Channel adjustments and long term vegetation dynamics

Channel adjustment over the last 6 decades was expressed initially through a phase of remarkable channel narrowing, followed by a phase of predominant channel widening

(Figure 8A). Like in other braided rivers in Italy (e.g. Surian and Rinaldi, 2003; Surian *et al*., 2009b), channel narrowing was associated with incision, estimated to be 0.5-1.0 m in the study reach. Incision was calculated by the difference between the average elevation of bars in 1954 and in 2005 (Figure 15). A comparison of cross sections was not possible for this reach, because cross sectional surveys only started in 1982. Channel adjustments can be explained in the study reach as mainly a response to in-channel sediment mining. This explanation is supported by two elements. First, the aerial photo interpretation showing that mining activity was carried out in the reach for about 30 years (1970s-1990s), with a peak of intensity in the 1980s (e.g. mining area was 0.74 km^2 in 1986). Second, the analysis of controlling factors carried out for the adjacent reach by Ziliani and Surian (2012) allowed us to rule out other potential factors such as changes in flow regime or the effects of change in land use at the catchment scale. Because gravel mining was the main driver of channel narrowing and incision, vegetation encroachment in formerly active channel areas was a consequence of incision and not its cause as previously surmised by Comiti *et al.* (2011) and Comiti (2012) for other rivers in the Italian Alps, and in contrast to what observed in some French rivers (e.g. Liébault and Piégay, 2002).

To explain the long-term trend (1954-2011) of in-channel vegetation cover (Figure 8B), we considered two further processes, erosion of marginal vegetation and mining activity, along with the flow regime. Large wood is a fundamental control on island development in the Tagliamento River (Gurnell *et al.*, 2001; Gurnell and Petts, 2006), therefore we assumed that erosion of marginal vegetation would promote island growth by increasing the input of large wood into the channel. As for mining, this activity directly removes sediment and vegetation patches from the channel but constitutes a disturbance to the entire system. As for the flow regime, cumulative discharges for the different time intervals were computed based on the threshold values obtained from the previous analysis (i.e.

Q=1155 m^3s^{-1}, RI=1.2 yr; and Q=1785 m^3s^{-1}, RI=2.5 yr for the upstream and downstream subreach, respectively). To identify which of these controlling factors was responsible for the long-term trend of in-channel vegetation, a chronology of factors and vegetation changes was created for the two subreaches (Figure 16). The temporal patterns differ by subreach and are described in detail below.

In the downstream reach, flow regime is the factor that best explains the changes in vegetated area within the channel (Figure 16). Cumulative effective discharges (i.e. sum of discharge above 1785 m^3s^{-1}) were relatively low in the period 1970-1993, when maximum expansion of vegetation occurred (from 6% in 1970 to 21% in 1986), while relatively high in the following period (1993-2005) when vegetated area decreased notably (down to 6% in 2005). The other two factors, erosion of marginal vegetation and mining activity, do not correlate well with temporal trend in vegetation cover and, in some cases, contrast to what would be expected. For instance erosion of marginal vegetation, and thus supply of large wood for island initiation, was high in the period 1993-2011, but in this period vegetation cover decreased substantially and then increased. As to sediment mining, the most intense phase of this activity matched vegetation expansion. Although these two factors are not the main drivers of vegetation dynamics in this subreach, they may still be additional controlling factors. Specifically, mining activity could explain the decrease in vegetation cover that occurred between 1986 and 1993, a period with few effective flow events. On the other hand, erosion of marginal vegetation would help to explain vegetation dynamics during the last period (2003-2011). Considering the flow regime during this period, specifically the occurrence of two periods with high (2003-2005 and 2010-2011) and one with low effective discharges (2006-2009), a reduction of vegetation cover would be expected, followed by an expansion and, finally, another reduction. This was not the case; vegetation expanded during the whole period, although with differing intensity. This suggests that in the period 2003-2011 erosion of marginal vegetation could have played a role in vegetation dynamics by increasing significantly the supply of large wood to the channel. In fact, the annual rate of vegetated area eroded from the river banks was in the range of 0.002-0.006 km^2 and 0.022-0.127 km^2 in the period 1954-1993 and 2003-2011 respectively. This means that wood supply was about one order of magnitude greater in the latter period, and was likely responsible for initiating the formation of new islands.

The explanation of the vegetation cover trend in the upstream subreach, characterized by a relatively low cover throughout the study period, is less straightforward (Figure 16). Flow regime explains the significant decrease of vegetation in the period 1997-2003 but does not explain vegetation changes in other periods. This could suggest that in a very dynamic reach, where vegetation cover is relatively low, the small changes that were observed could be due factors other than flow regime. For example, the vegetation reduction between 1970 and 1993 (from 9% to 6%) could be explained by mining activity, while the very slight vegetation expansion between 2003 and 2011 (from 4% to 5%) could be ascribed to the intense erosion of marginal vegetation as suggested also for the downstream subreach.

Such analysis of trends and controlling factors suggests that an expansion of in-channel vegetated areas (i.e. islands) can be envisaged for the next years because of a remarkable increase in the availability of wood from the channel margins, which are now much more forested than in the previous decades. This increase in supply of wood to the channel on the Tagliamento River is further compounded by the declining use of firewood by local population, which was traditionally collected from the channel bed.

Conclusions

Vegetation temporal dynamics and turnover were analyzed in a reach of the braided Tagliamento River at high spatial and high temporal resolutions (i.e. 10 sets of aerial photos, from 1954 to 2011). The results indicate that turnover is remarkably rapid with 50% of in-channel vegetation persisting for less than 5-6 years and only 10% of vegetation persisting for more than 18-19 years. Subreaches with different densities of vegetation cover show small differences, with turnover being shorter in the bar-braided subreach with less vegetation cover.

Our analysis shows that significant vegetation erosion occurs also with relatively frequent, low magnitude floods, i.e. floods with a RI ~ 1-2.5 years. These findings offer a new perspective on vegetation-geomorphic interactions because most studies have so far emphasized that only large floods (RI > 10-20 years) cause significant vegetation erosion. Furthermore, differences between the subreaches suggest that channel morphology influences the minimum threshold discharge for vegetation erosion. In the more dynamic subreach (a bar-braided with occasional islands) threshold discharge for vegetation erosion corresponds to floods with a RI = 1.2 yr, or even to more frequent floods, whereas the threshold discharge is higher in the subreach characterized by a greater vegetation cover and, locally, by an island-braided morphology (RI = 2.5 yr). Therefore, we conclude that vegetation erosion in the braided Tagliamento River is controlled not only by very large floods, but also by more frequent, lower magnitude floods, unlike other gravel-bed rivers with lower energy, where the "engineering" role of vegetation is stronger.

Besides flow regime, other factors should be taken into account to interpret in-channel vegetation dynamics over long timescales. Erosion of marginal vegetation, which supplies large wood into the channel, and mining activity, which causes the removal of vegetation patches, are important factors affecting vegetation cover. During the examined period, wood supply increased by approximately one order of magnitude, as a result of channel adjustment (i.e. narrowing and incision) and the consequent expansion of marginal vegetation. Wood supply is a fundamental control on island development in the Tagliamento River, so an expansion of in-channel vegetated areas is envisaged for the near future.

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Table I. Characteristics of the aerial photos used in this study

Year	Date	Pixel size (m)	Type: color (C), black and white (BW)	Discharge on the dates of photography (m^3s^{-1})
1954	14 Oct	1.0	BW	78.5
1970	-	0.7	BW	-
1986	24 Dec	1.0	BW	7.2
1993	22 May-16 July	1.6	BW	22.6 – 49.3
1997	16 Sept	1.7	C	52.1
1999	11 Sept	1.3	C	7.2
2003	14-27 Sept	0.5	C	< 7.0
2005	23 May	0.6	C	37.6
2009	14 May	0.25	C	56.6
2011	17 Aug	0.11	C	53.0

Table II. Feature classes used for aerial photo interpretation

	Features used in the first step of the analysis	Feature symbol	Features used in the second step of the analysis	Feature symbol	Features used in the third step of the analysis	Feature symbol
RIPARIAN ZONE	Riparian medium vegetation	RMV	Riparian forest	RF	Riparian forest	RF
	Riparian high vegetation	RHV				
	Riparian low vegetation	RLV	Riparian low vegetation	RLV	Riparian low vegetation	RLV
	Riparian channel	RC	Riparian unvegetated area	RUA	Unvegetated area	UA
	Lake	L				
	Bank protection strucures	BPS				
	Bare soil	BS				
	Urban/industrial areas	UIA				
	Agricultural area	AA				
	Mining site	MS				
ACTIVE CHANNEL	Flowing channel	C	Flowing channel	C		
	Non flowing channel	NC	Non flowing channel	NC		
	Exposed sediments	S	Exposed sediments	S		
	Channel low vegetation	CLV	Channel low vegetation	CLV	Channel low vegetation	CLV
	Channel medium vegetation	CMV	Channel vegetation	CV	Channel vegetation	CV
	Channel high vegetation	CHV				
	Bedrock	B				

Table III. The eight feature classes used to analyze vegetation erosion and establishment in the period 1986-2011 and the matrix obtained by intersection of features from two dates (e.g. 1986 and 1993), which defines processes over a specific time span. Feature classes: C: flowing channel; NC: non-flowing channel; S: exposed sediments; CLV: channel low vegetation; CV: channel vegetation; RF: riparian forest; RLV: riparian low vegetation; RUA: riparian unvegetated area. Processes: VES: vegetation establishment; LVES: low vegetation establishment; CS: channel stability; CD: channel dynamics; LVE: low vegetation erosion; VE: vegetation erosion; LE: lateral erosion; LVS: low vegetation stability; VS: vegetation stability; DI: dissection island; CNH: channel narrowing-high vegetation; CNL: channel narrowing-low vegetation; CNN: channel narrowing-no vegetation; RS: riparian stability

		Features of the second date							
		C	NC	S	CLV	CV	RF	RLV	RUA
Features of the first date	C	CS	CD	CD	LVES	VES	CNH	CNL	CNN
	NC	CD	CS	CD	LVES	VES	CNH	CNL	CNN
	S	CD	CD	CS	LVES	VES	CNH	CNL	CNN
	CLV	LVE	LVE	LVE	LVS	VES	CNH	CNL	CNN
	CV	VE	VE	VE	VE	VS	CNH	CNL	CNN
	RF	LE	LE	LE	LE	DI	RS	RS	RS
	RLV	LE	LE	LE	LE	VES	RS	RS	RS
	RUA	LE	LE	LE	LE	VES	RS	RS	RS

Table IV. Estimated threshold area (m^2) for photo pairs and the relative error estimated for vegetation erosion (VE) and vegetation establishment (VES) (errors in %, referring to the total vegetation erosion and establishment)

PERIODS	1986-1993	1993-1997	1997-1999	1999-2003	2003-2005	2005-2009	2009-2011
Error threshold (m^2)	190	125	110	80	95	70	61
Error VE (%)	1.7	1.2	6.1	1.1	7.9	13.3	16.9
Error VES (%)	0.7	2.7	13	4.2	10.6	3.3	11.1

Table V. Area of vegetation analyzed in the estimation of turnover (Step 3, Figure 3)

	Upstream subreach		Downstream subreach	
	Area (km²)	%	Area (km²)	%
Riparian vegetation	0.23	18.9	0.39	24.1
Vegetation during the whole period (1986-2011)	0.01	1.2	0.07	4.1
Vegetation in 1986	0.23	18.7	0.37	23.2
Vegetation in 2011	0.28	23.0	0.33	20.5
Vegetation for a time span between 1993 and 2009	0.47	38.2	0.45	28.0
Total vegetation	1.22	100.0	1.60	100.0

Table VI. Relationship between vegetation erosion rate and flow regime in the seven time spans analyzed. Flow regime is characterized as the number of events above a given discharge threshold and the magnitude of the largest event for each time span

Period	mean annual erosion rate as vegetated area percentage [%]	peak discharge at Venzone [m^3/s]	maximum event RI in the period [year]	total number of events above discharge thresholds			
				315 (RI<1)	735 (RI<1)	1,155 (RI=1.2)	1,785 (RI=2.5)
1986 - 1993	3.7	2,490	9.0	61	21	10	2
1993 - 1997	11.6	3,410	36.7	18	10	8	8
1997 - 1999	10.1	1,649	2.4	8	6	4	0
1999 - 2003	12.5	2,490	9.0	16	12	10	6
2003 - 2005	4.9	3,468	39.9	5	3	2	1
2005 - 2009	3.2	1,886	3.4	23	7	3	1
2009 - 2011	7.4	1,820	3.1	20	9	7	3

Figure captions

Figure 1. (A) The location of the study reach within the Tagliamento River catchment and the subreaches within the study reach, and aerial photos of the (B) upstream and (C) downstream subreaches.

Figure 2. The flow record at the Venzone gauging station in the period 1986-2011. The dashed vertical lines indicate the acquisition dates for the aerial photos. The horizontal lines indicate the four discharge thresholds considered in the analysis of vegetation erosion and establishment: the two lower discharges have RI < 1 yr, while RI of the other two is 1.2 yr and 2.5 yr respectively.

Figure 3. Flow-chart of the three-step analysis carried out in this study, detailing the results, the methods used to obtain them and the study areas and time periods they covered.

Figure 4. Example of the minimum area measured during aerial photo interpretation.

Figure 5. Examples of map intersection showing (A) vegetation erosion and (B) vegetation establishment. See Table III for explanation of the codes.

Figure 6. Estimation of vegetation age from aerial photos. Minimum and maximum turnover for vegetation patches are estimated according to presence of vegetation in subsequent photos (gray bars in the figure) and assuming that minimum time span for vegetation establishment is 1.5 year. The procedure to estimate maximum time for the areas vegetated in 1986 or 2011 is explained in the main text.

900 Figure 7. Example of the photo interpretation showing a subreach and 6 out of the 10 aerial photos that were used in the study. Legend: C: flowing channel; NC: non-flowing channel; S: exposed sediments; CLV: channel low vegetation; CMV: channel medium vegetation; CHV: channel high vegetation; RC: riparian channel; L: lake; RLV: riparian low vegetation; RMV: riparian medium vegetation; RHV: riparian high vegetation; BPS: bank protection structure; BS: bare soil; UIA: urban/industrial area; AA: agricultural area; MS: mining site; B: bedrock.

908 Figure 8. Changes in (A) absolute channel area and (B) relative vegetated area (ratio of vegetated area and channel area) over the period 1954-2011.

911 Figure 9. Annual rate of (A) vegetation erosion and (B) establishment in the whole study reach and in the two subreaches for the seven time spans analyzed. Percentage of erosion and establishment was calculated relative to the vegetation cover at the beginning of each time span.

916 Figure 10. The relationship between annual rate of vegetation erosion and cumulative discharges in the seven time spans; the relationship is shown for 4 increasing thresholds of discharge.

920 Figure 11. Minimum and maximum time of vegetation turnover in the two subreaches.

922 Figure 12. Comparison between maximum time of vegetation turnover in the two subreaches.

925 Figure 13. Vegetation turnover (years) for the two subreaches of the Tagliamento River.

Figure 14. Morphodynamic framework for the Tagliamento River. Thresholds are defined for different channel processes, and expressed in terms of discharge and RI. Data are derived from: Surian et al. (2009) and Mao and Surian (2010) (sediment transport in the channels, low bars and high bars); Bertoldi et al., 2010 (channel shift and in-channel bank erosion); this work (vegetation erosion); unpublished field surveys (sediment transport on high bars).

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Figure 16. Chronology of changes in vegetation cover and possible controlling factors for the two subreaches for the period 1954-2011. A grayscale is used to show the intensity of the single controlling factors: effective discharge is the cumulative discharges above (1) 1,155 m^3s^{-1}; and (2) 1,785 m^3s^{-1}; (3) annual rate of marginal vegetation erosion; (4) in-channel gravel mining area.

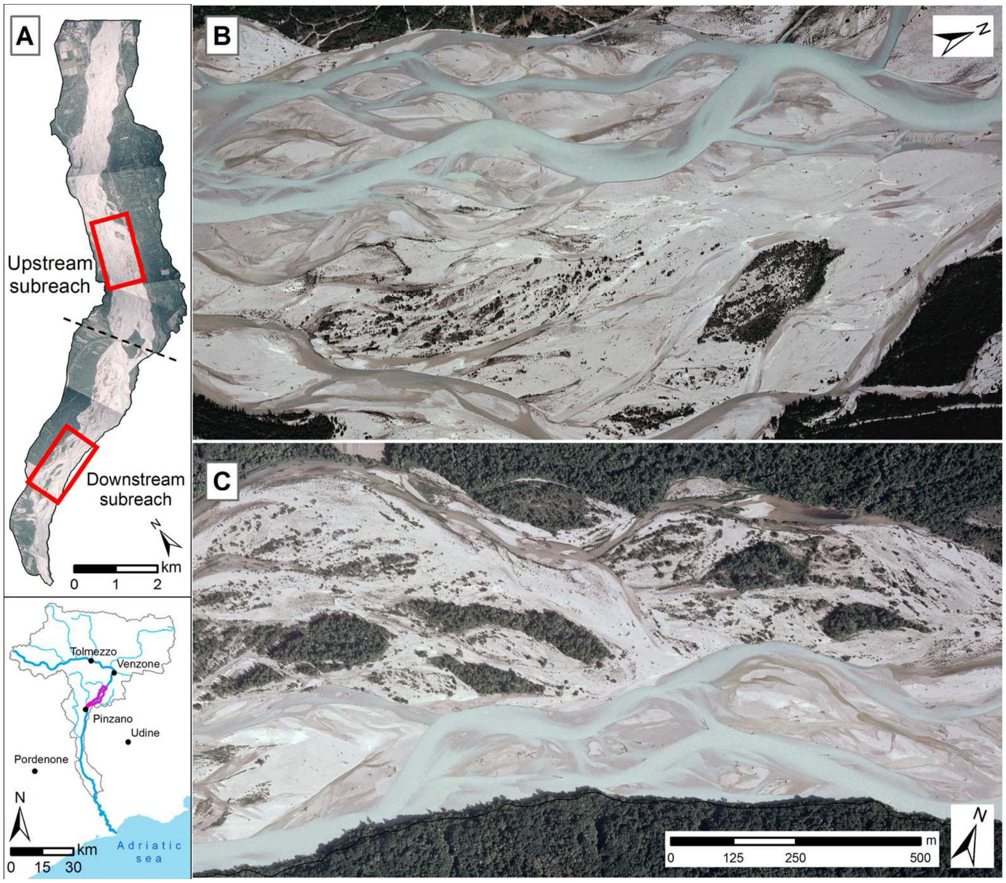

Figure 1. (A) The location of the study reach within the Tagliamento River catchment and the subreaches within the study reach, and aerial photos of the (B) upstream and (C) downstream subreaches.
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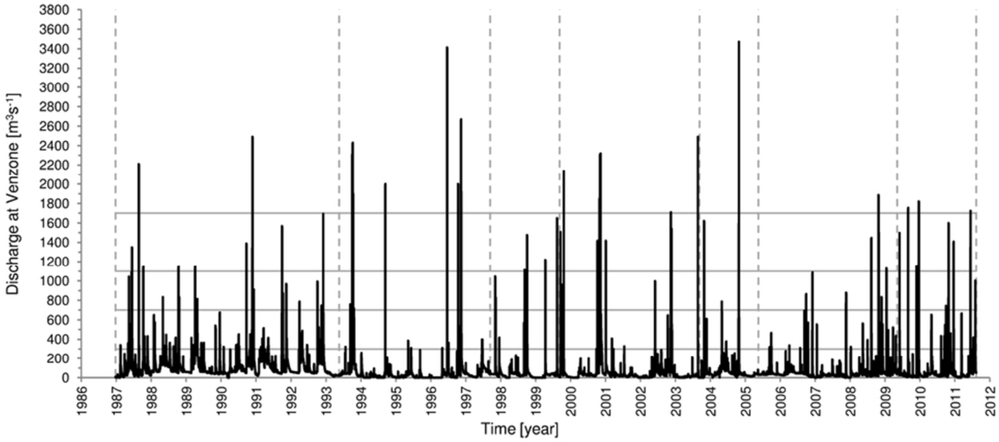

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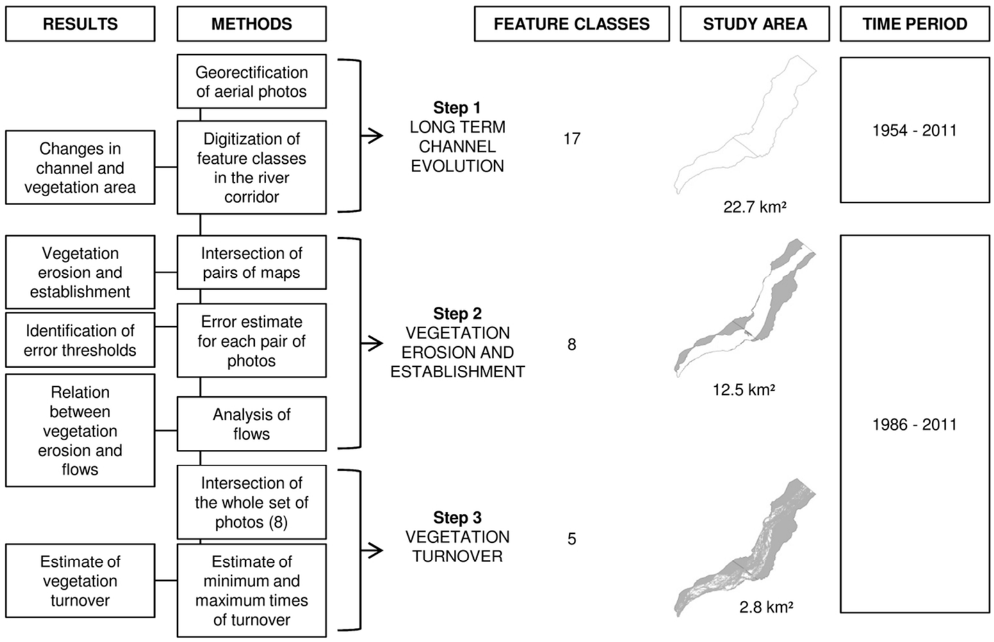

Figure 3. Flow-chart of the three-step analysis carried out in this study, detailing the results, the methods used to obtain them and the study areas and time periods they covered.
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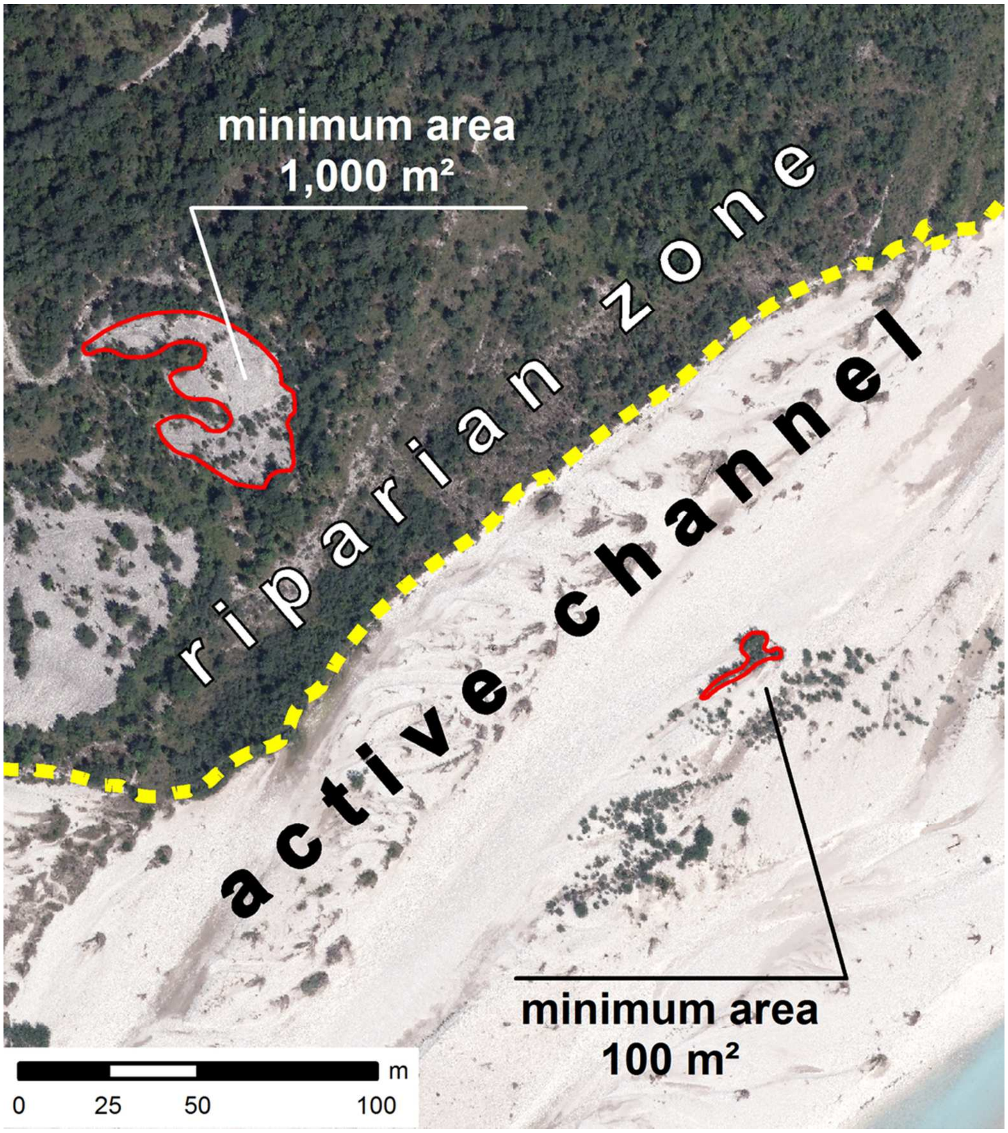

Figure 4. Example of the minimum area measured during aerial photo interpretation.
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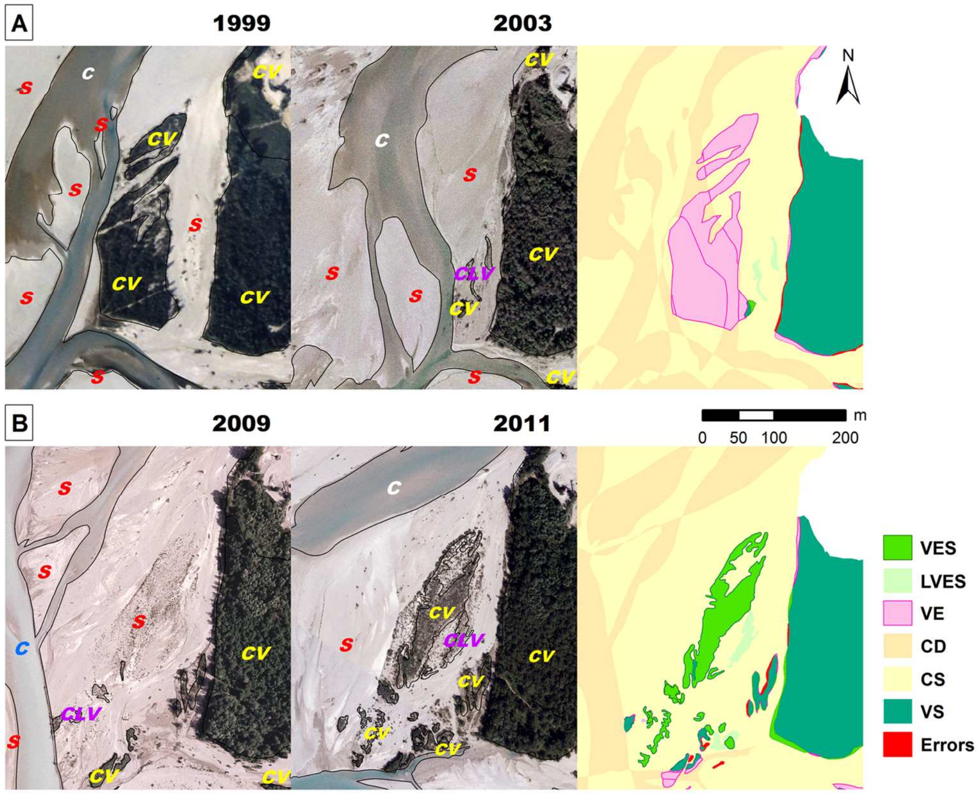


Figure 5. Examples of map intersection showing (A) vegetation erosion and (B) vegetation establishment. See Table III for explanation of the codes.
139x112mm (300 x 300 DPI)

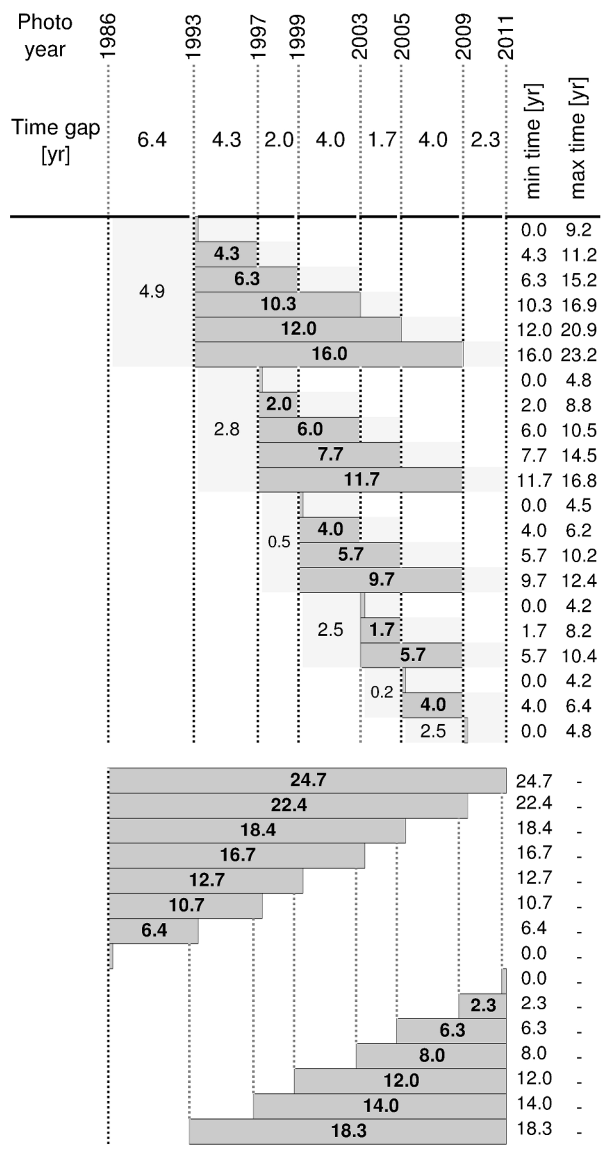
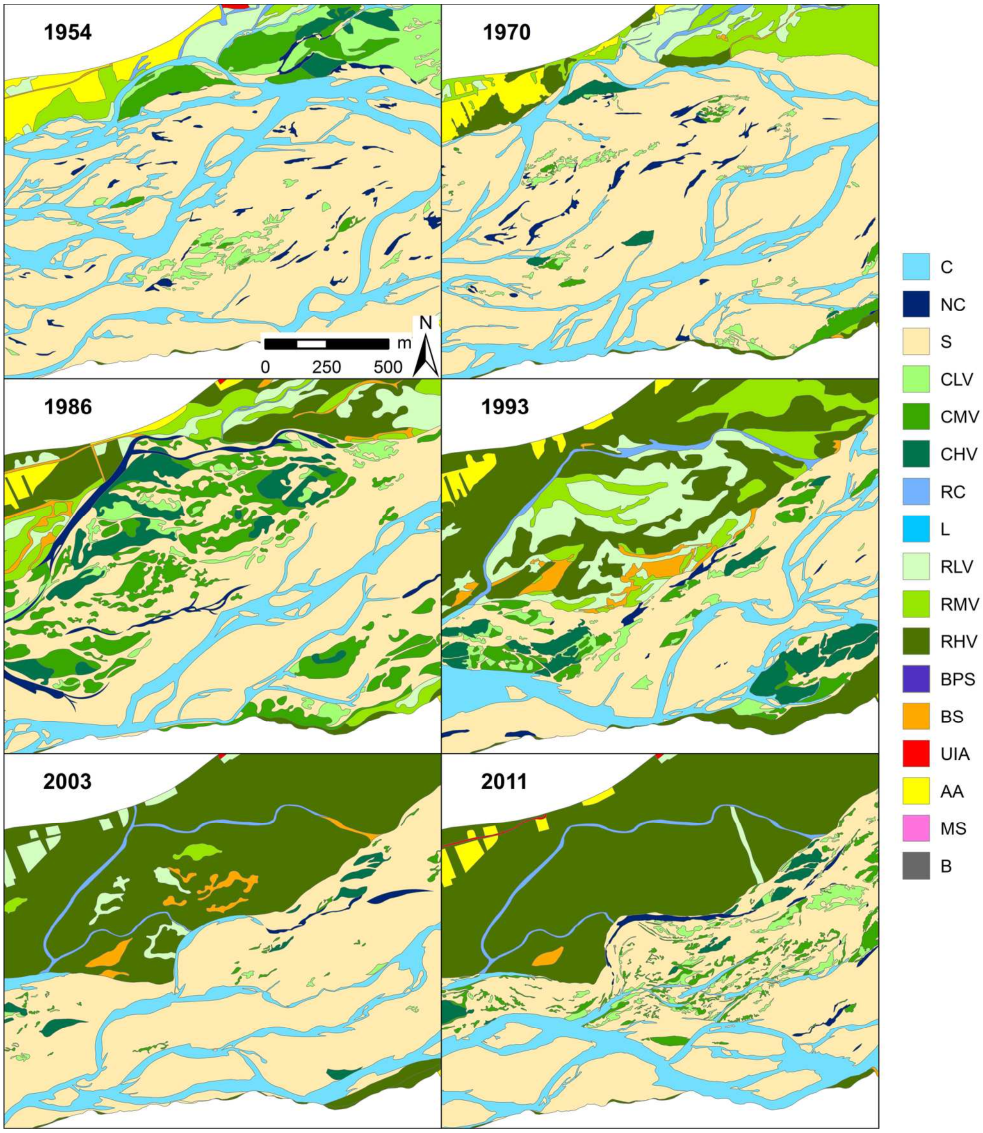


Figure 6. Estimation of vegetation age from aerial photos. Minimum and maximum turnover for vegetation patches are estimated according to presence of vegetation in subsequent photos (gray bars in the figure) and assuming that minimum time span for vegetation establishment is 1.5 year. The procedure to estimate maximum time for the areas vegetated in 1986 or 2011 is explained in the main text.
149x299mm (300 x 300 DPI)



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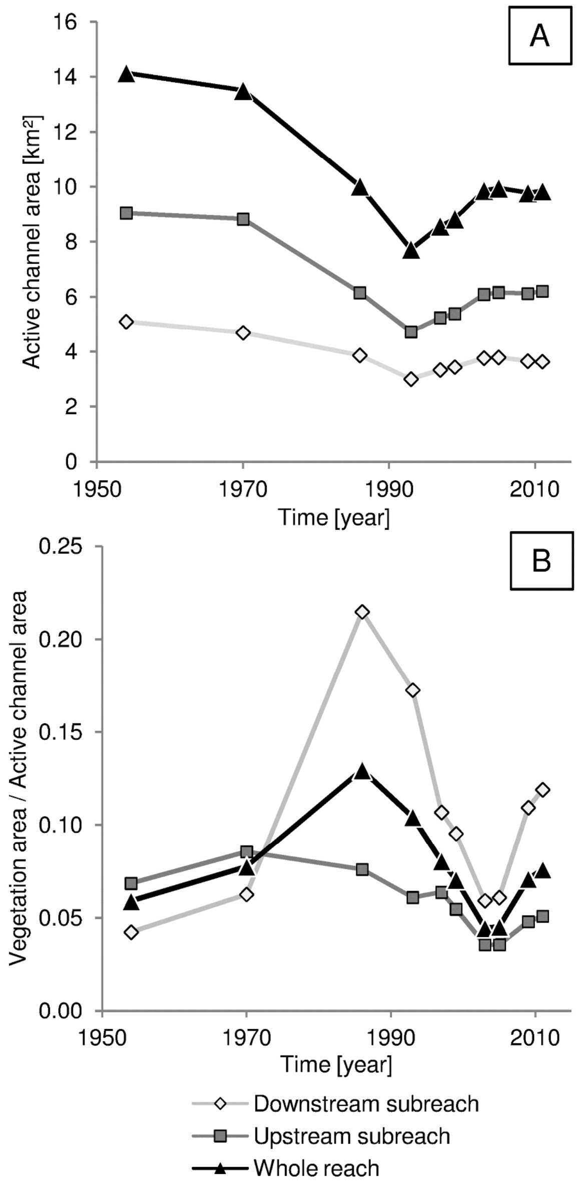

Figure 8. Changes in (A) absolute channel area and (B) relative vegetated area (ratio of vegetated area and channel area) over the period 1954-2011.
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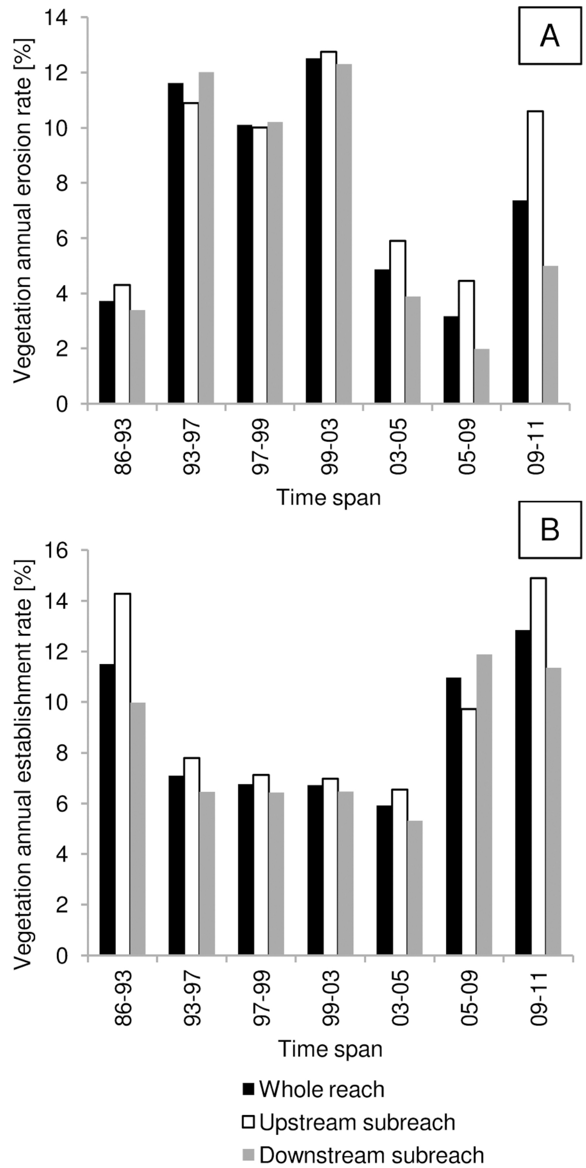

Figure 9. Annual rate of (A) vegetation erosion and (B) establishment in the whole study reach and in the two subreaches for the seven time spans analyzed. Percentage of erosion and establishment was calculated relative to the vegetation cover at the beginning of each time span.
149x299mm (300 x 300 DPI)

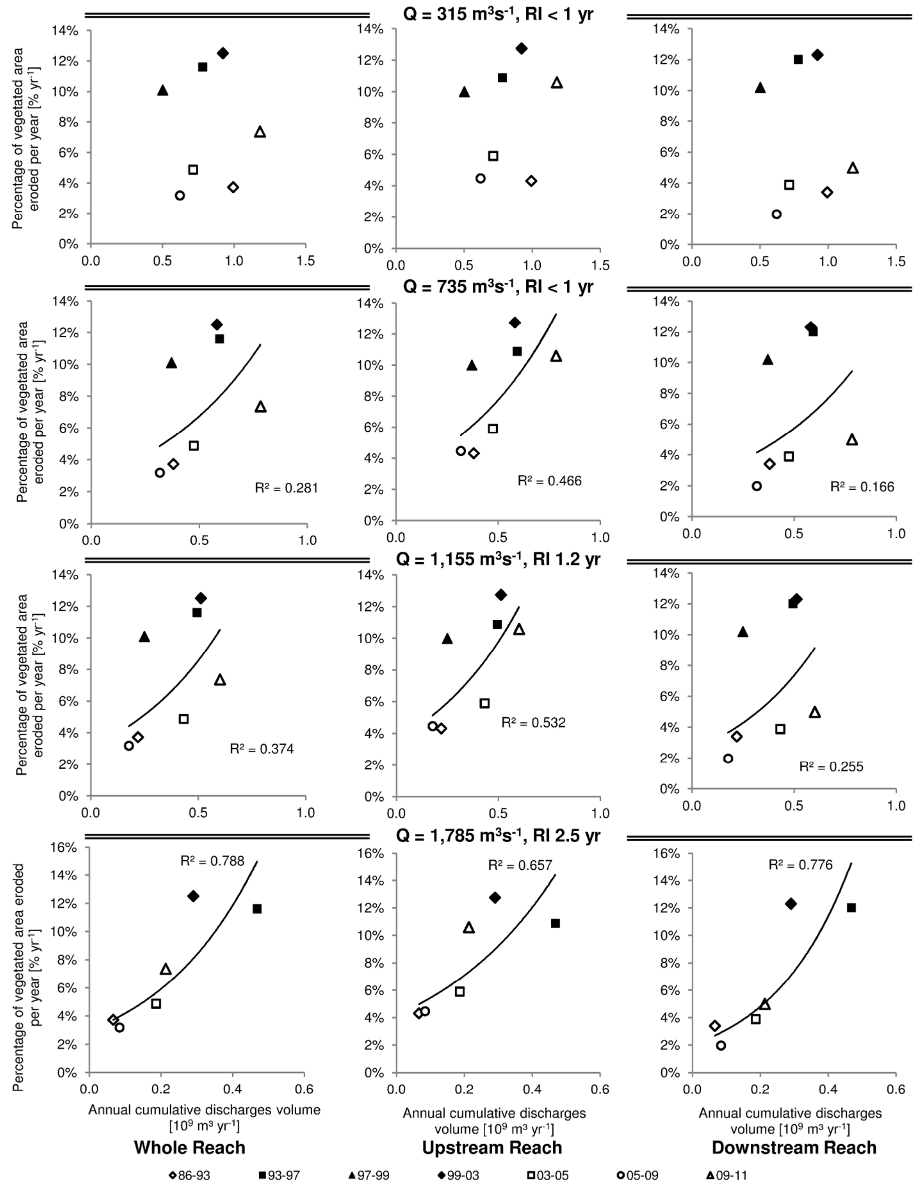

Figure 10. The relationship between annual rate of vegetation erosion and cumulative discharges in the seven time spans; the relationship is shown for 4 increasing thresholds of discharge.
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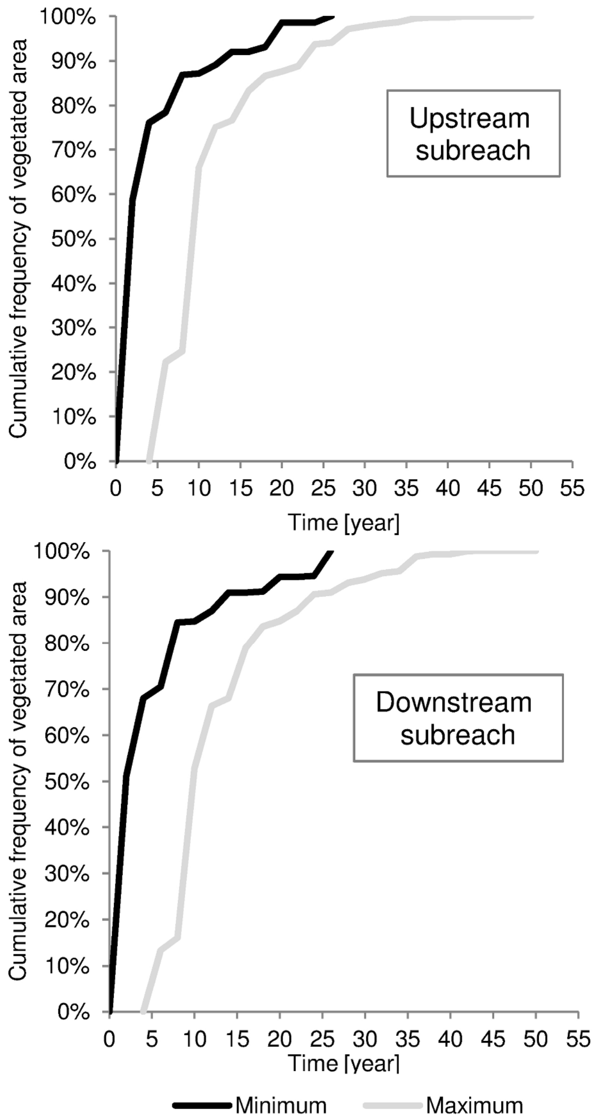

Figure 11. Minimum and maximum time of vegetation turnover in the two subreaches.
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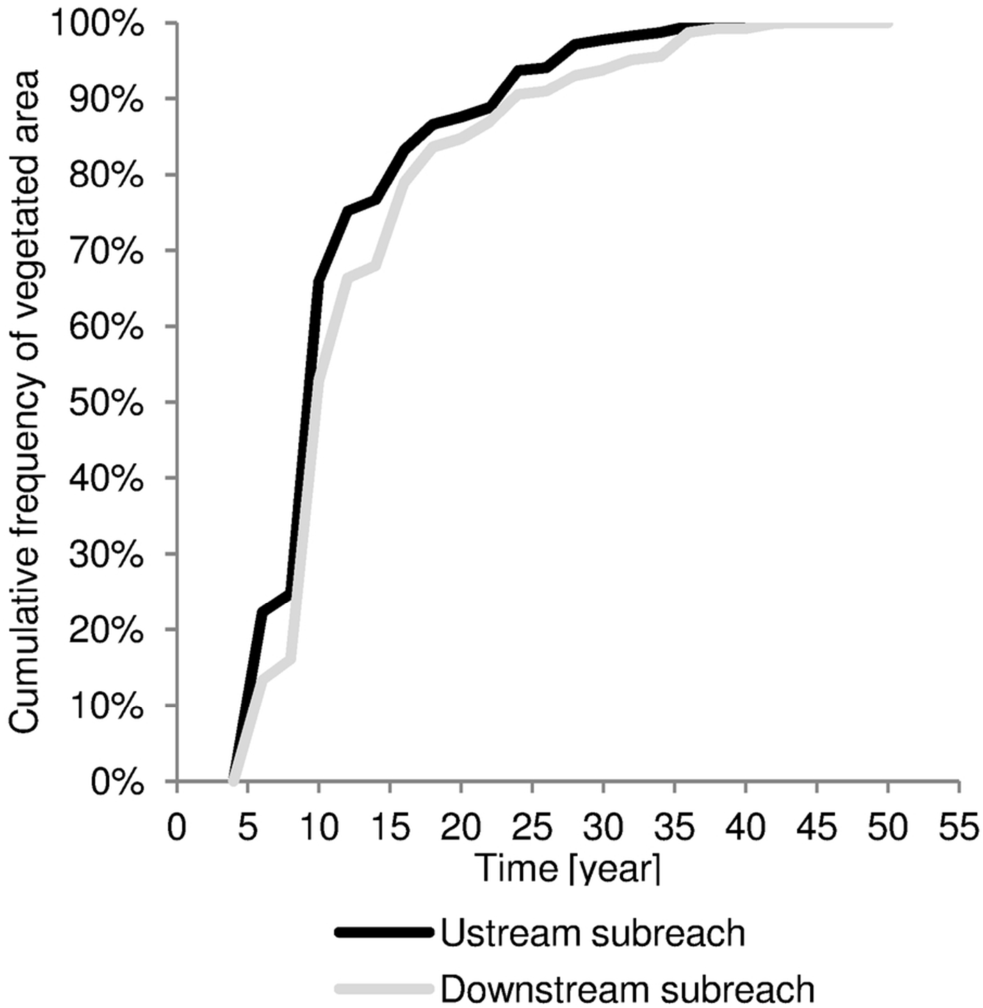

Figure 12. Comparison between maximum time of vegetation turnover in the two subreaches.
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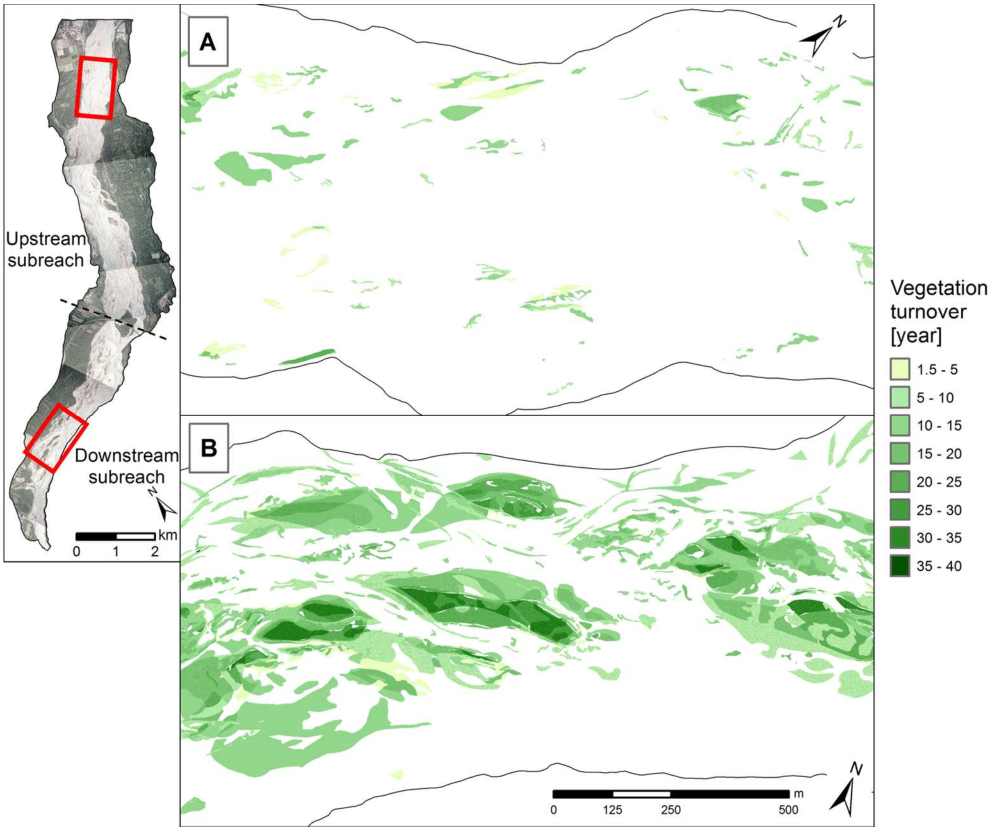

Figure 13. Vegetation turnover (years) for the two subreaches of the Tagliamento River.
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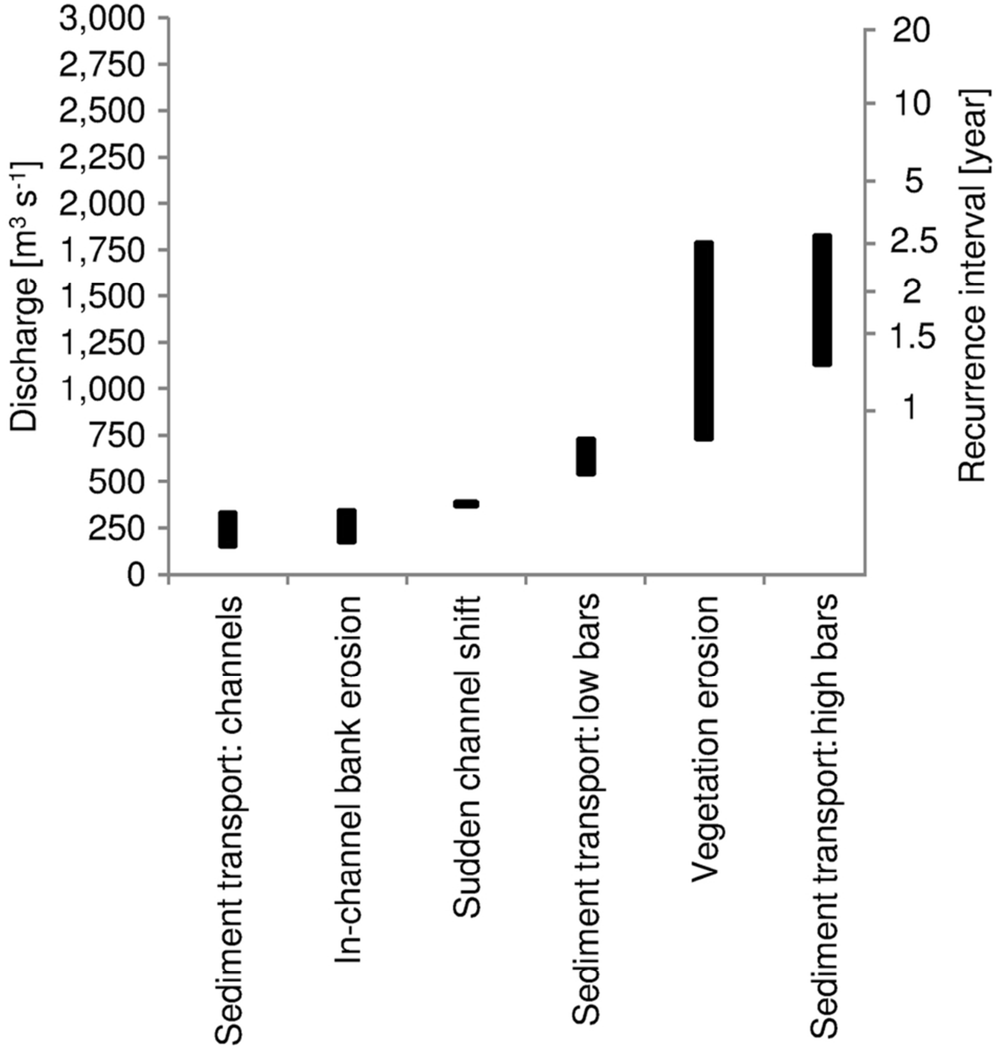

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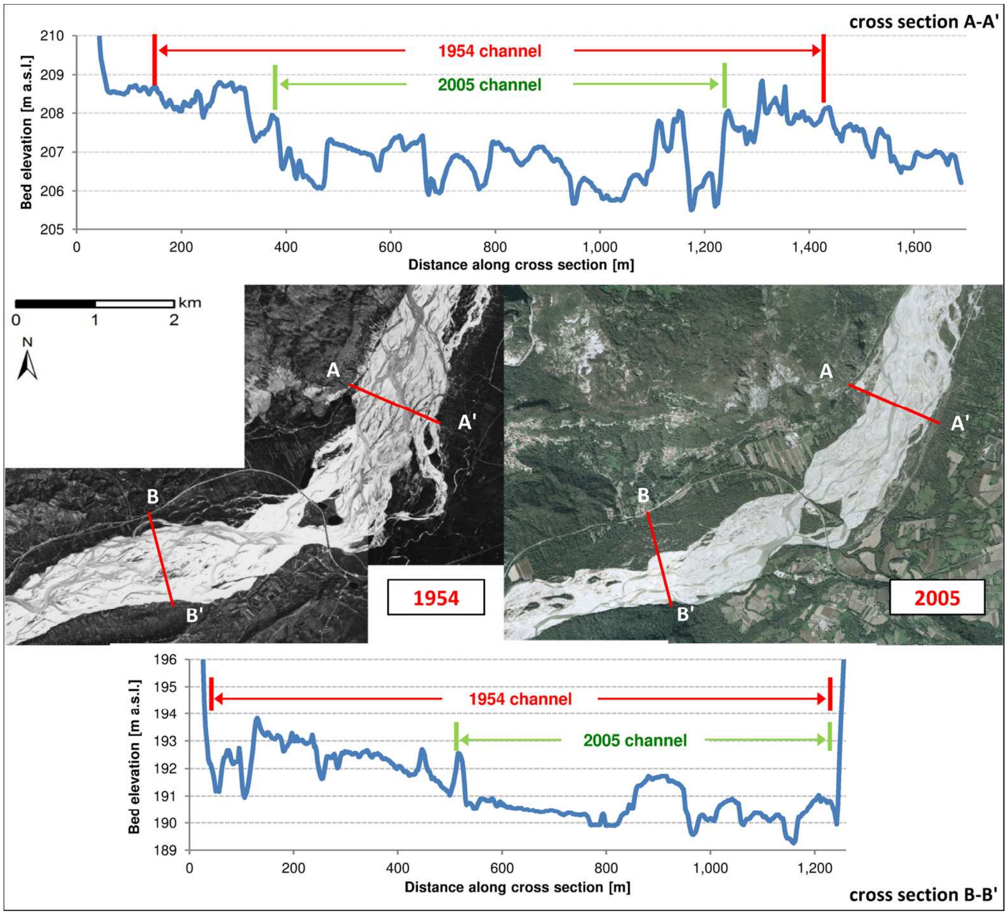

Figure 15. Cross sections showing channel incision in the upstream (A-A') and downstream (B-B') subreaches over the period 1954-2005.
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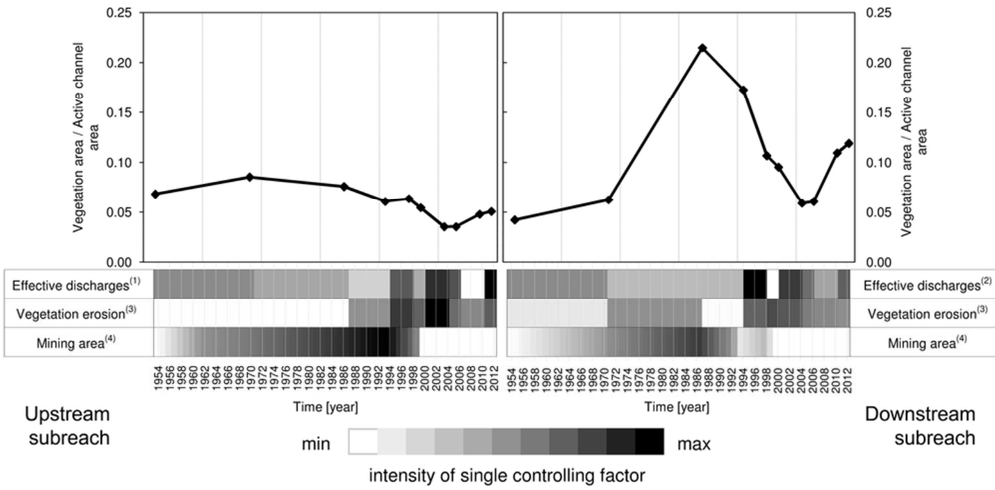

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85x42mm (300 x 300 DPI)