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Riverscapes downstream of hydropower dams: Effects of altered flows and historical land-use change

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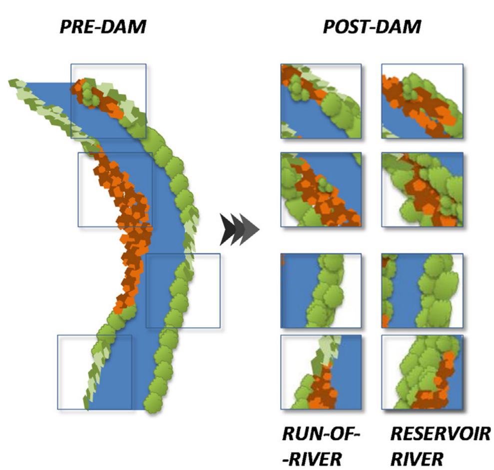
HIGHLIGHTS

- Riparian vegetation cover increased in riverbanks and banks in the post-dam period.
- Riparian patches downstream of dams were larger, but with lower spatial complexity.
- Riparian cover at the two reservoir rivers was greater than at the run-of-river setting.
- Riparian vegetation had different growth trajectories depending on type of dam-induced hydrologic alterations.
- Riparian changes were driven by LULC change and hydrology with complex interactions.

GRAPHICAL ABSTRACT



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ABSTRACT

Dams strongly impair the fluvial environment by altering downstream flows. We analysed riverscapes downstream of three dams and hypothesized that different dam types in rivers with diverse history of land-use and land cover (LULC) change have significant riparian cover differences at diverse biogeomorphic units (banks, riverbanks, islands). We performed a temporal comparison using pre-dam (1965) and post-dam (2013) high-resolution airborne imagery. A new approach was devised to correct the spatial offset between historical and contemporary imagery. Riparian vegetation and LULC (200 m-buffer) were mapped in three rivers of Portugal regulated by the dams Touvedo (run-of-river), Vilarinho das Furnas and Fronhas (storage reservoirs). Five landscape metrics, measures of shape complexity, area and edge effect of riparian patches were computed, including the Weighted Class Area, a metric developed to better interpret the landscape variation. Our findings provide support for the hypothesis of highly altered riverscapes in the post-dam period. For all case studies riparian patches are presently larger, but with less complex shapes and smaller edges. In the present study riparian patches encroach into the river channel, occupy more area and are larger at the two reservoir rivers than at the run-of-river setting. Riparian growth trajectory at the latter is mainly outwards from the active channel and non-vegetated areas in riverbanks and banks are significantly larger; likely due to the washing flows. Redundancy analyses indicated that riparian change was driven by both LULC (agricultural land abandonment and

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unmanaged forests) and hydrological alterations that jointly determine the structure and spatial trajectories of riparian expansion.

1. Introduction

Dams are undoubtedly one of the major driving forces of change in fluvial systems (Nilsson & Berggren, 2000; Poff, Olden, Merritt, & Pepin, 2007). They alter the aquatic and riparian ecology by affecting river hydrology in quality, quantity and timing of downstream flows (Alldredge & Moore, 2014; Poff & Zimmerman, 2010; Rood, Braatne, & Goater, 2010). The Mediterranean regions are recognized as one of the most affected regions of the world by stream flow alterations and dam management to meet summer water deficits and energy demands (González, Gonzalez-Sanchís, Cabezas, Comín, & Muller, 2010; Hooke, 2006). On the other hand, riverine landscapes in European Mediterranean regions are usually highly constrained by land-use (Aguiar & Ferreira, 2005; Allan, 2004; Cooper, Lake, Sabater, Melack, & Sabo, 2013). Both recent land-use cover changes and dam construction have placed pressure greater than ever in riparian ecosystems in Portugal and have affected their integrity in relation to species composition, functional diversity, longitudinal and transversal connectivity (Braatne, Rood, Goater, & Charles, 2008; Dufour, Rinaldi, Piégay, & Michalon, 2015; Nilsson & Swedmark, 2002).

Apart from the long-standing use of water resources and floodplains, there have been large societal changes in Portugal over the last 50–60 years, resulting in increasing urban and industrial development, along with a general decline of intensive agriculture and increase in forested areas (Ferreira, Aguiar, & Nogueira, 2005; Moreira, Rego, & Ferreira, 2001). In particular, Portugal has been recently recognized as a European hot-spot of land-use and land cover change (LULC) (Clerici, Paracchini, & Maes, 2014), and highly impaired by stream flow regulation (Liermann, Nilsson, Robertson, & Ng, 2012). Recent research in Portugal has addressed riparian vegetation flow-relationships to climate change (e.g. Rivaes et al., 2013), and explored how natural hydrology influences riparian tree species across the Ibero-Atlantic region (Aguiar, Cerdeira, Martins, & Ferreira, 2013; Rodríguez-Gonzalez, Stella, Campelo, Ferreira, & Albuquerque, 2010). However, studies on vegetation flow-relationships under dam-induced disturbances are still lacking in Portugal. Historical field records of riparian vegetation, i.e. species composition data before the construction of dams, are very scarce or scattered and do not provide enough detail. Image geometric analyses are alternative methods that can be used to study long-term dynamics at a landscape level in targeted temporal windows such as periods before and after impacts, as well as relevant effects of LULC. These approaches have been successfully applied in understanding river landscapes or 'riverscapes' dynamics (Carbonneau, Fonstad, Marcus, & Dugdale, 2012), for mapping, monitoring and managing riparian zones (e.g. Apan, Raine, & Paterson, 2002; Johansen, Arroyo, Armston, Phinn, & Witte, 2010; Kearns, Kelly, Carter, & Resh, 2005; Schuft et al., 1999; Yang, 2007), in assessing changes in composition and geomorphology of riparian corridors (e.g. Kondolf, Piégay, & Landon, 2007), and in quantifying the impact of the construction of dams (e.g. Kellogg & Zhou, 2014).

The geospatial mapping and analysis of riverscapes could be implemented via a 'landscape metric approach', which allows linkage between the spatial patterning and dynamics of agricultural land-use and forest change across the landscapes (Fernandes, Aguiar, & Ferreira, 2011; Geri, Rocchini, & Chiarucci, 2010; Lausch & Herzog, 2002). Several studies have used image geometric analyses to relate the spatial patterns of riparian woods to distinct land-use types and damming, providing insights on the direction of change with disturbance (Appendix A). Effects of agricultural activities are usually associated with constraints and fragmentation of riparian zones, with small riparian patches and simple spatial configurations (Aguiar & Ferreira, 2005; Apan et al., 2002; Burton, Samuelson, & Pan, 2005; Fernandes et al., 2011; Rex & Malanson, 1990). Indirect effects from agriculture include decreases in superficial and groundwater, and contamination with pollutants and fertilizers. There is also evidence that riparian forests under the influence of managed forests are frequently constrained and fragmented, with small structural complexity and increasing fire risk (Clerici et al., 2014). Similar spatial patterns were observed in urban catchments and riparian zones with nearby impervious lands, mostly due to fragmentation, increasing mortality rates and low nutrient uptakes (Allan, 2004; Burton et al., 2005; Burton, Samuelson, & Mckenzie, 2009; Ferreira, Aguiar, & Nogueira, 2005; Hooke, 2006). While studies of effects of agriculture, forestry and urban land-uses in riparian landscapes report similar results on the patterns of change, published literature using image spatial analysis for studying damming effects report distinct responses. We found evidence for channel encroachment of riparian vegetation in Mediterranean rivers resulting in an increase of the cover and density of woody vegetation (Bejarano & Sordo-Ward, 2011; Garófano-Gómez et al., 2013; Kondolf & Batalla, 2005). On the other hand, hydrologic alteration by dams also caused spatially disconnected riparian landscapes, senescence of non-pioneer forests, succession towards wood wetlands, increasing mortality, reduced grow rate, altered recruitment, failure of seedling establishment, amongst other effects on stream channel morphology (e.g. Belmar, Bruno, Martínez-Capel, Barquín, & Velasco, 2013; González et al., 2010; Nilsson & Svedmark, 2002; Merritt & Wohl, 2006; Poff & Zimmerman, 2010).

A growing number of authors warn of the need to address multiple drivers of riverscape change. For instance, Gordon and Meentemeyer (2006) studied the interacting effects of a dam and agricultural land-use on downstream changes in channel morphology and riparian vegetation, whereas Hoffman and Rohde (2011) and Dufour et al. (2015) explored how river dynamics, vegetation and land-uses have changed over time. Most of the produced knowledge relied on individual responses of riparian vegetation to a dominant land-use, or on the effects of hydrologic alterations in vegetation dynamics and river geomorphology. With the present study, it is our goal to quantify and understand the riverscape alterations and the effects of diverse hydrologic alterations caused by two different dam types – run-of-river dams and storage reservoirs – within the context of landscapes with complex anthropogenic influences.

These purposes lead us to formulate the following hypotheses organized in two parts:

i) Riverscape alterations:

- Hypothesis H1a (*Highly-altered riverscapes*): There are significant changes in area and location (banks, islands, riverbanks) of riparian woody vegetation in rivers altered by the construction of dams accompanied by significant LULC;

- Hypothesis H1b (*Hydrologic-based explanation*): Hydrologic alterations have a higher contribution to riparian vegetation changes than LULC.

ii) Dam type influence:

- Hypothesis H2a (*Hydrologic-based divergence*): Diverse types of dams (storage reservoirs and run-of-river dams) will induce diverse riparian cover changes;
- Hypothesis H2b (*Hydrologic naturalness*): Run-of-river dams induce smaller riparian cover changes in comparison with storage reservoirs.

We tested these hypotheses by performing temporal analyses downstream of dams at two rivers impacted by storage reservoirs ('reservoir rivers' sensu Welcomme, 1979) and one river impacted by a run-of-river dam ('run-of-river') in the context of highly altered riverscapes of the Mediterranean region.

2. Methods

2.1. Study reaches

The study was conducted in three river reaches downstream of hydropower dams in Portugal (Fig. 1). The region is characterized by a Mediterranean climate influenced by the Atlantic Ocean, with an inter-annual variation of rainfall and seasonal events of flooding and drying with low predictability. River reaches are bordered by alders (*Alnus glutinosa*), ashes (*Fraxinus angustifolia*), black willows (*Salix atrocinerea*) or Iberian endemic willows (*Salix salviifolia*). The lower riparian strata are composed by various hygrophyllous shrubs, such as the alder buckthorn (*Frangula alnus*), the common hawthorn (*Crataegus monogyna*), and the bay laurel (*Laurus nobilis*), and frequently by bramble tickets of diverse *Rubus* and *Rosa* species. Riverscapes are characterized by long-lasting human influence. At the beginning of the 20th century, local populations were devoted to agro-pastoralism, and cultivated mostly corn, potatoes and rye in terraces of mountainous valley floors (Pereira, Queiroz, Pereira, & Vicente, 2005), whereas floodplains were dominated by orchards and irrigation crops. After a demographic peak of 1950s, the emigration and rural exodus caused generalized agricultural land abandonment, followed by a general increase of shrublands and forest plantations (Regos, Ninyerola, Moré, & Pons, 2015).

To investigate riparian change in hydropower rivers, we selected two river reaches namely at River Alba and River Homem, regulated respectively by storage reservoirs – Fronhas and Vilarinho das Furnas – and one river reach, at River Lima, regulated by a run-of-river dam, with low regulation capacity and a toe-dam powerhouse – Touvedo.

Stream flow regime downstream of Fronhas and Vilarinho das Furnas vary greatly between the pre- and post-dam periods. The degree of the hydrologic alterations was classified as 'high' for the majority of flow components, namely for the magnitude, variability, duration and seasonality of low and high flow periods and rate of change or 'flashiness' (Cardoso, Portela, Aguiar, Martins, & Bejarano, 2013). In comparison, small differences were found in inflows and outflows from Touvedo dam and the post-dam hydrologic alterations downstream of Touvedo were considered mostly 'small' or 'moderate'. Exceptions were the number of days with zero flow, base flows and annual minima (1-day, 3-days, 7-days, 30 days). Despite the differences in catchment areas, River Alva (Fronhas case study) and River Homem (Vilarinho das Furnas case study) displayed hydrologic similarities downstream of dams (Table 1), with average maximum daily flows along the year (Qc) around 131 and 107 $m^3 s^{-1}$, and similar flashiness of floods, 0.374 and 0.431, respectively. After the Touvedo dam operation, River Lima revealed significant hydrologic differences when compared with the rivers Alva and Homem (Qc ≈ 594 $m^3 s^{-1}$; flashiness = 0.601) (Martins, 2012).

2.2. Study design and data collection

A temporal comparison using pre- vs. post-dam high-resolution aerial images was performed. All images were obtained from Direção-Geral do Território (http://www.dgterritorio.pt/). Contemporary images (post-dam construction) are high spatial resolution multispectral airborne images (50 cm spatial resolution) acquired during the Spring of 2013. The orthorectification was performed using a 5 m resolution raster Digital Elevation Model (DEM) and a true color composite image (blue, green and red bands) was used to visualize river reaches. Historical images (pre-dam construction) correspond to the first national aerial coverage mission in the study area, which occurred during the 1960s. The film was scanned with an Epson 1640 XL large format flatbed scanner at 1200 dpi in 8 bits for the panchromatic grayscale.

Historical imagery was mosaicked and georeferenced, using control points. Georeferencing was performed with ArcMap's Georeferencing Toolbar using as control points corners of houses, bridges and roads selected particularly in river vicinity, to reduce the distortion errors in the target area. All images were projected to the European Terrestrial Reference System 1989 (*ETRS89*) and resampled with the nearest neighbor method to 72 cm, the lowest spatial resolution obtained during the georeferencing process. We decided to resample to a common spatial resolution so that riparian patches appear with similar dimensions for the on-screen analysis, thus allowing comparison of riparian cover changes at the chosen scale across time, in a similar manner as for Libertéet al., (2004).

River reaches were firstly demarcated for the contemporary images, in order to have the location of the dam as a reference for the historical images. The river reaches did not include the initial 500 m downstream of dams given the physical disturbances directly caused by the engineering works, and their total lengths were determined by the first inflowing tributary downstream of dams to avoid the effects of external sediment and water supplies. The three river reaches were then partitioned into 250 m long sampling units (SUs), both for the historical and contemporary images, starting from the dam location. For each case study, the SU located right upstream the tributary entrance was not included in the study, and marked the end of the river reach. We obtained 76, 88, and 94 250 m-long SUs for River Lima, River Alba and River Homem, respectively corresponding to river reach extensions of 19 km, 22 km and 23.5 km downstream Touvedo, Fronhas and Vilarinho das Furnas dams.

We first manually delimited the riparian zone of each SU, by considering as riparian zone the area from the edge of the riverbank to the external visible line of the canopy where an abrupt change in vegetation height, type and amount occurs (Johansen & Phinn, 2006). Then, we visually mapped three river locations, taking into account hydrogeomorphical models based on the interplay of channel and streamflow dynamics, sediment load and vegetation development (Gurnell & Petts, 2002), namely the biogeomorphological structures (i) riverbanks; (ii) banks, which are intermingled with water, and (iii) islands. We attained 3381 riparian patches for the three case studies. These patches were then classified, in each river location, either as 'Trees' if they include trees and tall shrubs, or as 'Other' if they include bare ground or herbaceous vegetation. Thus, we considered six riparian classes: Riverbank Tree (1578 patches), Riverbank Other (807 patches), Bank Tree (443 patches), Bank Other (421 patches), Island Tree (73 patches) and Island Other (59 patches). Fig. 2a and b illustrates the sampling design and the classification system used. Appendix B contains the

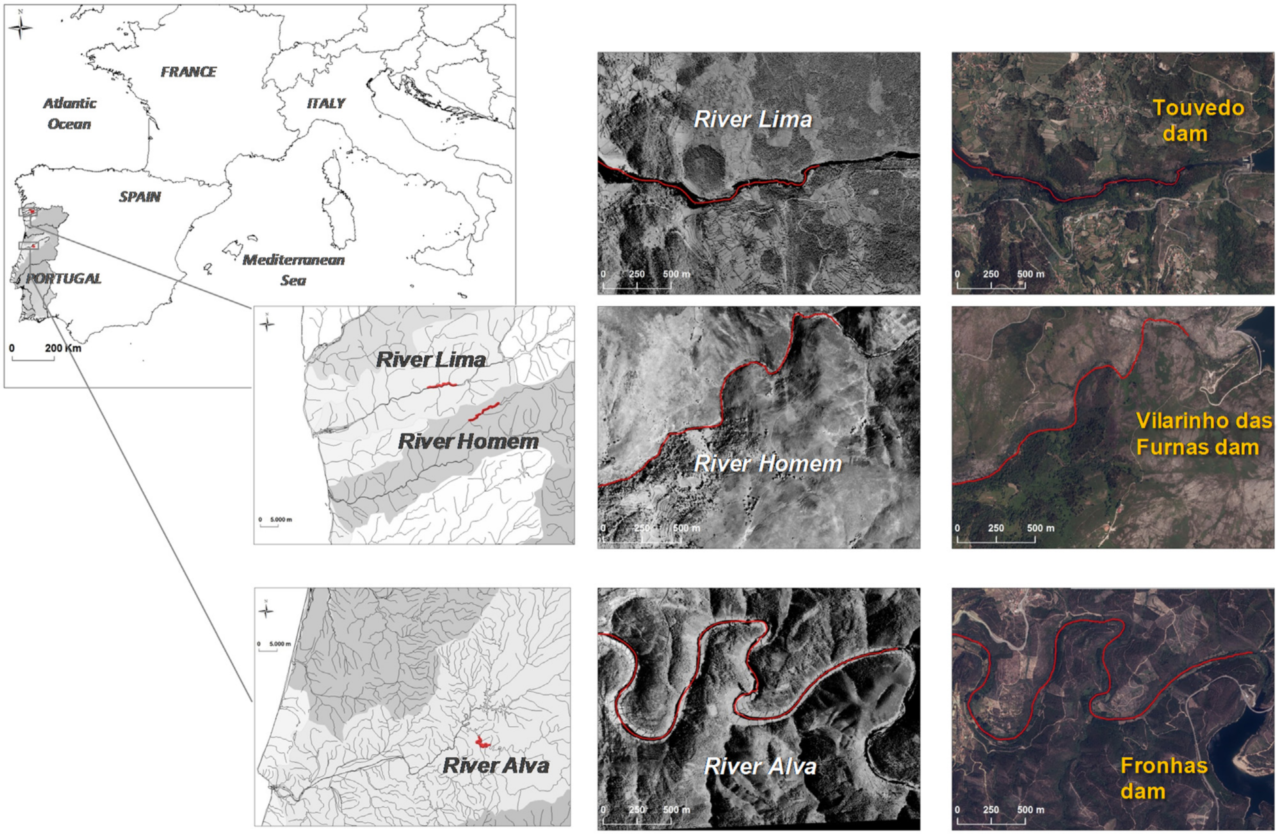


Fig. 1. Location map for Western Europe showing Portugal (grey area) and the three case studies: (a) Touvedo (River Lima), (b) Vilarinho das Furnas (River Homem) (c) Fronhas (River Alva). Background maps are mosaicked airborne digital images with flyover dates in 1965 (before dam construction—black composition images) and 2013 (actual dam location-color composition images). Red line in the maps represents the studied river reaches and corresponds to the thalweg in the digital imagery. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Description of case studies: dam characteristics and streamflow characteristics downstream of dams (data from EDP—Gestão da Produção de Energia SA, 2011; Martins 2012; Cardoso et al., 2013).

Case study	Touvedo	Vilarinho das Furnas	Fronhas
Acronym	TOU	VIL	FRO
Dam plant type	Run-of-river power plant	Storage reservoir; water transfer	
River ID	River Lima	River Homem	River Alva
Catchment area (km^2)	1700	77	652
System	Cávado-Lima	Cávado-Lima	Tejo-Mondego
Commissioning year	1993	1972	1985
Purpose and productivity	Energy (22 MW), irrigation, flood defence	Energy (125 MW), derivation	Energy (Aguieira-Fronhas-Raiva = 193 MW), derivation
Regulation capacity (%)	1.0	43.1	13.1
Annual average of mean daily inflows (Qnat; m^3 s^{-1})	49.6	5.4	16.3
Annual average of mean daily outflows (Qmod; m^3 s^{-1})	43.9	0.3	3.3
Average minimum daily flows along the year post-dam (Qs; m^3 s^{-1})	0.996	0.345	0.108
Average maximum daily flows along the year post-dam (Qc; m^3 s^{-1})	594.4	131.5	107.9
Coefficient of variation of the flushing flood series post-dam	0.601	0.374	0.431
Average of mean annual flows of a medium meteorological year post-dam (m^3 s^{-1})	1446.1	270.2	320.9

number of patches obtained for each riparian class in each one of the three case studies.

2.3. Landscape metrics

The landscape metrics Mean Patch Size (MPS), Patch Size Coefficient of Variation (PSCov), Area Weighted Mean Patch Fractal Dimension (AWMPFD), and Edge Density (ED) were computed for all riparian classes using the Patch Analyst extension for ArcGIS 10.1. These landscape metrics are related with area, shape complexity, and edge effect of riparian patches and were selected based upon similar studies in riparian landscapes (mostly Apan et al., 2002; Fernandes et al., 2011; Garófano-Gómez et al., 2013; Schuft et al., 1999), and correlation procedures. Table 2 describes the

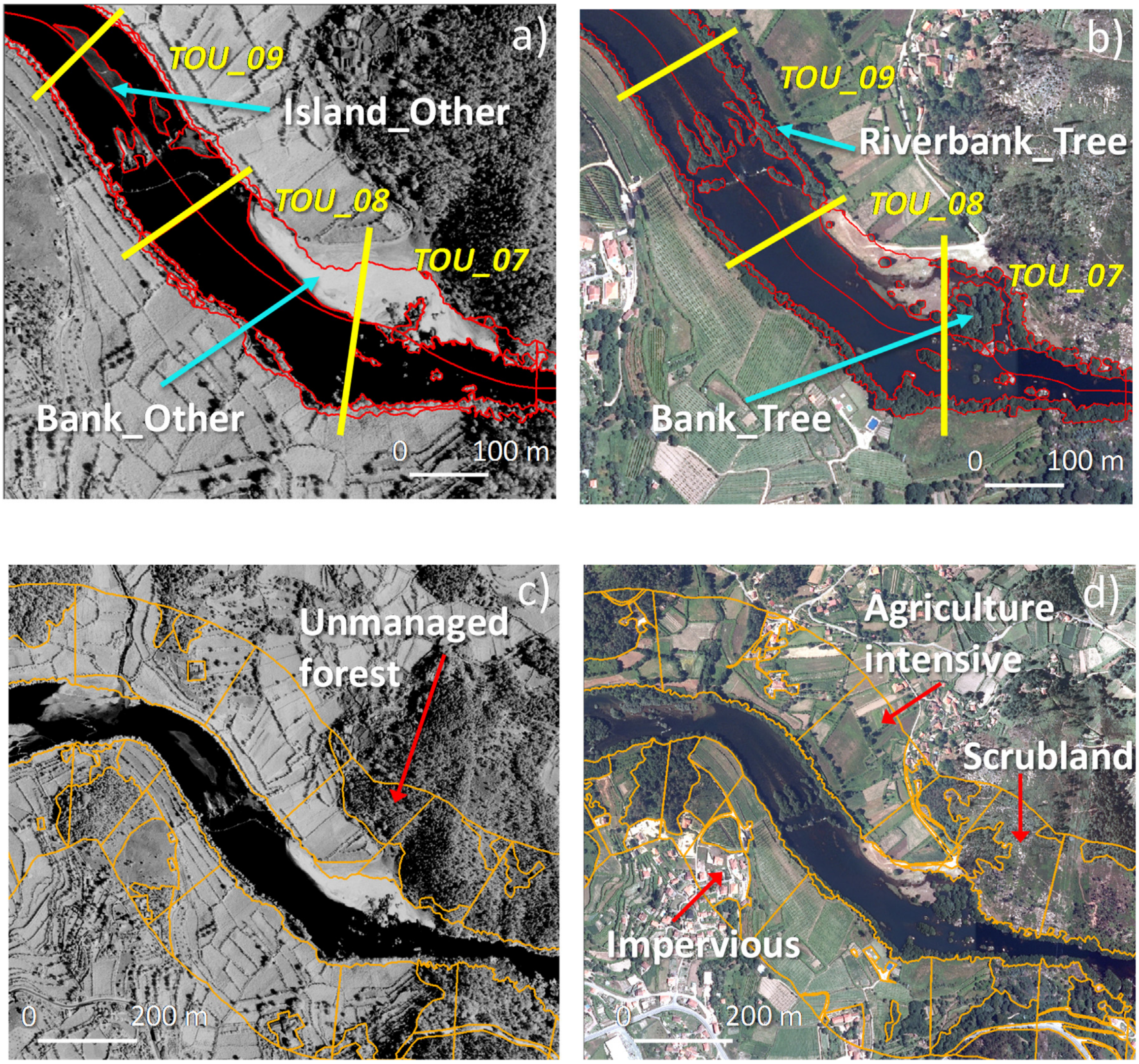


Fig. 2. Panels (a) and (b): illustration of delimitation of sampling units (yellow lines perpendicular to the thalweg divide continuous sampling units), riparian classes (tree and other) and river locations (riverbank, bank, and island) in blue arrows for (a) historical and (b) contemporary periods, for case study Touvedo (River Lima). Panels (c) and (d): illustration of the LULC patches within a 200 m buffer for a) historical and b) contemporary periods, for case study Touvedo (River Lima). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Landscape metrics used in the study and description. SU—sampling unit (250 m long river reach).

Category	Name	Acronym	Description	Proxy for riparian woodlands
Area	Mean Patch Size	MPS	Average area of all patches in the SU (ha)	Fragmentation
	Weighted Class Area	WCA	Relative class area (unitless) WCA = (Nump × MPS)/Total area of the SU	Density
Shape Complexity	Patch Size Coefficient of Variation	PSCov	Standard deviation of patch size divided by the mean patch size for the entire landscape (%)	Structural heterogeneity Landscape diversity
	Area Weighted Mean Patch Fractal Dimension	AWMPFD	The patch fractal dimension weighted by relative patch area (unitless)	Spatial complexity Naturalness
Edge	Edge Density	ED	Total length of all edge segments per ha for the landscape (m/ha)	

landscape metrics that were used and the underlying rationale regarding the structure and integrity of riparian forests.

The fraction of the area of each SU occupied by each class (Riverbank Tree, Riverbank Other, Bank Tree, Bank Other, Island Tree and Island Other), was determined by the formula,

$$\frac{Nump \times MPS}{Total\ area\ of\ the\ SU}$$

where *Nump* is the number of patches and *MPS* is the Mean Patch Size of the class in the SU.

This landscape metric, which we designated by Weighted Class Area (WCA), allows the assessment of the representativeness of each class in each SU, as well as to compare areas of riparian classes among distinct SUs and river locations.

2.4. Hydrologic data

The Indicators of Hydrologic Alteration (IHA; Richter et al., 1996) consist of a set of ecologically meaningful hydrogeological parameters of river hydrographs, derived from statistical methods that can be used to quantify change between 'pre-dam' and 'post-dam' periods induced by dams. We used the indicator High pulse duration (days) as a measure of hydrological alteration induced by Touvedo, Fronhas and Vilarinho das Furnas dams. Values were collected from Cardoso et al. (2013).

Ratios of IHA, i.e. ratios between the pre-dam and post-dam IHA values were used to test whether the hydrologic alterations had higher contributions to riparian cover changes than LULC (H1b, *hydrologic-based explanation*). To assess the influence of hydrology on riparian cover changes (H2b, *hydrologic-naturalness*) we used the single values of IHA obtained for the pre-dam and post-dam periods.

2.5. LULC data

LULC data were obtained also by on-screen photo interpretation of pre-dam (1965) and post-dam (2013) imagery. Land-use patches (3029 patches) were mapped in a 200 m-buffer at each river margin, and classified in six classes: Extensive Agriculture (pastures, non-irrigation crops, fallow ground; 266 patches), Intensive Agriculture (vineyards, orchards, olive yards, heterogeneous agricultural areas, irrigation crops; 561 patches), Unmanaged Forest (semi-natural or planted woodlands non-managed, mixed forests with deciduous oaks; 620 patches), Managed Forest (maritime pine forests, blue gum forests; 257 patches), Impervious (urban and industrial areas, roads, mines; 529 patches), and Scrubland (sparsely vegetated areas, sclerophyllous vegetation transition woodlands-scrublands; 796 patches) (Fig. 2c and d). Land-use patches were evaluated in percentage of area occupied in each SU. Appendix B contains the number of land-use patches delimited for each LULC class and at each case study, for the historical and contemporary imagery.

2.6. Spatial offset correction

To be able to accurately compare the riparian metrics among sampling units before and after the dam construction, it was necessary to account for the spatial offset between historical and contemporary images due to the combined effect of river dynamics and georeferencing process. To reduce the errors produced by the spatial offset, the historical and contemporary images were superimposed and the 250 m long SUs (C'_i) of the contemporary middle river line were orthogonally projected onto the historical middle river line, giving rise to the projected units (C'_i), overlapping the SUs (H_j) in the historical middle river line (see Fig. 3). In order to assess the pre- and post-dam evolution of a riparian metric accounting for these overlaps, the value obtained for a metric m in each SU H_j, $m(H_j)$, was compared to the average of the values obtained for the same metric in the SUs of the contemporary image, $m(C_i)$, weighted by the fractions of the SU H_j occupied by the projections C'_i in H_j. More precisely, each $m(H_j)$ was compared to $\sum_i m(C_i) \times \ell_{ij}/250$, where ℓ_{ij} denotes the length of the overlap between the middle river lines of C'_i and H_j. In Fig. 3 projected units, C'_{i-1}, C'_i and C'_{i+1}, overlap the SU H_j with overlap lengths a, b and c, respectively, $(a + b + c = 250)$, and therefore $m(H_j)$ may be compared with the weighted average $(m(C_{i-1}) \times a + m(C_i) \times b + m(C_{i+1}) \times c)/250$.

2.7. Statistical procedures for testing hypotheses

For each river location we calculated the differences between pre-dam and post-dam periods of the riparian metrics MPS and WCA with respect to every riparian class and every land-use class, hereafter respectively referred to as 'riparian variable-difference' and 'land-use variable-difference'. All differences were computed accounting for the spatial offset correction. In order to test hypothesis H1a (*Highly-altered riverscapes*), we analysed whether the means between pre-dam and post-dam periods of the riparian and land-use variables-difference were significantly different, using paired *t*-tests.

The metrics ED, AWMPFD and PSCov could not be processed in a similar way since no value could be set for the SUs without vegetation (note that in this situation the null value is not a good representative of the metrics). For those metrics, the differences of the means between the pre-dam and post-dam periods were tested using independent *t*-tests.

We performed a similar procedure to calculate the "LULC variable difference" in order to confirm the significance of the differences between pre-dam and post-dam land-use cover change. Also here the spatial offset correction was applied.

For testing hypothesis H1b (*Hydrologic-based explanation*) we used as data the 'riparian variables-difference' whenever the landscape metric allowed the paired analysis, namely for the WCA and MPS metrics at all SUs for the class Riverbank Tree. Starting from the complete RDA model relating the riparian variables difference with the six 'land-use variables-difference' and the hydrologic variable 'ratio of alteration of High pulse duration', a subset of explanatory variables was obtained by a combined backward-forward selection procedure using the function ordistep from the vegan R package. Permutation p-values were used for adding or dropping a variable from the model. Then, we carried out a Partial Redundancy analysis (pRDA) in order to relate the riparian cover changes with the selected variables (two land-use and hydrologic variables) and to determine if the hydrologic alterations contributed more to explain riparian cover changes than land-use cover change. Three RDA were performed: the partial model using the selected land-use variables as explanatory variables conditioned on hydrology, the partial model using the selected hydrologic variable as the explanatory variable conditioned on land-use, and the full model using both land-use and hydrologic variables as explanatory variables.

We ran permutation tests (ANOVA) for the pRDA in order to test the significance of the model and of the individual canonical axes. For the permutation tests, the rows of the matrix of the 'riparian variables-difference' are randomized repeatedly across some number of permutations.

To test the differences in riparian cover change between reservoir rivers and run-of-rivers (hypothesis H2a, *Hydrologic-based divergence*), we first tested if the run-of-river (RUN: Touvedo) and reservoir rivers (RES: Vilarinho das Furnas & Fronhas) had similar values for WCA and MPS for the riparian classes Banks Tree, Banks Other, Riverbanks Tree and Riverbanks Other before the dam construction. Then, we used *t*-tests to test whether the differences of the means between run-of-rivers and reservoir rivers of the 'riparian variable difference' for MPS and for WCA at riverbanks and banks were significantly different, and to test if the differences in the riparian cover were significantly smaller in run-of-rivers than in reservoir rivers (hypothesis H2b—*Hydrologic naturalness*).

Finally, we explored what variables had more influence in the riparian cover change for each river type. To accomplish this purpose we used the historical and contemporary datasets of WCA and MPS of the class Riverbank Tree, and a sub-set of land-use variables attained with backward-forward selection procedures carried out separately for RES and RUN. Only variables with $p < 0.05$ were included in the final models. RDAs were performed using the

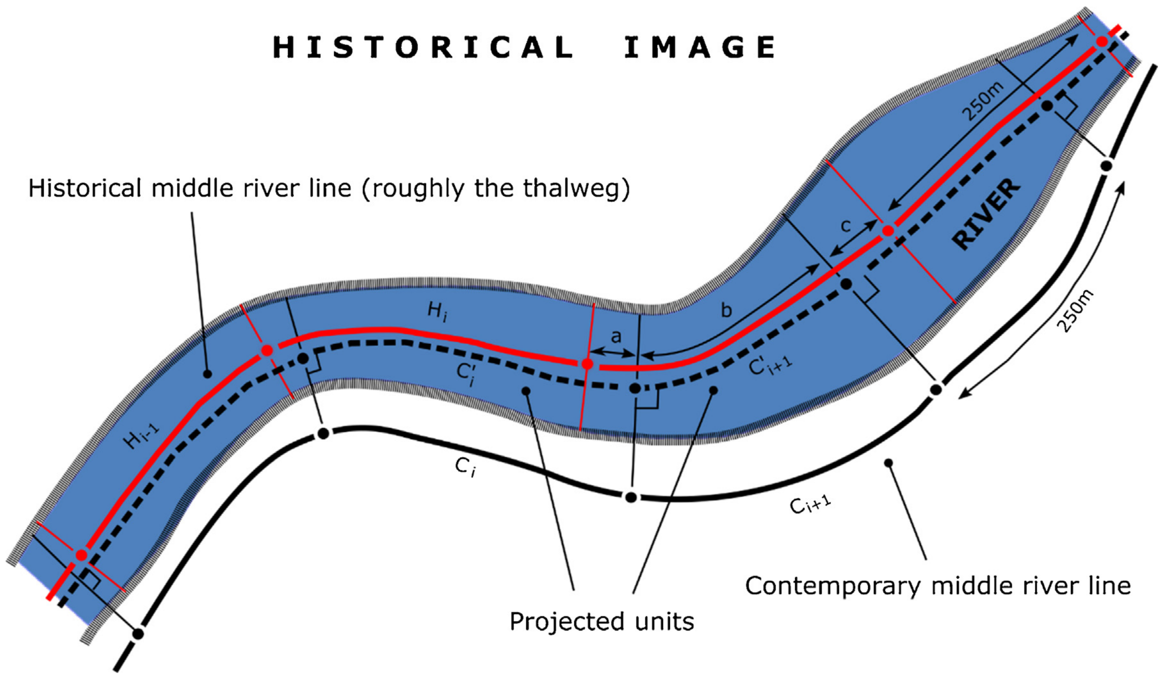


Fig. 3. Schematic representation of the spatial offset. The historical and contemporary images are superimposed and the 250 m long SUs(C_i) of the contemporary middle river line (solid black lines) are orthogonally projected onto the historical middle river line (solid red lines), giving rise to the units $\left(C_i'\right)$, depicted by dashed black lines. These projected units overlap some (usually two) SUs $\left(H_j\right)$ in the historical middle river line. The projected units C'_{i-1}, C'_i and C'_{i+1}, overlap the SU H_j with overlap lengths a, b and c, respectively ($a + b + c = 250$ m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

selected land-use variables set and the historical and contemporary values for hydrology (variable high pulse duration). We ran permutation tests (ANOVA) for the RDA in order to test the significance of the model and of the individual canonical axes.

All computations were performed using functions included in the vegan package of R statistical software (version R 2.14.2, Foundation for Statistical Computing, Vienna, Austria).

3. Results

Our findings provide strong evidence to support the hypothesis of highly-altered riverscapes observed 20–40 years after the dam commissioning date, both in LULC and riparian cover.

3.1. Highly-altered riverscapes—riparian cover change

We observed a common alteration pattern on the riparian vegetation for all case studies, from the pre-dam to post-dam periods (Fig. 4). The most evident trends were an increase in the total area of the riparian vegetation both in riverbanks and banks (WCA of Riverbank Tree and Bank Tree classes), and the increase of the size of riparian vegetation patches (MPS of Riverbank Tree and Bank Tree).

Fig. 4 On the other hand, in general, there was a reduction of shape complexity (AWMPFD; PSCov; ED) in the post-dam period in riparian tree patches, and especially in Riverbanks (Fig. 5a). Thus, post-dam riparian tree patches occupy more area, and are consistently larger, but have less complex shapes and lower edge density.

Appendix C presents the mean differences between historical and contemporary riparian metrics per class (Riverbank Tree, Riverbank Other, Bank Tree, Bank Other, Island Tree, Island Other) for each case study, and the results of paired *t*-tests for MPS and WCA and of the *t*-tests for the independent samples of AWMPFD, ED, and PSCov. In general, differences between the pre-dam and post-dam periods were significant, except for Island Tree. Although the Island Tree class presented an alteration pattern similar to Riverbank Tree and Bank Tree classes, the differences were not significant for the case studies where islands were recorded, namely Touvedo and Fronhas. The classes Island Tree and Island Other were removed from the following analyses, due to the small number of observations.

As a result of the increase of the Riverbank Tree and Bank Tree, we observed a reduction in the total area occupied by the herbaceous vegetation and bare soil in all biogeomorphic units. In other words, we observed a reduction in the MPS and WCA of the classes Riverbank Other, Island Other and Bank Other, except for the run-of-river (Touvedo case study; see Appendix C). Touvedo also showed in the post-dam period a high variability in the size of the riparian tree patches (PSCov) in banks, while for the other case studies (reservoir rivers) showed a more homogenous size of the patches (Fig. 5b).

Riverscapes downstream of Vilarinho das Furnas, a storage reservoir with high regulation capacity and large deviation from natural flows (Table 1), presented the major changes of riparian tree patches, both in total area (WCA; Fig. 4; Appendix C) and complexity (AWMPFD; Fig. 5b).

3.2. Highly-altered riverscapes—LULC

Before the dam construction, the Touvedo landscape was dominated by Intensive Agriculture (≈52% of total area), followed by semi-natural or unmanaged woodlands and mixed forests with deciduous oaks (Unmanaged Forests ≈ 30%). Vilarinho das Furnas landscape was mostly composed of sparsely vegetated areas, esclerophyllous vegetation, and transition communities of woodlands-scrublands (Scrublands ≈ 45%), along with semi-natural or non-managed woodlands (Unmanaged Forests ≈ 23%). The fluvial corridor was surrounded by agricultural terraces (so-called lameiros) that were established and cultivated with irrigation crops (≈45% of SUs had Intensive Agriculture). Fronhas

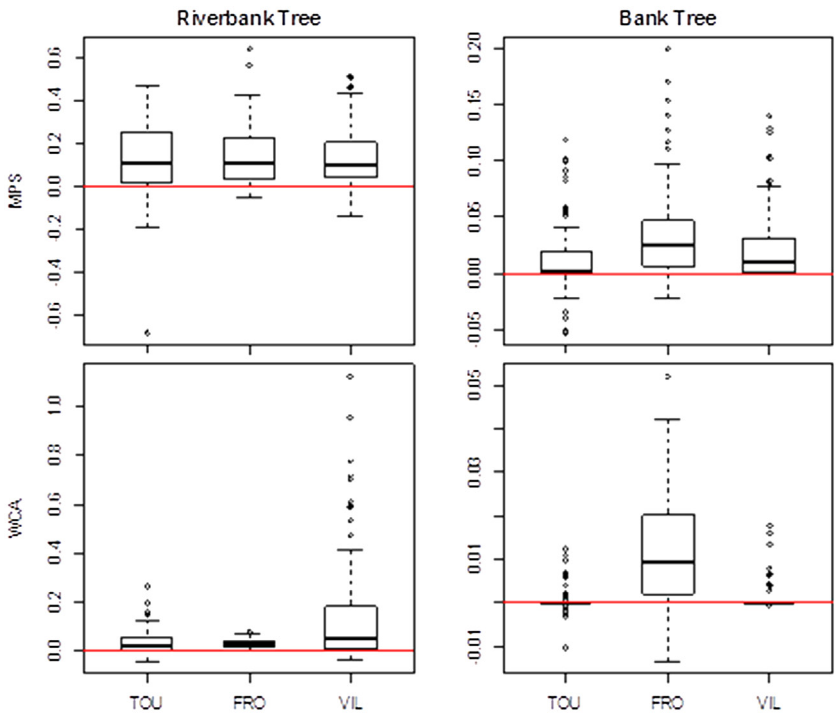


Fig. 4. Box-plots of the 'riparian variables-difference' for WCA (Weighted Class Area) and MPS (Mean Patch Size) for the classes Riverbank Tree and Bank Tree in the three case studies. Values above (below) zero (red line) correspond to an increase (decrease) of the contemporary values relative to the historical ones. TOU—Touvedo (River Lima); FRO—Fronhas (River Alva); VIL—Vilarinho das Furnas (River Homem). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

presented a similar overall land-use cover, though with higher occupation by forests (managed and unmanaged) and smaller cover of scrublands. The agricultural lands were widespread across the fluvial landscape, with almost all SUs recording intensive agricultural land-use (Appendix D).

Fig. 6 illustrates the results for 'land-use variable difference', and Appendix E shows the mean values and significance of paired *t*-tests between pre- and post-dam periods. Results revealed significant differences between historical and contemporary riverscapes for all land-uses and case studies (Appendix E). The only exceptions were for extensive agriculture and scrublands at Fronhas case study. The decrease of the Intensive Agriculture occurred in all case studies, along with an increase in impervious areas and in Managed Forests. The contemporary Vilarinho das Furnas riverscape (downstream of dam) has significantly more Unmanaged Forests (mean of differences = 20.92; $p < 0.0001$) than pre-dam construction, whereas Touvedo and Fronhas have undergone a significant decrease of Unmanaged forests (−26.95 and −14.02; $p < 0.0001$, respectively).

3.3. Hydrologic-based explanation for riparian cover change

The backward-forward procedure resulted in the selection of the variables difference Intensive Agriculture and Unmanaged Forests and also the hydrologic variable. The results of the RDAs indicated that both hydrologic and land-use variable difference contributed significantly to the explanation of the riparian cover variation (Fig. 7).

The increase of riparian cover change in the post-dam period both for WCA and for MPS were related to the increase of the land-use cover change and increase of the ratio of alteration of the variable High pulse duration. The partial RDA ordinations indicated that riparian cover change was mostly driven by LULC (the partial model using solely LULC variables contributes to 59.3% to the explained variance), whereas the partial model using the hydrologic variable contributed with 18.5%. The remaining 22.2% were contributed by the full model with both LULC and hydrologic variables (shared variance). While most of the variance remained unexplained, the pure (solely hydrology or solely LULC) and the shared models were highly significant ($p = 0.000999$).

3.4. Hydrologic-based divergence and hydrologic naturalness rationale

We first tested for significance the differences of riparian cover between RES and RUN case studies before the dam construction. No significant differences were observed between RES and RUN case studies for WCA of Riverbank Tree, Bank Tree, and Bank Other (Table 3). However, we observed differences of means of MPS for all classes and in particular, a relatively large difference of means between RES and RUN for the MPS of Bank Other (RES-RUN = 0.3; $p = 8.08E\text{-}05$). Hence interpretations of the riparian cover changes concerning this class should be done with caution.

Riparian patches of riverbanks and banks in reservoir rivers (River Alba and River Homem) occupied more area (WCA) than in run-of-rivers and riverbanks were significantly larger in the former, whereas the class Riverbank Other were significantly larger and had more area in RUN riverscapes (Table 4). In addition, Bank Other occupied more area in RUN than in RES, but differences were not significant ($p = 0.309$), while riparian patches continue to be larger (MPS) in the post-dam RES riverscapes.

Fig. 8 summarizes and illustrates the differences of area and size of riparian patches pre-dam and post-dam periods based on the results of Appendix C, Fig. 4, and among the RES and RUN case studies (Table 4).

Table 3
t-Tests of the differences of the means of MPS and WCA of riparian classes between the Reservoir (RES) and the Run-of-river case studies (RUN), **before dam** construction. P-values in bold indicate no significant differences between RES and RUN ($p < 0.001$).

Classes		nSUs		MPS (before dam)		WCA (before dam)	
		RUN	RES	Difference of means	p-value	Difference of means	p-value
Tree	Riverbank	73	168	0.08659	1.27E-06	−0.00039	**8.21E-01**
	Bank	21	25	0.01996	7.45E-04	0.00096	**4.77E-01**
Other	Riverbank	61	172	−0.04101	5.89E-03	−0.02045	5.44E-19
	Bank	46	117	0.30043	8.08E-05	0.00743	**8.57E-02**

Table 4
t-Tests of the difference of means of MPS and WCA (**variable difference**) between the Reservoir (RES) and the Run-of-river case studies (RUN). P-values in bold indicate significant differences for the diverse hypotheses of the difference of means between RES and RUN ($p < 0.05$).

Classes		variable difference	Difference of meansRES-RUN	H1: RES $\neq$ RUNp-value	H1: RES > RUNp-value	H1: RES < RUNp-value
Tree	Riverbank	MPS	0.01355	5.73E-01	2.87E-01	–
		WCA	0.05452	**1.46E-04**	**7.28E-05**	–
	Bank	MPS	0.01542	**9.55E-04**	**4.77E-04**	–
		WCA	0.00559	**1.32E-10**	**6.61E-11**	–
Other	Riverbank	MPS	−0.03002	**1.85E-02**	–	**9.26E-03**
		WCA	−0.01144	**4.74E-07**	–	**2.37E-07**
	Bank	MPS	0.07968	**2.61E-02**	**1.30E-02**	–
		WCA	−0.00230	3.09E-01	–	1.55E-01

Fig. 8 We analysed if the differences of riparian cover changes (MPS and WCA of Riverbank Tree) between RES and RUN riverscapes were influenced by hydrologic alterations and land-use cover (Fig. 9). RDA models were highly significant both for RES and RUN, and the land-use and hydrologic variables together explained 23.1% of the total variance for RUN, and 14.2% for RES. The hydrologic variable was first selected in both case studies ($p < 0.0001$), followed by the land-use variables. The area of riparian tree patches in riverbanks of RES increases with hydropulse duration and with the decrease of intensive agriculture (in opposition to the increase of unmanaged forests), whereas for RUN the high duration of hydropeaks and increase of unmanaged forests is related to higher riparian cover and smaller patches.

4. Discussion

In this section, we critically discuss the results obtained when testing the four hypotheses formulated in the introduction. Riverscapes are compared in reservoir rivers and run-of-rivers and the dynamics of change over a 20–40 year period post-dam were discussed.

4.1. Riparian vegetation dynamics in hydropower rivers

Riverscape ecosystems derive from co-varying abiotic and biotic components driven by both hydrogeomorphological and autogenic ecological processes following disturbance (Corenblit, Steiger, Gurnell, Tabacchi, & Roques, 2009). Some well-known concepts such as the extended serial discontinuity concept of Stanford and Ward (2001) and the telescoping ecosystem model (TEM) of Fisher, Grimm, Martí, Holmes, and Jones (1998) addressed the differential recovery trajectories of biota in disturbed rivers. Specifically, the parafluvial areas *sensu* Standford (2006) actuated by annual sediment scour and deposition are recognized as dynamic mosaics of sediments and vegetation mainly mediated by flooding events shifting in the short spatial and temporal scales. Those zones are recognized as highly impaired by connectivity gaps and altered hydropgraphs of the hydropower rivers (Standford, 2006). On the other hand, the riparian zones of these rivers are ecotones frequently interspersed in human-disturbed landscapes and thus re-worked by both the terrestrial ecosystems and by the suppression of the natural fluvial dynamics.

The first hypothesis formulated in the introduction of the emergent *Highly-altered post-dam landscapes* was corroborated in all case studies. The initial (pre-dam) riverscapes were composed mostly by a landscape with thin riparian galleries bordered by typical agricultural rectangle-terraces. This landscape was subjected in Portugal to land abandonment, mostly due to the rural depopulation (Pereira et al., 2005), and amplified by the lack of regional and local agricultural policies (Regos et al., 2015). Riparian ecotones that were historically constrained and fragmented by the long-lasting agricultural land-use reconquered part of the territory that was previously subjected to natural forest clearing, and recover the lateral connectivity with new deciduous woodlands and scrublands. This rural abandonment and forest recovery was also reported by Regos et al. (2015) for North-western Iberia and was considered the main driver affecting the spatio-temporal terrestrial landscape dynamics in the region. However, since riparian vegetation is closely connected with streamflow dynamics, we hypothesized that the alteration of natural flows provoked by dams could have a more relevant role in evolutionary and ecological processes of riparian vegetation than land-use variation. Looking to the case studies as a whole, the *Hydrologic-based explanation* hypothesis could not be supported by the results. Nevertheless, the major contribution in riparian dynamics of LULC compared to hydrology cannot be unequivocally assured, since it is difficult to unravel the diverse sources of variation. Run-of-river and storage reservoir dams in the cases studied here do alter hydrographs differently (Table 1; Cardoso et al., 2013; Martins, 2012). Reservoir rivers often experience very strong discharge fluctuations (hydropeaking), alterations of flow magnitudes, flow velocity and bed shear stress (Poff et al., 2007). In addition, the frequency and duration of bank flooding is reduced and often displaced in time, as well as groundwater recharge in the riparian zone (Nilsson & Berggren, 2000; Poff et al., 2007). In contrast, run-of-river plants having small

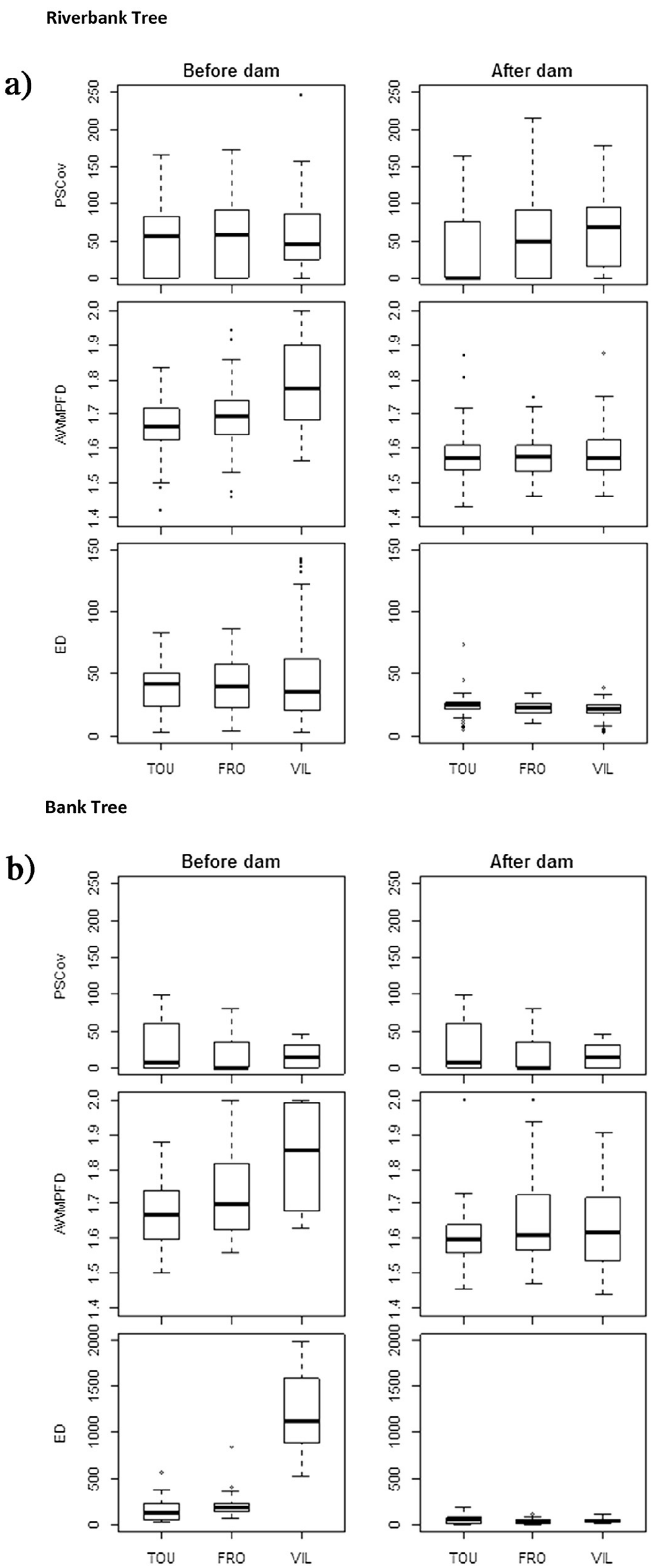


Fig. 5. Box-plots of riparian metrics in the pre-dam (left graphs) and post-dam periods (right graphs), for the class Riverbank Tree and Bank Tree for the three case studies. Acronyms for landscape metrics are given in Table 2. TOU—Touvedo (River Lima); FRO—Fronhas (River Alva); VIL—Vilarinho das Furnas (River Homem). (a) Riverbank Tree. (b) Bank Tree.

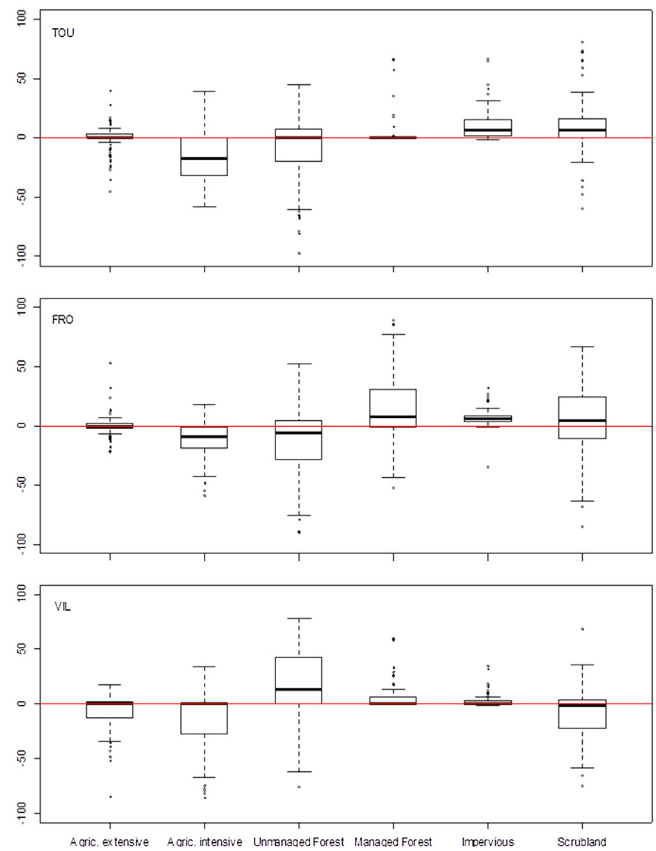


Fig. 6. Box-plots of the 'LULC variables-difference' in the three case studies. Values above (below) zero (red line) correspond to an increase (decrease) of the contemporary values relative to the historical ones. TOU—Touvedo (River Lima); FRO—Fronhas (River Alva); VIL—Vilarinho das Furnas (River Homem). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

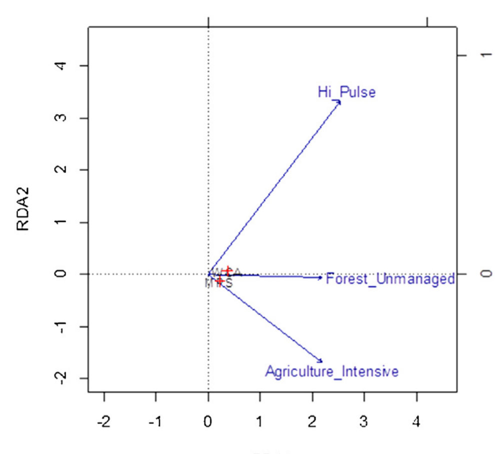
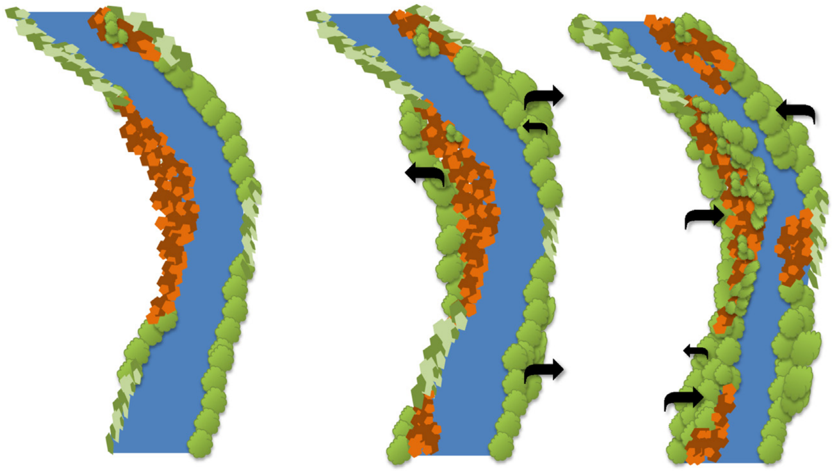


Fig. 7. Ordination biplot generated by RDA. The vectors of the selected LULC variables and hydrological variable are shown. Hi_Pulse—ratio for the indicator of hydrological alteration High pulse duration (days). Forest_Unmanaged, Agriculture_Intensive—variable difference for Unmanaged Forests and Intensive Agriculture, respectively. WCA—Weighted Class Area; MPS—Mean Patch Size for Riverbank Tree.



Pre-dam	Run-of-rivers (RUN)	Reservoir rivers (RES)	Comparison
	Post-dam		
Riverbank Tree	↑	↑	RES>RUN
Riverbank Other	↑	↓	RES<RUN
Bank Tree	↑ ns	↑	RES>RUN
Bank Other	↑	↓	RES>RUN

Feedback dynamics of riparian vegetation: magnitude and direction of expansion

Fig. 8. Generalized illustration of riparian cover changes at riverbanks and banks from the pre-dam period to the post-dam period for 'run-of-rivers' (RUN) and 'reservoir rivers' (RES) based on Appendix C, Table 3 and Table 4 for the three cases studied in this paper. Statistically significant results from paired analyses based on WCA and MPS are summarized; ↑—increase, ↓—decrease, ns- non significant.

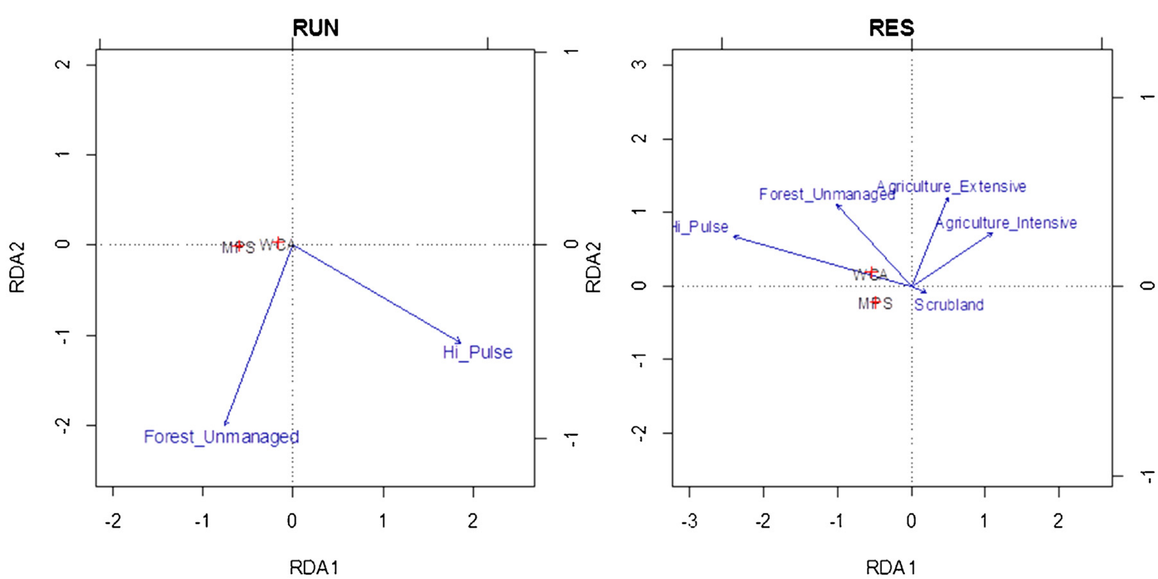


Fig. 9. RDA biplot for the run-of-rivers (RUN) and reservoir rivers (RES) for WCA (Weighted Class Area) and MPS (Mean Patch Size) of Riverbank Tree. The vectors of the selected LULC variables and hydrological variable High pulse duration (Hi_Pulse) are shown.

regulation capacity induced limited water level fluctuations downstream, which results in a hydrologic regime closer to natural hydrographs. Furthermore, the interaction between hydrology, geomorphology and land-uses jointly mediate the physical structure and dynamics of the riparian ecosystems (Poff, Bledsoe, & Cuhaciyan, 2006), and these effects are difficult to quantitatively measure and disentangle.

4.2. Post-dam patterns of riparian vegetation

Post-dam riparian tree patches, both in riverbanks and banks occupy more area, and are consistently larger, but have less complex shapes and lower edge density. The increase of size and area of riparian patches was concurrent with the decrease of the area occupied by herbaceous vegetation and bare soil in riverbanks (riparian zone) and banks (in-stream), except for the run-of-river (Touvedo case study). In general, the increasing regulation capacity of dams of the three case studies agreed with the magnitude of riparian cover changes (Touvedo < Fronhas < Vilarinho das Furnas). Touvedo also displayed in the post-dam period a high variability in the size of the riparian tree patches in comparison with the more homogeneous patches of reservoir rivers. All observations point to the existence of diverse patterns of recovery and vegetation establishment likely related to the type and magnitude of regulation, besides the LULC dynamics, which corroborate the *hydrologic-based divergence* and *hydrologic naturalness* hypotheses.

Though the area and size of patches increased in Touvedo, the major changes occurred in the riverbanks, whereas the colonization of in-stream biogeomorphic units (banks and islands) by riparian vegetation was not significantly altered in from the initial pre-dam state to the post-dam period. The expansion of riparian vegetation in the run-of-river happens with an outer enlargement of the riparian zone and to a much lesser extent the riparian encroachment in-stream (Fig. 8). In contrast, reservoir rivers experienced vegetation encroachment towards the river channel and colonization of the stabilized banks and islands. This difference between reservoir rivers and run-of-rivers is likely due to the reduced water level and altered seasonality of flows, with consequences in the extent of the actively linked riparian zone to the riverbed and groundwater table, and then to the colonization and establishment of riparian vegetation inside the channel. As was observed by Poff et al. (2006) in an overview of effects of damming and land-use across United States, run-of-rivers sustain overbank flooding by flow variability and flashiness in straight dependence of inflows upstream. The maintenance of most of the dynamic nature of the river hydrology and geomorphology results in non-forested bars and islands and also more complex and variable riparian patches in riverbanks. Whereas the increase in size and area of patches in riverbanks may be caused mostly by agricultural land abandonment, the maintenance of the hydrologic dynamism could be responsible to the reduced colonization of banks. In free-flowing Mediterranean rivers, such as the River Tech, France, a reciprocal adjustment between riparian vegetation and geomorphologic dynamics was observed via a cyclic biogeomorphological succession varying within the Mediterranean environmental context (Corenblit, Steiger, & Tabacchi, 2010). In fact, even in highly hydrologically disturbed reservoir rivers of the Mediterranean region, good performance of pioneer vegetation and its resilience allowed lateral expansion of riparian vegetation towards the floodplain and the active channel, even in extreme drought conditions of reduced flows (Rivaes et al., 2013, 2014). However, the relation of observed spatial patterns and the species composition of riparian forests and functional structure deserve attention, given the observation of a more homogeneous landscape structure of riparian patches. In agreement with these findings, Garófano-Gómez et al. (2013) observed an increase in riparian cover in a regulated Mediterranean Iberian river and a decrease in non-vegetated sediment bars, concurrent with a reduction in the complexity of the fluvial corridor. Also González et al. (2010) reported the degradation of healthy and dense forests of pioneer species in a large regulated Mediterranean river, with senescent forests having late-seral species with small-sized stems. The observed small spatial variability and complexity of riparian forests in the present study can also derive from the occurrence of monospecific stands of pioneer species with high successful vegetative reproduction following regulation (e.g. *Salix* sp.; Ferreira and Aguiar, 2006), or by the invasion of riparian forests by alien woody species.

4.3. Study limitations and caution

Assessing the dam effects in riverscapes resorting to observational data is difficult. First, there is the risk of disregarding causal relationships with fine-scale factors. Although we have considered the main broad scale key-variables (hydrology and land-use) several factors could not be assessed or modelled for the present study. Examples include the sediment amounts and substrate granulometry, or variables that were not measured in the pre-dam period, such as bed-mining and erosion. Additionally, outcomes resulting from comparison of metrics ED, AWMPFD and PsCov should be read carefully, due to the possible influence of progressive downstream flow decay with the distance from the dam, since the observed change could not be based on paired analysis. To circumvent these problems we used for the present study the most homogenous segments in relation to hydrology, sediment and bed load (see Section 2.2), acknowledging that the recovery of natural stream flow patterns downstream of dams will likely rely mostly in the inflowing tributaries (Braatne et al., 2008). Another potential source of variability can be attributed to the effect of diverse dam closure dates between case studies, which could induce differences in vegetation adjustments. Brandt (2000) reviewed the variability of channel changes in regulated rivers and concluded that a great amount of channel and sediment change took place relatively quickly after dam closure (1–2 years). In addition, there is evidence that the adjustment of riparian vegetation after strong channel disturbance can be as short as four years for both canopy development and basal area, as was found in Portugal for *Salix* communities in Sorraia river (Ferreira and Aguiar, 2006). In the present study, all case studies have at least ten years for readjustment of riparian vegetation, and thus we assumed that they are comparable in time, though we are aware that some variability could be attributed to the elapsed times between case studies.

An additional limitation derives from the small number of case studies: two reservoir rivers and one run-of-river, and generalizations based on comparison of these two dam operations should be done carefully. The inclusion of more rivers would permit to use more hydrological variables, increasing the robustness of the results.

5. Conclusions

In the study area, hydropower rivers exist in settings with continued land-use cover change, leading to new biogeomorphologic fluvial structures and riparian habitats. Our study found that vegetation feedbacks resulting from these changes had multiple patterns, which rely on the magnitude and type of hydrologic alterations coupled with the direct and indirect effects of land-use cover change. For our study area, we found that:

- Riparian vegetation occupies more area in hydropower rivers than in the preceding free-flowing rivers, but riparian patches have a significantly smaller spatial heterogeneity and complexity. An increase in riparian cover does not necessarily entail higher biodiversity values or more well-preserved riverscapes. Remnants of riparian vegetation can be as relevant for the conservation of landscapes;
- Hydrological alterations are a relevant driver of riparian change—the higher the dam regulation capacity (and rates of hydrological alterations) the larger the riparian cover changes downstream of dams. Environmental flows must be planned

accordingly, and resilience of the riparian vegetation must be investigated;

- Distinct growth trajectories of riparian vegetation were observed: (i) the reservoir rivers studied here experienced mostly vegetation encroachment towards the active channel by colonization of banks (in-stream) and un-forested portions of riverbanks; (ii) in the run-of-river case studied here, riparian vegetation mostly expanded outwards by enlarging the riparian ecotone towards the floodplain, requiring diverse management options to be implemented with respect to the environmental and LULC context;
- LULC and hydrology together explain riparian cover changes, but it was difficult to disentangle the diverse sources of variation. It should be recognized that for the management planning of dammed riverscapes, a multi-faceted view of sustainable local and regional land management policies along with the fluvial and riparian conservation needs is a requirement of capital importance.

Further research is needed to better understand and predict losses and gains of riverscape values downstream of dams. The incorporation of the socio-economical context along with field studies of biodiversity and integrity values at the reach scale could improve the prediction capability following anthropogenic disturbance.

Acknowledgements

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Appendix A. Drivers of change, main effects and major predictions of landscape metrics on riparian vegetation based on literature. MPS—Mean Patch size; AWMPFD—Area Weighted Mean Patch Fractal Dimension; ED—Edge density; PSCov—Patch Size Coefficient of Variation. ↓ decrease ↑ increase ↕ diverse effects

Drivers of change	Main effects on riparian woods	Major predictions on riparian metrics' change	References
Agricultural lands	Fragmentation Riparian vegetation clearing Shifts in species composition Constraints the riparian zone Contamination with pollutants Vegetation cutting for pumping Decrease of groundwater	↕MPS ↓PSCov ↓AWMPFD ↓ED	Aguiar and Ferreira (2005), Apan et al. (2002), Burton et al. (2005), Clerici et al. (2014), Fernandes et al. (2011), Hooke (2006), Rex and Malanson, (1990)
Managed forests	Increase of fire risk Riparian vegetation clearing Constraints of the riparian zone	↓MPS ↓PSCov ↓AWMPFD ↓ED	Clerici et al. (2014)
Impervious surfaces	Fragmentation Shifts in species composition Contamination with pollutants Increases mortality rates Disconnected riparian zones Decrease nutrient uptake	↓MPS ↓PSCov ↓AWMPFD ↓ED	Allan (2004), Burton et al. (2005, 2009), Hooke (2006)
Damming	Vegetation encroachment Hampering of natural regeneration Senescence of non-pioneer forests Succession towards wood wetlands Increasing mortality, reduced grow rate Altered recruitment Failure of seedling establishment	Various effects according to type of hydrologic alteration: ↕MPS ↓PSCov ↓AWMPFD ↓ED	Bejarano and Sordo-Ward (2011), Belmar et al. (2013), Dufour et al. (2015), Garófano-Gómez et al. (2013), González et al. (2010), Rivaes et al. (2014), Poff and Zimmerman (2010), Nilsson and Svedmark (2002)

Appendix B. Number of riparian patches manually digitalized of each riparian class and LULC class for the pre-dam and post-dam period at each case study. TOU—Touvedo (River Lima); FRO—Fronhas (River Alva); VIL—Vilarinho das Furnas (River Homem).

	TOU		FRO		VIL		Total
	pre-dam	post-dam	pre-dam	post-dam	pre-dam	post-dam	
Riparian classes							
Riverbank Tree	185	139	266	236	443	309	1578
Riverbank Other	166	65	186	81	189	120	807
Bank Tree	44	110	30	149	10	100	443
Bank Other	70	86	94	37	110	24	421
Island Tree	25	44	2	2	0	0	73
Island Other	38	17	4	0	0	0	59
Sub-total	528	461	582	505	752	553	3381
LULC							
Agric. Extensive	33	29	35	40	80	49	266
Agric. Intensive	117	130	127	91	54	42	561
Unmanaged Forest	113	131	86	93	100	97	620
Managed Forest	0	8	52	170	1	26	257
Impervious	74	136	59	147	32	81	529
Scrubland	67	187	104	247	96	95	796
Sub-total	404	621	463	788	363	390	3029
Total	2014		2338		2058		6410

Appendix C. Mean of the differences between historical and contemporary riparian metrics per class for each case study. Significant differences are in bold: paired *t*-tests; $p < 0.05$ for MPS—Mean Patch Shape; WCA—Weighted Class Area; ED—Edge Density. *t*-tests for independent samples of AWMPFD—Area Weighted Mean Patch Fractal Dimension; PSCov—Patch Size Coefficient of Variation. TOU—Touvedo (River Lima); FRO—Fronhas (River Alva); VIL—Vilarinho das Furnas (River Homem).

		Riverbank Tree		Riverbank Other		Island Tree		Island Other		Bank Tree		Bank Other	
		Mean	p-value	Mean	p-value	Mean	p-value	Mean	p-value	Mean	p-value	Mean	p-value
TOU	MPS	0.12	**1.9E-07**	4.60E-04	0.86	0.01	0.11	−0.06	**0.02**	0.02	0.10	0.25	**0.02**
	WCA	0.04	**2.5E-08**	2.59E-05	**8.9E-01**	2.4E-03	0.08	−4.9E-03	**8.3E-03**	4.3E-03	0.18	0.02	**0.04**
	ED	−12.93	**1.6E-08**	0.09	0.93	−4.36	0.82	23.35	0.05	−15.34	0.38	65.38	**2.1E-03**
	AWMPFD	−0.08	**1.5E-10**	−1.3E-03	0.95	−0.07	**0.01**	0.09	**0.03**	−0.06	**0.03**	0.07	**0.01**
	PSCov	−13.27	0.09	−24.51	**1.0E-03**	5.68	0.74	11.10	0.34	22.09	0.08	14.39	0.14
FRO	MPS	0.14	**1.1E-15**	−0.02	**3.0E-05**	2.8E-04	0.31	−6.0E-04	0.08	0.04	**6.9E-12**	−0.04	**2.8E-07**
	WCA	0.03	**1.0E-35**	−0.00736	**2.6E-11**	7.0E-05	0.29	−1.4E-04	0.07	0.01	**1.2E-14**	−0.01	**1.0E-08**
	ED	−18.61	**7.3E-14**	−2.38	0.76	−67.03	0.47	−44.25	0.05	−21.26	0.10	20.21	**0.01**
	AWMPFD	−0.11	**2.3E-18**	−0.05	**0.01**	−0.34	**0.03**	–	–	−0.09	**0.01**	0.11	**5.9E-05**
	PSCov	−3.72	0.60	−11.47	0.09	–	–	–	–	17.59	**0.03**	−14.12	**0.02**
VIL	MPS	0.14	**1.9E-16**	−0.10	**3.0E-07**	–	–	–	–	0.02	**5.4E-11**	−0.03	**4.8E-07**
	WCA	0.15	**9.7E-09**	−0.02	**2.6E-08**	–	–	–	–	8.5E-04	**9.1E-03**	−9.0E-03	**3.6E-08**
	ED	−21.55	**2.5E-06**	0.16	0.95	–	–	–	–	−49.33	0.14	8.77	0.29
	AWMPFD	−0.20	**2.2E-23**	−0.04	**3.4E-03**	–	–	–	–	−0.21	**0.02**	0.01	0.51
	PSCov	5.72	0.40	−0.92	0.88	–	–	–	–	6.70	0.49	−18.99	**1.5E-03**

Appendix D. LULC classes used in the study. Mean (standard deviation) of LULC in the 200 m buffer before the dam construction for each case study. Proportion of Sampling Units (SUs) contributing to each LULC class for each case study across the landscape. TOU—Touvedo (River Lima); FRO—Fronhas (River Alva); VIL—Vilarinho das Furnas (River Homem).

Designation	TOU		FRO		VIL	
	LULC (% buffer)	SUs (%)	LULC (% buffer)	SUs(%)	LULC (% buffer)	SUs (%)
Agriculture Extensive	5.43 (11.42)	32.9	3.62 (7.05)	33.0	9.71 (15.15)	52.1
Agriculture Intensive	51.62 (29.80)	90.8	23.64 (18.97)	93.2	21.05 (30.56)	44.7
Unmanaged forest	30.58 (28.63)	82.9	21.91 (25.70)	67.0	23.17 (26.68)	64.9
Managed forest	–	0	19.47 (27.03)	43.2	0.04 (0.38)	1.1
Impervious	4.22 (10.85)	53.9	2.57 (5.94)	43.2	0.65 (1.82)	22.3
Scrubland	8.15 (12.69)	61.8	28.79 (23.57)	81.8	45.37 (39.99)	77.7

Appendix E. Differences (mean values; %) between historical and contemporary LULC for each case study. Significant differences are in bold (paired *t*-tests; p < 0.05). TOU—Touvedo (River Lima); FRO —Fronhas (River Alva); VIL—Vilarinho das Furnas (River Homem).

LULC	TOU		FRO		VIL	
	Mean	p-value	Mean	p-value	Mean	p-value
Agriculture Extensive	29.93	**2.10E-11**	0.29	0.77	−6.32	**2.13E-04**
Agriculture Intensive	−30.07	**6.26E-09**	−12.20	**1.72E-11**	−15.46	**1.43E-07**
Unmanaged Forest	−26.95	**2.12E-13**	−14.02	**1.54E-05**	20.92	**2.60E-09**
Managed Forest	15.89	**2.05E-09**	13.45	**1.6E-04**	5.91	**5.32E-05**
Impervious	13.82	**1.46E-05**	6.53	**5.48E-12**	2.89	**1.92E-05**
Scrubland	27.21	**1.22E-10**	4.96	0.16	−8.55	**4.89E-05**

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