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Evolution of the Riparian Forest Corridor in a Large Mediterranean River System

Fernando Magdaleno[1*]

José A. Fernández-Yuste[2]

[1]CEDEX (Ministry of Public Works – Ministry of Agriculture, Food and Environment). Alfonso XII, 3. 28014 Madrid, Spain

[2]Lab. of Hydraulics and Hydrology. Technical College of Forest Engineering. Polytechnic University of Madrid. Avda. Ramiro de Maeztu, s/n. 28040 Madrid, Spain

Abstract

The central reach of the Ebro River, one of the largest rivers in the Mediterranean region, is characterised by a meandering channel that develops into a wide floodplain. In the present study, we analysed the evolution of the landscape structure and function of riparian forests in the Middle Ebro River (~ 250 km long) in 1927, 1957 and 2003 in order to evaluate the forest dynamics in this river corridor.

In the 20th century, the Ebro floodplain suffered a dramatic hydromorphological transformation as a result of urban and agricultural encroachment on the river territory and modifications to its flow regime. This study assesses the overall morphology and connectivity of riparian forest patches in the study area using a wide range of parameters. The influence of the hydromorphological changes of the river system on the general status of the riparian forests was then determined.

The analysis revealed a profound trend toward the homogenisation and isolation of forest patches. Habitat loss and landscape fragmentation were the dominant processes in the study area and were especially intense in some river segments, where large forest patches and high connectivity once prevailed. Landscape modification and overall homogenisation intensified during the second half of the last century. The results for the entire set of parameters can be used to identify guidelines for the effective attenuation of these trends and for the progressive rehabilitation of the dynamics of the Middle Ebro landscape.

Keywords

Riparian pattern • Floodplain • River landscape • Biogeomorphology

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1. Introduction

Riparian forests are one of the most dynamic components of river ecosystems, providing a wide range of ecosystem services. They help to balance energy and matter flows, reduce streamflow nutrient load and supply particulate organic matter to the aquatic biota. They also have an active role in the geomorphic pattern of the river, retaining sediments in the channel and adjacent floodplain and reducing erosion of the banks. Additionally, they improve the quantity and quality of aquatic and riparian habitats, and are essential for maintaining biodiversity and landscape values in the river system [1-3].

However, riparian forests frequently experience changes due to river regulation and modification of land use in the river system. Flow regulation alters commonly the most environmentally meaningful flow features in the river. These changes may lower species diversity and rapidly homogenise the spatial structure of the forest [4-6]. A reduction in flooding frequency can reduce, or even eliminate, the processes involved in creating new fluvial forms. This reduction may alter the composition of riparian vegetation communities and cause the local disappearance of species adapted to the natural flood regime. Diverse vegetation and rare species would thus only be favoured in cut-off channels, where water levels may have a higher range of fluctuation [7-9].

Certain human activities in floodplains, such as the increase of agricultural or urban uses in previously forested areas, may also have a significant influence on the pattern of a river's geomorphology and its associated riparian forests [10]. In the context of agro-landscapes, the ecological functions of riparian corridors are of utmost interest, considering the overall degradation of the surrounding matrix [11]. The relationship between the channel and its floodplain is a key factor in understanding the composition and species richness of a river ecosystem [12,13]. The exchange of nutrients, sediments and organic matter and the associated biotic processes are the basis for these interactions [14]. Changes in riparian vegetation catalysed by the construction of lateral dikes have been analysed by different authors [15-17]. Other defensive types of structures, such as rip-raps and groynes, contribute to the reduction of the lateral connectivity of channels because they hinder the lateral migration of the channels and the refreshment of fluvial forms [18]. Other studies [19,20] have shown that high biodiversity

* E-mail: fernando.magdaleno@cedex.es

can be maintained in river ecosystems by conserving the river's natural attributes and functions that are directly connected to the river. The connectivity of channels within a floodplain (transfer of matter, energy and organisms) is thus a basic means of protecting river biodiversity [21,22].

Concerning the riparian forest complexity and habitat diversity in the riparian corridor, a successional vegetative gradient was found from upper to lower reaches of different Mediterranean rivers with a concomitant increase in both woody cover and habitat diversity [23]. The increase in the complexity and heterogeneity of river habitats was especially remarkable in the mature communities in the low-gradient river reaches. Although numerous authors have found that the highest species richness and habitat diversity occurs in the intermediate reaches of rivers where environmental heterogeneity is greatest [24], the gradient of vegetation in Mediterranean rivers—characterised by high flow variability—shows a different pattern. This could be due to the different temporal scale of flooding, which only allows floods of great magnitude to substantially perturb plant communities [25]. Other researchers have found evidence of high structural homogeneity (horizontal and vertical) in human-altered riparian forest patches, which contrasts the high levels of biodiversity typical to riparian corridors [23].

Regarding the analysis of the ecological functions of riparian forests, different authors have suggested that the forest width may be addressed as best indicator of its functioning [26,27]. Thus, forest width is the most common metric used for making management recommendations and in developing best practice guidelines for these systems. This principle is based on the assumption that the area occupied by a riparian forest is correlated with biodiversity and that border effects are more intense in small or narrow forest patches [28]. However, this paradigm does not adequately take into account the influence of the landscape matrix. The composition and spatial configuration of this matrix may greatly affect the colonisation and dispersion dynamics of vegetation. For instance, fragmentation of landscape matrix influences the associated plant communities [29,30]. Thus, it is necessary to provide new procedures, based on the multiple scales and processes that characterize the status and trend of riparian forests, to analyze their evolution. These procedures should consider the roles riparian forests play in the river system, and the continuous interactions they have with the fluvial forms and the geomorphic activity in the channel and floodplain.

The Ebro River (located in Northeastern Spain) is one of the largest rivers in the Mediterranean region. In the last century, its natural flow regime has been significantly altered [6,31-33], and human uses have progressively encroached upon its floodplain [6,33-36]. The river system has evolved dramatically, and one of the main trends in its evolution has been the intense modification of its associated riparian vegetation patterns. However, there is a limited knowledge about the structure and functioning of the riparian forest corridor in the floodplain of the whole middle Ebro River and the evolution of this system throughout the 20th century. Additionally, scarce detailed analyses have been done about the landscape characteristics of the riparian forest in large riparian corridors. This study aimed to cover some of these gaps, assessing in detail the structure of the riparian forest as a large corridor, by answering the following questions:

i. Which was the evolution pattern of the riparian vegetation in the central sector of the Ebro River during the 20th century?
ii. Which are the forest structure parameters that best describe the ecological dynamics of large riparian forests?
iii. Which are the most convenient strategies to improve the status of the riparian corridor of the Ebro River, taking into account the hydromorphological alterations of the river system?

2. Materials and methods

2.1 Study area

The river area analysed in this study comprises the floodplain of the central, meandering sector of the Ebro River (located in NE Spain) between Rincón de Soto and a small dam in Alforque (La Zaida). The chosen reach is situated in the centre of the Ebro Depression and in the central sector of the Ebro Basin. The reach is approximately 250 km in length (Figure 1). This reach includes the majority of the meandering, wide-floodplain area of the river. A short, meandering sub-reach may be still found upstream of the upper end of the study area. However, no historical cartographic materials are available for this area, and this portion of the river was omitted from our analysis.

The Ebro basin covers an area of approximately 85,530 km^2. The Ebro River is the second largest river in the Iberian Peninsula, both in length (930 km) and in water volume debouched to the Mediterranean Sea (~460 m^3/s) [37]. The average width of its floodplain is 3.2 km, with a maximum of 6.0 km. The floodplain in the central sector of the Ebro River is 739 km^2 in area, and its sinuosity index was 1.505 in 2003 [32]. Fluvial forms include vegetated and non-vegetated bars and islands, although not so common as in the first decades of the 20th century. The floodplain is occupied by mature (mostly linear) riparian forests of three softwood species: white poplar (Populus alba), European black poplar (P. nigra) and white willow (Salix alba), and five hardwood species: saltcedar (Tamarix gallica, T. africana and T. canariensis), narrow leaf ash (Fraxinus angustifolia) and field elm (Ulmus minor) (Figure 2) and is characterised by agricultural land uses and poplar cultivation. Upland vegetation is dominated by steppe species in the Ebro Depression, and pine (Pinus sp.), oak (Quercus sp.), beech (Fagus sylvatica) and mixed forests in higher altitudes.

2.2 Materials and procedure

Aerial photographs from 1927 and 1956-57 (hereafter referred to as 1957) and digital orthophotographs from 2003 were used as raw materials for the assessment of the channel's evolution. Aerial photographs from 1927 (black & white; approximate scale 1:10,000) and digital orthophotographs from 2003 (colour; approximate scale 1:1,000) were obtained from a compilation work done by the Ebro Basin Agency (Confederación Hidrográfica del Ebro) [38]. Aerial photographs from 1957 (black & white;

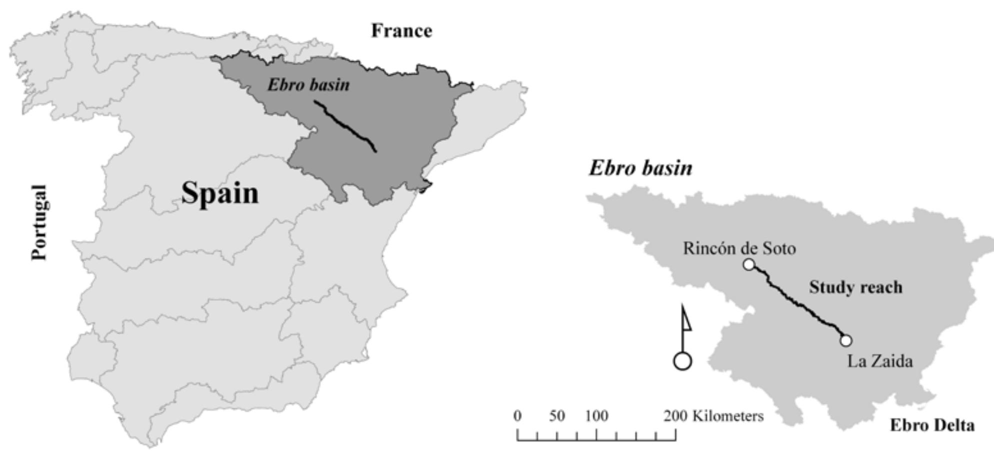

Figure 1. *Location of the study area in the Ebro basin (NE Spain). The reach analysed in this study is located in the central sector of the Ebro River and is characterised by a meandering pattern and a wide alluvial floodplain.*

Figure 2. *Two views of the study reach near Pina de Ebro (Zaragoza) in August 2010, where the linear structure of the vegetation along the channel can be seen.*

approximate scale 1:10,000) were donated by the Centre of Hydrographic Studies of CEDEX.

The photographs from 1927 and 1957 were digitised in a scanner at 600 dpi. After the digitisation of the images, they were geographically referenced with Erdas 8.3 and exported into a geographical information system (Esri, ArcMap 9.1). A minimum of six control points were used during the georeferencing process, and in most cases, ten points were used. The UTM coordinate system (Zone 30) was used. International 1909 was the chosen spheroid, and the selected datum was European 1950. The nearest neighbour resampling method was applied, and control points were chosen to avoid a concentration of points in specific regions of the images. In all cases, the reference points were easily identifiable features and were not subject to significant spatial-temporal variations. The total error analysis parameter (e_T) generated during the geographical referencing of the photographs was under 2 metres in the vast majority of cases. This value is extremely low considering the size of the study area and the dimensions of the analysed parameters.

The dynamics of the riparian vegetation were assessed through morphometric (quantitative measurements of the form of patches) and connectivity (structural and functional continuity of those patches) analyses over the channel and floodplain. The forest patches were represented as polygonal entities associated with autochthonous woody riparian vegetation. Their minimum area was fixed at 0.1 ha for the three time records (1927, 1957 and 2003). Woody vegetation was identified through the consideration of patches composed of visible plant crowns. Very regular distributions of stems were esteemed as proof of human-based plantations, and were cause for rejection of those non-natural patches.

A number of configuration metrics were formulated for the assessment of vegetation dynamics, either in terms of individual patches or in terms of class or landscape, depending on the desired work scale. Typically, these metrics are spatially explicit at the patch level and not at the class or landscape level [39]. The principle aspects of this configuration are as follows [40]: i. patch size distribution and density; ii. patch shape complexity (geometry of patches); iii. core area (i.e., interior area of patches after a user-specified edge buffer is eliminated); iv. isolation/proximity (i.e., tendency for patches to be relatively isolated/spatially distant from other patches of the same or similar class); v. contrast (i.e., relative difference among patch types); vi. dispersion (i.e., tendency for patches to be regularly or contagiously distributed with respect to each other); vii. contagion and interspersion (i.e., tendency for patch types to be spatially aggregated); viii. subdivision (i.e., degree to which a patch type is fragmented into separate patches); ix. connectivity (i.e., functional connections among patches). These metrics were used to define the morphometric and connectivity parameters selected for this study.

i. Morphometric parameters

Ten morphometric parameters were used in this study. They were calculated independently for each one of the three years. The total autochthonous riparian forest area (F1), the number of forest patches (F2), the average area occupied by those patches and their standard deviation (SD) (F3) were all calculated. The fragmentation index (F4) was calculated as the ratio between the number of patches and their average area. The average perimeter of the patches and their SD (F5), the area-perimeter ratio (F6) and the largest patch index (F7) were also computed, with F7 being the ratio of the largest patch area to the total riparian forest area.

Finally, the Patton diversity index [41] (F8) was determined. The index was calculated with the formula $F8 = Pp / 2[(\pi Ap)^{0,5}]$, where Pp the average perimeter of all patches, and Ap their average area. The inverse value of the Patton index is referred to as the compactness index (F9) in various studies. This index was incorporated to include the most common indices used in analogous studies, although its contributions to the analyses are nearly identical to those of the Patton index.

Additional values necessary for calculations were the area occupied by the floodplain and by the active channel, and the length of banks. Floodplain area is 739 km^2 [32] (floodplain limits were delineated by the extent of unconsolidated depositional river material). Bank lengths in 1927 (688,381.23 m), 1957 (633,334.02 m) and 2003 (598,336.10 m), and the area occupied by the active channel in 1927 (3,602.16 ha), 1957 (3,468.39 ha) and 2003 (3,136.79 ha) were extracted from the same work [42].

ii. Connectivity parameters

The analysis used the following connectivity parameters, again for the three years: the number of discontinuities (cover gaps) in the corridor of the forested banks (C1), the average length of those discontinuities (C2), considering the lower threshold for a gap as 10 meters), the total length of the longitudinal banks of forested corridors (C3), and the maximum length of the transversal forested corridor (C4). The average distance among the entire range of patches (C5) was measured with the software Conefor Sensinode 2.2 [43]. The patch density (ratio between the total forest area and the floodplain area, C6) and the edge density (ratio of the total forest perimeter to the overall floodplain area, C7) were also determined. Patch density has been positively correlated to spatial heterogeneity and species diversity, and edge density illustrates the complexity of the shape of the patches [44,45].

Additionally, the number of core areas (C8) and the average surface area occupied by them (C9) were determined. The minimum buffer distance to non-forested soil was established as 100 m. The total core area (C10) (defined as forest at least 100 m from non-autochthonous or non-forested areas) was also determined, including an optional 50-meter threshold (C10bis). Non-autochthonous vegetation areas were defined as those covered by alien species, be they planted or not. Finally, additional parameters were calculated, such as the ratio between forest and channel habitats. C11 describes the ratio of forest perimeters to bank length, and C12 represents the ratio between the areas occupied by riparian forests and active channels.

3. Results

i. Morphometric parameters

The data in Table 1 indicate that the total area occupied by autochthonous woody riparian vegetation (F1) decreased by

Table 1. Morphometric parameters of the riparian forests (F1-F9) of the Ebro River in 1927, 1957 and 2003.

Code	Parameter	Representative aspect	1927	1957	2003
F1	Total area of riparian forests (ha)	-	3,693.51	3,402.64	2,389.02
F2	Number of riparian forest patches	Subdivision & Isolation	403	425	480
F3	Average patch area (ha) (Standard deviation)	Patch size & Subdivision	9.17 (17.79)	8.01 (13.80)	4.98 (8.09)
F4	Fragmentation index (ha^{-1})	Patch size & Subdivision & Isolation	0.44	0.53	0.96
F5	Average perimeter of patches (m) and (Standard deviation)	Patch shape complexity	1,732.65 (1815.48)	1,754.08 (1690.83)	1,423.50 (1262.99)
F6	Area-perimeter ratio (m^2/m)	Patch shape complexity	52.63	45.45	34.48
F7	Largest patch index (ha/ha)	Patch size & Subdivision	0.046	0.038	0.032
F8	Patton diversity index	Patch shape complexity	1.61	1.75	1.80
F9	Compactness index	Patch shape complexity	0.031	0.028	0.025

approximately 8% between 1927 and 1957, while the decay between 1957 and 2003 increased by a factor of four. Thus, forest cover in the study area declined by 35% compared with that in the original record. The number of forest patches registered in the analysis (F2) increased progressively. In the first interval (until 1957), the change was smooth (22 additional patches), but when the overall change was considered, the increase was approximately 20% (+77 patches).

The progressive reduction in forest cover and the constant increase in the number of forest patches evidenced a trend of patch fragmentation. The average area (F3) of these patches was almost halved over the time interval investigated. The standard deviation of the area of patches (F3) was also halved, especially because of the major changes to this parameter in the second half of the 20th century. Thus, the patches became considerably smaller and, by 2003, fostered considerably less diversity. The fragmentation index (F4) increased by more than 200%, confirming this trend of decreasing patch size.

The average perimeter and SD of the patches (F5) remained consistent until 1957 and clearly decayed from that date onward by almost 20%. The area-perimeter ratio (F6) progressively decreased throughout the 20th century, but its rate of reduction doubled from 1957 to 2003 compared with that from 1927 to 1957. Thus, forest patch area experienced the highest rate of change among all forest patch dimensions, although patch size changed concurrently with patch shape.

The parameter F7 (largest patch index) also indicated a substantial decrease in the size of the largest patches. The rate of decay was similar (approximately 16%) in the two sub-intervals. This result may indicate that changes to the spatial structure of the riparian forest were initiated by modifications to what were the largest patches in 1927.

The Patton diversity (F8) and compactness (F9) indices both registered changes to the morphology of the forest patches. The composite value of these indices changed by approximately 20% from 1927 to 2003, indicating that the forest became more homogenous in the human-altered fluvial environment.

ii. Connectivity parameters

The connectivity parameters also indicated that major changes occurred during the period in question (Table 2). The number of discontinuities (C1) increased, especially in the second half of the 20th century. However, their average length (C2) decayed by more than 30% from 1927 to 2003. In this time period, the total length of longitudinal forested corridors on both banks (C3) increased considerably (by 60% in 1927-2003); the formerly non-vegetated banks are now covered in most cases by riparian vegetation. These three parameters interpreted together reveal a trend of forest patch fragmentation (C1) and indicate that these fragmented patches were replaced by a linear and narrow (C2) forest corridor along the main channel (C3).

The maximum length of transversal forested corridors (C4) decreased by half, indicating that the transition of the patches towards the channel was based on the loss of the largest patches and transversal corridors. This finding reinforces the main results obtained from the analysis of the morphometric parameters. The average distance among the whole set of forest patches (C5) also supported this finding because the rate of decay from

Table 2. Connectivity parameters of the riparian forests (C1-C12) of the Ebro River in 1927, 1957 and 2003.

Code	Parameter	Representative aspect	1927	1957	2003
C1	Number of discontinuities (both banks)	Subdivision & Isolation	218	220	249
C2	Length of discontinuities (m)	Subdivision & Isolation	545,218.82	469,076.62	370,107.80
C3	Total length of longitudinal forested corridors on both banks (m)	Subdivision & Isolation & Connectivity	143,162.41	164,257.40	228,228.30
C4	Maximum length of forested corridor transversal to the river axis (m)	Subdivision & Isolation & Connectivity	2,135.54	1,550.89	1,023.37
C5	Average distance between forest patches (m)	Isolation & Dispersion & Contagion	60,581.04	52,049.14	54,693.38
C6	Patch density (ref. to floodplain area in [32]) (n/100 ha)	Patch size	0.55	0.58	0.65
C7	Edge density (ref. to floodplain area in [32]) (m/ha)	Patch size	9.45	10.09	9.25
C8	Number of core areas (buffer of 100 m)	Core Areas	90	81	51
C9	Average area occupied by core areas (buffer of 100 m) (ha)	Core Areas	6.13	4.57	2.60
C10	Total core area (minimum 100 metres) (ha)	Core Areas	551.86	370.49	132.45
C10b	Total core area (minimum 50 metres) (ha)	Core Areas	1,346.62	1,046.29	533.44
C11	Forest perimeter (m) vs. Bank perimeter (m)	Connectivity	1.014	1.177	1.142
C12	Forest area (ha) vs. Active channel area (ha)	Connectivity	1.025	0.981	0.762

1927 to 1957—caused by decreased patch size—was partially compensated in 2003 by a greater linear connection between the patches.

Regarding the ecological role of the forest patches throughout the Ebro River floodplain, the parameters C6 (patch density) and C7 (edge density) showed that the riparian corridor had already undergone significant transformation even in the first decades of the 20th century. The results for C6 and C7 are both very low, and these figures indicate that there is very low spatial heterogeneity in the floodplain landscapes of the Ebro River.

The decay of the most ecologically valuable sites in the floodplain is highlighted by the changes to the number of core areas (C8). By 2003, the value of this parameter had decreased by half (45) from an initial 90 sites. Additionally, the average area occupied by the remnant core areas (C9) decreased by 60%. Both results show the overall loss of the largest and most ecologically intact patches in the study area. The remnant core sites survived, albeit in much smaller areas.

The total core area (considering 100-m or 50-m buffers, parameters C10 and C10b, respectively) mirrored the trends of the core areas by decaying greatly; however, there were several differences in the rate of reduction for this variable. The rate of decay was homogeneous in the two sub-intervals for C10, but it was notably higher from 1957 to 2003 in C10b. This finding suggests the presence of a mechanism mentioned previously; until 1957, the most degraded patches were the largest ones. However, from that date on, changes to the forest spread over the whole range of forest patches, independent of their size.

Finally, the parameters C11 and C12 provide valuable information about the relationship between the forest and aquatic habitats in the study area. The ratio of edge habitats (C11) increased until 1957 (+10%). This change shows that, prior to 1957, the reduction of bank habitats occurred faster than the decay of forest edge habitats. In the following interval, the situation was maintained in an almost invariant manner, indicating that the rate of destruction of both habitat types was quite similar in the second half of the century.

The ratio between surface forest habitats and active channel habitats (C12) declined remarkably (-26%) over the entire time interval investigated. Most of this change took place in the second half of the 20th century. The decrease in C12 values was the result of vegetation loss being greater than the loss of the area of active channel after 1957. These results are consistent with the aforementioned results for parameter C11 and show that alterations to the forest landscape increased over time and were preceded by the degradation of the geomorphological functioning of the study reach.

The historical changes to the main parameters may also be represented graphically as indicators of changes to the fragmentation and connectivity of the forest patches (Figure 3). As shown in this figure, fragmentation increased and connectivity quality decreased at a greater rate in the second half of the 20th century. The modification of the forest structure and the decay of ecological connections were two of the most remarkable processes suffered by the forest corridor.

4. Discussion

The structure of the Ebro River's riparian forests has undergone significant fragmentation and homogenisation following fundamental changes to its (formerly dynamic) hydromorphological pattern throughout the 20th century [6,32,46]. From 1927 to 2003, there was a relative reduction in flood activity, and the frequency of low flow volumes increased significantly as a result of river regulation for agricultural uses. Thus, the hydrological patterns of the river tended to become more regular. In particular, significant changes to the summer volume of the river could have facilitated core modifications to the structure of the Middle Ebro's riparian forests. Over the last several decades, human encroachment on the river's floodplain also fostered the alteration of the forest, given that the width of the river channel has been halved. The loss of fluvial territory has been especially significant to the areas of the river that were formerly the widest, and changes to the hydromorphology have modified the structure of riparian vegetation.

Habitat fragmentation is a combination of the following three processes: (1) habitat loss, (2) true fragmentation (i.e., decreased

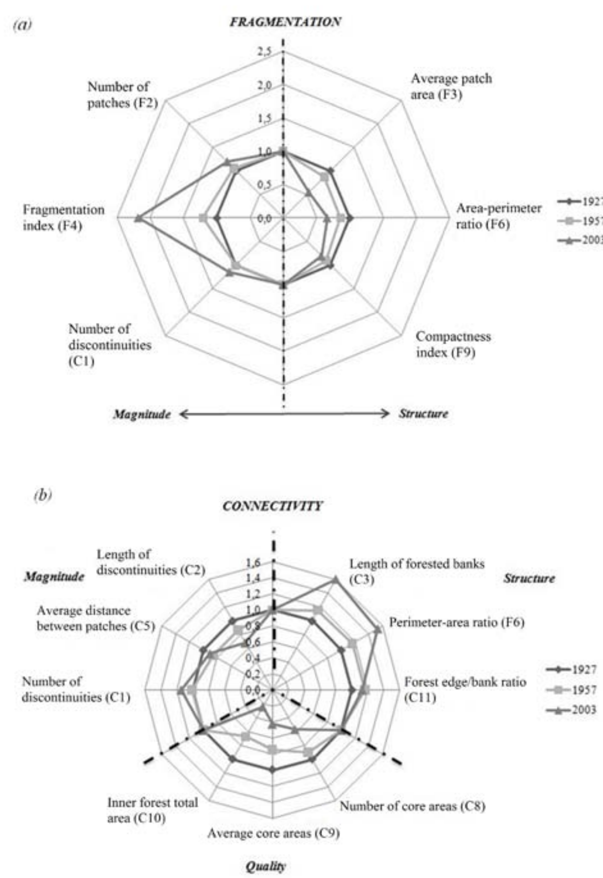

Figure 3. Graphical representation of changes to the main components of fragmentation (a) and connectivity (b) patterns of the riparian forests in the Middle Ebro between 1927, 1957 and 2003 (change (y.19xx) = parameter (y.19xx)/parameter (y.1927)). In this figure the parameters are aggregated in terms of magnitude, structure and quality of fragmentation or connectivity trends, so that their relative modifications can be better visualized and understood.

patch area and increased isolation of patches) and, as a result, (3) changes in habitat quality due to edge effects [47,48]. True fragmentation can have either a negative or positive effect on biodiversity (as moderate disturbances may increase the heterogeneity of the landscape), while habitat loss is the most detrimental aspect of habitat fragmentation [49]. Among the three components of habitat fragmentation, habitat degradation is the prevailing process in the Ebro and needs to be especially taken into account in management plans.

The distribution of riparian trees represents a compromise between their requirements for high levels of soil moisture and sunlight and their vulnerability to floods [12,13,50,51]. Their location is also influenced by the surrounding environmental conditions at the time measures for disturbance control (flow and flood regulation in this case) are initiated [52]. The landscape structure of the floodplain forest of the Ebro is a manifestation of these processes. The duration and magnitude of summer droughts further constrains the development and distribution of pioneer and non-pioneer forests, and previous research has found that summer drought dynamics actively influence the ecology of the Ebro River [6]. The river's confinement and the lack of disturbance events could have also led to other negative ecological processes in wetlands of the study area, which could also be affecting the riparian vegetation (e.g. water salinisation, eutrophication, habitat homogenisation) [53].

Non-pioneer forests occupy a greater portion of the Middle Ebro than they did in the absence of regulation. Most of the existing forests in the Middle Ebro will persist, at least in the medium-term, regardless of whether the current hydrogeomorphic patterns are maintained [35]. New pioneer forests will thus be confined to smaller and more dynamic areas of the river, where flooding remains a recurring and destructive force (usually close to the main channel or in-channel areas).

The results of this research indicate that the once substantial riparian forests in the Ebro floodplain became increasingly fragmented throughout the 20th century. In 1927, the riparian landscape of the Ebro had already been affected by a long history of human land use. At that time, the relatively active hydromorphological pattern of the river allowed for the maintenance of large and heterogeneous forest patches dominated by pioneer species. The parameters related to form analysed in this study clearly exhibit rapid homogenisation in both the size and the shape of patches along the river corridor, and these changes were especially significant between 1957 and 2003.

Most remarkably, the parameters related to connectivity show that changes to the forest mosaic, which is characterised by a decrease in patch area and a progressive elongation and adjustment to the channel edges, were accompanied by an increase in forest discontinuity along the meandering corridor (Figure 3). The patch (C6) and edge (C7) density were considerably lower compared to those obtained in other similar studies [44,45,54]. The most altered patches are those associated with the most ecologically valuable core areas. The new forest is characterised by a linear structure and small patches that lack continuity. Pioneer forests have been marginalised because the progressive narrowing and stabilisation of the river channel [46] hampers the creation of new shallow sites that are connected to the channel and conducive to colonisation. These results confirm the hypothesis described by some authors of a decrease in the area occupied by pioneer forests due to the proliferation of mature stands [35]. In this context, pioneer forests can only colonise in-channel islands and small riparian areas where the river dynamics maintain some of their former activity [42].

A similar study concluded that patches with low interior to edge ratios should be a priority for short-term initiatives, whereas those with high ratios are better suited to long-term purchase and reserve programs [55]. The former may be more immediately vulnerable, and the latter may better establish large-scale landscape continuity. Thus, patch shape should be considered when devising strategies for the restoration of the riparian zones in the Middle Ebro.

The parameters related to connectivity in the Ebro floodplain also indicate that changes to the region's hydromorphological pattern preceded the transformation to its riparian forests. In recent decades, the stabilisation of forms and ecological processes may have been fostered by biogeomorphic forces, preventing the dynamic evolution of the Ebro´s ecomorphology. The alteration process may then lead to substitution and degradation of the forest playing a dominant role in the river floodplain. The connectivity parameters also could be indicating an accelerated rate of encroachment on the fluvial territory. The proliferation of urban and agricultural uses, which were supported by hydrogeomorphological alterations to the river system, confined the forest to areas close to the channel, and the spatial structure of the riparian landscape was mostly lost.

5. Conclusions

In the early 20th century, the central portion of the Ebro River (ca. 250 km long) was a freely meandering river system with functioning and dynamic ecological and geomorphological processes. These processes have been increasingly limited over the last eight decades. Riparian forests have adapted to this more-constrained river system, showing significant structural changes. This report identifies the key changes to these forest patches by adopting a twofold approach related to the evolution of forms and connectivity. The landscape structure of the forest is currently characterised by dramatic fragmentation and habitat loss, given that its quality decayed significantly from 1927 to 2003. Some key trends in this decline are, at the floodplain scale, (i) the decrease in the total forest area, (ii) the reduction of the patch area (which is especially evident in formerly large patches), (iii) the progressive isolation and fragmentation of the forest patches, (iv) the overall loss of connectivity in the landscape pattern. While at the more local scale, it was found (v) the trend of riparian forests becoming more linear and bank-associated in lands adjacent to river channel.

The major changes in the forest structure developed progressively throughout the study period, but the rate of these changes increased significantly in the last four decades. Moreover, these changes were preceded by the dramatic modification of the hydrologic and geomorphic functioning of the river system. As a result, the biogeomorphic activity of the channel seems to have facilitated a process of structural homogenisation, and the system is moving towards a state of geomorphic equilibrium. Currently, the structure of the riparian forest is completely associated with the river banks and exhibits little capacity for altering the channel dynamics.

These dynamics could lead to a forest dominated by mature, non-pioneer stands, with a land-use matrix dominated by agricultural activity and poplar cultivation. Isolated forest patches could mature, and juvenile sprouts of pioneer species could be confined to in-channel islands and to the few remnant dynamic sub-reaches in the study area. This lack of connectivity between forest and wetland patches could enhance the loss of biodiversity in the Ebro floodplain and further degrade the quality of remnant habitats.

Any restoration to the ecological functions of the Ebro system should address the following: (i) the conservation of the remnant geomorphic activity of the meandering corridor and the active rehabilitation of its most active sub-reaches; (ii) the conservation of the largest forest patches and the few remnant core areas to protect the biodiversity and dynamic reservoir of the previously free-meandering channel; (iii) the rehabilitation of the fluvial territory to its core dimensions (at least) prior to the last significant alteration of the river's pattern, as this could facilitate the reconnection of the floodplain wetlands with the main channel and allow the collapsed forest patches to be replaced with a more active, pioneer-dominated, and durable forest structure; and (iv) the identification of the patches that are most vulnerable to exogenous pressures, or the preservation of patches that are most likely to be resistant to such pressures. This scenario could be the only strategy capable of restoring function to the ecological and geomorphological structure of the Ebro system over the long term, and does so in accordance with current legal and scientific requirements and recommendations.

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