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Toward floodplain rejuvenation in the middle Ebro River (Spain): From history to action

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Abstract

The Mediterranean region is recognized as one of Earth's biodiversity hotspots, but disconnection of habitats and fluxes of energy and nutrients have made them particularly vulnerable to external perturbations in the current context of global warming. This paper presents a multitemporal approach to understand how past human impacts have led to present deficits in fluvial dynamics and to propose and assess possible future restoration scenarios. First, biogeomorphic regression and progression dynamics of the middle Ebro River (Spain) were studied at the reach scale over a period of 90 years (1927-2014). River bank fixations, flood defenses, and incision have caused a disconnection between the river and its floodplain leading to a remarkable tendency for stabilization and vegetation progression to forest. Restoration of processes is necessary for those rivers where rejuvenation is no longer occurring. Second, the selected restoration target for the studied middle Ebro River section focuses on the improvement of lateral hydrological connectivity and partial recovery of regression processes (bank erosion and riverbank vegetation succession disruption). Besides the base scenario (situation in 2014), three more restoration scenarios include levee opening, levee complete removal, and side channel reactivation. Finally, results from two-dimensional hydraulic simulations allow for sensitivity analysis, comparing the current situation with the proposed scenarios. The study of shear stress is used as a proxy for the initiation of side erosion and vegetation succession disruption. Outcomes indicate that scenarios would create conditions for mobilization of habitat patches in formerly stable floodplain areas, especially with the scenario of levee removal. The possibility of regaining channel mobility and floodplain connection would allow the fluvial system to increase its water retention capacity and, thus, to adapt to floods and droughts associated to climate change.

Keywords: biogeomorphology; process-based restoration; scenarios; middle Ebro River.

1. Introduction

Historical human transformation of rivers has left a legacy of damming, straightening, and embankment intended for water supply, energy production, flood control, land reclamation, and in larger rivers, for navigation too (Tockner et al., 2010). Despite their potential ecological complexity, many rivers are now simplified, reduced to channels that conduct flow; formerly braided channels have become meandering, and single channels have narrowed and incised (Surian and Rinaldi, 2003). Connectivity within the fluvial system plays a key role in the propagation of changes and so the extent of discontinuities and buffers, either natural or anthropogenic, determines the capacity of the system to adapt (Hooke, 2006). Worldwide, floodplains are disconnected from the vital source of water and sediment that allows for the constant renewal of ecosystems and, therefore, they are composed of aged and simplified habitat patches of limited ecological value (Díaz-Redondo et al., 2017a).

Mediterranean rivers are highly diversified ecosystems, with a distinctive interdependence between flow regime and biota (Bruno et al., 2014). The native biological communities of these rivers are adapted to the typical Mediterranean hydrological variability, characterized by peaks of rainfall in autumn and spring, but especially by a distinctive summer drought (Kondolf et al., 2013). However, these rivers are amongst the most regulated in the world, with a particular dam operation that inverts the seasonal hydrological patterns (Magdaleno and Fernández, 2011) and thus strongly impacts Mediterranean communities (Bruno et al., 2014). In the past, a close relation between climate, flooding, and channel changes existed, but after major damming in the Mediterranean zone (since the 1950s), natural river adjustments have almost disappeared (Hooke, 2006).

Among Mediterranean rivers, the Ebro River is the longest within the European context (930 km, followed by the Rhône River, 812 km, and the Po River, 652 km); and until the first decades of the twentieth century, it concentrated the most active fluvial dynamics in the Iberian Peninsula (Magdaleno and Fernández-Yuste, 2011). In particular, the wandering central sector presented exceptional examples of meander cutoffs and concave bank erosion (Ollero, 1992) that have progressively been limited by dams, land use changes, and construction of flood defenses (Ollero, 2010).

Under the biogeomorphic perspective adopted in this study, channel-floodplain habitats and dynamics are mainly controlled by interrelations between vegetation and hydrogeomorphological processes (water flow and sediment transport and deposition), with an ideal balance between regenerative forces driven by the hydrological regime and resistive forces essentially exerted by vegetation (Corenblit et al., 2010; Gurnell et al., 2016). As a consequence of flow alteration and river-floodplain disconnection, biogeomorphic interactions in the middle Ebro River are greatly affected, resulting in a reduction of natural regenerative dynamics and a dominance of mature stages of riparian vegetation (Cabezas et al., 2009), favored by commercial forest plantations of poplar species in the riparian fringe (Magdaleno et al., 2012). Sediment retention by reservoirs has led to a reduction on the size of alluvial bars as well as to channel incision, especially in those reaches where levees are located close to the active channel (Ollero, 2010).

Process-based restoration precisely focuses on reversing these unidirectional tendencies by promoting natural biogeomorphic dynamics (e.g., erosion/sedimentation, channel migration, flooding, vegetation rejuvenation/succession), so the riverine ecosystem can recover its self-adjustment capacity with minimal corrective intervention (Beechie et al., 2010). This restoration perspective is especially relevant as a way to promote resilience to future perturbations, such as climate change; thus, rejuvenation processes can lead to an increase in floodplain water retention capacity, balancing nature conservation goals with flood damage prevention (Baptist et al., 2004).

Because river restoration can be a costly, lengthy, and controversial process, particularly for large rivers, new evaluation approaches can provide a good justification of the necessary investment (Buijse et al., 2005). Despite the amount of research devoted to river restoration in general, a limitation still exists on the availability of prognostic tools that allow assessing the success of proposed measures (Reckendorfer et al., 2005). The development of simulation models along with a good selection of variables for assessment permits examination of possible scenarios and selection of the most convenient future restoration solution (Baptist et al., 2004).

Moreover, as river restoration practices advance, more interdisciplinarity is required (Vaughan et al., 2009), such as the integration of socioeconomic aspects within the evaluation of measures, as a result of the implementation of the European Water Framework Directive (Bergstrom and Loomis, 2017). In this sense, presenting the recovery of natural dynamics remains still a challenge in terms of welfare impacts as, from an anthropogenic point of view, processes are not perceived as of direct value to people (Brouwer et al., 2016). Instead, attention should be driven toward the generation of what we know as goods and services; for example, natural processes are responsible for purifying water for drinking, and for supporting wildlife and fish for recreation (Bergstrom and Loomis, 2017). The attention of society can be directed to the maintenance of these services in order to stop degradation and call for restoration (Palmer et al., 2014). Despite a few approaches over the past decade, this is still a rising perspective and much research has to be done so it can help river restoration practitioners and water managers in gaining public acceptance.

In the present study, a middle Ebro River section has been selected for the application of a comprehensive methodology that faces past, present, and future in an integrative view that must guide river restoration practice. Objectives of the research include (i) identifying a historical reference dynamic state or benchmark and the subsequent biogeomorphic deficits throughout the last century (1927-2014), (ii) selecting a realistic process-based restoration target that takes into account current limitations, (iii) assessing process recovery through a sensitivity analysis of restoration scenarios and socioeconomic impacts, and (iv) discussing implications for water management in the context of climate change.

2. Methods

2.1. Study area and historical background

The Ebro River follows a northwest-southeast direction and forms a delta in the Mediterranean Sea, its river basin constituting the largest (≈85,000 km^2) of the Mediterranean rivers in the Iberian Peninsula (Ollero, 2010). The central sector, located between Logroño and La Zaida (345 km), stands for one of the most relevant European examples of a free meandering channel within a wide floodplain (Ollero, 1992). The hydrological regime of the middle Ebro is mixed pluvionival, the greatest contributions coming from Pyrenean tributaries, with a maximum in February and a marked minimum flow in August (Magdaleno and Fernández, 2011). Catastrophic flooding has been documented since the seventieth century; but the most recent ones, especially in February 2003 and February-March 2015, have been aggravated by the prolonged time of overflowed water in crop fields, largely caused by the counter-effect of levees that do not allow the return of water to the main channel (Sánchez et al., 2015). On the other hand, the number of small to moderate floods have declined as a result of increased regulation along the second half of the twentieth century (Ollero, 2010).

The study reach (**Fig. 1**) is located immediately after the town of Castejón (Navarra, Spain) and ~12 km downstream from the incorporation of the Arga-Aragon complex that often adds discharges even higher than those carried by the Ebro River itself, with 230.7 m^3/s being the mean annual discharge in Castejón gauging station. It is a 10.4-km-long, free-flowing and naturally meandering section, typical of the middle Ebro River (the sinuosity index is 1.512); and it is located downstream from the Navarra motorway (AP15) bridge until the end of the protected area *Murillo de las Limas groves*, where the river changes its direction from northwest-southeast to north-south. With a channel bottom height that ranges from 254.5 to 251.5 m asl the average channel slope in this stretch is 0.03%.

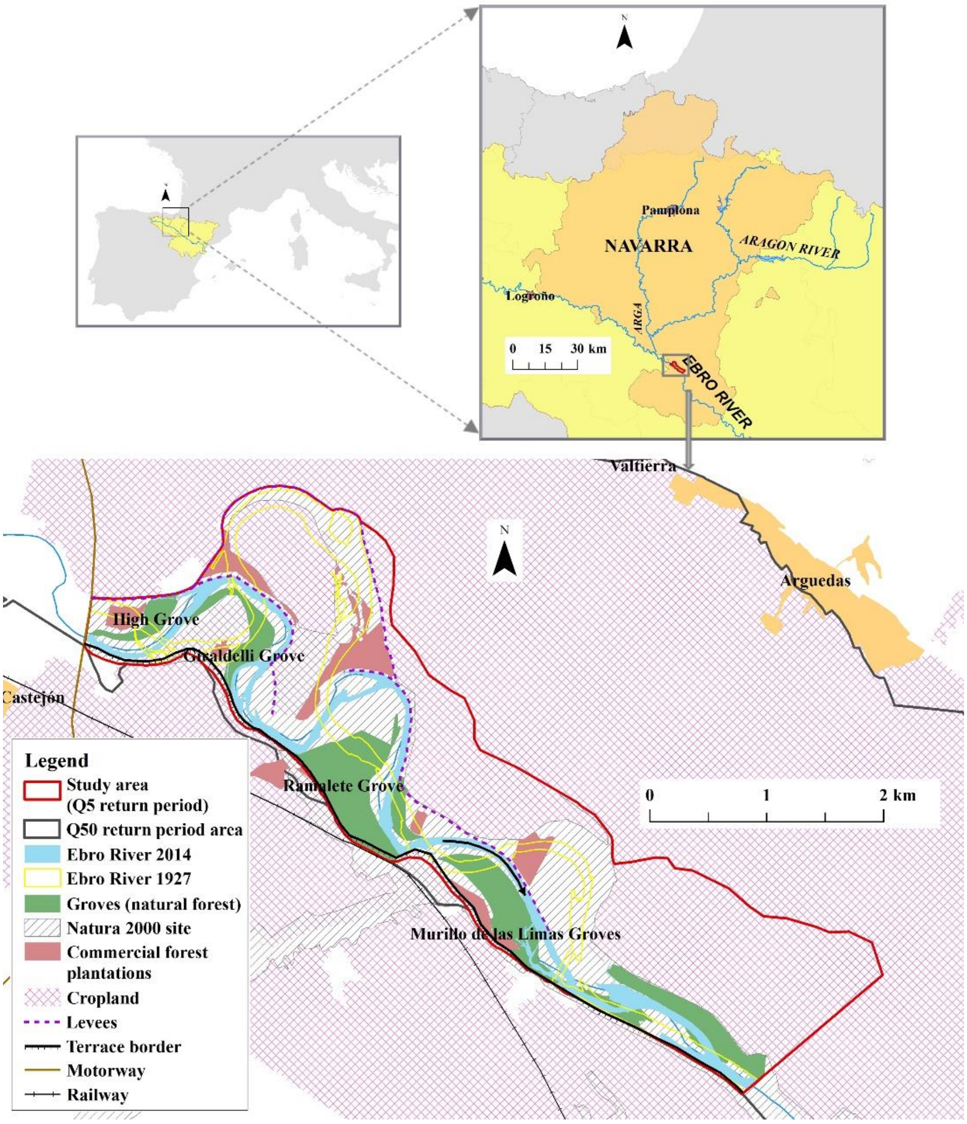

Fig. 1. Location of the study site within the Ebro River basin (upper left) and the Region of Navarra (upper right). River flow direction is northwest-southeast (black arrow, lower figure). The situation of the channel in 1927 (yellow line, lower figure) gives an indication of the extent of meanders in former times.

The study area (1017 ha; 1.2 km average width) is defined according to the definition of *Fluvial Territory* (Ollero et al., 2014), comprising the maximum extension of the riverside passageway in the last century, abandoned channels and areas flooded by a 5-year return period. An escarpment linked to a terrace on the right margin of the river has conditioned the historical river mobility and floods toward the north. Almost the entire area has been declared a Site of Community Importance (*Ebro River*, site code: ES2200040) for the conservation of natural habitats, and it also encompasses groves that are protected under regional laws as nature reserves and natural beauty spots. These groves (i.e., natural forest patches) appear spatially distant from one another along the middle Ebro River, with no longitudinal continuity, and mainly located in convex banks (Magdaleno and Fernández-Yuste, 2013).

Concave banks are fixed with rip-rap and levees of up to 3 m high that have suppressed channel mobility but have proved to be ineffective for flood protection owing to recurring leakages (Sánchez et al., 2015). Incision has been detected (Ollero et al., 2015), therefore adding up to the river-floodplain disconnection and favoring the human occupation of former meanders by croplands.

Hence, this section has been selected for its potentiality for process-based restoration measures, based on its natural biodiversity (although mainly composed by aged and disconnected habitat patches), its high historical mobility, and its still hydrological dynamism, with overflows around 1.2 times per year (Ollero, 1992).

In a similar way to other Mediterranean rivers (Hooke, 2006), the middle Ebro has undergone a long history of river management to deal with flash floods and summer water deficits, but along the last century, the number and size of dams and flood defenses have increased in an almost exponential trend (Magdaleno et al., 2012). From the basis of the work of Ollero (1991), the recent temporal evolution of fluvial dynamics in the study area has been studied from 1927 (year of the first reliable aerial images) until 2014, with the following classification of periods according to historical hydromorphological impacts:

- **Benchmark or preregulation period:** 1927-1957. Until the mid-twentieth century, the river showed a highly dynamic geomorphological situation (Magdaleno and Fernández, 2011). This cannot be assumed as the representation of a *natural* state because of the historical human use of the floodplain, especially cultivation (Hooke, 2006). However, it can be considered a reference state in terms of lack of regulation and embankment and also for a less intensive agricultural use.
- **Regulation period:** 1958-2001. The Reinosa reservoir in the Ebro River (540 hm^3, located ~400 km upstream from the study site), built in 1945, was put into operation in 1954, followed in 1960 by the Yesa reservoir in the Aragón River (447 hm^3, 210 km upstream), and in 2001 by the Itoiz reservoir (586 hm^3, 240 km upstream) in the Irati River, tributary of the Aragón River (Magdaleno and Fernández, 2011). This progressive regulation has led to altered hydrology (e.g., reduction of minor flood episodes) and sediment retention that have resulted in vertical incision and channel narrowing (Ollero et al., 2015). Within the study area, rip-rap and levees for flood protection were constructed, especially between 1960 and 1985 (Ollero, 2010). In this period, the increase in farming of the floodplain and river banks is remarkable (Ollero, 2010) along with the great spread of forest plantations, normally composed of *Populus* species (Magdaleno et al., 2012).
- **Current situation or post-regulation period:** 2002-2014. Stabilization prevails in the meandering channel and riverbanks (Magdaleno and Fernández, 2011), and vegetation has progressed toward maturity (Cabezas et al., 2009; Ollero, 2010).

2.2. Diachronic analysis of river-floodplain dynamics

Seven sets of aerial images (**Table 1**) were used to study the spatiotemporal dynamics evolution along the three periods considered. Only the 1927 aerial photographs had to be georeferenced using ArcGIS 10.3.1.®, the other sets of images were already georeferenced. The projection coordinate system was set for all GIS analyses with the ETRS 1989 UTM Zone 30. All aerial photographs until 1985 were in black and white, and orthophotographs from 2005 and 2014 were in true-color.

Table 1

Aerial photographs used in the present study[a]

Period	Year	Type	Scale or resolution	Source
Preregulation (benchmark)	1927	BW	1:10,000	CHE
	1946	BW	1:43,000	SITNA
	1957	BW	1:32,000	SITNA
Regulation	1966	BW	1:45,000	SITNA
	1985	BW	1:30,000	CNIG
Current situation	2005	C	0.5 m resolution	CNIG
	2014	C	0.5 m resolution	CNIG

[a] BW: black and white; C: colored. CHE: Confederación Hidrográfica del Ebro (Ebro River Basin Agency); SITNA: Sistema de Información Territorial de Navarra (Navarra Geoportal); CNIG: Centro Nacional de Información Geográfica (National Center of Geographic Information).

Seven habitat maps (see **Appendix A**) corresponding to each of the seven time steps considered were created by delineating seven categories of habitat patches (six of them natural, and the last two anthropic): (i) water, (ii) gravel/sand bar, (iii) grassland, (iv) shrubland, (v) forest, (vi) cropland and (vii) forest plantation. The distinction of habitat patches was made visually, based on the differences in polygon texture, color, density, and size of vegetation. This classification (based on Ward et al., 2002) does not provide any distinctions between species or between softwood and hardwood forests.

For the analysis of processes, each of the seven habitat maps was intersected with the subsequent use of the Geoprocessing tools of ArcGIS 10.3.1.® in order to obtain six intersection maps (see **Appendix B**). Thus, the intersected areas define the trajectories of habitat change (based on Díaz-Redondo et al., 2017, with modifications by the authors) between two time steps. A first classification of four main categories (changeless, progression, regression, and anthropization) is followed by a subclassification of ten subcategories according to biogeomorphic dynamics, i.e., interrelations between vegetation and hydrogeomorphological processes (**Table 2**).

Table 2

Classification of trajectories of change and associated biogeomorphic dynamics used in the multi-temporal analysis

Main trajectory	Hydrogeomorphological and vegetation process	Description
Changeless (areas that show no change)		
Progression (trajectory onward: habitat development toward forests):		
	Aggradation-progression	Water → gravel/sand bar
	Colonization-natural	Water or gravel/sand bar → grassland
	Transition-natural	Any natural habitat type (except forest) → shrubland or forest
	Transition-land abandonment	Croplands or forests plantations → shrubland or forest
Regression (trajectory backward: resetting of floodplain habitats):		
	Side erosion-channel shift	Any habitat type → water
	Aggradation-regression	Any habitat type (except water) → gravel/sand bar
	Regression-natural	Forest or shrubland → grassland; Forest → shrubland
	Regression-land abandonment	Cropland or forest plantation → grassland
Anthropization (exclusively human-induced changes):		
	Cultivation	Any habitat type → cropland

Main trajectory	Hydrogeomorphological and vegetation process	Description
	Forest plantation	Any habitat type → forest plantation

Progression and regression processes include the possibility that, owing to land abandonment, natural habitats may occupy those abandoned areas; on the contrary, anthropization processes refer to direct change of habitats into human uses. The change from cropland or forest plantation to shrubland or forest was regarded as a form of progression linked to land abandonment. On the other hand, the change from cropland or forest plantation to grassland was considered as natural regression, as an increase in fluvial dynamics.

Because the seven time steps differ in length (from 9 to 20 years), annual rates of change (ha/y) for each category were estimated as an indication of the historical evolution of fluvial dynamics (Garófano-Gómez et al., 2017). This annual rate is calculated by the mean of area differences between one time step and the preceding one and divided by the number of years for each time step.

2.3. Restoration target and scenarios

In our study zone, the predominant use in the floodplain is agriculture, which can be exposed to periodical occurrence of flooding (Ollero, 2010). However, downstream from this area, the town of Tudela has registered 93 historical flood events since records began; and the Ebro River in Tudela is declared as an area with a potential significant flood risk because of the exceedance of the natural fluvial capacity (Flood Risk Management Plan of the Ebro River Basin, approved by Royal Decree 18/2016). Moreover, no restriction but promotion of river restoration measures applies for this middle Ebro section (Ebro River Basin Management Plan, approved by Royal Decree 1/2016), we have established as a boundary condition for the restoration target selection that the flooded area in the town and infrastructures of Tudela would not be increased.

Therefore and after analyzing restoration projects in other European large rivers (Díaz-Redondo et al., 2018), the proposed restoration target for this middle Ebro River reach is mainly directed toward the promotion of key currently diminished regression processes (i.e., side erosion and vegetation rejuvenation) that will allow for initiating habitat renewal. Besides, while regaining lateral hydrological connectivity, the study area will also increase its water retention capacity (**Table 3**).

Table 3

Restoration target for the middle Ebro River section

Restoration target: enhancement of lateral hydrological connectivity and regression processes (bank erosion and riverbank vegetation succession disruption)	
Objectives	**Measures**
• Increase side erosion processes • Improve riparian vegetation composition and structure by disruption of mature stages • Enhance lateral hydrological connectivity between the river channel and its floodplain (additionally increasing floodplain's natural water retention capacity)	• Partial levee opening • Total levee removal • Partial rip-rap removal • Reactivation of disconnected side channels
Boundary conditions: no increase in flooded area in downstream urban settlements and infrastructures	

Once the restoration target was put forward, a series of scenarios were generated to assess the effects of the selected process-based restoration measures in the river-floodplain system:

- Base scenario (current situation, **Fig. 2A**): it represents the condition in August 2014. A digital elevation model (hereinafter DEM) was provided by the Ebro River Basin Agency with 1-m resolution, already including bathymetric data. The DEM area (5700 ha) for the hydraulic simulations was established much larger than the study area (1017 ha), as it covers the area flooded by a 50-year return period and downstream encompassing the town of Tudela.
- Scenario 1 (**Fig. 2B**): partial opening of levees (six openings, average length: 50 m, average width: 30 m) with a total excavated volume of 12,610 m^3. The locations of the openings are based on the existence of flood preferential circulation lines, as studied by Ollero (1992); and the average width has been selected according to the mean width of former meanders on historical aerial photographs. The total length of openings is 300 m, which corresponds to 5.8% of the total length of levees.
- Scenario 2 (**Fig. 2C**): total removal of levees (three levees, total length: 5200 m; average width: 30 m), including the removal of the upper part of the rip-rap just below the levee (around 0.5 m), with a total excavated volume of 221,393 m^3.
- Scenario 3 (**Fig. 2d**): total levee removal (similar to scenario 2) and side channel reconnection (total length: 2500 m; average width: 20 m). The old meander of La Barca, active in 1927, is recovered. The total excavated volume of this scenario is 260,298 m^3.

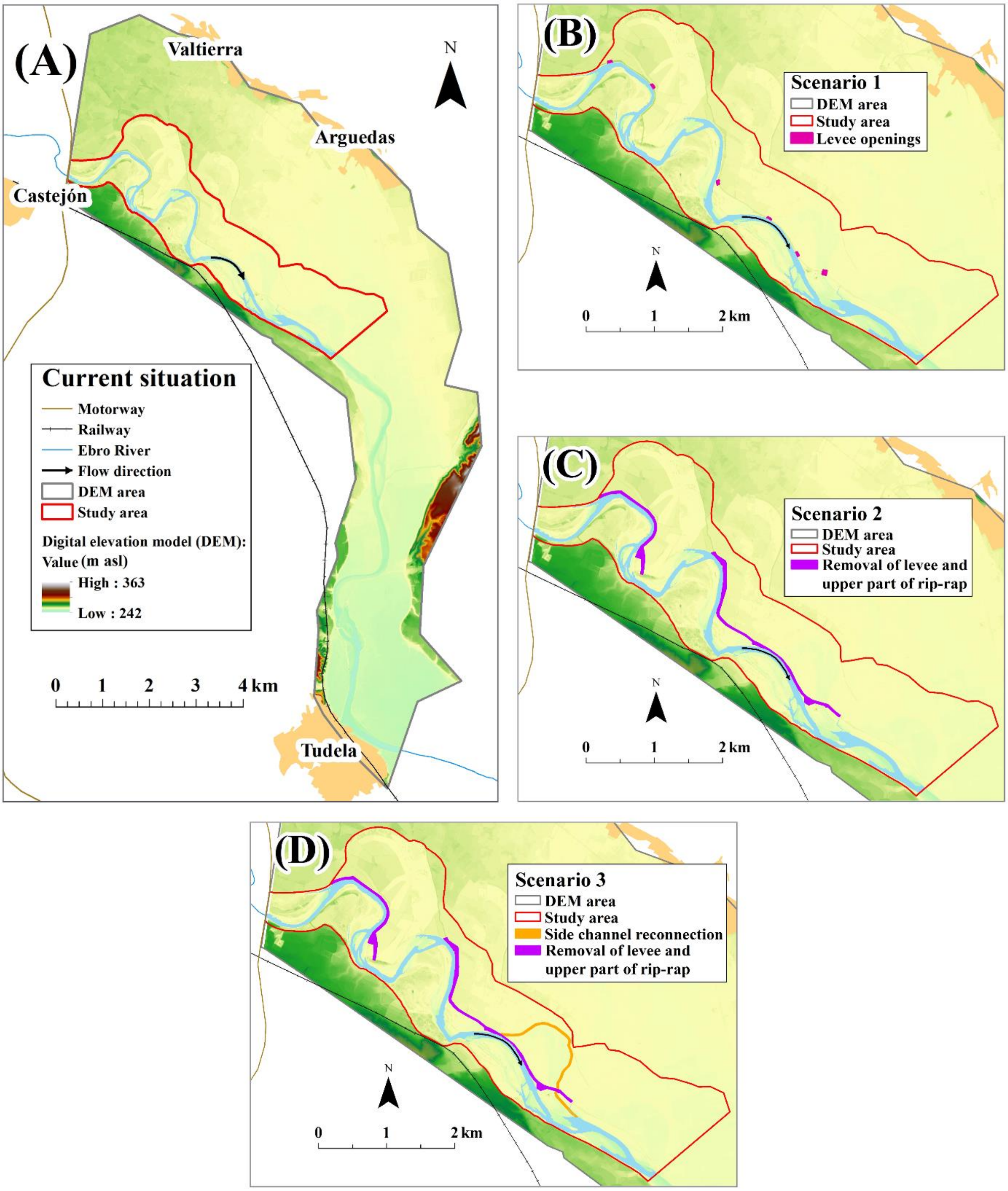

Fig. 2. Location of the Digital Elevation Model (DEM) area constituting the (A) base scenario and location of measures in (B) scenario 1, (C) scenario 2, and (D) scenario 3. The study area (red polygon, 1017 ha) is included within the DEM area (grey polygon, 5700 ha).

The final DEMs of the current situation and the three restoration scenarios were created with Global Mapper v17.0®; and owing to the requirements of the hydraulic modelling program, they were converted from 1-m to 2-m resolution ASCII files.

The free software IBER 2-D (Bladé et al., 2014) was selected for running the scenario simulations, particularly its hydrodynamic module that solves the two-dimensional, depth-averaged shallow water equations (2D St. Venant equations). This model has been widely applied in the occidental Mediterranean and Latin American contexts. Therefore, hydraulic simulations were run for three different discharges: (i) MCO (bankfull discharge, associated to a 2.5-year return period): 2198.63 m^3/s, (ii) Q5 (5-year return period): 2672 m^3/s, and (iii) Q25 (25-year return period): 3522 m^3. Discharge data were retrieved from the Automatic Hydrologic Information System of the Ebro River Basin (SAIH Ebro) for the Castejón gauging station (http://www.saihebro.com/saihebro/index.php?url=/datos/ficha/estacion:A002, accessed 22 July 2017). Calibration was achieved by comparing the simulated MCO flooded area in the current situation with the official MCO flooded area from the Ebro River Basin Agency (National Flood Zone Mapping System;(http://iber.chebro.es/SitEbro/sitebro.aspx?SNCZI, accessed 12 October 2017); differences in areas were <3%.

2.4. Assessment of process reactivations and socioeconomic impacts

Although sediment transport and deposition is influenced by parameters such as bed topography and turbulence intensity, the entrainment or mobilization of particles is largely determined by a threshold, or critical shear stress, associated to their size, where larger sizes require higher shear stress values to be set in motion (Powell, 1998; Vericat and Batalla, 2006). In addition, a shear stress threshold limits the potential for plants to endure in a particular location (Gurnell et al., 2016), usually referred to as vegetation shear stress resistance threshold (Rivaes et al., 2012).

In the present study, we have selected shear stress (N/m^2) as a proxy for assessing the activation of regression dynamics, i.e., river bank erosion and vegetation succession disruption through geomorphological mobilization of habitat patches (hereinafter called habitat patches mobilization). On the one hand, for substrate erosion, previous research on gravel-bed rivers support the use of 14 N/m^2 as a reference shear stress for the mobilization of particle sizes (D50, median diameter) in the range of 30 mm (Wilcock and Crowe, 2003; Petit et al., 2015), as it is the case of bedload mean particle size in the middle and lower Ebro River sections (Vericat and Batalla, 2006). On the other hand, vegetation shear stress resistance values have been selected from the literature (based on Egger et al., 2012, and García-Arias et al., 2012 with modifications by the authors). Therefore, we propose the following shear stress thresholds according to the classification of the channel-floodplain habitats:

- No mobilization: 0–14 N/m^2
- Mobilization of gravel/sand bar and grassland patches: >14–30 N/m^2
- Mobilization of shrubland and cropland patches: >30–100 N/m^2
- Mobilization of forest and forest plantation patches: >100 N/m^2

Despite the implicit reductionism of this approach and because many processes are involved in channel development (Michaelides and Wainwright, 2005), our purpose is to perform a sensitivity analysis where changes in shear stress values will be compared between the current situation and the different scenarios regarding areas exceeding threshold values per habitat type.

Ultimately, we introduce a final element on the sensitivity analysis of the three restoration scenarios, as it is the evaluation of socioeconomic impacts. Here, two metrics are considered, the excavated volume required by the proposed measures for each scenario, and the area of land uses (croplands and forest plantations) that could be affected; i.e., area mobilized according to shear stress thresholds. These two variables are evaluated as opposed to the sum of areas where natural regression could occur, i.e., where shear stress values exceed thresholds for natural habitats for the three discharges (MCO, Q5, and Q25) per scenario. The potential space given to the river is understood as a proxy for the augmentation of the hydraulic capacity in the floodplain.

3. Results

3.1. Multitemporal analysis of river-floodplain processes: benchmark and biogeomorphic deficits

The analysis of dynamics evolution in terms of ratios (ha/y) per historical interval indicates a clear decreasing tendency in progression and regression trajectories in the regulation and post-regulation period (**Fig. 3A**), when compared with the prechannelization period (benchmark). Conversely, the changeless ratio has been increasing in the last recent periods, with around 75% of the changeless area corresponding to the sum of cropland and forest, denoting a clear tendency toward stability and vegetation maturity (**Fig. 3B**).

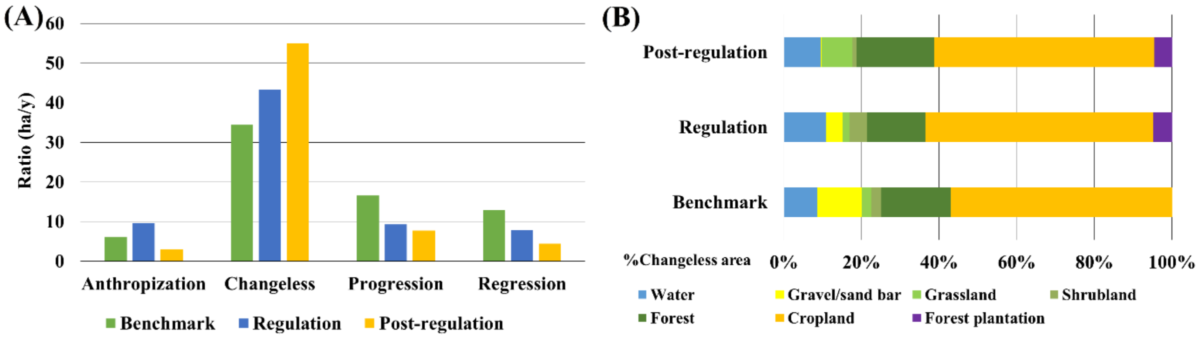

Fig. 3. (A) Ratio (area/y) of main trajectories of change; (B) percentage (%) of habitats within the changeless area. Historical periods: benchmark (1927-1957), regulation (1958-2001), and post-regulation (2002-2014).

All categories of progression processes (**Fig. 4A**), except transition-land abandonment, present a decreased tendency, being remarkable the reduction of colonization-natural ratio; transition-natural ratio has descended from the benchmark situation but has maintained equivalent values in the most recent periods. As for regression processes (**Fig. 4B**), we have to acknowledge a clear reduction trend on natural regression and erosion-channel shift, which indicates a decrease in fluvial dynamics such as channel migration. Finally, although anthropization increased in the regulation period, it has dropped now in the post-regulation period, mainly caused by a progressive decrease in cultivation and a sharp reduction in forest plantation ratios (**Fig. 4C**).

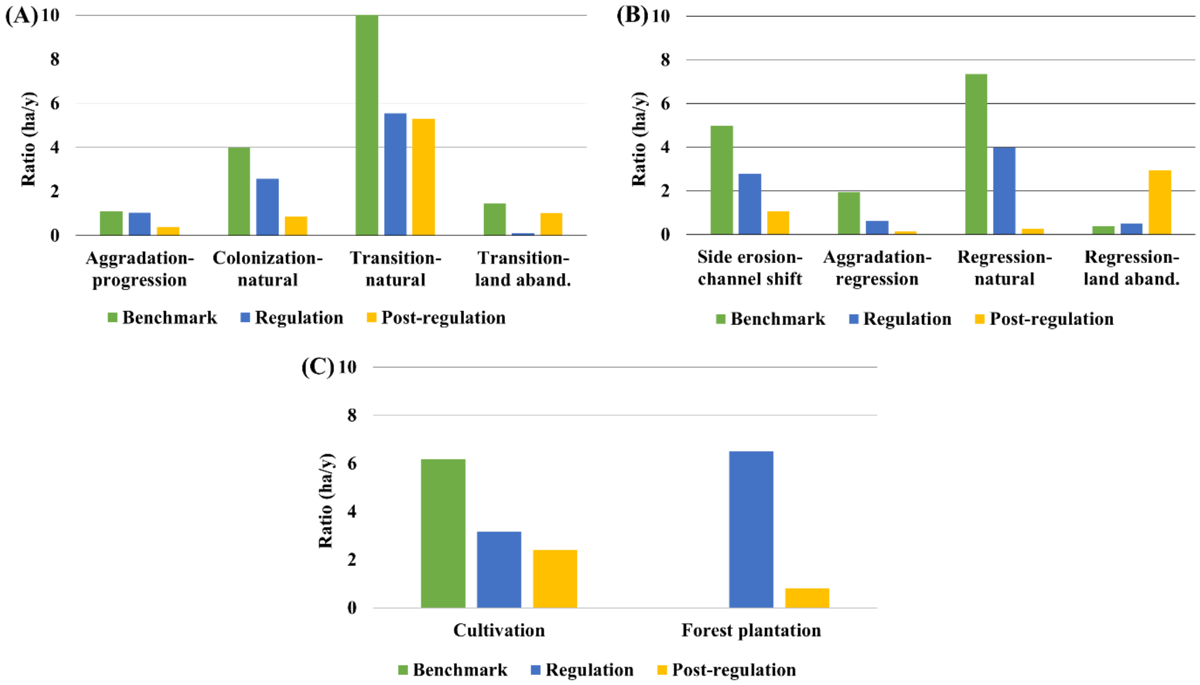

Fig. 4. Ratio (area/y) of (A) progression, (B) regression, and (C) anthropization processes.

3.2. Initiation of regression dynamics and potential socioeconomic impacts

The generated shear stress data enabled us to compare scenarios by means of habitat patches areas that could be mobilized when a specific threshold is exceeded. Here, those possible activated areas are presented as a percentage of each habitat type (**Fig. 5**). The percentage of *gravel/sand bar* area that could be eroded is very high for all simulations (over 50%) but it is lower for the three scenarios than for the current situation. The *grassland* area that could be mobilized in the base scenario and in scenario 1 is very similar, and no difference exists between scenarios 2 and 3 for discharges MCO and Q25; however, there is an exceptional increase in scenario 2 for discharge Q5 (from 10% in the current situation to 18% in scenario 1).

Regarding *shrubland*, we can appreciate slightly higher percentage values for scenarios 2 and 3 with MCO, and a maximum percentage achieved for scenario 2 and discharge Q5; no significant differences exist among scenarios for discharge Q25. Mobilization of *forest* patches associates with very high shear stress values (>100 N/m^2), and so the percentage of this habitat category is in generally very low; in any case, scenarios 2 and 3 present higher values, the peaks occurring again for scenario 2 and Q5.

The lowest percentage of mobilized habitat patch area would correspond to *cropland* and *forest plantation*, being <1 % for all simulations. In both cases, differences exist between the current situation and the three restoration scenarios, with higher percentages for Q25. In particular, mobilization of forest plantation patches would only occur with the proposed scenarios, scenario 1 being the most effective for MCO and Q5 and scenarios 1-3 in almost equal terms for Q25.

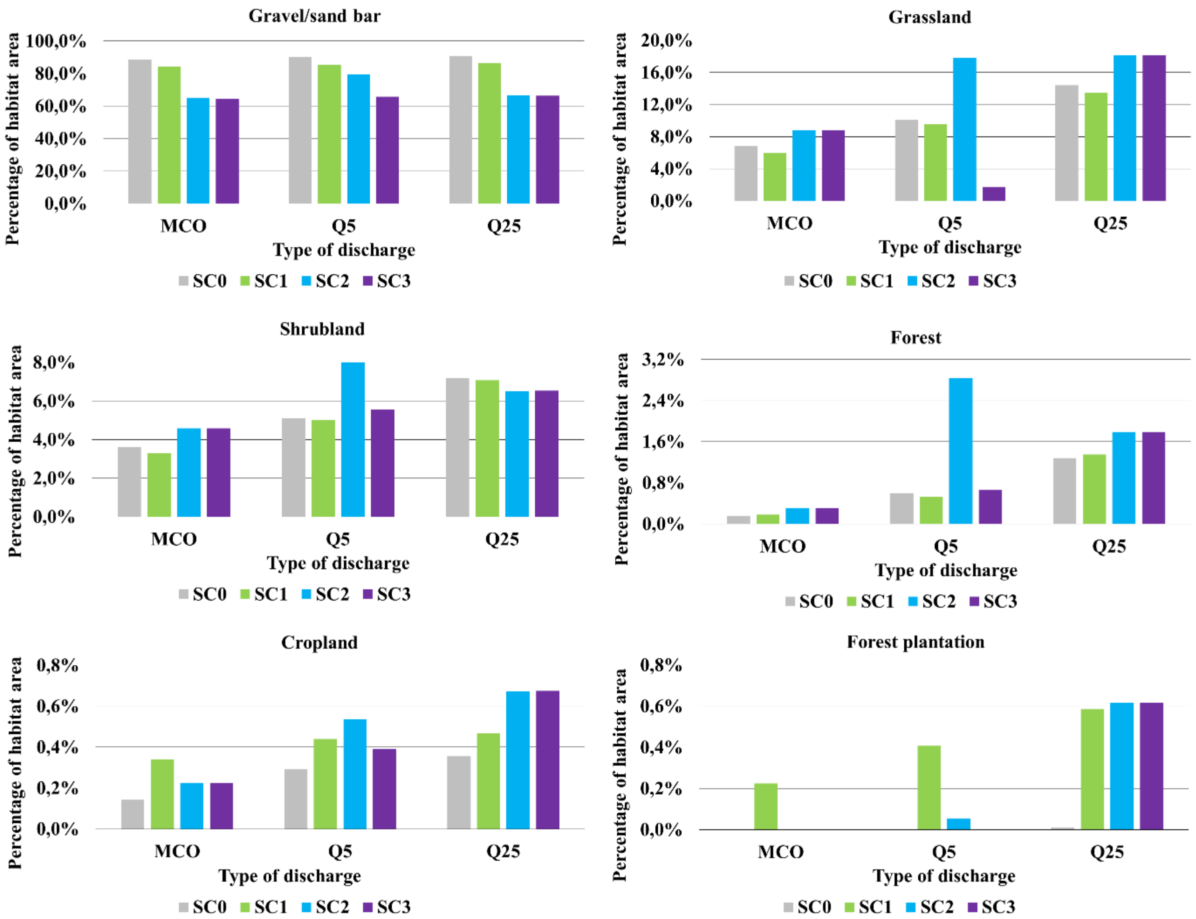

Fig. 5. Percentage (%) of each habitat type area where shear stress values exceed the corresponding threshold, in the current situation (SC0) and the three restoration scenarios (SC1, SC2, and SC3). Note that the *y*-axis scale is different for almost all habitat categories. MCO (bank-full discharge, associated to a 2.5-year return period): 2198.63 m^3/s, Q5 (5-year return period): 2672 m^3/s, and Q25 (25-year return period): 3522 m^3.

When we proceed to analyze the location of possible habitat patches that could be mobilized, for example for a 5-year return period (**Fig. 6**), we can appreciate that the areas of forest plantation and cropland that would be shifted in scenario 1 (**Fig. 6B**), though very small, would result from the location of the levee openings directly toward these zones. On the one hand, cropland and forest plantation patches closer to the river are mainly protected behind the levees, and on the other hand, geomorphological mobilization of forest patches requires exceeding a very high shear stress threshold (>100 N/m^2). Consequently, when levee removal is simulated in scenario 2 (**Fig. 6C**), we can observe very significant changes compared to the current situation (**Fig. 6A**), not only for the forest area that could be shifted but also for the possible mobilization of cropland and grassland patches in the concave bank. On the other hand, the meander reconnection on scenario 3 seems to lead to energy dissipation as evidence of the reduction in shear stress values (**Fig. 6D**) when compared with the other three scenarios.

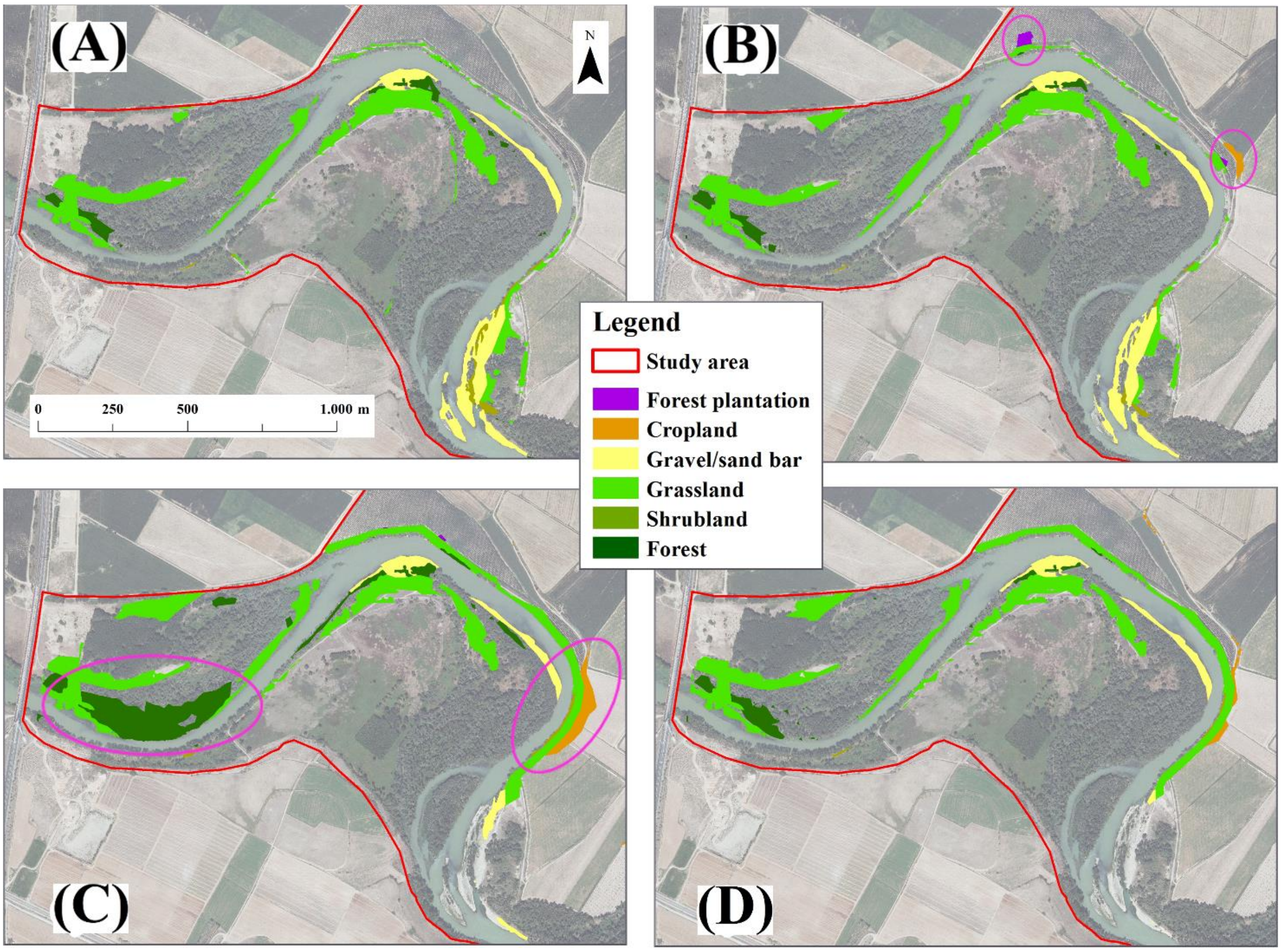

Fig. 6. Possible mobilized habitat patches areas for a Q5 discharge in (A) the current situation, (B) scenario 1, (C) scenario 2, and (D) scenario 3. Circles in pink indicate the located mobilization owing to punctual openings in (B), and the effects on forest and concave bank area after levee removal in (C).

For the final step in the sensitivity analysis of restoration scenarios, we compared total mobilized area of natural habitat patches (m^2) versus the total excavated volume (m^3) and versus the area of human land uses that could be affected (m^2). As mentioned before, the area of human land uses (cropland and forest plantation) that would be subjected to shifting is very low (<1%). Therefore, we can appreciate that scenario 2 produces more remobilization against land uses affected (260.5 m^2 of natural habitat patches area is mobilized per m^2 of possible land uses affected), being the greatest difference with scenario 1 (**Table 4**). However, we have to highlight that, when compared with the excavated volume, scenario 1 would achieve the highest ratio (229.5 m^2 of natural habitat patches area mobilized per m^3 of excavated volume required).

Table 4

Scenario evaluation of natural habitat patches mobilization versus socioeconomic impacts (excavated volume and land uses affected)

Variables	**SC1**	**SC2**	**SC3**
Total natural habitat mobilized (m^2) / land uses affected (m^2)	164.9	260.5	229.8
Total natural habitat mobilized (m^2) / excavated volume (m^3)	229.5	12.8	9.5

Finally, we checked that no increase occurs in flooded area in the town of Tudela between the current situation and the three restoration scenarios (the increase in area percentage is 0.0% for scenarios 1 and 2 and -0.1% for scenario 3). This final step is key to complete our scenario assessment in order to check that the proposed measures would comply with the established boundary conditions.

4. Discussion and conclusions

4.1. Floodplain habitat rejuvenation through process-based restoration

Currently, many thousands of kilometers along large rivers present different degrees of disconnection with their once considerable floodplains, becoming almost separate entities (Buijse et al., 2005). As a consequence of losing the natural balance of dynamic interactions between hydrogeomorphology and vegetation, unidirectional trends guide the fluvial system toward channel incision and narrowing, floodplain aggradation, and vegetation succession (Surian and Rinaldi, 2003; Tockner et al., 2010; Ollero et al., 2015; Gurnell et al., 2016).

The middle Ebro River is no exception in that regard. Our study has proved that until the mid-twentieth century in the selected benchmark period (1927-1957), comparable ratios of progression and regression processes can be associated with a balance between habitat patches destruction and creation forces in a very active system, as stated by Magdaleno and Fernández-Yuste (2011). In contrast, subsequent historical periods present decreasing ratios of natural progression, but particularly of regression dynamics. The decline in channel shift ratios is remarkable, and the cause can be mainly attributed to an intensive construction of bank fixation between 1960 and 1985 and to channel incision as a consequence of regulation (Ollero, 2010).

Moreover, areas that do not change are clearly predominant, revealing a strong system stability, despite the fact that recent outstanding flood episodes have occurred recently (floods over bankfull discharge) in 2003, 2007, and 2015 (Sanchez et al., 2015). At the same time, the area corresponding to native forest has been progressively augmenting and, in the last year examined (2014), forests occupy 22% of the study area. All this exposes the current situation of many regulated rivers worldwide, characterized by the loss of natural rejuvenation mechanisms and the dominance of mature vegetation (Buijse et al., 2005). Other authors have identified these conditions in the middle Ebro River (Cabezas et al., 2009; Ollero, 2010; Magdaleno and Fernández-Yuste, 2013) and in other large rivers too, such as the Waal River in the Netherlands (Baptist et al., 2004) and the Danube River in Austria (Hohensinner et al., 2010).

The present research seeks not only evidence of biogeomorphic deficits of the fluvial system and the causes behind them, but to propose a reasonable restoration target that acknowledges human constraints and to approach an evaluation of process recovery through sensitivity analysis. Therefore, we have selected a series of restoration scenarios, run two-dimensional simulations, and outcomes are assessed from the perspective of process initiation by classifying shear stress values within thresholds of habitat patch mobilization. Hence, we have noticed that the percentage of values exceeding the shear stress threshold for the mobilization of gravel/sand bar patches is higher in the base scenario and that values are progressively lower in the following restoration scenarios. This would indicate that shear stress values are higher within the channel in the current situation and that, by levee opening or removal, shear stress values increase in those areas closer to the river channel. The partial opening of levees (scenario 1) leads to a quite localized shifting of habitat patches, especially directed toward forest plantations and cropland patches behind levees.

The highest mobilization values for almost all landscape elements occur with scenario 2, which includes total levee removal, and where a 5-year return period discharge appears to lead to certain shifting of forest patches and mobilization of other habitat patch areas in concave banks. Yet these higher frequency return period events would also contribute to expand the periodical provision of nutrients and aquatic habitats to those floodplain areas regained by levee removals (Guida et al., 2015). Besides that, no significant increases appear between scenarios 2 and 3, which could indicate that the reconnection of the meander in scenario 3 produces an energy dissipation that results in the decrease of the shear stress values. In general, the total levee removal in scenarios 2 and 3 needs a 25-year return period to mobilize discrete areas of tree vegetation, as disruption of mature ecotope succession requires considerable river disturbance regimes (Corenblit et al., 2010).

As studied by Peters and Stoesser (2001) in scenarios of river widening in the Rest Rhine (France, Germany), increases and decreases of shear stress values can be associated with consequent geomorphic effects of particle erosion and sedimentation. Yet other hydraulic parameters condition disturbance regime effects, such as sediment transport capacity and bank stability (Formann et al., 2014). In turn, previous research on vegetation resistance to shear stress across Europe and America has highlighted that differences can also be found depending on species and communities and that flood inundation duration likewise plays a critical part (Egger et al., 2012; García-Arias et al., 2012; Rivaes et al., 2012; Serlet et al., 2018). Since this study assumes a simplification of complex natural processes, results here presented should be carefully interpreted. Further research could include the application and analysis of results from a sediment transport model and comparison with previous morphosedimentary investigations, as well as the inclusion of parameters related to vegetation characteristics (root density, age, species, etc.), among others.

4.2. Integrated assessment of fluvial dynamics reactivation

Following on with our scenario sensitivity analysis, we have used habitat patch areas prone to mobilization as an indicator of augmenting water retention capacity in the floodplain, and we have compared this metric with possible socioeconomic impacts of the proposed measures. In doing so, we pretend to highlight the difficulty and importance of presenting variables on the recovery of ecosystem processes or functions so that they are finally understood as useful for people (Brouwer et al., 2016; Bergstrom and Loomis, 2017).

In the Ebro River case study, we have concluded that the levee opening scenario (scenario 1) achieves a higher rate of natural habitat patch mobilization compared with possible socioeconomic impacts of volume excavation. Yet we have to highlight that this scenario would possibly intensify the effects of current levee leakages in terms of backwater retention, associated slow flow velocities, and increased flood stages (Guida et al., 2015). Conversely, the levee removal and meander reactivation scenario (scenario 3) presents the lowest ratios of habitat patch mobilization versus socioeconomic impacts. Besides, this scenario would not be of much success in erosion reactivation and vegetation succession disruption; quite the opposite, it could reduce shear stress values in other parts of the floodplain and lead to more sedimentation (Formann et al., 2014). Because of channel incision and floodplain agricultural occupation, old channel reactivation is extremely complicated and would require large soil excavations. Experience from past projects has shown that this type of measure must be radical, such as complete rip-rap removal down to the low water level proposed for the upstream surface connection of side channels with the Danube River (Reckendorfer et al., 2005). Other authors have also pointed out the necessity of floodplain lowering (Peters and Stoesser, 2001; Baptist et al., 2004; Straatsma et al., 2009).

Meanwhile the total levee removal scenario (scenario 2) presents the greatest proportion of natural mobilized habitat patch areas versus land uses affected. Consequently, we would like to stress the implications of levee removal in river-floodplain processes reactivation and especially the linked removal of the upper part of the rip-rap defenses, which have proved to promote lateral erosion and consequent channel mobility in Danube restoration projects (Reckendorfer et al., 2005; Jungwirth et al., 2014). Moreover, levee removals eliminate the backwater problem associated with them and allow for an effective flood-peak reduction (Guida et al., 2015). Thus, we consider that scenario 2 would allow triggering process recovery despite being more expensive from the socioeconomic point of view presented here.

Notwithstanding, the final success of the restoration scenarios proposed here in terms of process reactivation can potentially be the subject of much debate and therefore, the application of a range of indicators (e.g., eroded area, new gravel/sand bar area, overbank flood frequency, etc.) is certainly advisable, as indicated by previous restoration practices analyses (Morandi et al., 2017).

Not many studies have presented methods for assessing scenarios by integrating geomorphology, ecology, and sociology; but Guida et al. (2015) evaluated scenarios of levee removal and setbacks along the lower Tisza River against population impacted, levee removal costs, wetland area reconnected, and flood height changes. We acknowledge the rough approach to such a complex matter but point out the necessity of progressively incorporating this type of indicator of the positive benefits of the recovery of natural processes into river restoration practice. Clearly, future large river rehabilitation will need more research on those socioeconomic foundations to help water managers (Buijse et al., 2005). This perspective is especially relevant in the context of the European Water Framework Directive, which emphasizes economic valuation of measures within river management plans (Brouwer et al., 2016).

4.3. Implications for water management

The seasonal Mediterranean climatic regime along with intensified human activities within the river basin, especially agriculture and urbanization, have contributed to an increasing frequency of devastating floods in the last century (Hooke, 2006). At the reach level, without any natural rejuvenation, riverine vegetation progresses to forest leading to higher hydraulic roughness values and consequent water levels which, combined with ineffective dykes that retain flooded waters, results in aggravated flood damages (Buijse et al., 2005; Cabezas et al., 2009).

In this regard, our restoration target seeks to balance natural process recovery with the boundary condition of not increasing flooded areas in urban areas downstream. Therefore, results have been checked to confirm that no increase in flooded area will be occurring in the town of Tudela downstream from our study zone. Hence we propose the recovery of a channel migration zone in a not populated area, where the river can flood, erode, deposit, and shift its course (Kondolf et al., 2013; Guida et al., 2015). Moreover, while regaining lateral channel movement, the objective is also to promote river-floodplain connection and natural water retention in the study area in order to mitigate the socioeconomic effects of flooding and droughts.

This vision lies within the conceptual framework of strategies such as the *Room for the River*, which defends the *self-regulating nature* or *let the river do the job* principle, as well as the *Cyclic Floodplain Rejuvenation*, which reconciles objectives of nature rehabilitation with flood management (Baptist et al., 2004; Fliervoet et al., 2013). These principles have also been applied in the preceding research on the use of hydrodynamic and geospatial modelling for assessing restoration scenarios. Accordingly, Guida et al. (2015) concluded that significant river-floodplain reconnection could be achieved with levee removal and setback scenarios in the lower Tisza River, while reducing flood levels. Likewise, Straatsma et al. (2009) presented scenarios of dike relocation and embankment removal in the River Waal in the Netherlands with the aim of positive effects regarding flood peak reduction sediment deposition and potential biodiversity.

When put into practice, recent restoration projects in nearby areas have proved to be successful for inverting the degrading trends and improving overall dynamics. On the one hand, the restoration project in Soto de Tetones (113 ha, 3 km upstream from Tudela) was undertaken between 2006 and 2010 and included the removal of embankments to increase flood frequency and reactivate natural channel-floodplain processes (Gumiero et al., 2013; Ollero et al., 2015). On the other hand, among the range of measures carried out between 2010 and 2015 in the lower reaches of the Aragón and Arga rivers within the framework of the European LIFE+ 09 NAT/ES/000531 Project Mink Territory, extensive levee and rip-rap removals were undertaken to recover the natural floodplain and the natural habitats on which the mink depends. Lately, the Ebro River Basin Agency has initiated a project focused on the relocation of up to 8 km of levees in the Alfaro area (CHE, personal communication), which is located just upstream from our study site; and so the proposal presented here will logically match the current line of action adopted by the water management authorities. Overall, these initiatives fit within the scope of three EU directives: the Water Framework Directive, the Floods Directive, and the Habitats Directive.

Under global warming scenarios of climate change, the Mediterranean region will be subjected to an increasing propensity to flash flooding and droughts (Schneider et al., 2013). As floods will continue to occur in the future, efforts must focus on stopping investments in measures that have proved to be unsuccessful, such as dredgings, and on finally adhering to management strategies that allow for flood risk reduction and for river conservation, i.e., giving more space for the river, as was proposed for the Aragonese section in the Environmental Plan of the Ebro River (Sánchez et al., 2015). Moreover, the applicability of this approach has been developed in detail for the Ebro River and tributaries in the works of Ollero (2007) and Ollero et al. (2015).

Finally, a clear effort has to be made on the part of researchers in translating scientific outcomes into practical application and effectively transmitting them to all stakeholders (Buijse et al., 2005). The presented approach is transferable to other river-floodplain systems, not only in the Mediterranean context, as regaining fluvial mobility and rejuvenation mechanisms promotes an overall ecologically dynamic river system, self-sustaining and resilient to external perturbations such as the impacts of climate change.

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