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Title: Regional planning of river protection and restoration to promote ecosystem services and nature conservation

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Highlights

- An integrated regional spatial planning approach for river ecosystems is presented.
- Conservation goals and ecosystem services were combined in regional planning.
- Mountain areas were identified as key areas for protection of services and habitats.
- Riparian forest restoration in river valleys can benefit habitats and soil erosion.
- The approach fosters articulation between nature and water directives goals.

Abstract

As global environmental changes intensify, there is a pressing need to balance human demands on freshwater ecosystems with ecological integrity ensuring biodiversity conservation and sustainable management of water resources.

In this study, we develop an integrated spatial planning approach for river ecosystems by combining nature conservation and ecosystem services. We assess the regional distribution of conservation value habitats and ecosystem services supply and then investigate how they are associated to develop spatial planning for management interventions that benefit both goals.

We illustrate the approach with two riverine habitats protected under the EU Habitats Directive representing in-stream (Habitat 3260) and riparian (Habitat 91E0*) fluvial compartments, and two key water ecosystem services ("Surface water for nutrition, materials or energy" and "Control of erosion rates"). Working across the three River Basin Districts of North Portugal, we identify key areas where protection and restoration actions can benefit both habitat conservation goals and ecosystem service supply. Our results suggest the need for landscape-level protection of upstream mountain areas, often included in protected areas, to safeguard ecosystem services in addition to habitats. The results also suggest the need for complementary restoration of riparian areas in river valleys outside protected areas.

This study illustrates the added-value for river management of considering both ecosystem service supply and nature conservation in regional and catchment-level spatial planning. By integrating multiple goals, our approach fosters the implementation of integrated river management, contributing to the articulation between nature and water directives and the design of blue-green infrastructure networks.

Keywords: integrated management; freshwater; Habitats Directive; Water Framework Directive

1. Introduction

International conservation and sustainability agendas (CBD, 2010; European Union, 2011; IPBES, 2018; United Nations, 2018) have repeatedly called for conservation, restoration and sustainable use of biodiversity as well as the enhancement of ecosystem services and benefits to society. These calls are particularly relevant for freshwater ecosystems, which combine conservation interest and high societal value through the supply of multiple ecosystem services (Tharme, Tickner, Hughes, Conallin, & Zielinski, 2018). Freshwater habitats and biodiversity are also amongst the most threatened worldwide, due to a broad range of anthropogenic pressures (IPBES, 2018; Reid et al., 2019). In the European Union, 63% of river and lake habitats protected under the Habitats Directive (HD) are considereld to hold “Unfavourable” conservation status, and 60% of water bodies evaluated in the Water Framework Directive (WFD) are not in “Good” ecological status (IPBES, 2018).

The WFD (2000/60/EC (European Commission, 2000)), the core water policy instrument at European level, does not mention ecosystem services explicitly, however, it does call for sustainable and integrated management of freshwaters that promotes ecosystem health and sustainable use of water resources, in articulation with other directives including the HD (European Commission, 2011). Recent reports and policy instruments have further highlighted this need, explicitly including the ecosystem services framework (European Commission, 2012) as a key approach to reconciling societal needs with conservation goals.

There is growing evidence of the value of maintaining freshwater ecosystems in good ecological condition (Grizzetti et al., 2019), and that conservation priorities focused on biodiversity conservation or ecosystem service supply may not be mutually exclusive (Abell et al., 2019; Harrison et al., 2016). Spatial planning incorporating biodiversity conservation, ecosystem service supply, and the synergies and trade-offs between the two, can be a key instrument in harmonizing different policy objectives (Albert, Fürst, Ring, & Sandström, 2020). Identifying win-win opportunities in landscape planning benefits the development and implementation of management plans (Terrado et al., 2016). It supports measures to achieve good ecological status and highlights the benefits of investing in river restoration and nature conservation (Feld et al., 2018; Grizzetti, Lanzanova, Liquete, Reynaud, & Cardoso, 2016). However, successfully achieving those multiple goals requires data on how conservation-interest features and the supply of ecosystem services are distributed at scales relevant for river management, namely regional and river basin scales (Albert et al., 2020). This is key to enable the identification and prioritization of mutually beneficial (win-win) management strategies, including protection of key intact areas, restoration or rehabilitation of degraded ecosystems, or investment in green infrastructures (Green et al., 2015; Vörösmarty et al., 2018).

Model-based approaches are frequently applied to understand and project systems behaviour in space and time and therefore to overcome gaps in available data or mismatches in spatial coverage and/or resolution. In the biodiversity conservation domain, predictive modelling approaches, namely habitat suitability modelling, are widely used to tackle these issues (Guisan, Thuiller, & Zimmermann, 2017) and have been applied before to predict the regional distribution of riverine habitats (Metzger et al., 2013). In the ecosystem service domain, statistical or process-based models are often employed (Carvalho-Santos, Honrado, & Hein, 2014) since direct or indirect measurements of ecosystem services are seldom available (Burkhard & Maes, 2017).

In this study, we aim to develop a spatially-explicit analytical approach to support regional-level integrated planning and management of river ecosystems. In our approach we aim to balance habitat conservation and ecosystem services supply and foster synergies between different EU policies, particularly those related to nature conservation (HD) and water resources (WFD). At each step of our approach we aim to answer the following questions: (i) How are key conservation-interest habitats and water ecosystem services distributed at a regional scale? (ii)

Do regional patterns of conservation-interest habitats and water ecosystem services supply overlap, and at what levels of service provision? (iii) Can we identify regional priority areas for intervention that can promote synergies between conservation and ecosystem services and between policies, based on habitats-ES regional overlap patterns and information on ecological linkages between vegetation types and ecosystem service supply?

Our approach focuses on a regional scale, specifically on a regional hydrographic level, an important level for technical decision-making on river planning and management. This allows to overcome recurrent issues of scale in river management, namely the scale mismatch between management actions, typically local, and the broader scale socio-ecological processes that determine the final management outcomes (Gurnell et al., 2015; Small, Munday, & Durance, 2017). We apply widely used models and freely available remote-sensing products to overcome common data limitations such as the uneven spatial distribution of data and the frequent lack of direct measurements.

We illustrate our framework across North Portugal - a transition zone between the Temperate-Atlantic and the Mediterranean climates, with two habitat types protected under the HD representing in-stream and riparian fluvial compartments (91E0* - *Alluvial Alnus forests* and 3260 - *Watercourses with Ranunculus vegetation*) and two key water ecosystem services ("Surface water for nutrition, materials or energy" and "Control of erosion rates").

The novelty of the study lies in the combination of river and riparian habitats and water ecosystem services modelling in the development of a multi-watershed, regional spatial planning approach to guide freshwater ecosystem management. This spatial planning approach promotes synergies between nature conservation and ecosystem services, and different policies, by incorporating linkages between ecosystem functions and ecosystem services supply in a straightforward methodological workflow with moderate data requirements.

2. Methods

2.1. Methodological Workflow

The methodological workflow developed here consists of three main steps: (i) assessment of the current distribution of habitat types and the potential supply of ecosystem services through spatially-explicit modelling; (ii) analysis of the spatial association between habitat types and ecosystem services; and (iii) identification and spatial planning of mutually beneficial landscape and river management interventions (Fig. 1). The workflow was designed to produce spatially explicit outputs at every step. The study area and the methods applied in each step are detailed in the following sections.

2.2. Study Area

The study area is the North Portugal hydrographic region, comprising three River Basin Districts (RBD's): the Minho and Lima RBD, the Cávado and Ave RBD, and the Douro RBD (Fig. 2) it encompasses 24 606.79 km^2 corresponding to 27.6% of mainland Portugal. The management of water bodies and water resources in this area is overseen by a single authority, the North River Basin District Administration, a regional department for water resources of the National Environment Agency ('Agência Portuguesa do Ambiente').

The study area is particularly suitable for our approach since it encompasses a broad climatic gradient that shapes river flows, biodiversity and vegetation, and a diverse array of interactions between people and nature. Due to the influence of the Atlantic Ocean and the barrier effect of mountain ranges, the study area encompasses a sharp west-east climatic gradient that spans the transition between Temperate-Atlantic and Mediterranean climates. In the river basins of the northwest, annual average temperatures are relatively low (12-13°C), especially in mountain areas (11°C), and annual average precipitation is high, over 1900 mm in the mountains and around 1200 mm in the lowlands (INAG, 2008). In the river basins of the Northeast, annual average temperatures are slightly higher (13°C) and annual average precipitation is substantially lower (and rainfall is more seasonal), with an average of 670 mm at medium-high elevations and 600 mm in lowlands (INAG, 2008).

Also, the study area hosts several species and communities of riparian and aquatic plants of high conservation-interest along with several habitat types protected under the European Union's HD (ICNF, 2013).

The environmental heterogeneity of the study area is also interconnected with human occupation and land cover/use patterns. The northwest is densely populated (104.4 – 843.1 inhabitants/km^2) and hosts a mosaic of urban, agricultural and forestry areas, whereas the northeast is mainly occupied (19.5 – 47.5 inhabitants/km^2) by forest, scrub, and rain-fed agriculture (Fig. 2e) (DGT, 2007; PORDATA, 2020).

2.3. Nature conservation

2.3.1. The target habitat types

To illustrate our approach, we selected two habitat types representing the riparian and in-stream fluvial compartments of river ecosystems, as proxies of river conservation value across the study area. Specifically, we selected the habitat types "91E0* - Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior*" and "3260 - Water courses of plain to montane levels with the *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation" protected by the HD Annex I (hereafter "*Alluvial Alnus forests*" and "*Watercourses with Ranunculus vegetation*", respectively). These habitat types were selected due to their regional and European relevance for conservation, current unfavourable conservation status, and ecological importance (European Environment Agency, 2014). Additionally, the *Alluvial Alnus forests* are considered a priority habitat type by the HD. In the study area, these habitat types are among those with the highest conservation value associated with rivers (Molina, 2017).

2.3.2. Habitat distribution modeling

The information available on the occurrence of the two habitat types in the study area suffers from restricted spatial coverage and coarse spatial resolution. Official datasets are restricted to Natura 2000 network sites, and the distribution of habitats outside these sites is largely unknown and their status is not monitored (ICNF, 2013). Besides, available datasets are too coarse (10 km resolution) or habitats with linear or point occurrence are underrepresented (ICNF, 2018).

To overcome these gaps, habitat suitability modelling (Guisan et al., 2017) was used to predict the potential distribution of the two habitat types in the study area. Habitat suitability models quantify the relationships between a biological entity (e.g. species, communities, ecosystems) and the environment to predict the geographical distribution of the biological entity (Guisan et al., 2017).

We collected three types of habitat occurrence data: (i) presence records of the habitat itself (i.e. reported as such); (ii) presence records of indicator phytosociological associations; and (iii) presence records of indicator species listed in the national factsheets for the HD (ALFA, 2004). Records were obtained from habitat monitoring projects, WFD surveillance campaigns, online databases, herbarium collections, and literature (see Supplementary Material 1). The occurrence dataset included 666 records for *Alluvial Alnus forests* and 606 records for *Watercourses with Ranunculus vegetation* (1 km spatial resolution). To decrease clustering and sampling biases in the records dataset, we applied a spatial thinning method with the package spThin (Aiello-Lammens, Boria, Radosavljevic, Vilela, & Anderson, 2014) in the R environment (R Core Team, 2018). The final dataset used for modelling included 200 records for *Alluvial Alnus forests* and 102 records for *Watercourses with Ranunculus vegetation* (Fig. 2 and Supplementary Material 1).

An initial list of 36 candidate environmental predictors was compiled based on a literature review and previous research on the target habitats in the study area (Lumbreras, Pardo, & Molina, 2013; Metzger et al., 2013). The final set of predictors was then selected based on ecological relevance, availability of continuous spatial information, and contribution to the overall environmental variation based on variable contribution from a Principal Components Analysis (Dormann et al., 2013). In addition, we assessed collinearity between variables through pairwise Pearson correlation and variance inflation factors (Supplementary Material 3). These procedures where used sequentially to select ecologically relevant variables while avoiding multicollinearity. The final predictor dataset included ten variables describing the climatic, topographic, hydrological, hydromorphological and land cover conditions of the study area (Table 1).

The distribution of each habitat type in the study area was modelled in the R environment with the “biomod2” package (Thuiller, Georges, & Engler, 2013). We used 10 techniques available in the package to model the distribution of the two habitat types (Guisan et al., 2017). Model evaluation was performed using a repeated (15 repetitions) random partition of the presence data into training (80%) and test (20%) data (Guisan et al., 2017). Model performance was assessed through the Area Under the Curve (AUC) of the Receiver Operator Characteristic (ROC) and the True Skill Statistic (TSS) (Guisan et al., 2017). Models with AUC values between 0.5 and 0.7 are considered “poor”, between 0.7 and 0.9 are considered “useful”, and above 0.9 are considered “good” (Guisan et al., 2017; Swets, 1988). Models with TSS values <0.4 were considered “poor”, between 0.4 and 0.75 “good” and >0.75 as “excellent” (Eskildsen et al., 2013; Landis & Koch, 1977).

The best performing models (included in the top 25th quantile) were combined using the average of their predictions weighted by their AUC scores to obtain an ensemble (consensus) forecast (Gonçalves, Honrado, Vicente, & Civantos, 2016). The resulting maps of environmental suitability for habitat occurrence were then converted into presence/absence predictions according to a threshold maximizing the AUC evaluation score (Guisan et al., 2017). Values below the threshold were transformed to zero since the habitat was considered absent, whereas for values above the threshold the habitat was considered present and the suitability values were kept and used for subsequent analyses. This procedure aimed to exclude from the spatial planning analysis areas where the habitat is more likely to be absent and therefore not as relevant in spatial analysis, while maintaining probabilistic data reflecting a continuous variability in environmental suitability and model uncertainty (Domisch et al., 2019; Tulloch et al., 2016).

2.4. Potential supply of water ecosystem services

We followed the Common International Classification of Ecosystem Services (CICES V5.1) (Haines-Young & Potschin, 2018) to facilitate a common understanding of the ecosystem services targeted. We selected two water ecosystem services (*sensu* Grizzetti et al. (2016)) with high relevance for human well-being and freshwater management to illustrate our approach: a provisioning service - “Surface water used for nutrition, materials or energy”; and a regulation service - “Control of erosion rates”.

The selection of ecosystem services does not intend to be exhaustive, but instead to illustrate the approach to river management proposed here with important services for authorithies and decision-making in the study area. We focused on the potential supply of the two ecosystem services, not on demand or actual usage since supply is more directly related with ecosystem functioning and integrity (Grizzetti et al., 2019) and can thus be improved through management interventions. “Surface water used for nutrition, materials or energy” (hereafter “Surface water”) includes all water available for drinking and non-drinking purposes (Haines-Young & Potschin, 2018). We considered only the quantity dimension of this service, i.e., the amount of water. The “Control of erosion rates” service consists of the reduction in soil loss rates due to the stabilizing effects of vegetation (Haines-Young & Potschin, 2018), therefore it corresponds to the amount of soil that is retained by vegetation.

The potential supply of “Surface water” was estimated using an indicator of annual average water quantity (water yield) obtained through a water balance equation. The amount of water available corresponds to the amount of precipitation not lost due to evapotranspiration, given the vegetation characteristics (Bosch & Hewlett, 1982; Carvalho-Santos et al., 2014) (see Supplementary Material 2). The potential supply of the “Control of erosion rates” service was estimated using the average annual amount of soil not eroded due to the effect of vegetation. To assess the contribution of the ecosystem to soil retention we applied the approach developed by Guerra, Pinto-Correia, and Metzger (2014), which builds on the Revised Universal Soil Loss Equation (RUSLE), widely used to calculate soil loss (Renard, Foster, Weesies, McCool, & Yoder, 1997). To compute soil retention by the ecosystem, this approach subtracts the actual soil loss from the structural impact, i.e., the erosion that would ensue if vegetation was absent (see Supplementary Material 2).

Information on the datasets used to compute both services is provided in Supplementary Material 2. The input datasets were resampled to 1km resolution to match the resolution of the habitat distribution maps. All calculations to obtain water quantity and soil retention estimates were performed in ArcMap 10.5 (ESRI, 2012).

2.5. Spatial association between habitat types and ecosystem services

The spatial association between the potential occurrence of the target habitat types and the ecosystem services potential supply was assessed through (i) spatial overlap, (ii) global Pearson correlation, and (iii) local Pearson correlation. We selected these metrics based on existing literature investigating ecosystem services bundles, synergies and trade-offs (Egoh, Reyers, Rouget, Bode, & Richardson, 2009), and more general literature on spatial analysis (Anselin, 1995).

The suitability for habitat occurrence and the units of ecosystem services supply were both normalized on a 0 to 1 scale for comparison. For the spatial association analyses, we only considered those pixels with suitability values above the threshold for habitat presence (see section 2.3). To assess the spatial overlap between the suitability for habitat occurrence and the ecosystem service potential supply, we reclassified each map into three categories - low, medium and high - using a tercile classification. The reclassification procedure allowed the identification of areas with high service provision and habitat suitability, helping the interpretation of overlap analysis (Egoh et al., 2009). The reclassified maps were then summed to assess the overlap of the three different classes and the results aggregated for interpretation as shown in Table 2. All the calculations were performed in ArcMap 10.5 (ESRI, 2012).

The global Pearson correlation coefficient between suitability for habitat occurrence and ecosystem service potential supply was calculated in the R environment with the “Hmisc” package (Harrell, 2018). Since the global Pearson correlation does not reflect fine-scale spatial patterns, we also performed a local Pearson correlation using the function “corLocal” available in the R package “raster” (Hijmans, 2014). We tested the effect of neighbourhood size by performing correlations for three neighbourhood sizes (3, 5 and 9 neighbouring cells).

2.6. Spatial planning of river protection and restoration

We considered two management actions that could promote mutually beneficial outcomes for the habitat types and ecosystem services: river protection and river restoration. River protection measures can ensure the simultaneous protection of key biodiversity features and the sustained supply of ecosystem services through the designation of protected areas and the implementation of conservation-oriented management (Abell et al., 2019). Therefore, to identify areas for river protection we selected locations where high suitability for habitat occurrence coincides with a high potential supply of one or both ecosystem services.

River restoration can improve the status of habitats and improve ecosystem service supply through interventions aimed at shifting a degraded river ecosystem towards a natural reference state, restoring degraded habitats alongside with ecosystem functions and processes (Palmer et al., 2005). To illustrate this, we focused on the “Control of erosion rates” service, since riparian and aquatic vegetation has a significant role in sediment retention and weathering prevention, and can retain sediment from surface runoff (Feld et al., 2018; Jones, Collins, Naden, & Sear, 2012). The ‘Surface Water’ supply service was not considered in this analysis because it is largely dependent on broader landscape factors (Carvalho-Santos et al., 2014). To identify areas for river restoration we selected locations that exhibit high suitability for habitat occurrence, but with no confirmed presence records in our dataset, with low values of service supply. The two habitat types were considered separately since they require different river restoration measures.

To further illustrate the connections of different policy objectives in this analytical approach we prioritized potential sites for protection and restoration according to the WFD protection and ecological status, respectively. Potential protection sites were prioritized if they overlapped with subbasins designated for the protection of drinking water, shellfish and economically significant freshwater species. Potential restoration sites were prioritized if they coincided with subbasins with less than good (bad to moderate) ecological status. In addition, to assses the degree of feasibility of protection and restoration interventions we calculated the dominant land cover in each subbasin.

3. Results

3.1. Potential distribution of habitat types

Models generated for the two habitat types performed well, with average AUC values across algorithms, ranging between 0.74 and 0.82 for *Alluvial Alnus forests* and between 0.67 and 0.83

for *Watercourses with Ranunculus vegetation* (Supplementary Material 3). Average TSS values across algorithms ranged between 0.47 and 0.57 for *Alluvial Alnus forests* and between 0.35 and 0.6 for *Watercourses with Ranunculus vegetation* (Supplementary Material 3). The final ensemble models for *Alluvial Alnus forests* obtained a AUC value of 0.87 and a TSS value of 0.6, while the models for *Watercourses with Ranunculus vegetation* obtained a AUC value of 0.90 and a TSS value of 0.6 (Supplementary Material 3). For both habitats, the most important predictor was the watercourse density weighted by Strahler's order ("hierarchical line density"; see Supplementary Material 3), followed by bioclimatic variables. Topographical and hydromorphological variables attained lower importance scores.

The two habitats showed different responses to common environmental predictors, resulting in distinct distributions (Fig. 3). The *Alluvial Alnus forests* habitat is predicted to occur mainly in medium to high order streams and rivers, however, there is a clear difference between the northwest and the northeast, shaped by differences in annual precipitation and seasonality (Fig. 3a). The *Watercourses with Ranunculus vegetation* habitat is predicted to occur in low to medium order streams and rivers (usually Strahler order lower than 3), especially in the northeast portion of the territory (Fig. 3b).

3.2. Potential supply of ecosystem services

For the "Surface water" service, our estimates of average annual water quantity ranged from 81.42 mm/yr to 1171.67 mm/yr. The highest water quantity values were generally found in the northwest (Fig. 4a), especially in mountain areas (>1000 mm), where high precipitation generates high water yields despite the high evapotranspiration in some areas. The lowest values of water quantity were found in river valleys of the northeast, where low precipitation coincides with warm temperatures.

For the "Control of erosion rates" service, our estimates range between 0.24 ton/ha/yr and 2654.27 ton/ha/yr of soil retained by vegetation (Fig. 4b) and we did not observe a clear regional pattern. High soil retention values (>200 ton/ha/yr) were found in forest, scrub and grassland vegetation cover types throughout the study area. Low soil retention values were mainly found in areas with sparse vegetation or dryland annual crops.

3.3. Spatial association between habitat types and ecosystem services

High values of suitability for habitat occurrence overlapped with high potential of ecosystem service supply in mountain areas and along some of the larger rivers of the study area (Fig. 5). The high potential supply of surface water coincided with high suitability for both habitat types in mountain areas, whereas low values of supply and suitability coincided with the larger rivers of the northeast (Fig. 5). Regarding soil retention, high values generally coincided with high suitability for both habitat types in mountain areas and larger rivers of the northeast (Fig. 5).

The global Pearson correlation coefficients between potential habitat presence and the supply of ecosystem services were very low for all combinations (Supplementary Material 4). The local correlation analysis revealed large spatial variations while generally supporting the patterns identified in the overlap analysis (Supplementary Material 4).

3.4. Spatial prioritization of river protection and restoration

The potential locations for protection of river habitat types and ecosystem services supply are concentrated in mountain areas and major river valleys, generally coinciding with legally protected areas (including national protected areas, Natura 2000 and Ramsar sites) (Fig. 6a). Conversely, most of the potential locations where restoration should be prioritized are found outside protected areas (Fig. 5b and c). Potential locations where restoration could improve the supply of soil retention services and the *Alluvial Alnus forests* were mainly found in the northwest (Fig. 6b), while, in contrast, for the *Watercourses with Ranunculus* vegetation were mostly found in the northeast (Fig. 6c).

The potential locations for protection coincided with 1286 subbasins protected under the WFD most of them dominated by open forests (40.67%) and agriculture (27.76%). The potential locations for restoration of *Alluvial Alnus forests* coincided with 1119 subbasins with less than good ecological status most of them dominated by agriculture (38.96%) and the restoration of *Watercourses with Ranunculus* coincided with 554 subbasins most of them dominated by open forests (39.17%) and agriculture (39.89%) (Fig. 6).

4. Discussion

4.1. Spatial planning of river management interventions

The analytical approach described here allows the identification of win-win management solutions by combining conservation value and ecosystem services supply in a spatially-explicit workflow. The regional scale of the approach can help maximize the probability of success, cost-effectiveness and complementarity of management actions (Green et al., 2015; Palmer et al., 2005) by providing an instrument to develop a frame of reference for coordinated action.

This analytical approach provides an instrument to support the integration of different policies in the spatial planning process, particularly the EU HD and the WFD, but also the European Biodiversity Strategy and the Blueprint to Safeguard Europe's Water Resources (Voulvoulis, Arpon, & Giakoumis, 2017). In addition, the approach contributes to key areas identified by the European Environment Agency as promising for the improvement of the implementation of the WFD and supporting the achievement of its goals which include the protection of aquatic systems and their services and the restoration of degraded water systems (European Environment Agency, 2018). The two directives have different objectives and monitoring targets however, they are coherent as they aim to protect and enhance aquatic ecosystems by protecting species and habitats and the sustainable use of water resources. Their integration has been advocated namely through harmonized monitoring and planning of integrative programmes of measures within the WFD's river basin management plans (European Commission, 2011). Moreover, our analytical approach can also contribute to the articulation with EU's Green Infrastructure Strategy, which includes the HD and the Natura 2000 network as a fundamental backbone, as well as rivers and floodplains as key elements (European Union, 2011). Overall, the identification of areas for protection and restoration through this combination of modelling and spatial analyses can support the planning of blue-green infrastructure networks at the river basin and regional scales.

The inherent simplicity and moderate data requirements of the proposed workflow facilitate its scale up and the application to other socio-environmental contexts, supporting spatial planning and management at regional and national levels. However, in our illustration we have included a small set of key habitats and services, which would need to be expanded upon in 'real-world' applications by including other protected habitats (e.g. Habitats 91B0 and 3280) and other services (e.g. regulation of the chemical condition of freshwaters) relevant in the study area. Habitat modelling is often constrained by the quality, accessibility and up-to-dateness of distribution data. Most studies on water ecosystem services quantify three or fewer services and only some simultaneously quantify biodiversity and ecosystem services (Durance et al., 2016; Funk et al., 2019; Hanna, Tomscha, Dallaire, & Bennett, 2018). Multiple ecosystem service assessments can be time-consuming, require high expertise and therefore often involve trade-offs in service selection (Bagstad, Semmens, Waage, & Winthrop, 2013). In addition, difficulties in data acquisition and robustly modelling services of different nature often hinder the inclusion of a large number of services (Hanna et al., 2018; Langhans et al., 2019). Recent studies, focused on the issue of integrated spatial planning in freshwaters through the framework of ecosystem-based management, have described similar difficulties for researchers as well as planners (Domisch et al., 2019; Funk et al., 2019; Langhans et al., 2019). Considering those difficulties and additional constraints such as availability of human and financial resources in regional and local authorities, the selection of biodiversity and ecosystem services features has to be adapted in most cases, to carefully select key habitats and services for the area considering the freshwater systems and management objectives (Langhans et al., 2019). We aimed to reflect this in our choices of habitats and ecosystem services, by choosing priority habitats that occupy different fluvial niches with local and EU level relevance, and by choosing ecosystem services that are important for the management authorities.

Similar studies on integrated spatial planning for freshwaters have mostly privileged fishes, amphibians and water birds as biodiversity surrogates (Domisch et al., 2019; Funk et al., 2019) overlooking the structural role of river and riparian vegetation in ecosystem functioning and the supply of several water ecosystem services as well as in providing habitat for several of those taxonomic groups (Feld et al., 2018; Riis et al., 2020).

4.2. River habitats and ecosystem services in the study area

The broad regional patterns found here for the *Alluvial Alnus forests* are in line with previous modelling exercises for this habitat type (Metzger et al., 2013; Monteiro-Henriques, González, & Albuquerque, 2014). Model predictions for the *Watercourses with Ranunculus vegetation* are also in line with previous studies reporting a transitional Atlantic-Mediterranean character for some plant assemblages that characterize this habitat (Molina, 2017) as well as an affinity of its indicator species with higher summer aridity (Lumbreras et al., 2013). The habitat models could be further improved with data on water quantity and quality variables and some authors have used hydrological variables estimated by hydrological models to improve habitat distribution models (Kuemmerlen et al., 2014). However, the application of hydrological models is very difficult in our region that encompasses four large river basins, three of which starting in Spain, making calibration process unfeasible due to the lack of a robust time series for discharge and other variables. The lack of wide-range hydrologic data along with the low quality of monitoring time-series hinder the inclusion of these key predictors in habitat models applied to freshwater ecosystems (Domisch, Jähnig, Simaika, Kuemmerlen, & Stoll, 2015).

Moreover, our knowledge on the distribution of habitats, particularly riparian habitats, could be improved in the future through the use of remote sensing techniques to effectively map habitats (Huylenbroeck et al., 2020).

As reported in previous studies (Carvalho-Santos et al., 2014) mountain areas are key for the supply of surface water in the study area at the regional scale, due to their role in capturing precipitation. The soil retention service is mainly shaped by vegetation and land cover, and to a lesser extent by the amount of structural impact, an effect previously reported (Burkhard & Maes, 2017).

4.3. Spatial association between habitat types and ecosystem services

The agreement between the target habitat types and ecosystem services in mountains is the result of their climatic, topographic, hydrologic and ecological conditions. Mountain areas combine high precipitation that translates into a high supply of surface water with legal protection for nature conservation, as well as the socio-environmental conditions (climate, topography, land use) that allow for the occurrence of riparian vegetation as well as in-stream *Ranunculus* vegetation. The high agreement between the target habitats and the “Control of erosion rates” service was found along medium-large rivers of the study area. This is mainly related to the persistence of riparian forests with high sediment retention capacity (Feld et al., 2018) along these watercourses where there is a high probability of occurrence of Alluvial Alnus forests.

We found a fine-scale variation in the agreement between suitability for habitat occurrence and ecosystem service supply, especially when considering the different habitat-service combinations (Fig.5). This may be related with the different spatial configuration of habitats and ecosystem services, the former presenting a linear pattern along with the river network, whereas the latter is influenced by landscape processes and therefore continuous throughout (Carvalho-Santos et al., 2014). These differences may also explain the low global correlation values. Other studies also found variations in the degree of overlap between biodiversity and ecosystem services hotspots depending on the taxonomic group and ecosystem service considered and their spatial patterns at different scales (Carvalho-Santos, Sousa-Silva, Gonçalves, & Honrado, 2015; Egoh et al., 2009).

4.4. Implications for regional planning and river management

Our approach identified the protection of mountain areas combined with the restoration of riparian and stream habitats as key features for devising a regional strategy that would maximize the benefits from river management actions.

The benefits obtained from the protection of mountain areas are not limited to water ecosystem services and the habitats studied here. Mountain areas are also key areas for the supply of other ecosystem services, such as carbon sequestration, water flow regulation, fodder production, reared animals, symbolic or bequest value plants and animals and outdoor recreation (Grêt-Regamey, Brunner, & Kienast, 2012; Schirpke et al., 2019). They also harbour headwater streams with high conservation value, due to the presence of unique species and habitats, as well as overall high biodiversity levels (Biggs, von Fumetti, & Kelly-Quinn, 2017). Headwater streams are also crucial at a regional scale since they comprise the majority of river networks receiving a large proportion of river discharge contributing to ecosystem integrity by delivering sediments and organic material downstream that support secondary productivity, providing spawning habitats and contributing significantly to the river network taxonomic diversity (Biggs et al., 2017; Colvin et al., 2019; Freeman, Pringle, & Jackson, 2007). However, the WFD's Common Implementation Guidelines limited the inclusion of smaller water bodies (< 10 km^2 catchment area), therefore headwaters and small streams are generally not considered under the WFD's environmental objectives, monitoring and reporting obligations and overlooked in River Basin Management Plans (Baattrup-Pedersen et al., 2018; Flávio, Ferreira, Formigo, & Svendsen, 2017; Lassaletta, García-Gómez, Gimeno, & Rovira, 2010). Results from our spatial analyses and the studies cited above support the view that mountain areas and respective headwaters should be targeted for protection under river basin management plans (Chan, Shaw, Cameron, Underwood, & Daily, 2006; Harrison et al., 2016).

Our results also suggest that existing riparian forests along medium-large rivers, including EU priority habitats for conservation, can also play an important role in regional river management by contributing to the “Control of erosion rates” ecosystem service. They can also deliver other benefits for biodiversity conservation, by providing habitat and connectivity corridors (de la Fuente et al., 2018), linking protected areas (e.g. Natura 2000) and enabling species to follow future climatic shifts (Krosby, Theobald, Norheim, & McRae, 2018). The restoration of watercourses and riparian areas has proven to deliver multiple benefits, with studies reporting an improvement of ecosystem services supply and biodiversity (Dybala, Matzek, Gardali, & Seavy, 2019; Gerner et al., 2018).

We identified potential locations for the restoration of the *Alluvial Alnus forests* in the northwest of our study area, where suitability for habitat occurrence is high but riparian forests are often eliminated or reduced to a single line of trees due to the conversion into agricultural or urban areas (Amigo, Rodríguez-Guitián, Honrado, & Alves, 2017). Promoting the recovery of riparian habitats outside protected areas would improve the supply of the soil retention service in agricultural areas through sediment filtration in the riparian buffer and stabilization of soil in river banks, potentially improving the ecological status of the water bodies through decreases in suspended sediment loads and improved hydromorphological conditions in river banks (Feld et al., 2018). Nevertheless, the effectiveness of riparian buffers depends on longitudinal location. Riparian buffers cannot mitigate sediment pollution from upstream locations, therefore they must cover the entire segment subjected to lateral diffuse sediment inputs (Feld et al., 2018). *Ranunculus* vegetation can promote soil retention through an increased accumulation of fine sediments, nevertheless the rate of accumulation changes with seasonal variations in macrophyte biomass (Jones et al., 2012).

River protection and restoration face some challenges, particularly outside protected areas. River restoration in urban areas is usually difficult and expensive due to the presence of infrastructure such as buildings and roads, a highly fractioned pattern of ownership and high property values (Bernhardt & Palmer, 2007). In rural areas dominated by agriculture, open and production forests restoration interventions such as riparian buffer strips typically represent a decrease in profit for farmers and landowners. As a consequence, similar studies have even excluded these areas from restoration prioritization (Funk et al., 2019). However, river restoration in agricultural areas can be particularly useful in improving the status of rivers and habitats by mitigating the physical and chemical impacts of agricultural activities in freshwaters. In this context, stakeholder engagement is critical to develop tailored solutions that minimize costs and provide financial incentives to farmers through subsidies or payments for ecosystem services schemes (Flávio et al., 2017; Sone et al., 2019).

Our analytical approach supports the development of integrative spatial planning at a multi-catchment regional scale, providing a regional frame of reference for harnessing potential synergies between conservation and ecosystem services and between policies. This initial effort must then be downscaled to the relevant river basins and river segments where more detailed field based information such as fine-scale habitat mapping and status assessment, as well as local stakeholder engagement are required to develop detailed conservation, restoration and management plans (Gurnell et al., 2015).

5. Conclusion

Our analysis reinforces the importance of the protection mountain areas together with the protection and restoration of riparian forests to preserve and improve the status of protected habitats (and the biodiversity therein), and the supply of ecosystem services at regional scales. Overall, our approach offers an adaptable instrument to support integrated regional planning and coordinated action among different directives and strategies by promoting synergies between ecosystem services and nature conservation in river planning and management. The regional scale allows the development of a frame of reference to balance nature conservation and ecosystem service supply and coordination between policies, that must then be operationalized in detailed conservation, restoration and management plans that incorporate fine-scale information and stakeholder engagement.

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6. List of Tables

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Table 1. Environmental predictors selected for modelling the potential distribution of each of the habitat types (91E0* - Alluvial Alnus forests and 3260 - Watercourses with Ranunculus vegetation) and respective sources.

Category	Environmental factor	Variable	Source	Habitat 91E0*	Habitat 3260
Climatic	Mean Temperature	BIO1 - Annual Mean Temperature	Fonseca and Santos (2018)	X	X
	Annual Precipitation	BIO12 - Annual Precipitation	Fonseca and Santos (2018)	X	X
	Summer aridity	BIO15 - Precipitation Seasonality	Fonseca and Santos (2018)	X	X
Topographic	Slope	Mean Slope	Calculated in ArcMap 10.5 (ESRI, 2012) from EU-DEM (European Environment Agency, 2016)	X	X
	Terrain ruggedness	Topographic Roughness Index	Calculated in SAGA-GIS (Conrad et al., 2015) from EU-DEM (European Environment Agency, 2016)	X	X
	Valley bottom position	Multi-Resolution Valley Bottom Flatness	Calculated in SAGA-GIS (Gallant and Dowling, 2003) from EU-DEM (European Environment Agency, 2016)	X	
Hydrogeomorphological	Stream slope	Downslope gradient	Calculated in SAGA-GIS from EU-DEM (Hjerdt et al., 2004)		X
Hydrologic	Water permanence and quantity	Flow accumulation	Calculated in ArcMap 10.5 (ESRI, 2012) from the EU-DEM (European Environment Agency, 2016)	X	X
		Hierarchical line density weighted by Strahler's order	Calculated in ArcMap 10.5 (ESRI, 2012) using a hydrological network derived from the EU-DEM (European Environment Agency, 2016) with ArcHydro 2.0 (Maidment and Morehouse, 2002)	X	X
Land cover	Water nutrient levels	Percentage of agriculture	Calculated in ArcMap 10.5 (ESRI, 2012) from the national Land cover database (Direcção-Geral do Território, 2007)		X

Table 2. Framework for the aggregation of the results of the spatial overlap analysis.

		Suitability for Habitat occurrence		
		Low	Medium	High
Ecosystem service potential supply	Low	↓↓ Agreement - Low	↓→ Partial Agreement - Medium Low	↓↑ Disagreement – High Habitat
	Medium	↓→ Partial Agreement - Medium Low	→→ Agreement - Medium	↑→ Partial Agreement - Medium High
	High	↓↑ Disagreement – High ES	↑→ Partial Agreement - Medium High	↑↑ Agreement - High

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9. Figures

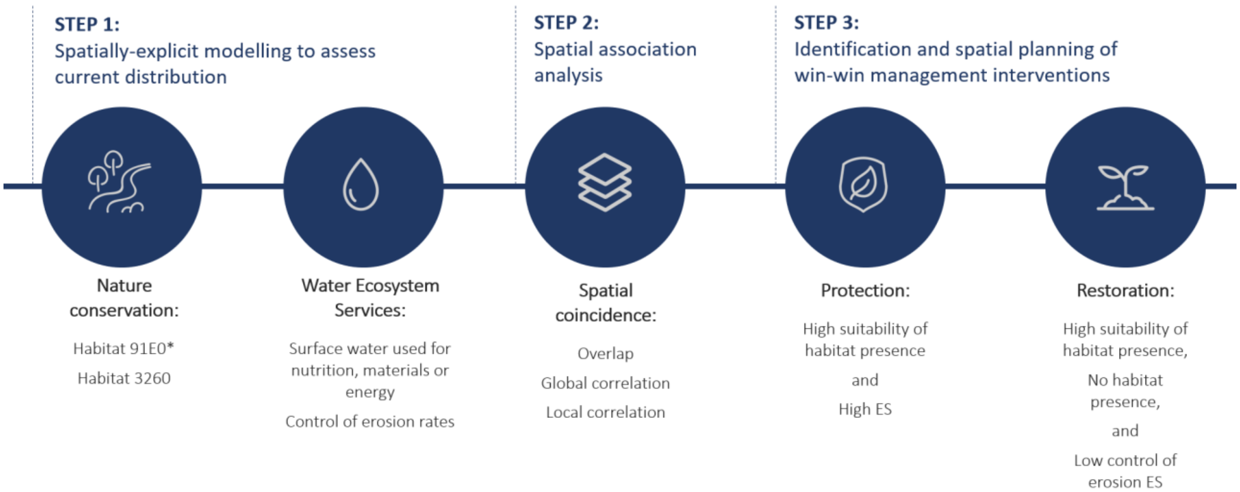

Fig.1. Workflow sequence used to assess the spatial association between conservation value and ecosystem services supply to identify and develop spatial plans for management actions. Icons from the "The Noun Project".

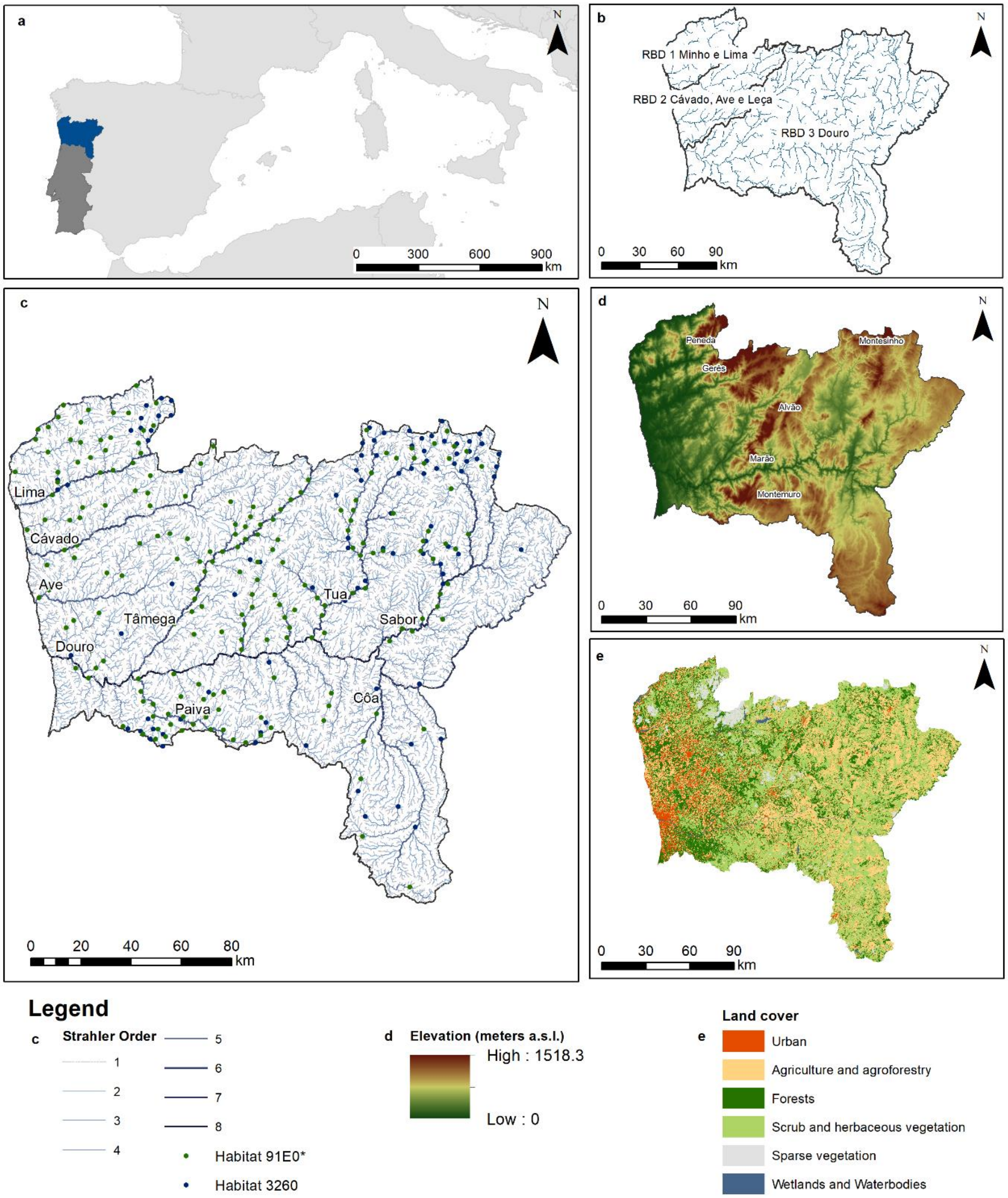

Fig.2. Geographical context of the study area (highlighted in blue) in Europe (a). Administrative division of the study area according to the Water Framework Directive River Basin Districts (RBD) (b). The hydrographic network of the study area (c) with rivers symbolized by Strahler's Order, and the filtered records (see Section 2.3) of the habitat types 91E0* - *Alluvial Alnus forests* and 3260 - *Watercourses with Ranunculus vegetation*. Elevation (in meters a.s.l) and major land cover types are presented in (d) and (e), respectively.

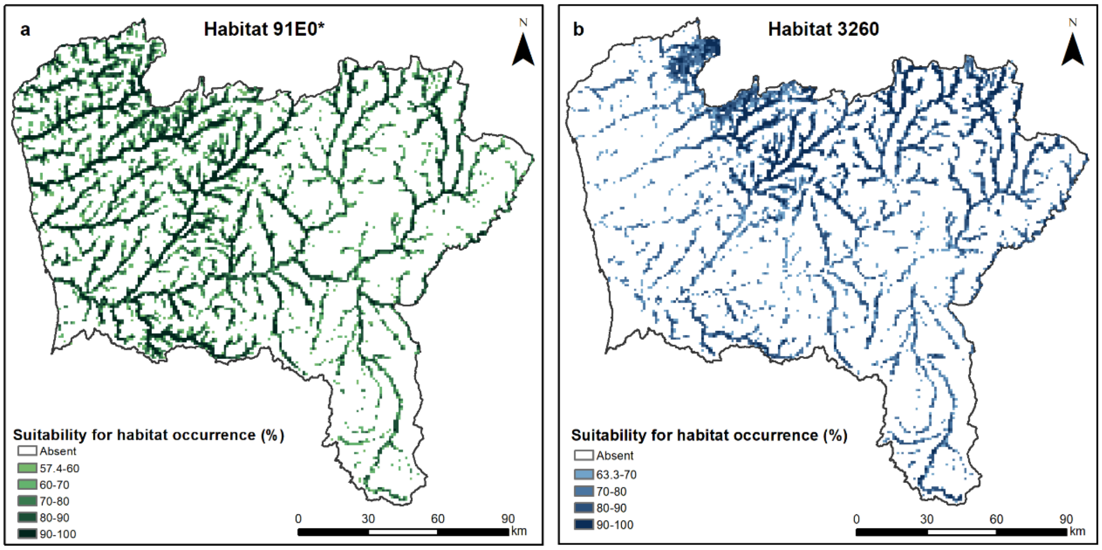

Fig. 3. Suitability for habitat occurrence for habitat types 91E0* - *Alluvial Alnus forests* (a) and 3260 - *Watercourses with Ranunculus vegetation* (b), expressed in percentage (above the binarization threshold). The hydrographic network is shown in the background for context.

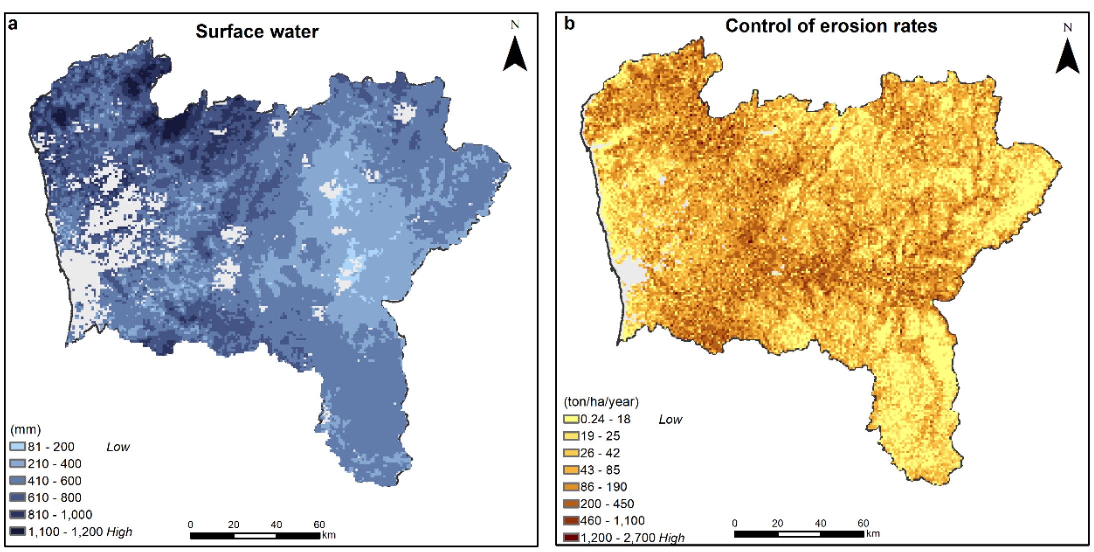

Fig. 4 Potential supply of ecosystem services in the study area: "Surface water used for nutrition, materials or energy" (a), and "Control of erosion rates" (b).

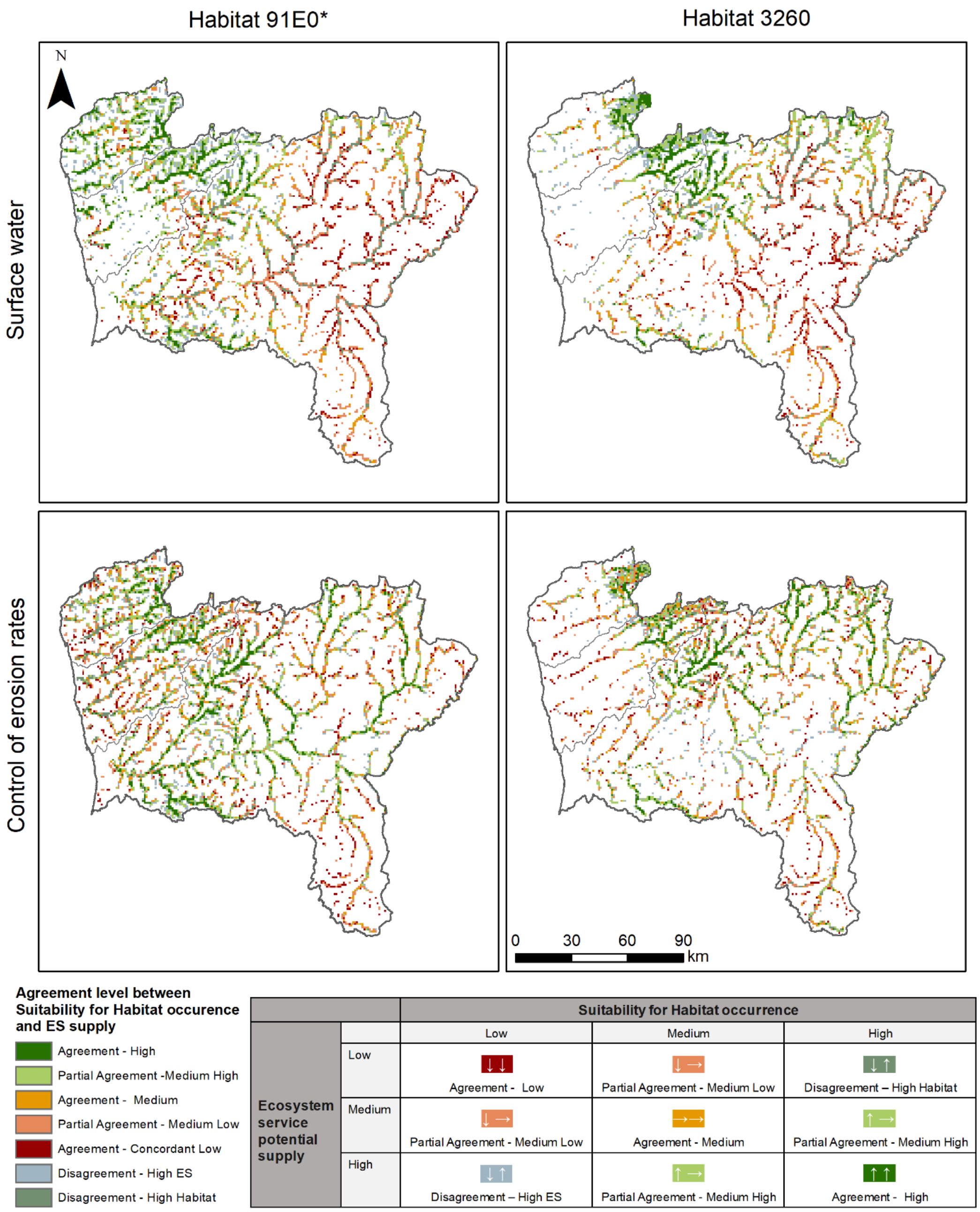

Fig. 5. Spatial agreement between the suitability for habitat occurrence and the supply of ecosystem services. We considered areas of agreement all the locations where both elements are in the same category (e.g. high habitat probability of presence and high ecosystem service supply). Conversely, all areas where the elements are in opposing categories are areas of disagreement (e.g. high habitat probability of presence and low ecosystem service supply). The level of agreement was further described using the following category levels: low, medium, high, to indicate the level of the habitat’s probability of presence and ecosystem service potential supply.

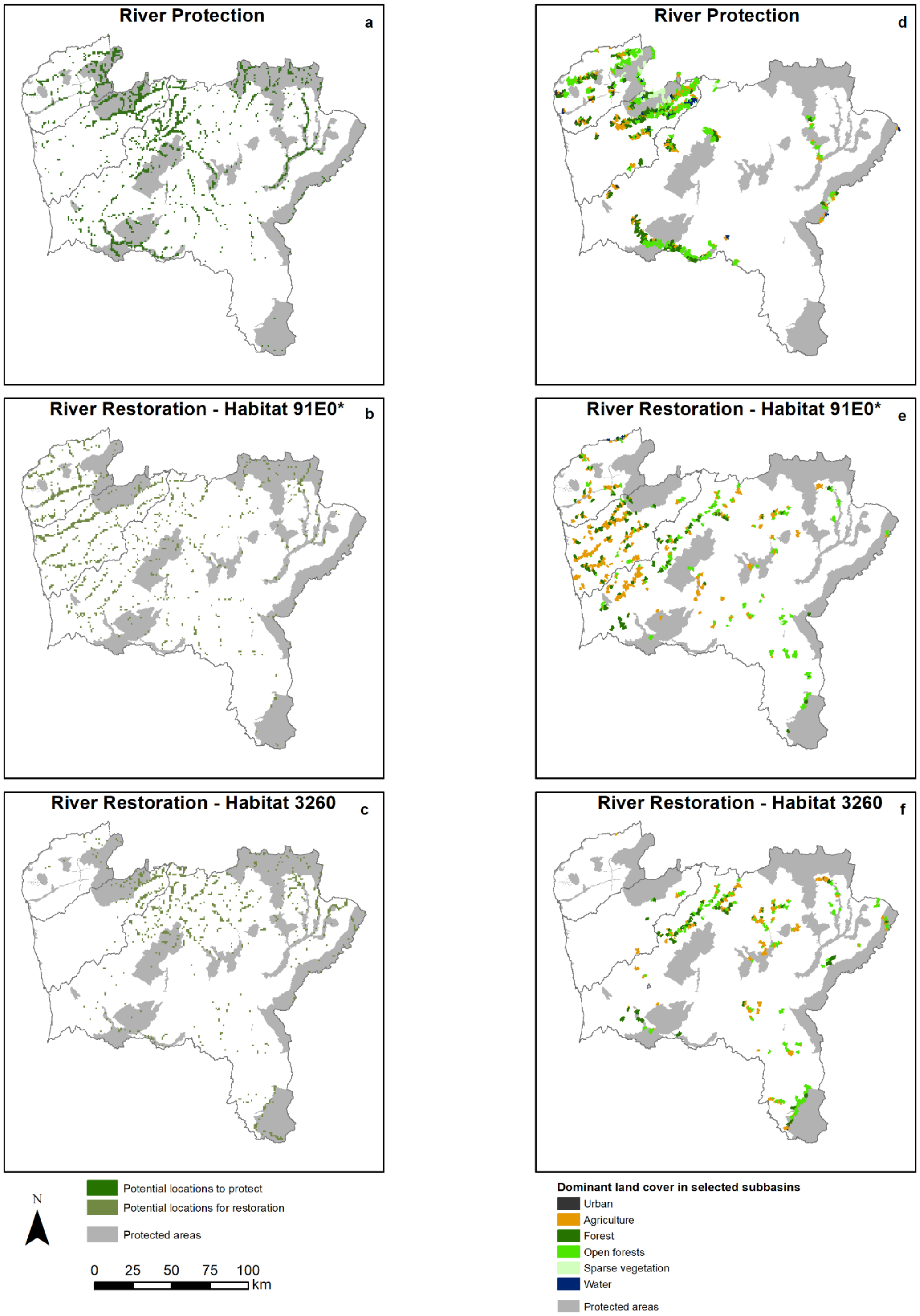

Fig. 6. Potential locations for protection (a) and restoration (b,c) of habitat types and ecosystem services on the left and subbasins prioritized for protection (d) and restoration (e,f) on the right, all shown over the national network of protected areas, Natura 2000 and Ramsar sites in the study area. Potential locations for protection of both the habitat

types and ecosystem services in the study area are shown in (a) and potential locations for river restoration targeting the habitats 91E0* - *Alluvial Alnus forests* or the habitat 3260 - *Watercourses with Ranunculus vegetation* and improving the “Control of erosion rates” service are shown in (b) and (c) respectively. Subbasins prioritized for protection coincide with areas designated for the protection of drinking water, shellfish and economically significant freshwater species under the WFD (d). Subbasins prioritized for restoration coincide with waterbodies with less than good ecological status (e,f). Prioritized subbasins are symbolized by dominant land cover.

CRediT author statement

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