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

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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, biodiversity and ecological functions 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 are considered to hold "Unfavourable" conservation status, and 60% of water bodies are not in "Good" ecological status (IPBES, 2018).

The Water Framework Directive (2000/60/EC (European Parliament, 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, in articulation with other directives including the Habitats Directive (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, such as River Basin 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 develop a spatially-explicit approach to address the current needs for integrated planning and management of river ecosystems. We do this by combining nature conservation and ecosystem service supply in a joint assessment and regional management plan. 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 assess the spatial association (coincidence or mismatch) between conservation-interest features and ecosystem service supply to identify win-win management actions and develop regional management plans.

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 Habitats Directive 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"). We identify areas where river protection or restoration actions could contribute to meet habitat conservation goals and to promote ecosystem service supply at a regional scale. Finally, we also discuss the added-value and potential difficulties of applying our approach in different socio-environmental settings.

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 around 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 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 Habitats Directive (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 Habitats Directive 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 Habitats Directive. 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 Habitats Directive (ALFA, 2004). Records were obtained from habitat monitoring projects, Water Framework Directive 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 Principal Components Analysis as well as by checking multicollinearity between variables through pairwise Pearson correlation with package “raster” (Hijmans, 2014) and variance inflation factors with package “usdm” (Naimi, 2017). The final predictor dataset included 12 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) (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).

The best performing models (included in the top 25^{th} 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.

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. 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 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). Overall, the larger neighbourhood sizes were found to smooth local variation excessively, and therefore they are only presented in Supplementary Material 4.

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.

3. Results

3.1. Potential distribution of habitat types

Models generated for the two habitat types achieved good performance, with average AUC values across *biomod2* algorithms ranging between 0.74 and 0.82 for *Alluvial Alnus forests* and between 0.68 and 0.82 for *Watercourses with Ranunculus vegetation*. The final ensemble models obtained AUC values of 0.87 for *Alluvial Alnus forests* and 0.90 for *Watercourses with Ranunculus vegetation*. For both habitats, the most important predictor was the watercourse density weighted by Strahler's order ("hierarchical line density"; see Supplementary Material 2), followed by precipitation variables (total annual and during the driest quarter) and elevation. Topographical and hydromorphological variables attained lower importance scores.

The two habitats showed different responses to the same 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, and only the correlations with the soil retention service were significant (Supplementary Material 4). The local correlation analysis revealed large spatial variations while generally supporting the patterns identified in the overlap analysis, particularly for the soil retention service (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 (69.12%) (Fig. 5b and c). Potential locations where restoration could improve the supply of soil retention services and the *Alluvial Alnus forests* were found mainly in the northwest (Fig. 6b), while, in contrast, for the *Watercourses with Ranunculus* vegetation were mostly found in the northeast (Fig. 6c).

4. Discussion

4.1. Spatial planning of river management interventions

The 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). The inherent simplicity and moderate data requirements of the proposed workflow will enable the application of the approach in other socio-environmental contexts, supporting spatial planning and management at regional and national levels. Moreover, it can also foster the further implementation of the integrated view on water management advocated by the Water Framework Directive (Voulvoulis, Arpon, & Giakoumis, 2017), by promoting a clear linkage with to the European Habitats Directive conservation goals.

In a broader context, the identification of areas for protection and restoration through this combination of modelling and spatial analyses can support the design and development of blue-green infrastructure networks at the river basin and regional scales. Our approach can also contribute to the implementation of the EU's Green Infrastructure Strategy, namely concerning the goals of halting biodiversity loss and enabling the supply of ecosystem services, using the Habitats Directive and the Natura 2000 network as a fundamental backbone (European Union, 2011).

Further studies and applications of the approach considering more ecosystem services (e.g., water quality regulation, leisure and tourism) and conservation elements (other habitat types, species of conservation concern) in different socio-environmental settings, will provide further evidence of its general applicability and establish guidelines to overcome its limitations. However, 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). Few studies on water ecosystem services have quantified simultaneously biodiversity and ecosystem services or assessed interactions between services (Durance et al., 2016; Hanna, Tomscha, Dallaire, & Bennett, 2018).

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). Models could be further improved with data on water quantity and quality variables. However, this information is not available for the study area in a spatially-explicit format, as is frequently the case for freshwater ecosystems (Domisch, Jahnig, Simaika, Kuemmerlen, & Stoll, 2015).

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 (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 contribute to ecosystem integrity and a large proportion of the river discharge (Biggs et al., 2017).

Nevertheless, headwaters and small streams are generally not considered under Water Framework Directive monitoring and reporting obligations (Baattrup-Pedersen et al., 2018). 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). In a European context, this would enable exploring the links between the Habitats Directive and the Water Framework Directive to prioritize win-win management options.

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, thereby improving the ecological status of the water bodies. 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).

As shown by the examples above, our framework can provide a robust basis for the development of regional or RBD level plans for river restoration, however, this initial spatial planning framework must then be complemented by watershed-scale information on pressures, field assessments, cost-benefit analyses and public engagement (Palmer et al., 2005).

5. Conclusion

This study illustrates the opportunities that can arise when ecosystem services and nature conservation are both considered in river management decision-support systems. The protection of mountain areas together with the protection and restoration of riparian and in-stream habitats simultaneously promotes the conservation of protected habitats (and the biodiversity therein), the improvement of ecological status, and the supply of multiple ecosystem services. Our results thus show that ecosystem services assessment can provide additional arguments to promote protection or restoration measures to meet the goals of both the Habitats Directive and the Water Framework Directive. Nevertheless, the development of such management strategies must consider basin-scale patterns, processes and stressors in a fully integrated spatial planning framework. We found that a combination of standard models for protected habitats and ecosystem services, together with spatial analyses, allows the identification of win-win management solutions, based on limited data, a common constraint when developing integrated river management plans. Moving forward, similar approaches could benefit the development of river basin and regional river restoration plans and the creation of blue-green infrastructure networks.

6. References

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7. List of Tables

8. Tables

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
	Summer Temperature	BIO9 - Mean Temperature of Driest Quarter	Fonseca and Santos (2018)	X	X
	Annual precipitation	BIO12 - Annual Precipitation	Fonseca and Santos (2018)	X	X
	Summer aridity	BIO17 - Precipitation of Driest Quarter	Fonseca and Santos (2018)	X	X
Topographic	Altitude	Mean Elevation	Europe Digital Elevation Model (EU-DEM) (European Environment Agency, 2016)	X	X
	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	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	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

9. List of Figures

10. Figures

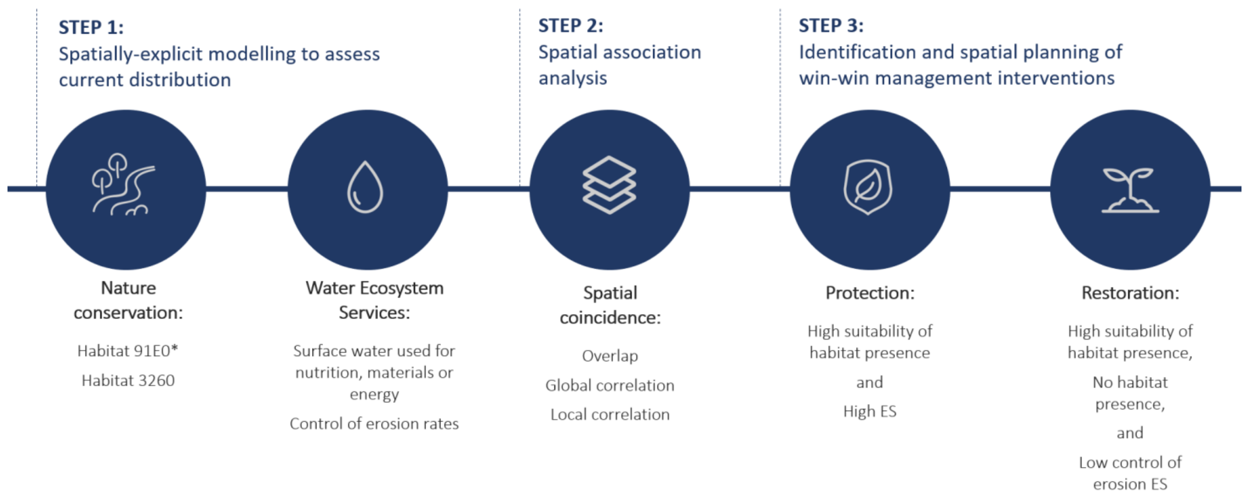


Fig.1. Workflow sequence used to assess the spatial association between conservation value and ecosystem services supply to identify and develop spatial plans for management actions. Icons from the "The Noun Project".

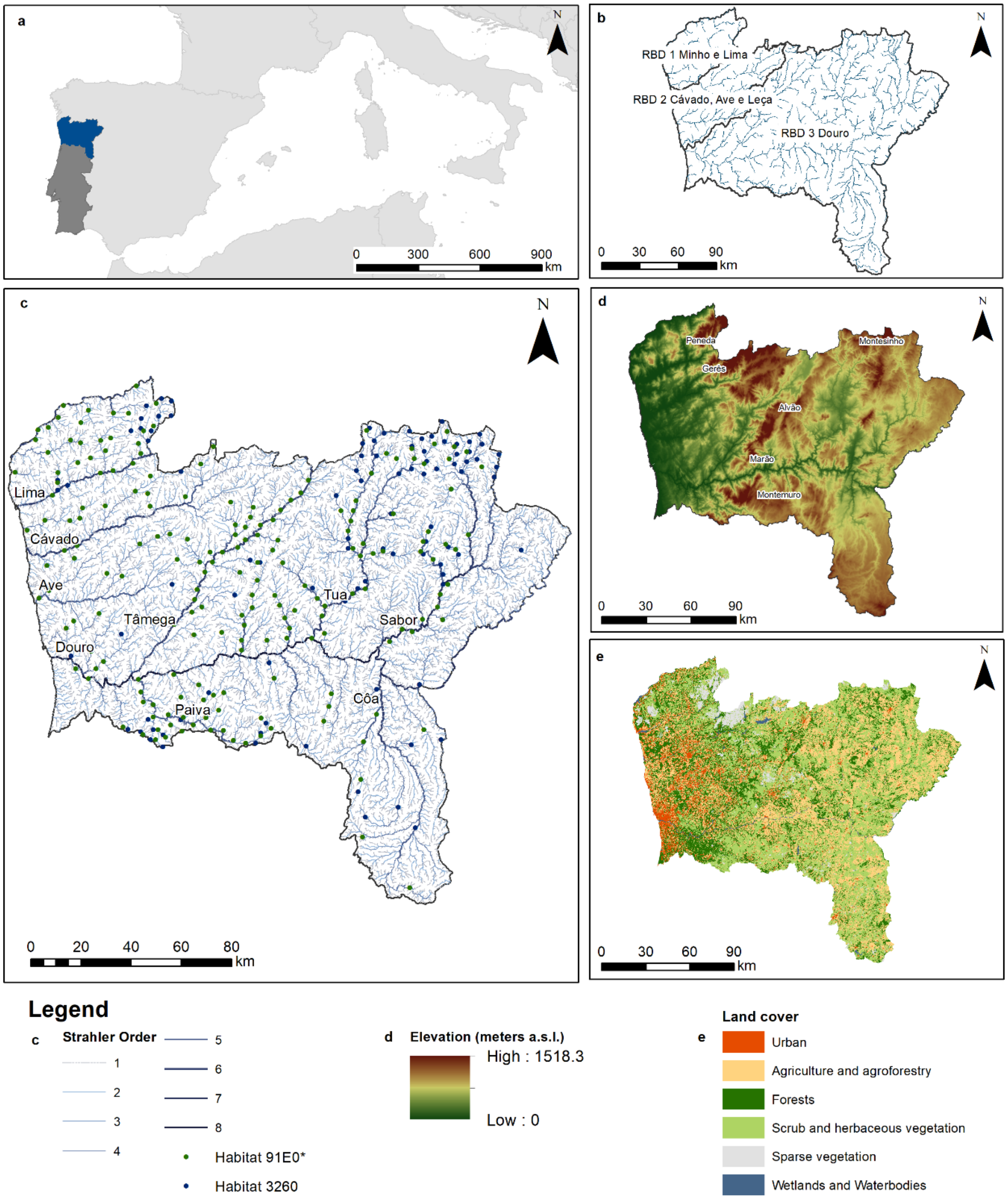


Fig.2. Geographical context of the study area (highlighted in blue) in Europe (a). Administrative division of the study area according to the Water Framework Directive River Basin Districts (RBD) (b). The hydrographic network of the study area (c) with rivers symbolized by Strahler's Order, and the filtered 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.

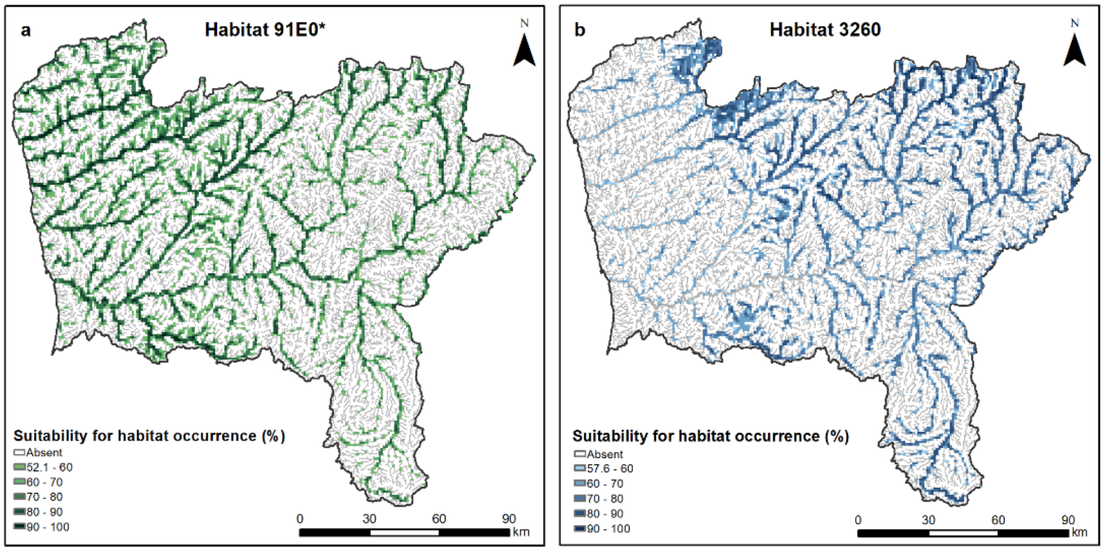


Fig. 3. Suitability for habitat occurrence for habitat types 91E0* - *Alluvial Alnus forests* (a) and 3260 - *Watercourses with Ranunculus vegetation* (b), expressed in percentage (above the binarization threshold). The hydrographic network is shown in the background for context.

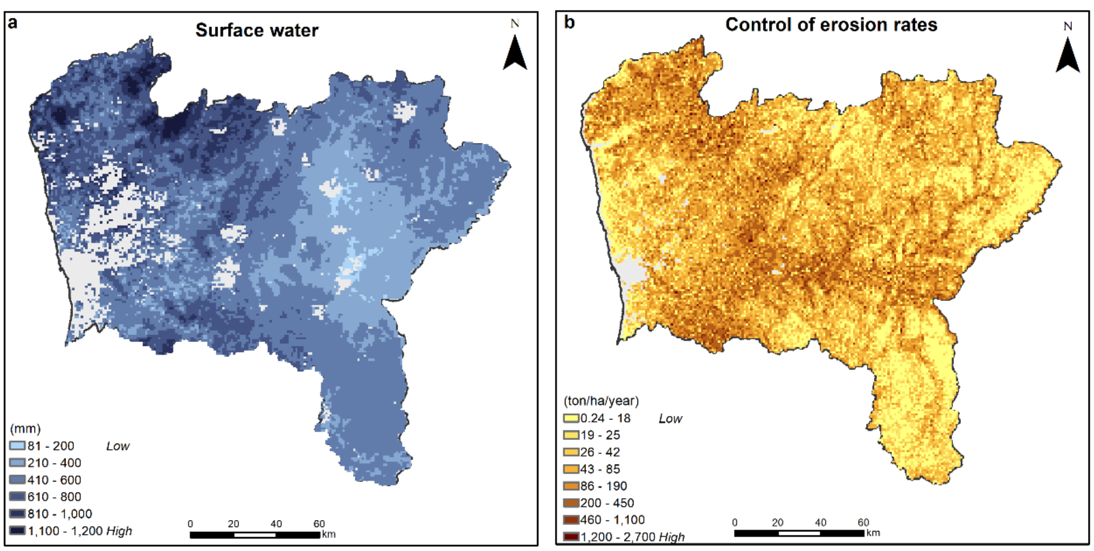


Fig. 4 Potential supply of ecosystem services in the study area: “Surface water used for nutrition, materials or energy” (a), and “Control of erosion rates” (b).

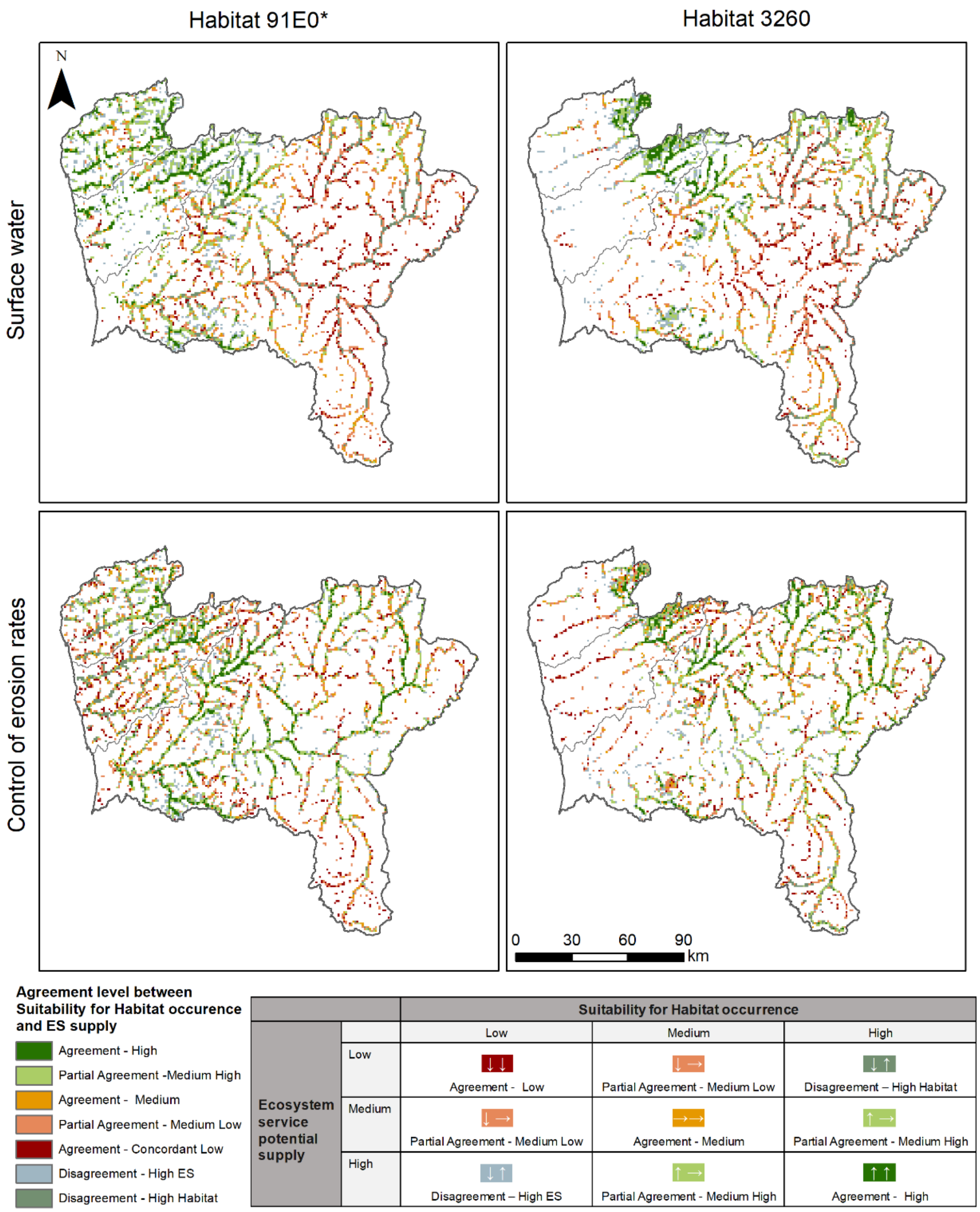


Fig. 5. Spatial agreement between the suitability for habitat occurrence and the supply of ecosystem services. We considered areas of agreement all the locations where both elements are in the same category (e.g. high habitat probability of presence and high ecosystem service supply). Conversely, all 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.

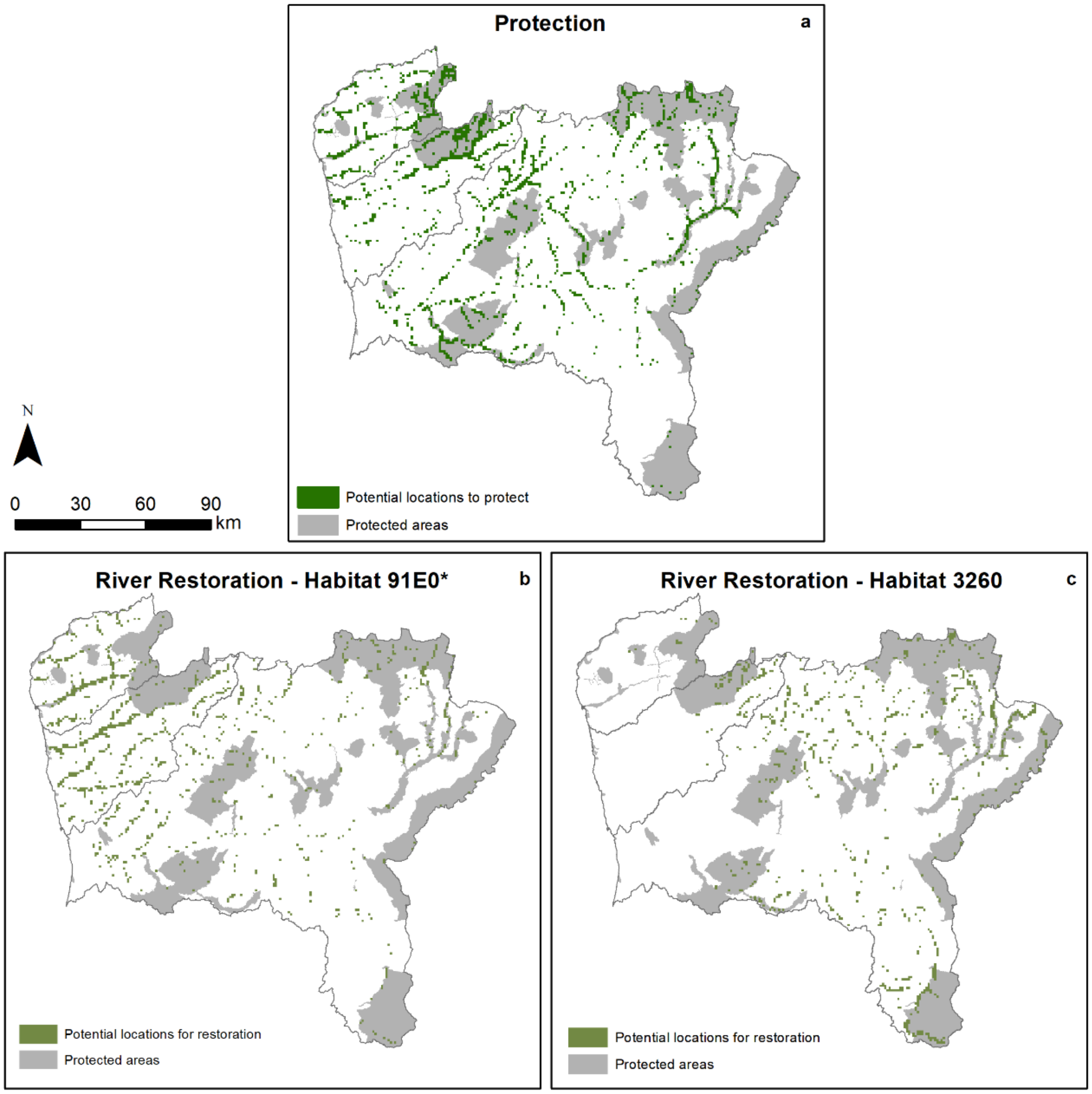
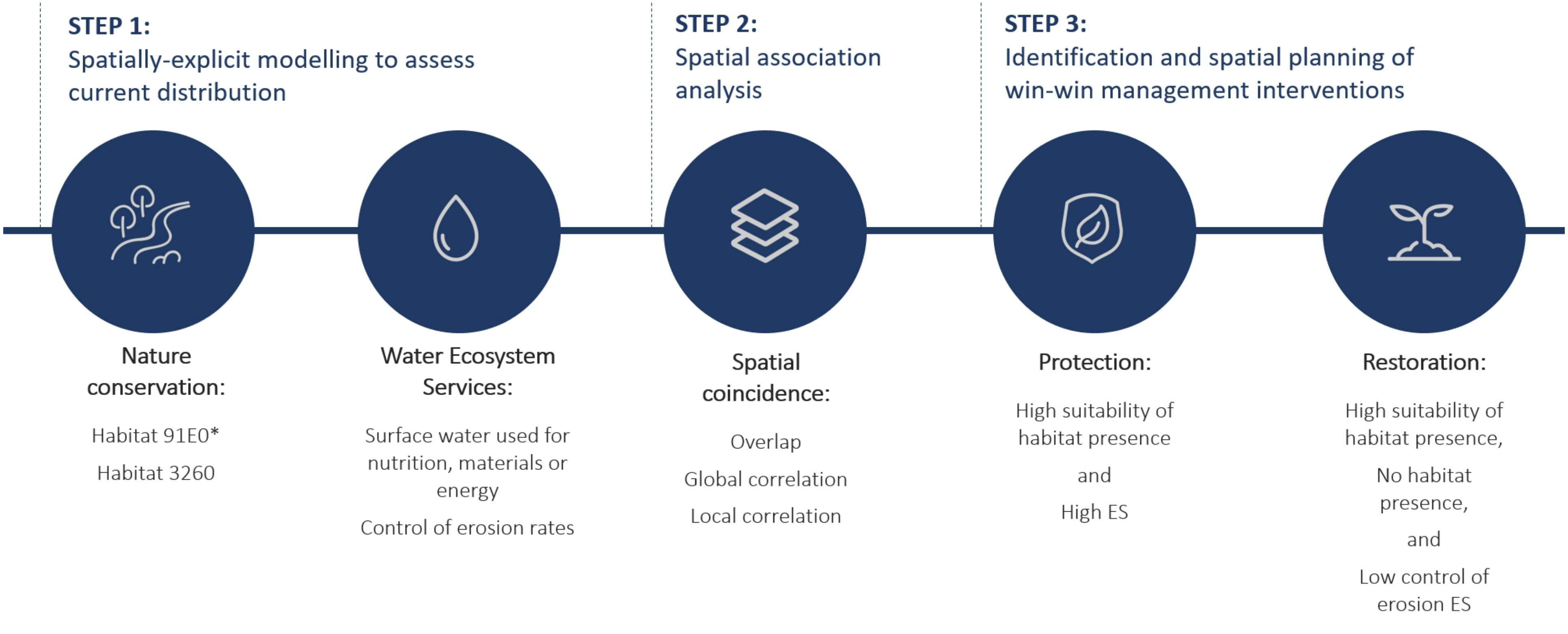
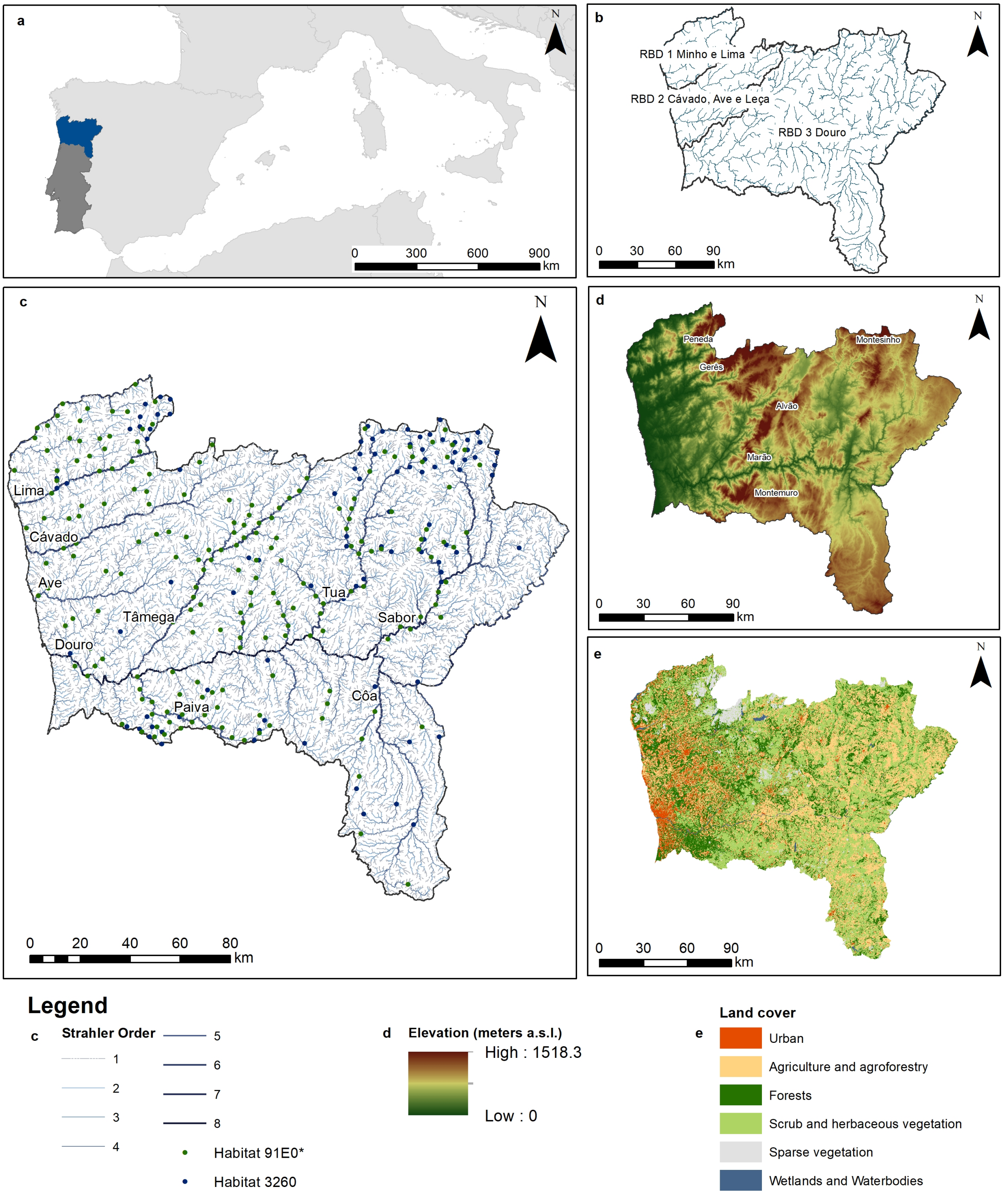


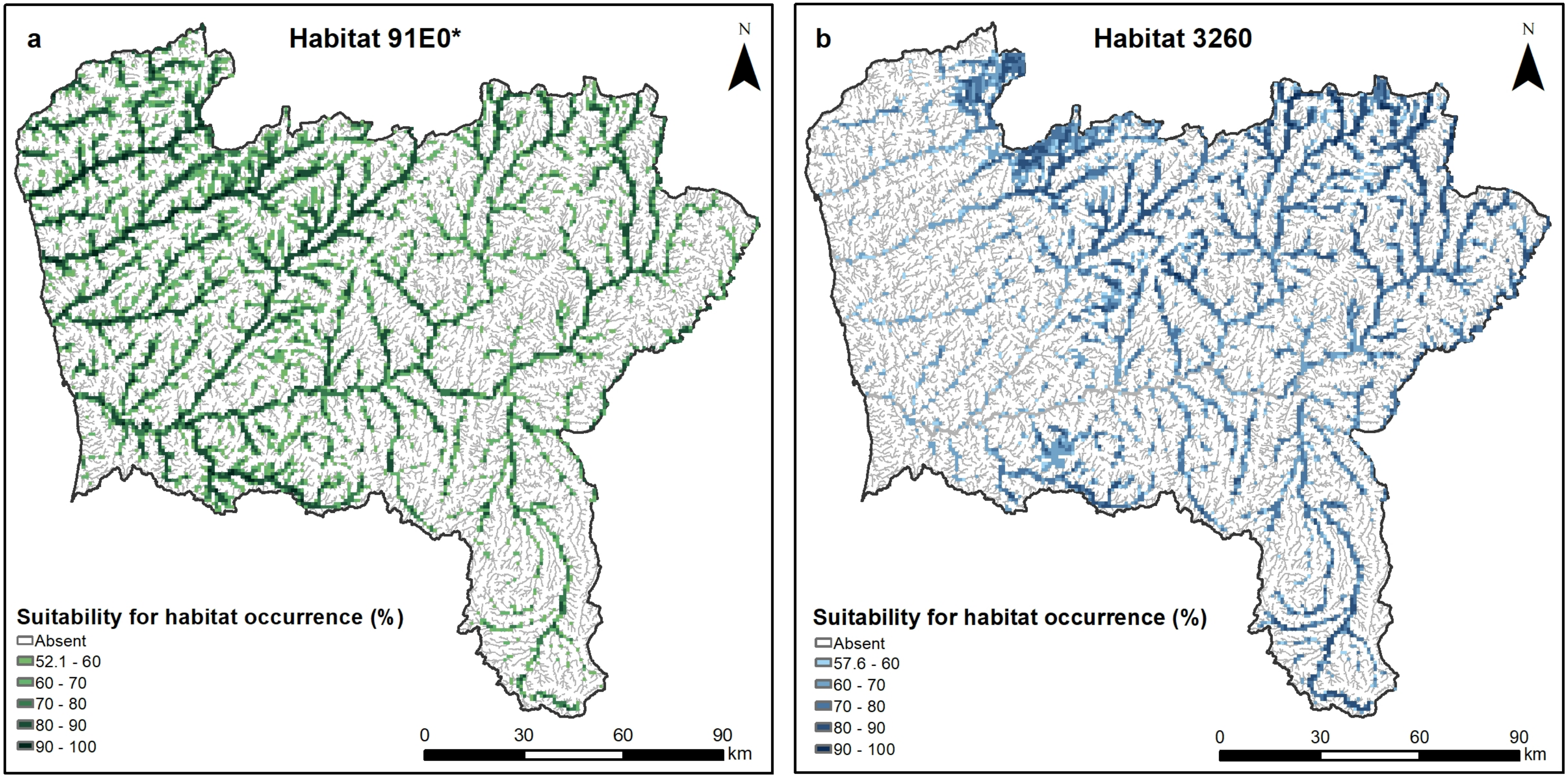
Fig. 6. Potential locations for protection of both the habitat types and ecosystem services over the national network of protected areas, Natura 2000 and Ramsar sites in the study area (a). Potential locations for river restoration targeting the habitats 91E0* - *Alluvial Alnus forests* (b) or the habitat 3260 - *Watercourses with Ranunculus vegetation* (c) and improving the “Control of erosion rates” service.

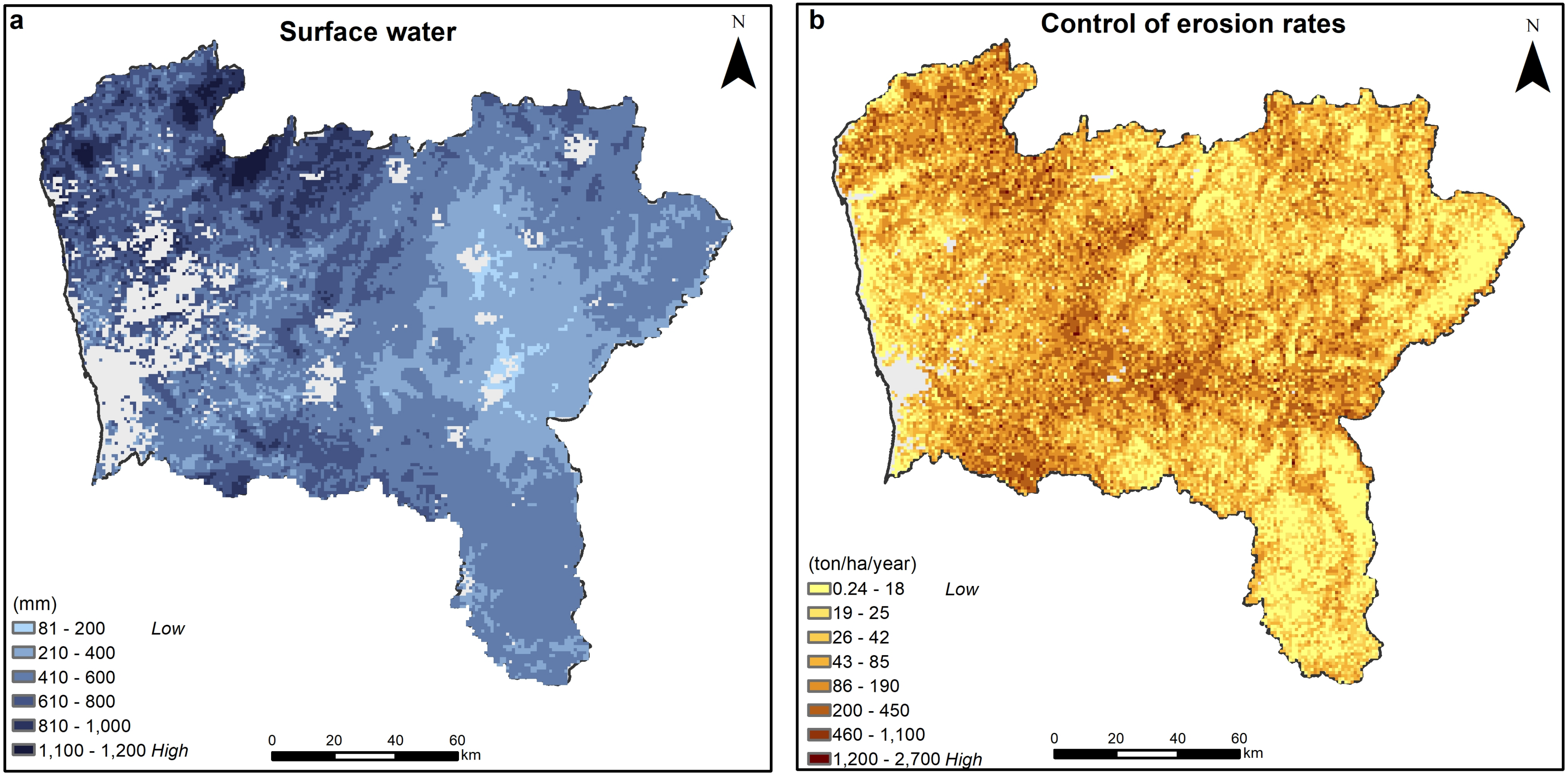
Acknowledgements

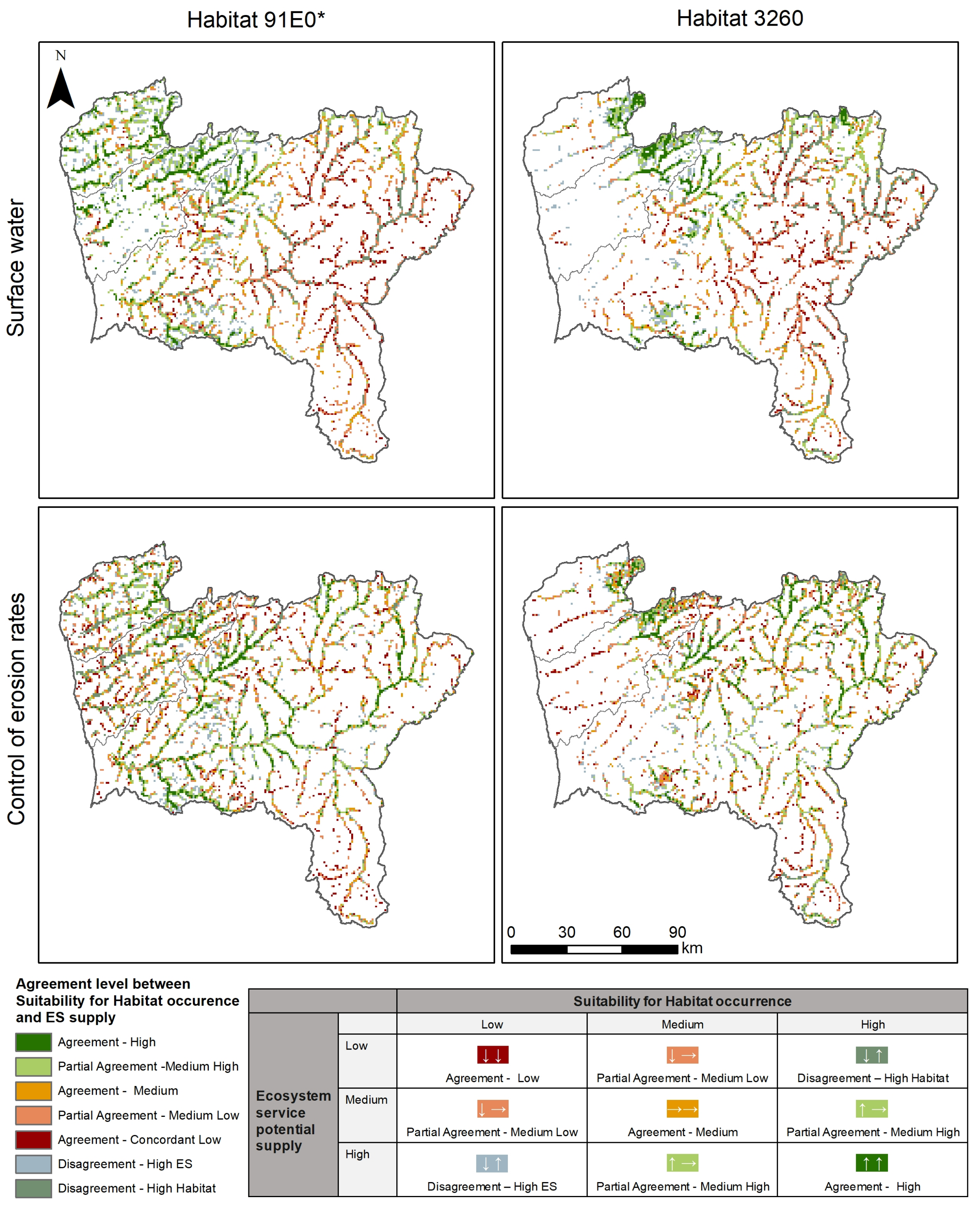
APP is funded by Fundação para a Ciência e Tecnologia (FCT) under a Doctoral fellowship (SFRH/BD/115030/2016) through Programa Operacional Capital Humano (POCH) co-financed by the European Social Fund and national funds from the Ministério da Ciência, Tecnologia e Ensino Superior (MCTES). CV would like to acknowledge the support of the Portuguese Infrastructure of Scientific Collections (POCI-01-0145FEDER-022168) (PRISC.pt).


STEP 1:
Spatially-explicit modelling to assess current distribution
STEP 2:
Spatial association analysis
STEP 3:
Identification and spatial planning of win-win management interventions
Nature conservation:
Habitat 91E0*
Habitat 3260
Water Ecosystem Services:
Surface water used for nutrition, materials or energy
Control of erosion rates
Spatial coincidence:
Overlap
Global correlation
Local correlation
Protection:
High suitability of habitat presence
and
High ES
Restoration:
High suitability of habitat presence,
No habitat presence,
and
Low control of erosion ES

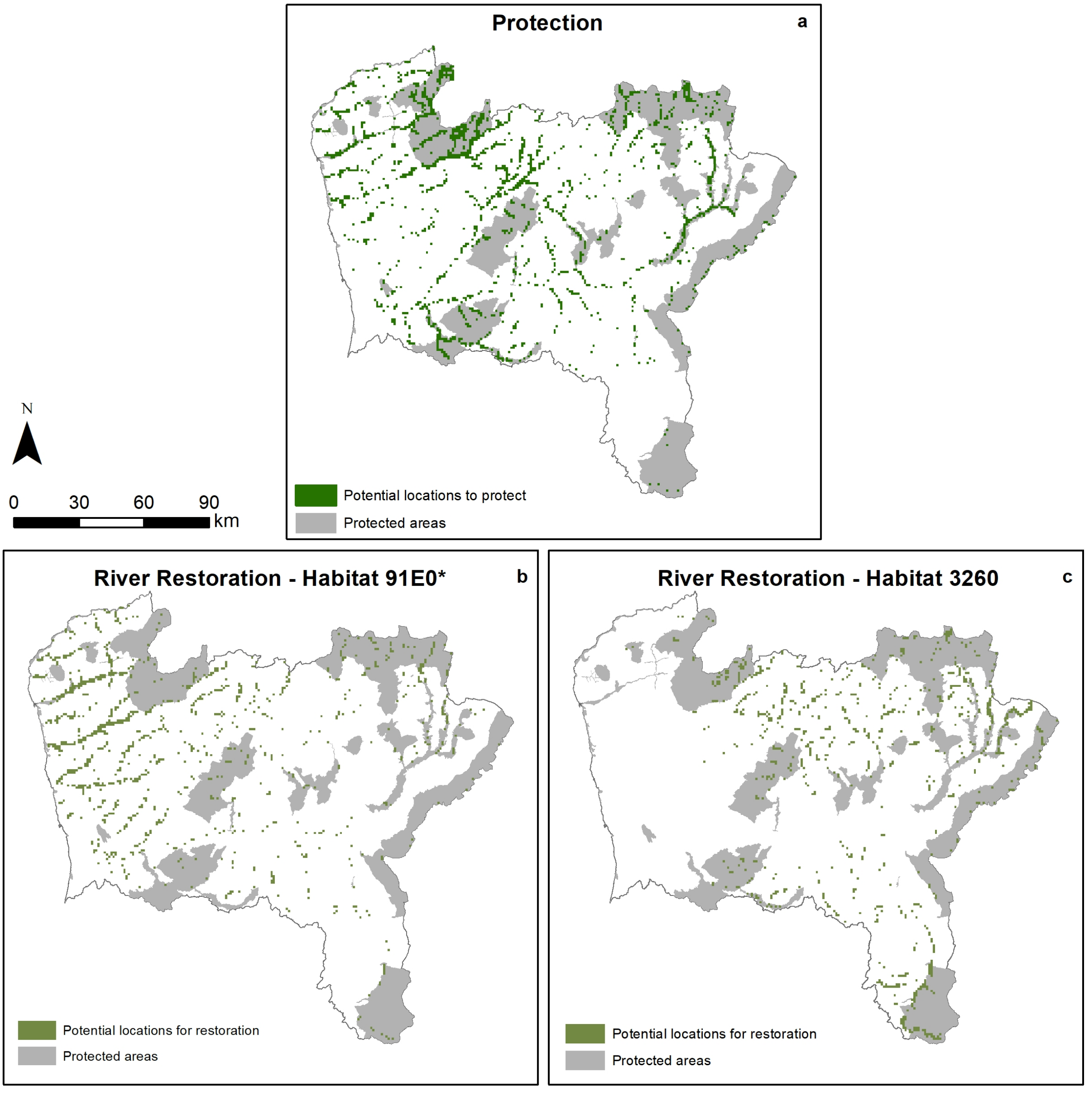

a
N
0 300 600 900
km
b
N
RBD 1 Minho e Lima
RBD 2 Cávado, Ave e Leça
RBD 3 Douro
0 30 60 90
km
c
N
Lima
Cávado
Ave
Tâmega
Douro
Tua
Sabor
Paiva
Côa
0 20 40 60 80
km
d
N
Peneda
Gerês
Montesinho
Alvão
Marão
Montemuro
0 30 60 90
km
e
N
0 30 60 90
km
Legend
c
Strahler Order
1
2
3
4
5
6
7
8
Habitat 91E0*
Habitat 3260
d
Elevation (meters a.s.l.)
High : 1518.3
Low : 0
e
Land cover
Urban
Agriculture and agroforestry
Forests
Scrub and herbaceous vegetation
Sparse vegetation
Wetlands and Waterbodies


a
Habitat 91E0*
N
Suitability for habitat occurrence (%)
Absent
52.1 - 60
60 - 70
70 - 80
80 - 90
90 - 100
0
30
60
90
km
b
Habitat 3260
N
Suitability for habitat occurrence (%)
Absent
57.6 - 60
60 - 70
70 - 80
80 - 90
90 - 100
0
30
60
90
km


a
Surface water
N
(mm)
81 - 200 Low
210 - 400
410 - 600
610 - 800
810 - 1,000
1,100 - 1,200 High
0 20 40 60
km
b
Control of erosion rates
N
(ton/ha/year)
0.24 - 18 Low
19 - 25
26 - 42
43 - 85
86 - 190
200 - 450
460 - 1,100
1,200 - 2,700 High
0 20 40 60
km



Habitat 91E0*
Habitat 3260
Surface water
Control of erosion rates
N
0 30 60 90
km
Agreement level between Suitability for Habitat occurence and ES supply
Agreement - High
Partial Agreement -Medium High
Agreement - Medium
Partial Agreement - Medium Low
Agreement - Concordant Low
Disagreement - High ES
Disagreement - High Habitat
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



Protection
a
Potential locations to protect
Protected areas
N
0
30
60
90
km
River Restoration - Habitat 91E0*
b
Potential locations for restoration
Protected areas
River Restoration - Habitat 3260
c
Potential locations for restoration
Protected areas

Supplementary Material 1

The occurrence data for the two habitat types was obtained from several sources. Only records that were georeferenced at least at 1km^2 resolution were kept. All the data was aggregated at 1 km resolution and all the duplicates were eliminated from the final dataset. The final occurrence dataset is presented in the Fig. S1.1 and the thinned dataset used for modelling (please see Methods section 2.2) is presented in Fig. S1.2.

Table S1.1. Data sources for occurrence data of the Habitat types divided by types of occurrence data.

Occurrence Data types	**Habitat**	**Syntaxa**	**Indicator Species**
Sources	Research and monitoring projects: • Project SIMBioN: Sistema De Informação E Monitorização Da Biodiversidade Do Norte De Portugal • Flora e Vegetação do Parque Arqueológico do Vale do Côa • Aproveitamento Hidroeléctrico de Foz Tua	On-line databases: • Sistema de Informácion de la Vegetación Ibérica e Macaronésica (SIVIM)(Font et al., 2011)	Water Framework Directive: • Macrophyte and River Habitat Survey Sampling (Agência Portuguesa do Ambiente – Administração da Região Hidrográfica Norte)
	Field observations: • A.P. Portela (2018) • C. Vieira (2018) • C. Vila-Viçosa (2018)	Thesis: • Almeida (2009)) • Aguiar (2000)) • Santos (2010))	Herbarium Collections: • Herbarium of the University of Porto (PO) (in situ consultation) • Herbarium of University of Coimbra (COI) (http://coicatalogue.uc.pt/)
		Articles: • Honrado (2004)) • Honrado, Alves, Alves, and Caldas (2002))	On-line databases: • GBIF.org (27 July 2018) GBIF Occurrence Download https://doi.org/10.15468/dl.60b
			Thesis: Vieira (2008))

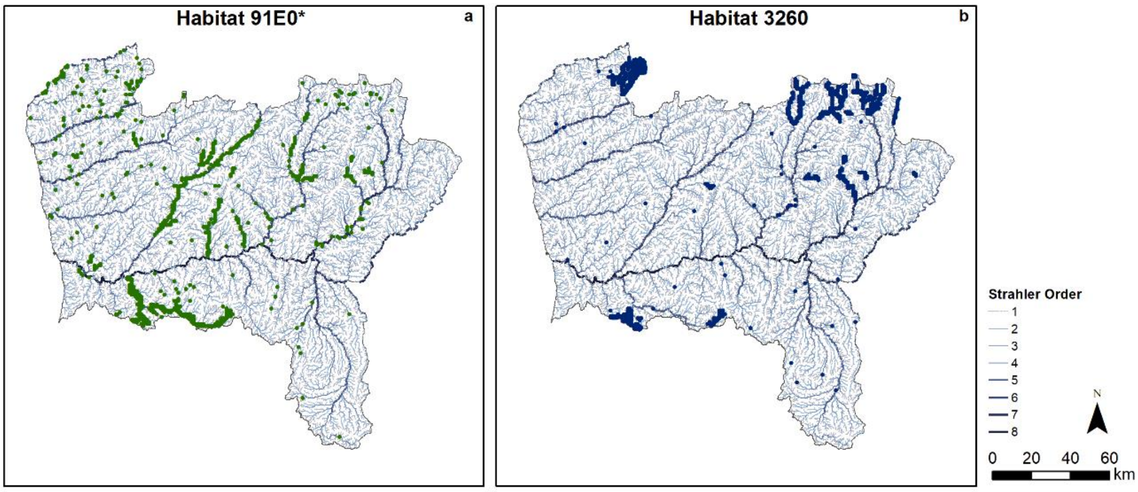


Fig. S1.1. Final dataset of habitat occurrence points obtained from the sources listed in the Table S1.1, over the hydrographic network symbolized by Strahler order.

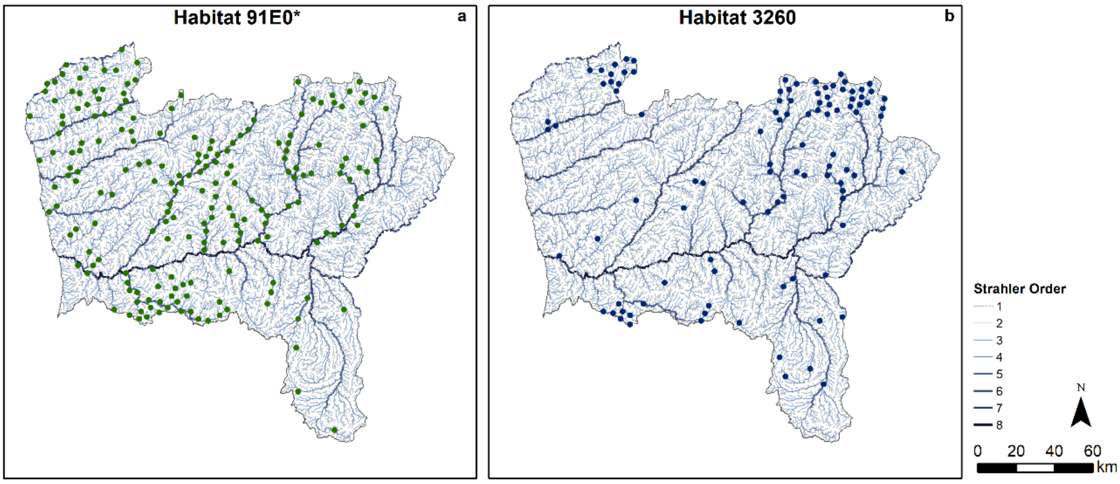


Fig. S1.2. Filtered dataset of habitat occurrence points obtained with “spThin” R package from the dataset presented in Fig.S1.1, over the hydrographic network symbolized by Strahler order.

References:

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Honrado, J., Alves, P., Alves, H. N., & Caldas, F. B. (2002). XXXIII: Ten new syntaxa from the Miniensean biogeographic subsector (northwestern Portugal). *Silva Lusitana, 10*, 247-259.

Santos, T. M. H. d. (2010). *Landscape and phytosociology of the Paiva River's hydrographical basin.* (Doctoral dissertation), Universidade Técnica de Lisboa, Lisboa.

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Supplementary Material 2

Methodological description and inputs for the calculation of the potential ecosystem service supply.

S2.1 Surface water used for nutrition, materials or energy

The potential supply of “surface water for nutrition, materials or energy” service was estimated using an indicator of annual average water quantity (also referred to as water yield) obtained through a water balance equation. We used Budyko’s curve equation (Eq.1) to relate annual average precipitation (P) and annual average evapotranspiration (ET), to obtain the annual average water quantity (Y).

$$Y = \left(1 - \frac{ET}{P}\right) \times P \quad (1)$$

Annual average precipitation was obtained from climatic models refined for Portugal (Fonseca & Santos, 2018) (Fig. S3.1). Annual average evapotranspiration was obtained from NASA’s MODIS global evapotranspiration product MOD16A3 (yearly/500m) (Numerical Terradynamic Simulation Group, 2018) averaged for the period between 2000 and 2014 (Fig. S3.1). All the calculations were performed in ArcMap 10.5 (ESRI, 2012).

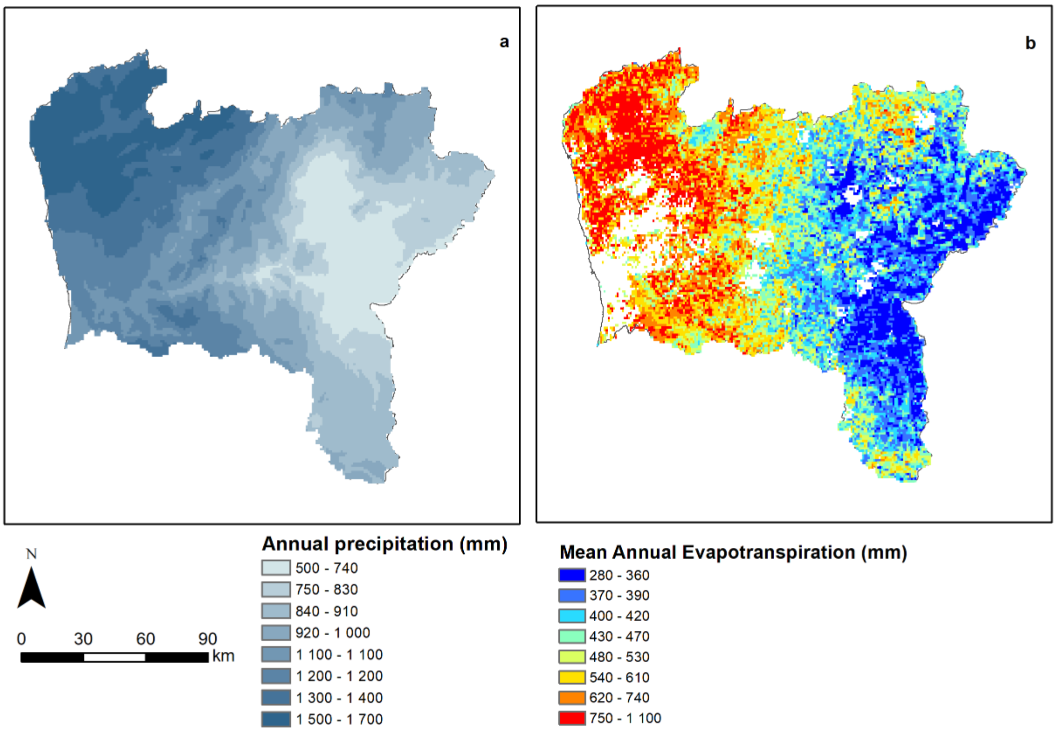

Fig. S2.1. Inputs for the calculation of annual average water quantity, namely annual precipitation (a) and evapotranspiration (b).

S2.2 Control of erosion rates

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. This indicator was obtained through the framework developed by Guerra, Pinto-Correia, and Metzger (2014), building on the RUSLE equation, to assess the contribution of the ecosystem to soil retention.

The Revised Universal Soil Loss Equation (RUSLE) equation estimates annual soil loss through the product of rainfall erosivity (R), soil erodibility (K), cover-management factor (C) and slope length and steepness factor (LS) and the conservation practices factor (P) (Eq.2).

$$A = R \times K \times LS \times C \times P \tag{2}$$

To compute soil retention by the ecosystem and thus the actual service supply, this framework considers two components: the structural impact, i.e., the erosion that would ensue if vegetation was absent (Eq. 3) and the actual soil loss (Eq. 4).

$$S = R \times K \times LS \tag{3}$$

$$A = R \times K \times LS \times C \tag{4}$$

To estimate soil retention by the ecosystem, the actual soil loss (Eq.3) is subtracted from the structural impact (Eq.5).

$$ES = S - A \tag{5}$$

The cover-management factor values were obtained from Pimenta (1999) and combined with national land cover data (DGT, 2007) (Table. S3.1 and Fig. S3.2). Rainfall erosivity and soil erodibility were obtained from the European Soil Data Centre (ESDAC) of the European Commission Joint Research Centre (Panagos et al., 2015; Panagos, Meusburger, Ballabio, Borrelli, & Alewell, 2014) (Fig. S3.2). The slope length and steepness factor (Fig. S3.2) was calculated from the European Digital Elevation Model

(European Environment Agency, 2016) with SAGA GIS software (Conrad et al., 2015) using the algorithm developed by Desmet and Govers (1996). The calculation of structural impact (Fig. S3.3) and actual soil loss (Fig. S3.3) and the final service were performed in in ArcMap 10.5 (ESRI, 2012).

Table. S2.1. Cover management factors based on Pimenta (1999) applied to the land cover classes in the study area.

Land Cover Class	Factor C
Urban	
Continuous urban fabric	0.005
Discontinuous urban fabric	0.01
Industrial or commercial units	0.01
Road and rail networks and associated land	0.01
Port Areas	0.01
Airports	0.01
Mineral extraction sites	0.5
Dump sites	0.1
Construction sites	0.01
Green urban areas	0.02
Sport and leisure facilities and historical areas	0.01
Agriculture	
Annual non-irrigated crops	0.4
Greenhouses and plant nurseries	0.001
Annual irrigated crops	0.2
Rice fields	0.05
Vineyards	0.2
Vineyards with orchards	0.15
Vineyards with olive groves	0.2
Orchards	0.05
Orchards with vineyard	0.1
Orchards with olive groves	0.1
Olive groves	0.1
Olive groves with vineyard	0.1
Olive groves with orchards	0.1
Permanent pastures	0.02
Annual non-irrigated crops with vineyards	0.3
Annual non-irrigated crops with orchards	0.2
Annual non-irrigated crops with olive groves	0.2
Annual irrigated crops with vineyards	0.3
Annual irrigated crops with orchards	0.2
Annual irrigated crops with olive groves	0.2
Annual crops and pastures associated with permanent crops	0.4
Complex cultivation patterns	0.2
Agriculture with significant areas of natural and semi-natural vegetation	0.3
Agro-forestry areas	0.3
Forests and seminatural areas	
Cork oak forest	0.1
Holm oak forest	0.1
Other Oaks forest	0.1
Chestnut forests	0.1
Eucalyptus forests	0.2

Broad-leaved forests	0.1
Mixed Broad-leaved forests	0.1
Maritime Pine forests	0.05
Stone Pine forests	0.05
Pure Coniferous forests	0.05
Mixed coniferous forests	0.05
Mixed Forests	0.05
Natural grasslands	0.05
Moors and heathland	0.02
Sclerophyllous vegetation	0.02
Open forests, forest cuts and new plantations	0.1
Fire breaks	0.4
Open spaces with little or no vegetation	
Beaches, dunes, sands	0.05
Bare rock	0.01
Sparsely vegetated areas	0.5
Burnt areas	0.5
Wetlands and Water bodies	
Inland marshes	0.005
Peat bogs	0
Salt marshes	0.005
Salines and coastal aquaculture	0.005
Water courses	0
Water bodies	0
Coastal lagoons	0
Estuaries	0
Ocean	0

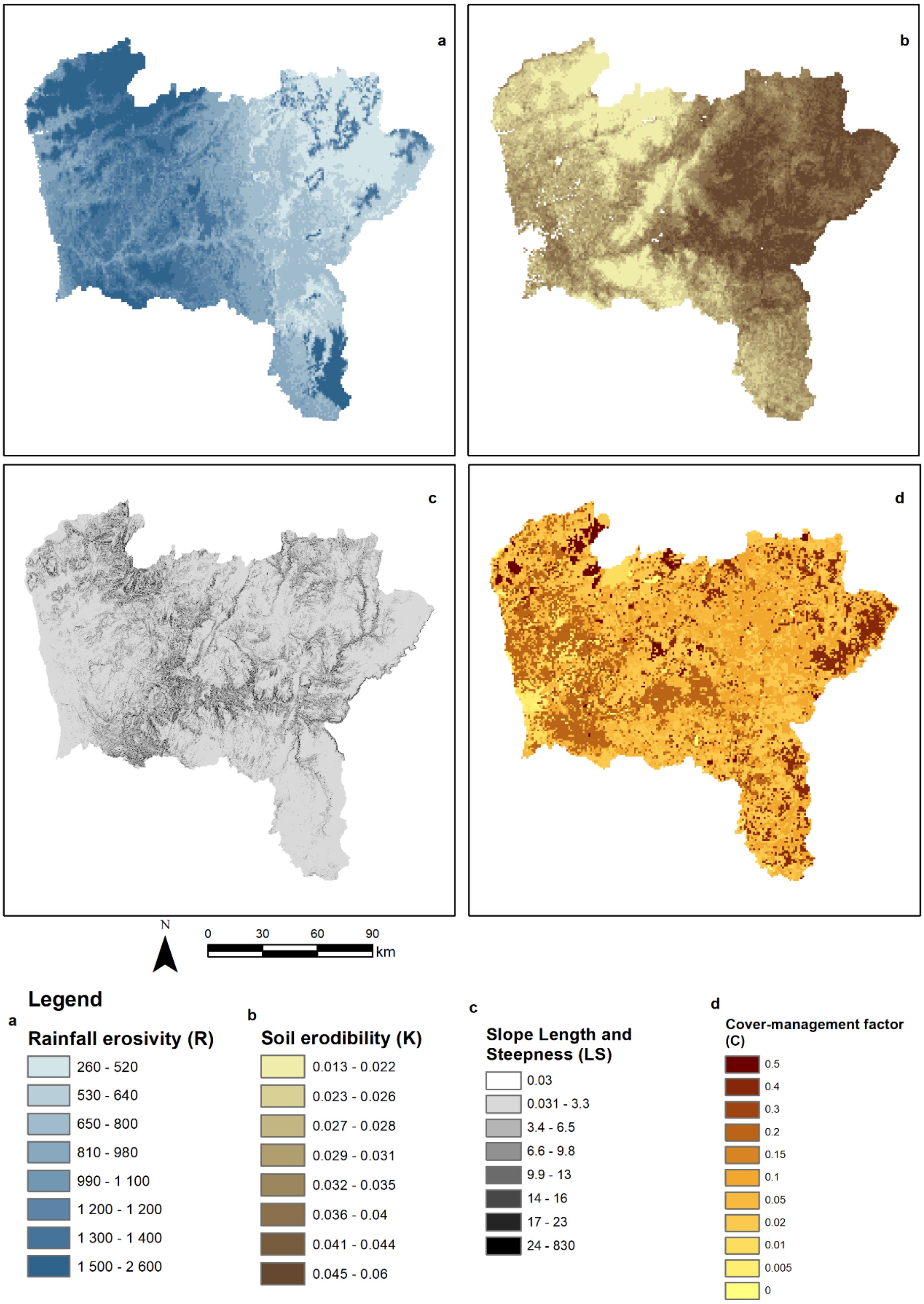

Fig. S2.2. Inputs for the calculation of the potential soil retention by the ecosystem, namely rainfall erosivity (a), soil erodibility (b), slope length and steepness (c) and cover management factor (d).

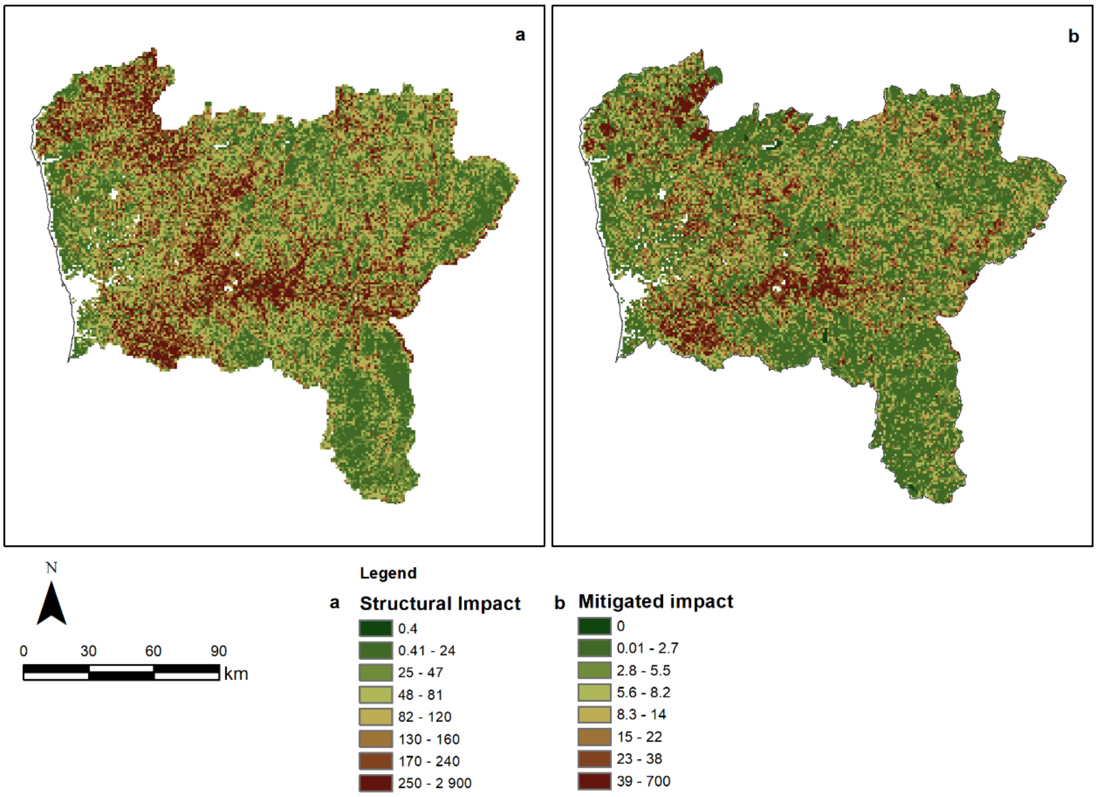

Fig. S2.3. Components of the calculation of the soil retention by the ecosystem, namely the structural (a) and the mitigated impact, i.e. actual soil loss (b).

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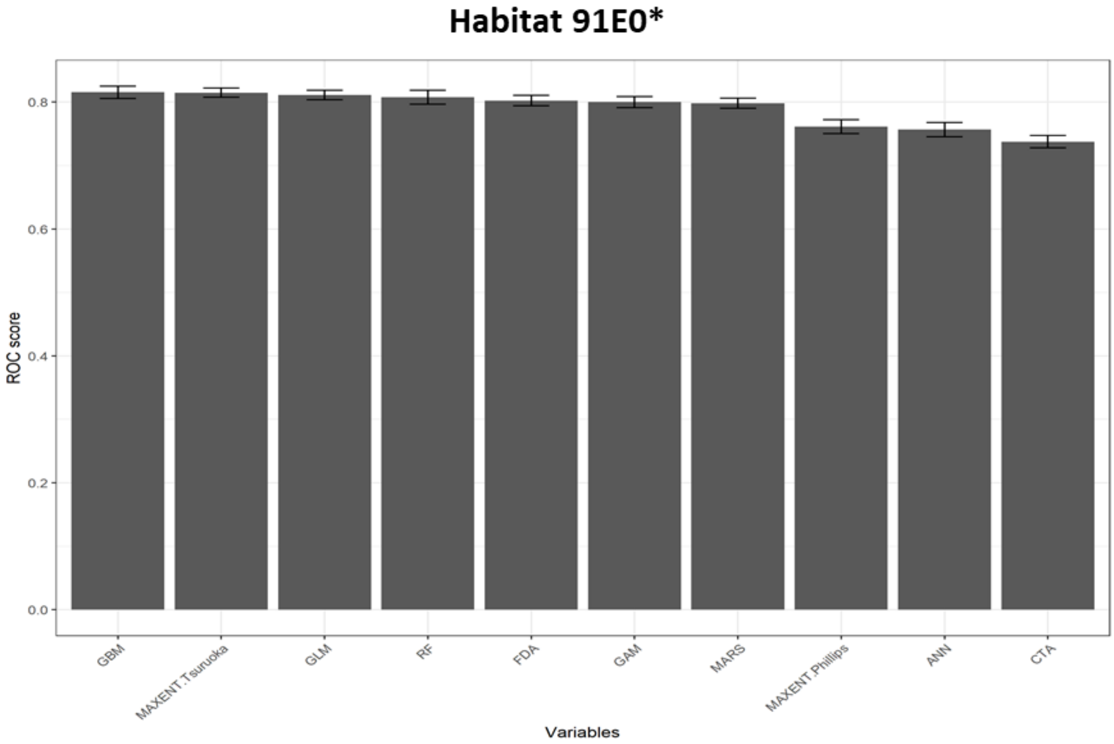
Supplementary Material 3

Results from the species distribution modelling procedure for the habitat types 91E0* and 3260.

Fig S3.1. Average evaluation score by algorithm.



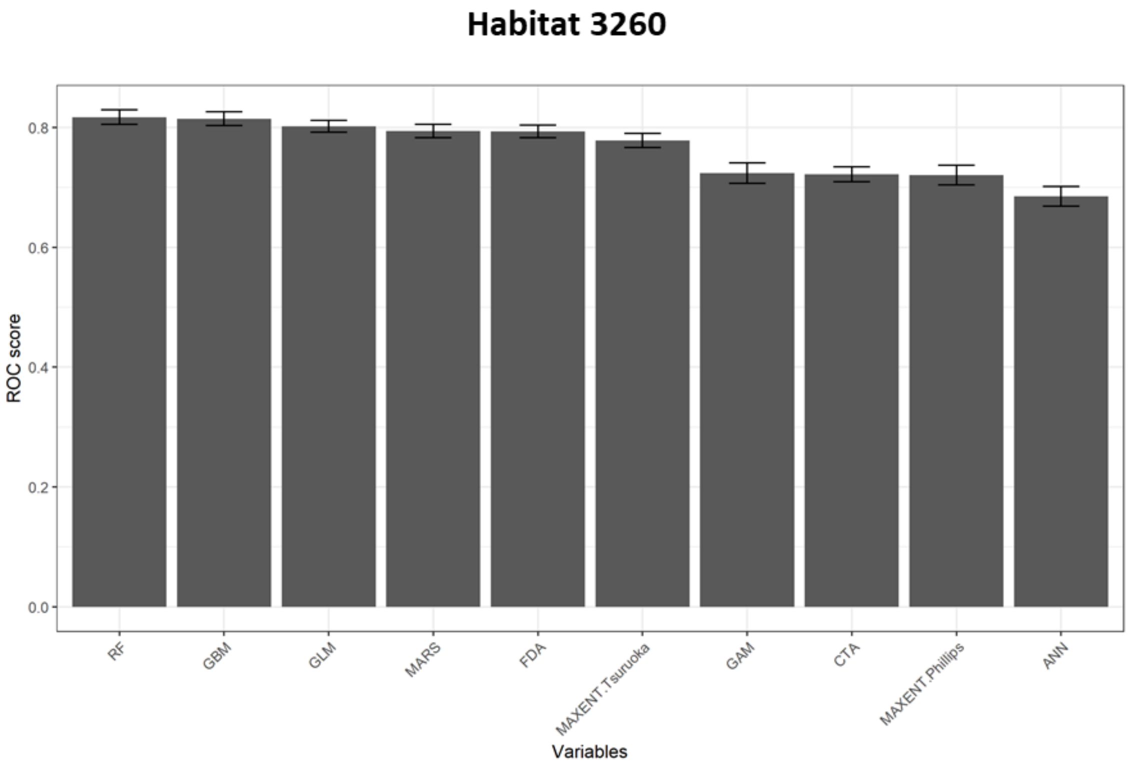
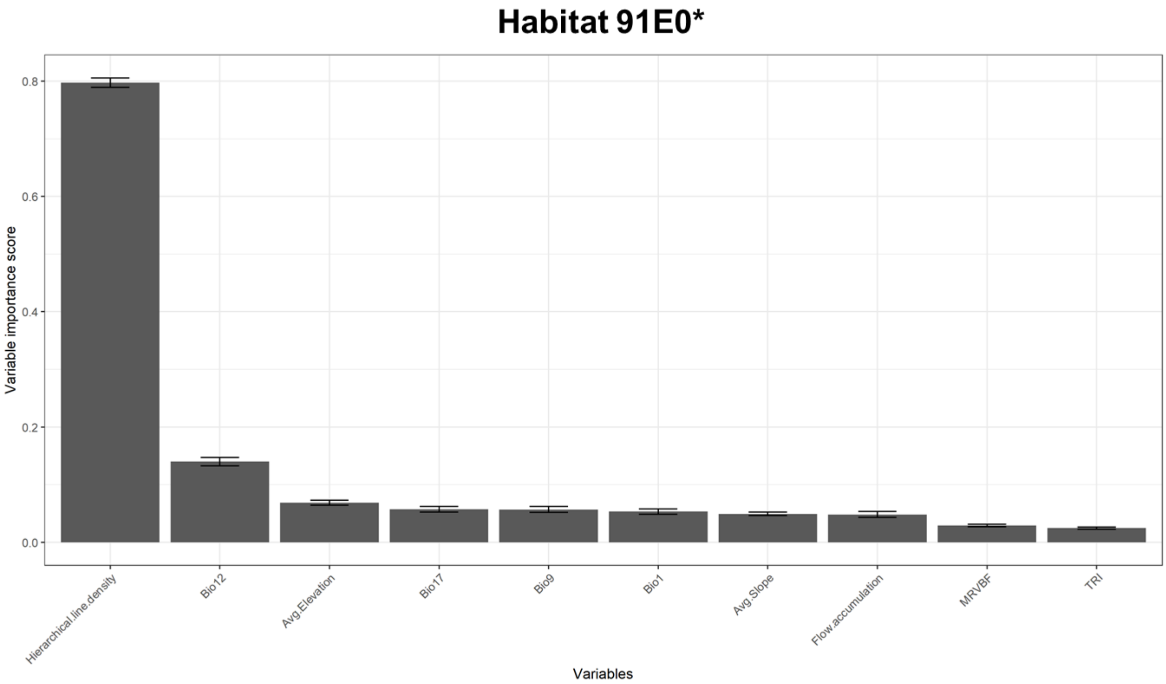
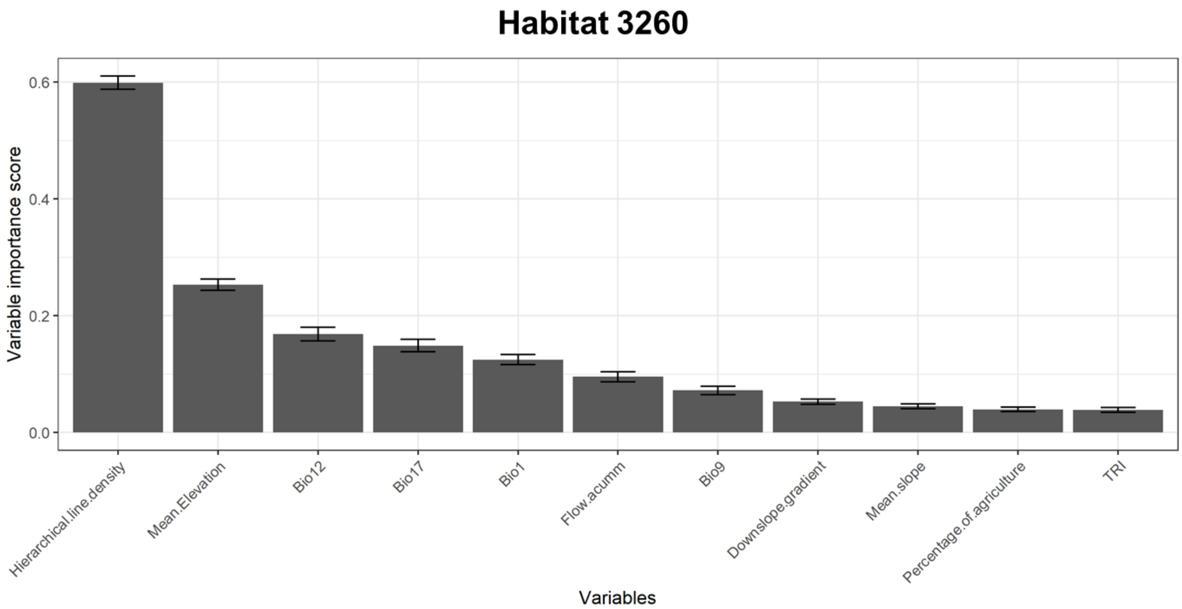


Table S3.1. Evaluation ROC scores for the average ensemble methods.

Ensemble method	Habitat 91E0*	Habitat 3260
	AUC	AUC
Weighted mean by ROC	0.866	0.901
Mean by ROC	0.865	0.9

Fig S3.2. Average variable importance score across pseudo-absence datasets, algorithms and evaluation rounds. The abbreviations





Supplementary Material 4

Global Pearson correlation and local Pearson correlations between habitat types probability of presence and the ecosystem service supply.

Table S4.1. Global correlation between habitat types' probability of presence (91E0* - Alluvial Alnus forests and 3260 - Watercourses with Ranunculus vegetation) and the supply of ecosystem services (p value < 0.05 marked with an asterisk).

Global correlation	Habitat 91E0*	Habitat 3260
Surface water used for nutrition, materials or energy	-0.014	-0.026
Control of erosion rates	0.037*	0.038*

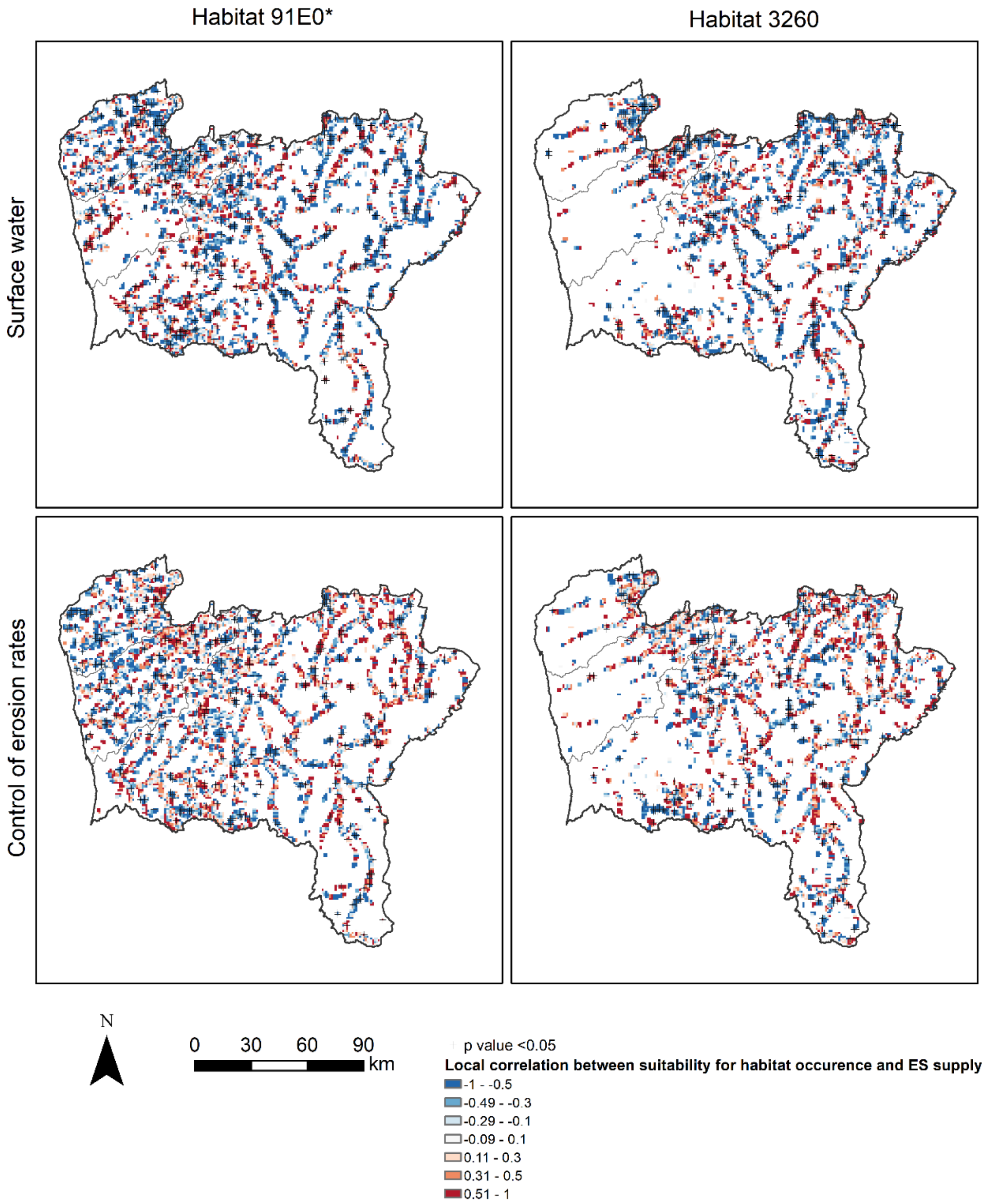


Fig. S4.1. Local correlation between the habitat types' probability of presence and the supply of ecosystem services, considering a neighbourhood of 3 cells. Cells that presented significant correlation (p value < 0.05) are marked with the symbol +.

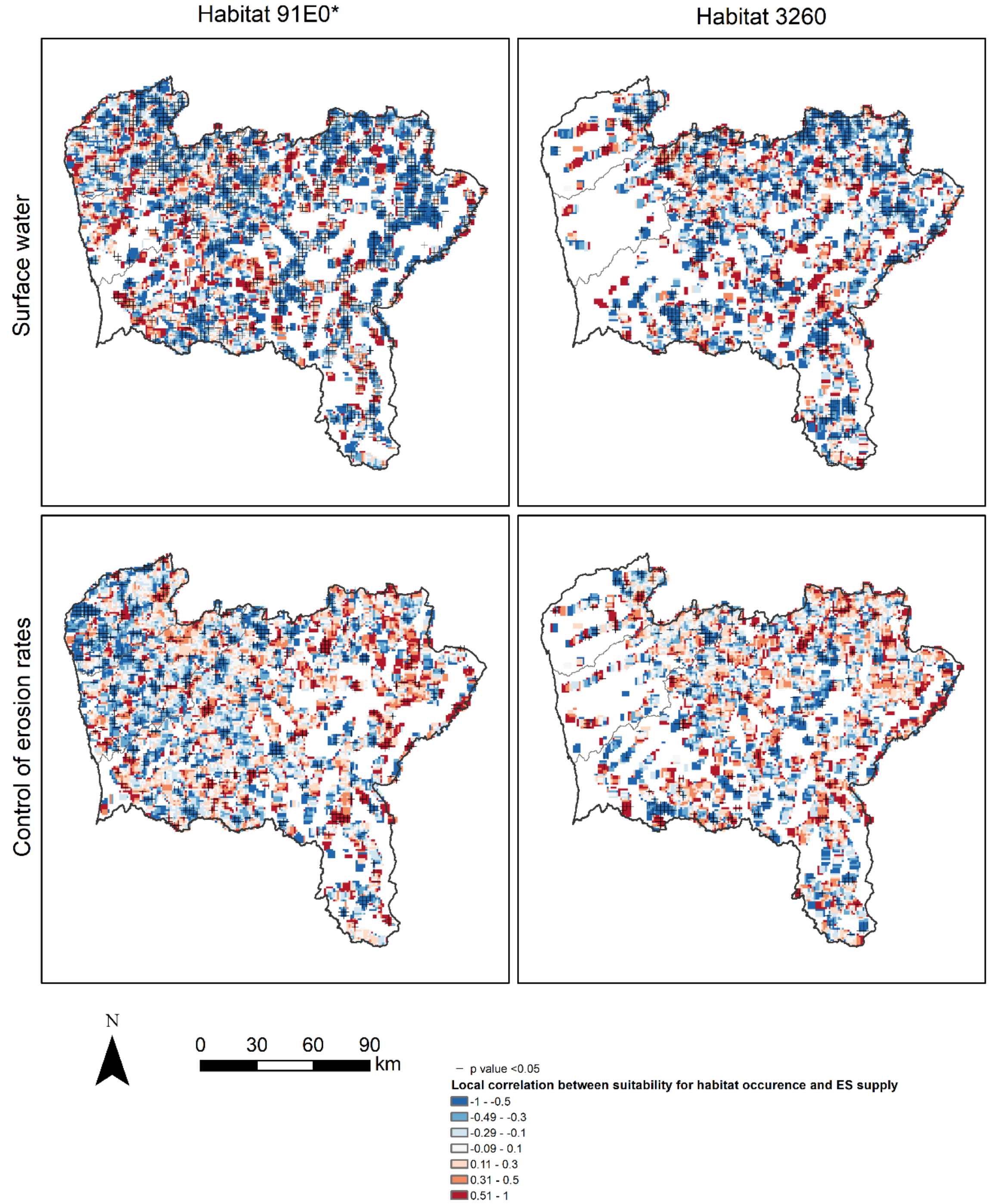


Fig. S4.2. Local correlation between the habitat types' probability of presence and the supply of ecosystem services, considering a neighbourhood of 5 cells. Cells that presented significant correlation (p value < 0.05) are marked with the symbol +.

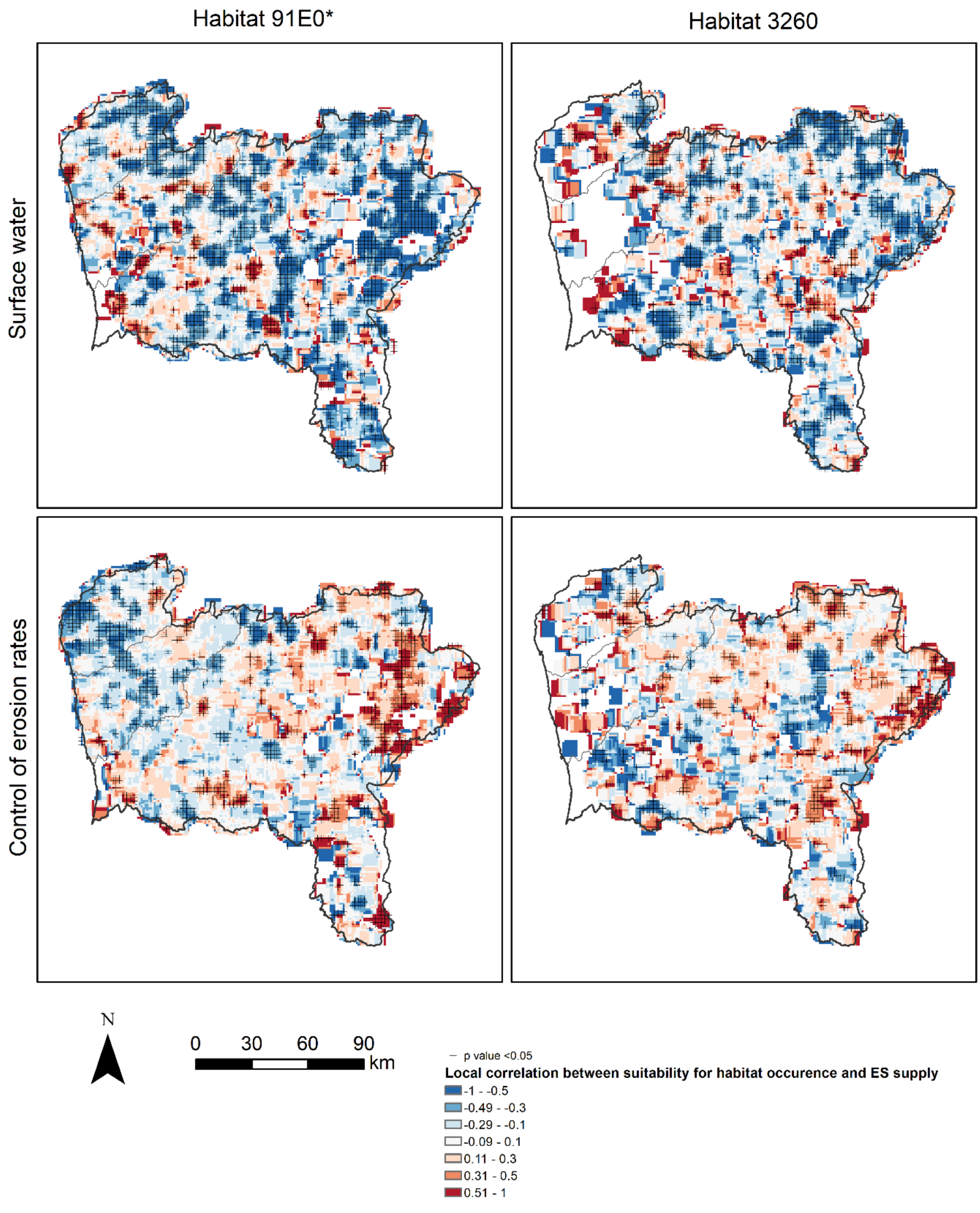


Fig. S4.3. Local correlation between the habitat types' probability of presence and the supply of ecosystem services, considering a neighbourhood of 9 cells. Cells that presented significant correlation (p value < 0.05) are marked with the symbol +.