

Article

Headwater Systems as Green Infrastructure: Prioritising Restoration Hotspots for Sustainable Rural Landscapes

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Abstract

This study aims to assess the role of headwater systems (HS) in enhancing ecological connectivity and supporting Green Infrastructure in the Centre Region of Portugal. Specifically, it identifies restoration opportunity areas within HS by analysing land-use changes over the past 70 years, modelling land-use scenarios to promote ecological resilience, and evaluating connectivity between HS and Natura 2000 sites. The methodology integrates spatial analysis of historical land-use data with connectivity modelling using least-cost path approaches. Results show substantial transformation in HS areas, notably the expansion of eucalyptus plantations and a decline in agricultural land. Approximately 58% of the HS are identified as requiring restoration, including areas within the Natura 2000 network. The connectivity assessment reveals that HS can function as effective ecological corridors, contributing to improved water regulation, soil conservation, gene flow, and wildfire mitigation. A total of 61 potential ecological linkages between Natura 2000 sites were identified. These findings highlight the strategic importance of integrating HS into regional and national Green Infrastructure planning and supporting the implementation of the EU Biodiversity Strategy for 2030. The study recommends prioritising headwater restoration through multi-scale planning approaches and active involvement of local stakeholders to ensure sustainable land-use management.

Keywords: landscape connectivity; spatial planning; landscape scale; restoration



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1. Introduction

1.1. Planning Green Infrastructure in Rural Landscapes

Green Infrastructure (GI) is defined as a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services, applicable to urban and rural environments [1]. Despite its recognition and incorporation into spatial planning, as outlined in the EU Biodiversity Strategy for 2020 [2], the EU GI strategy failed to meet its targets due to landscape fragmentation, land-use changes, and natural resources exploitation [3]. In response, the EU Biodiversity Strategy for 2030 emphasises the need for effective restoration measures, including the development of Nature Restoration Plans under the First Nature Restoration Law [4]. This initiative prompts discussions at the European and national levels about the content of these plans. Restoration of connectivity and landscape defragmentation should also be a priority in developing strategic planning. In the context of the UN Decade for Ecosystem Restoration, the European Habitats Forum [5] recommends providing space for natural processes to restore and sustain ecosystem functionality and resilience and stimulate partnerships with economic sectors in developing nature-based economies.

Green Infrastructure is more extensively researched in urban environments than in rural landscapes. Several studies emphasise the importance and benefits of green infrastructure in urban areas, particularly in mitigating urban heat islands, improving air quality, and enhancing human health [6–12]. These studies often explore the interactions between green infrastructure and the built environment, highlighting the systemic behaviour and socio-ecological impacts within urban contexts [6,7,9]. However, there is a notable scarcity of studies and research focusing on green infrastructure in rural areas [13]. Some studies state that the concept of green infrastructure is acknowledged in rural settings [13–15]. However, it is seldom discussed or implemented compared to urban areas. Regarding planning and policies, discussing green infrastructure is also frequently focused on city planning to address environmental challenges and improve urban resilience [8,9,11,16]. In contrast, rural green infrastructure planning is often discussed in the context of broader developmental goals and sustainable land use practices [13]. The literature highlights the lack of research on green infrastructure in rural settings and emphasises the need for a holistic and participatory planning approach in these areas. Addressing green infrastructure in rural landscapes is crucial, as it functions as a spatial tool for biodiversity conservation, enhances the delivery of ecosystem services—such as flood protection, erosion control, and carbon sequestration—supports community well-being, and strengthens strategic planning and risk management, such as floods and wildfires [17]. Moreover, it enables the identification of potential areas for ecological restoration [18].

1.2. Headwater Systems as Green Infrastructures: The Mountain Corridors

When mapping green infrastructure, there are commonly two primary components: the hubs of natural vegetation, other open spaces or areas of known ecological value; and the links, which are the corridors that connect the hubs [19]. The form, function, and character of these links are significant, as they can possess ecological value and natural vegetation while also serving as hubs that reflect the complexity of managing the landscape. The role of continuous mountain landscape systems along ridgelines is often overlooked in green infrastructure planning, both as hubs—due to their ecological importance within watershed contexts—and as links—by facilitating connectivity between diverse landscape features. These systems are defined as Headwater System Areas due to their crucial role in providing ecosystem services such as water regulation, biodiversity enhancement, and soil conservation [20], and also in wildfire regulation through the use of green firebreaks [21]. Despite their importance, these areas have not received as much attention regarding their role in providing landscape continuity and prioritisation of restoration compared to other ecosystems like river corridors. In this paper, the Headwater System areas are considered green infrastructure as a strategically planned network [1] or ecological infrastructure as critical landscape structures [22], capable of providing a wide range of ecosystem services. A biodiversity hotspot refers to an area of significant ecological value [23,24], where conservation is a priority [25]. These areas are often characterised by unique or endangered species and critical habitats [26]. A restoration hotspot, on the other hand, is an area where ecological restoration efforts can maximise multiple benefits [24,27]. These include positive impacts on specific plant and animal species, as well as broader improvements in ecological functioning and the delivery of ecosystem services. According to some authors [28], restoration hotspots are also places where restoration opportunities are greatest, combining high restoration feasibility with significant socio-environmental benefits.

In the European Union, GI includes the Natura 2000 network as well as other natural and semi-natural spaces outside Natura 2000 to guarantee biodiversity conservation. Natura 2000 is a network of protected areas across the European Union, established to ensure the long-term survival of Europe's most valuable and threatened species and habitats.

Despite its efforts, biodiversity loss continues, indicating that Natura 2000 alone may not be sufficient to halt this trend [29]. The network needs to be part of a broader strategy that includes natural processes and ecological mechanisms.

According to the results from reporting under the nature directives between 2013 and 2018 [30], the Natura 2000 network has improved habitat and species conservation but needs to move beyond surface area targets to enhance effectiveness. Strengthening connections between protected areas and expanding the functional network are essential for coherence, resilience, and ecosystem services, including carbon storage. Accordingly, this network should facilitate species migration, expand coverage, and improve functional connectivity to support biodiversity and ecosystem benefits.

1.3. Ecological Connectivity in Portuguese National Spatial Planning Policy Programme

Since the 1990s, with the publication of Decree-Law 380/99, Portugal established an integrated, hierarchical system of planning tools at national, regional, and local levels. This framework differentiates between strategic, development-oriented spatial plans and regulatory land-use plans. The National Spatial Planning Policy Programme (PNPOT) is a higher-level spatial planning instrument that defines strategic, place-based policies for territorial organisation and development. It includes a territorial model integrating a vision for resilience, development, and cohesion while guiding public policies and investments. This model is structured into five systems: natural, urban, social, economic, and connectivity.

According to [31], the identification and mapping of a basic conservation infrastructure is crucial for planning and management, considering the protection scales from international to local and the diversity of stakeholders involved, from the State, local authorities, and private entities. In the PNPOT [32], the Fundamental Network for Nature Conservation (RFCN) is referred to as a way to affirm biodiversity as a territorial capital. The RFCN combines classified and non-classified areas to ensure ecological connectivity. Classified areas fall under the National System for Classified Areas (SNAC), including those protected at national (RNAP), European (Natura 2000), and international levels (e.g., Ramsar sites, UNESCO Biosphere Reserves). Non-classified areas, such as those within the National Ecological Reserve (REN), National Agricultural Reserve (RAN), and Water Public Domain (DPH), guarantee the continuity of ecological networks.

Also, in the PNPOT, green infrastructure is referred to as something that must be strengthened to reduce habitat fragmentation, enhance connectivity, and integrate sectoral policies. The ecological connectivity that can be gathered through green infrastructures is pointed out to be established through ecological corridors defined by the hydrographic network, national and international rivers, the main headwaters systems, the coastal system, and the fundamental network of protected areas. The concept is outlined and presented schematically; however, it lacks depth in defining the key areas or establishing territorial priorities, which could be further explored at regional scales.

The Report on the State of Spatial Planning (REOT) [33] is the evaluation instrument for implementing the National Spatial Planning Policy Programme (PNPOT). The National REOT is produced every two years by the Directorate-General for Territorial Planning, in collaboration with various entities, including contributions from the public discussion. Recently, in early 2025, the public discussion of the REOT concluded.

In this report, concerning nature conservation, it is emphasised that simply protecting classified areas is insufficient. It is equally necessary to ensure genetic flow between these areas to guarantee the long-term viability of populations. The continuity of areas within the Fundamental Network for Nature Conservation is highlighted, particularly areas from the REN, which, due to their biophysical characteristics, contribute to consolidating the struc-

ture that ensures connectivity between regions crucial for biodiversity conservation. For ecological connectivity, the Iberian scale is emphasised due to the shared major rivers and the continuity of nature conservation areas. The critical land-sea connection (estuaries) is underscored, alongside connectivity provided by the primary hydrographic network (river corridors), the headwater systems of major river basins (mountain corridors), the coastal system, and classified nature conservation areas, including the corridors linking them.

1.4. Goal of This Study

In this context, where it is recognised that protecting classified areas alone is not enough and acknowledging that green infrastructure can play a crucial role in defining ecological continuities across its various systems, the aim is to go a step further in identifying linkages to restoration by exploring the role of headwater systems.

The goal of this paper is to explore the role of headwater system planning in rural landscapes as part of Green Infrastructure, focusing on identifying restoration opportunity areas and enhancing the holistic function of landscapes. Specifically, this paper aims to: (1) examine land use change in headwater systems over the past 70 years; (2) identify the need for transformation, identify restoration hotspots, and envision future possibilities for these areas; and (3) investigate how headwater systems could improve landscape connectivity between Natura 2000 sites.

2. Materials and Methods

The case study area is located in Portugal’s Centre Region, between Longitudes $-9^{\circ}30'26.668''$ and $-6^{\circ}46'2.457''$ and Latitudes $38^{\circ}55'2.527''$ and $41^{\circ}2'3.148''$. This study considers the NUT 2023 boundary, encompassing an area of 2,819,935 hectares. The region contains 24 Natura 2000 sites, covering 13.6% of the Centre Region (terrestrial). These sites are isolated, and the mapped habitats do not fully cover their areas. The study focuses on headwater systems, which are critical for landscape connectivity and ecological dynamics. These systems comprise 26.7% of the case study area, encompassing 753.510 hectares (Figure 1). The study also considered the Natura 2000 areas near the Centre Region boundary.

The methodology was developed in three phases: (1) Land-use change analysis, (2) Proposed Land-Use change scenario, and (3) Connectivity Assessment between Headwater Systems and Natura 2000 sites. All methods were performed within a Geographic Information System using ArcGIS Pro version 3.0.3 software from @Esri (United States of America). The materials—databases—used to perform the research study are detailed in Table 1.

Table 1. GIS Data used in the study, source, and authors.

GIS Data	Source	Authors
Agricultural and Forest Map of Mainland Portugal 1951–1980	https://snig.dgterritorio.gov.pt/ (accessed on 4 October 2024)	ISA, DGT, ICNF
Land Use and Land Cover Map of Mainland Portugal 1995	https://snig.dgterritorio.gov.pt/ (accessed on 4 October 2024)	DGT
Land Use and Land Cover Map of Mainland Portugal 2018	https://snig.dgterritorio.gov.pt/ (accessed on 4 October 2024)	DGT
Headwater Systems of Mainland Portugal	http://epic-webgis-portugal.isa.ulisboa.pt/ (accessed on 8 October 2024)	ISA: Pena et al. 2018 [20]
Special Areas of Conservation (SAC) -Natura 2000	https://geocatalogo.icnf.pt/ (accessed on 6 January 2025)	ICNF

ISA—School of Agriculture from the University of Lisbon; DGT—Directorate-General for Territory from Portugal; ICNF—Institute for Nature Conservation and Forests from Portugal.

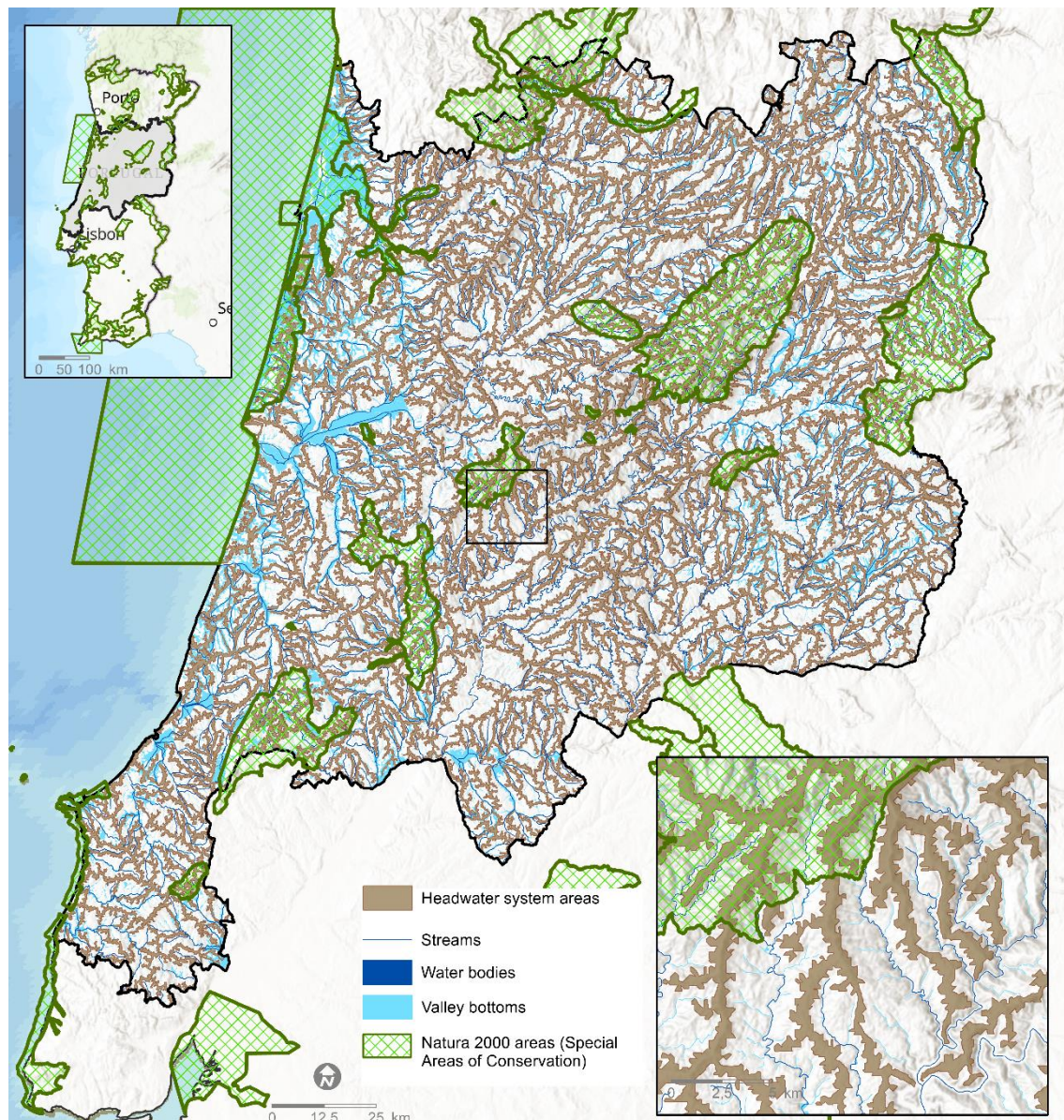


Figure 1. Headwater Systems in the Centre Region and Natura 2000 Areas.

2.1. Phase 1—Land-Use Change Analysis

To assess land-use evolution in the headwaters, data from three sets were analysed, using official land-use maps corresponding to land-use maps between 1951 and 1980 (referred to here as 1951), 1995, and 2018. The analysis was conducted using spatial analysis methods in ArcGIS Pro, which allowed for identifying land-use change trends. These time periods under study are not equivalent due to a lack of data, but each reflects distinct moments of landscape transformation that were intended to be captured. Specifically, the first period (1951–1980) corresponds to the onset of major forest changes in Portugal, marked by large-scale afforestation plans and incentives for monoculture plantations. The second period aims to capture the end of the 20th century, while the third represents the most recent land use and land cover (LULC) mapping, from 2018. The method involves evaluating land use classes for each period in terms of area and percentage, as well as constructing land use transition matrices for the periods 1951–1995 and 1995–2018, in order to identify which land use categories have changed and what they have transitioned into.

2.2. Phase 2—Proposed Land-Use Change Scenario—Identification of Restoration Hotspots

Based on the observed land use patterns and the ecological importance of Headwater System (HS) areas, particularly their role in water, soil, and biodiversity dynamics, a land-use change proposal was developed to enhance their ecological functioning. The proposal incorporates strategic reforestation, assisted natural regeneration, and promotes agrosilvopastoral and sustainable agricultural systems to enhance landscape resilience and support biodiversity. This land-use approach aligns with the goals of Landscape Fire Resilience and is grounded in ecological land suitability principles [32]. The following principles guide the proposed land-use strategy for Headwater System areas:

- The ideal land use is mixed woods with native broadleaved species to maximise water infiltration and soil conservation, provide a biodiversity hub and reduce fire spread; Mixed woods are generally better at guaranteeing water infiltration due to improved soil hydraulic properties, higher infiltration rates, and better water storage capacity. These benefits are attributed to the diversity in root systems, litter composition, and complementary ecological functions of mixed-species forests [34,35]. In contrast, monoculture plantations, such as eucalyptus, while economically valuable, often have shallower roots and higher water consumption rates, which can lead to reduced soil moisture and increased erosion risk [36]. Understanding these differences is crucial for optimising land-use strategies that balance ecological functions, restoration goals, and economic considerations.
- If agriculture or pastures exist, they should be kept, only adding sustainable management actions and hedges; A hedge is a linear feature composed of closely planted shrubs or trees that serves as a boundary marker, windbreak, or habitat corridor in rural and agricultural landscapes. Hedges provide ecological functions such as offering shelter and food for wildlife, facilitating species movement, reducing soil erosion, and contributing to landscape connectivity.
- If high-quality soils are present—such as fertile soils—agricultural land use may be proposed, accompanied by sustainable management practices and the integration of hedges.
- The settlements located in the headwaters system should include agriculture or pastures in the wildland-urban interface;
- The existing shrubs are important in biodiversity, soil and water conservation, and economic add-in (aromatic, honey, etc). Their regeneration can be assisted.

During this phase, areas that require a change in their current land use or management practices are systematically identified. These designated restoration hotspots are characterised by a range of factors, including topographical features such as slope, historical land use patterns, and the potential for natural vegetation recovery. Given the diversity of these characteristics, each restoration hotspot necessitates a tailored approach that takes into account its unique ecological and physical conditions to maximise the effectiveness and sustainability of restoration efforts.

2.3. Phase 3—Connectivity Assessment Between Headwater Systems and Natura 2000 Sites

To evaluate the role of headwater areas in defining a linkage infrastructure between the existing Natura 2000 network, the cost connectivity tool in ArcGIS Pro was applied to understand the role of headwaters in providing linkages. These methods allowed for the assessment of functional connectivity, identifying key areas for intervention to optimise habitat corridors and strengthen ecological networks. The 'Input Raster or Feature

Region Data’ corresponded to the Special Areas of Conservation (SACs) from Natura 2000 (Habitat Directive).

The hierarchical structure informed the assignment of values to the cost surface of the river basin network. In this approach, higher-order basins were assigned lower resistance values to reflect their greater potential for ecological connectivity. The cost surface—defined through the ‘Input Cost Raster’ parameter—was derived from the Headwater System Areas, with ranked classes corresponding to river basin hierarchy (1 = first order, 2 = second order, 3 = third order). Areas outside the headwater systems were assigned ‘NoData’ values to ensure that the connectivity analysis was restricted exclusively to headwater areas. The resulting output is a feature class of neighbouring connections, representing the least-cost paths between each SAC and its adjacent SACs. This allows for the prioritisation of headwater areas that most effectively enhance connectivity among the SACs within the Natura 2000 network.

3. Results

3.1. Land Use Change

The analysis of land use changes in Headwaters System Areas over the three studied years (1951, 1995, and 2018) reveals significant transformations in the landscape (Figure 2). One of the most striking trends is the expansion of eucalyptus forests, which increased from 4% to 18% over this period (Figure 3).

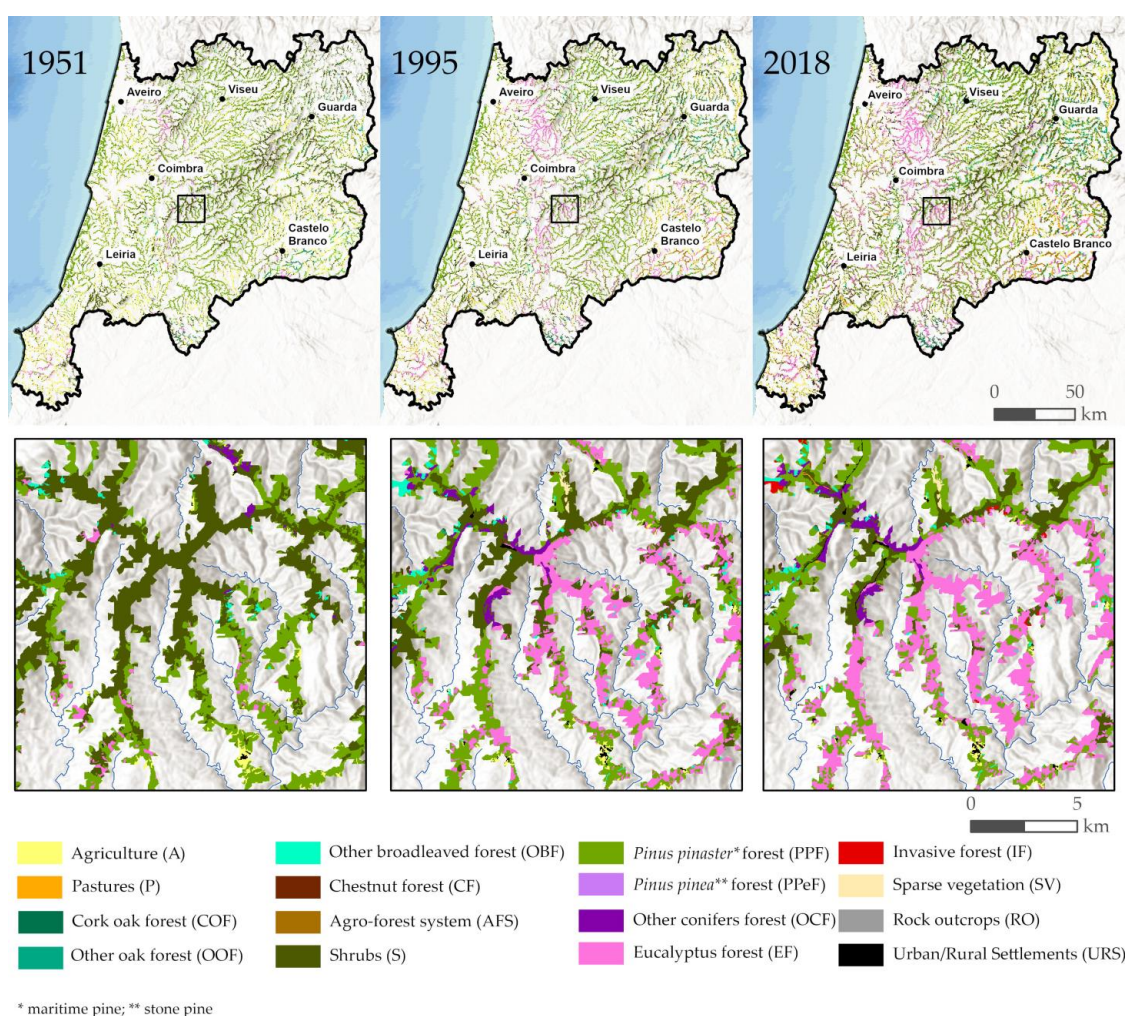


Figure 2. Land use maps of the headwater systems from three years: 1951, 1995, and 2018.

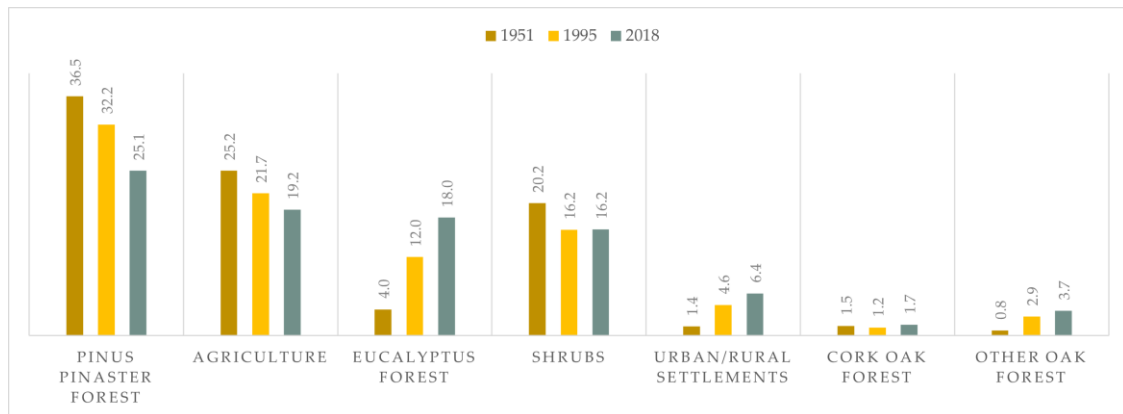


Figure 3. Evolution of land use in the headwater system during three periods: 1951, 1995, and 2018 (Only classes representing more than 1% were considered).

Conversely, the extent of *Pinus pinaster* Aiton forests and agricultural lands has steadily declined. The land use transition matrix between 1951 and 1995 (Table 2) and between 1995 and 2018 (Table 3) allows us to verify how different types of land use converted into another. For example, regarding the eucalyptus forest, most of the 1995 eucalyptus class came from *Pinus pinaster* conversion (43.9%), shrubs (15.4%), and agriculture (12.3%). Also, between 1995 and 2018, the majority of the eucalyptus class came from former *Pinus pinaster*, shrubs, and agriculture class. In Tables 2 and 3, the values highlighted in bold denote the land use classes that account for the largest proportion of land use transitions.

Table 2. Land use transition matrix between 1951 (columns) and 1995 (rows). Percentage in relation to LULC 1995 classes.

LULC 1951																			
LULC 1995	A	AFS	CF	COF	EF	OBF	OCF	OOF	P	PPeF	PPF	RO	S	SV	URS	W	IF	Nodata	Area (ha) 1995
A	65.2	0.6	0.4	0.5	0.8	0.3	0.0	0.5	0.1	0.1	8.2	0.0	4.5	0.0	1.0	0.0	0.0	17.6	163,581
AFS	18.6	5.4	0.4	29.3	0.4	0.5	0.0	34.6	0.0	0.2	1.6	0.0	7.3	0.0	0.1	0.0	0.0	1.6	11,498
CF	12.1	0.5	27.3	0.0	1.0	7.1	0.2	4.2	0.0	0.0	22.7	0.0	18.2	0.0	0.1	0.0	0.0	6.7	947
COF	27.0	3.9	0.2	36.4	1.2	0.5	0.0	4.2	0.0	0.0	4.6	0.0	20.1	0.0	0.1	0.0	0.0	1.9	9110
EF	12.3	0.5	0.1	1.4	23.6	0.4	0.1	1.2	0.0	0.1	43.9	0.0	15.4	0.0	0.0	0.0	0.0	1.0	90,292
OBF	19.3	0.2	1.1	0.6	2.1	3.9	0.2	1.8	0.0	0.3	41.3	0.3	19.6	0.2	0.5	0.1	0.0	8.5	9254
OCF	13.9	0.1	0.1	1.6	1.9	1.1	1.9	3.4	0.0	0.1	22.7	0.0	49.3	0.0	2.5	0.0	0.0	1.5	2350
OOF	14.8	2.1	2.8	1.6	0.2	5.8	0.1	19.5	0.1	0.0	20.7	0.0	23.8	0.0	0.1	0.0	0.0	8.3	27,352
P	47.4	2.2	0.2	2.3	1.1	0.3	0.0	3.5	0.3	0.0	5.9	0.1	24.0	0.0	0.3	0.0	0.0	12.3	28,917
PPeF	25.8	0.6	0.0	2.0	1.7	2.0	0.0	4.1	0.1	15.0	30.6	0.0	16.4	0.0	0.8	0.0	0.0	0.8	1748
PPF	7.7	0.1	0.2	0.3	2.2	0.5	0.1	0.3	0.0	0.3	71.4	0.0	14.5	0.0	0.1	0.0	0.0	2.3	242,869
RO	0.7	0.1	0.1	0.0	0.3	0.0	0.0	0.7	0.0	0.0	13.4	3.5	79.3	0.0	0.0	0.3	0.0	1.4	1124
S	11.6	0.2	0.2	0.4	0.4	0.5	0.1	0.8	0.1	0.1	23.6	0.0	55.2	0.0	0.1	0.0	0.0	6.5	121,671
SV	0.8	0.1	0.0	0.1	0.0	0.2	0.0	0.4	0.0	0.0	10.9	0.4	78.3	5.3	0.1	1.1	0.0	2.3	7441
URS	39.3	0.3	0.1	0.3	2.1	0.2	0.0	0.3	0.1	0.2	16.7	0.1	5.9	0.0	22.9	0.0	0.0	11.3	35,022
W	29.4	0.9	0.0	1.2	3.9	0.0	0.0	1.8	0.0	0.7	10.1	0.6	13.9	1.6	0.4	34.6	0.0	1.0	172

A—Agriculture; AFS—Agro-forest system; CF—Chestnut forest; COF—Cork oak forest; EF—Eucalyptus forest; IF—Invasive Forest; nodata—no information mapped; OBF—Other broadleaved forest; OCF—Other conifers forest; OOF—Other oak forest; P—Pastures; PPeF—*Pinus Pinca* forest; PPF—*Pinus pinaster* forest; RO—Rock Outcrops; S—Shrubs; SV—Sparse vegetation; URS—Urban/Rural Settlements; W—Water. The grey color represents the percentage of each land use category that remained unchanged, while the values in bold indicate the land use classes with the highest proportion of transitions.

Despite these trends, urban and rural settlements have expanded, particularly in coastal areas. This urbanisation process reflects broader demographic shifts, economic development, and infrastructural improvements that attract populations toward more urbanised regions. These changes highlight the complex interactions between socio-economic factors, land management, and ecological dynamics in shaping the evolution of Headwaters System Areas.

Table 3. Land use transition matrix between 1995 (columns) and 2018 (rows). Percentage in relation to LULC 2018 classes.

LULC 1995																	Area (ha) 2018
LULC 2018	A	AFS	CF	COF	EF	OBF	OCF	OOF	P	PPeF	PPF	RO	S	SV	URS	W	
A	87.9	0.1	0.0	0.1	0.7	0.3	0.0	0.5	2.2	0.0	3.6	0.0	2.9	0.0	1.6	0.0	144,796
AFS	2.2	87.4	0.0	2.2	0.7	0.0	0.0	4.4	1.8	0.0	0.6	0.0	0.7	0.0	0.1	0.0	10,886
CF	16.3	0.0	64.5	0.0	0.2	0.5	0.0	0.9	0.6	0.0	8.3	0.0	8.6	0.0	0.2	0.0	1341
COF	9.8	3.8	0.0	65.7	2.2	0.0	0.0	0.4	9.2	0.0	2.9	0.0	5.8	0.0	0.1	0.0	12,481
EF	3.3	0.0	0.0	0.2	62.3	0.3	0.0	0.1	0.5	0.0	29.6	0.0	3.3	0.0	0.3	0.0	135,591
IF	3.1	0.0	0.0	0.0	2.2	51.3	0.0	0.4	0.4	0.1	33.8	0.0	8.1	0.1	0.5	0.0	3224
OBF	15.9	0.0	0.0	0.1	1.7	57.5	0.1	0.3	1.3	0.1	16.6	0.0	5.6	0.0	0.7	0.0	9931
OCF	20.6	0.0	0.0	0.0	0.6	0.3	48.4	1.0	5.1	0.0	8.6	0.0	15.1	0.0	0.1	0.0	4325
OOF	4.3	1.3	0.0	0.1	0.2	0.1	0.0	86.7	1.4	0.0	1.3	0.0	4.4	0.1	0.1	0.0	28,250
P	23.6	2.3	0.0	0.2	0.8	0.2	0.0	0.8	62.7	0.0	1.9	0.0	6.9	0.1	0.4	0.0	30,772
PPeF	20.9	0.3	0.0	0.5	1.6	0.9	0.0	0.4	5.7	50.2	13.9	0.0	4.8	0.0	0.8	0.0	3013
PPF	2.9	0.0	0.0	0.0	0.8	0.2	0.1	0.2	0.5	0.0	90.8	0.0	4.1	0.0	0.3	0.0	189,468
RO	0.7	0.1	0.0	0.0	0.1	0.0	0.0	0.8	0.8	0.0	1.8	88.2	5.6	1.8	0.1	0.0	1143
S	4.7	0.0	0.0	0.1	0.4	0.2	0.0	0.5	1.3	0.0	12.7	0.0	79.6	0.2	0.2	0.0	122,038
SV	0.3	0.0	0.0	0.0	0.1	0.7	0.0	0.3	0.5	0.0	1.3	0.1	5.1	91.5	0.1	0.0	7618
URS	14.9	0.2	0.0	0.1	3.8	0.6	0.0	0.3	1.6	0.1	10.0	0.0	3.3	0.1	65.1	0.0	48,184
W	13.3	1.4	0.0	1.4	2.4	0.1	0.0	1.6	4.9	0.0	16.4	0.2	3.7	1.3	1.5	51.8	290

A—Agriculture; AFS—Agro-forest system; CF—Chestnut forest; COF—Cork oak forest; EF—Eucalyptus forest; IF—Invasive Forest; OBF—Other broadleaved forest; OCF—Other conifers forest; OOF—Other oak forest; P—Pastures; PPeF—*Pinus Pinea* forest; PPF—*Pinus pinaster* forest; RO—Rock Outcrops; S—Shrubs; SV—Sparse vegetation; URS—Urban/Rural Settlements; W—Water. The grey color represents the percentage of each land use category that remained unchanged, while the values in bold indicate the land use classes with the highest proportion of transitions

3.2. Proposed Land-Use Change Scenario—Identification of Hotspots

A hotspot is a place of opportunity where restoration should occur, benefiting water and soil conservation, increasing biodiversity, reducing risks, and providing ecological connectivity. The long-term vision for these areas is mixed woodlands composed of species from the region's natural potential vegetation. The natural potential vegetation presupposes a clear correspondence between a uniform combination of bioclimatic stage and lithology, given the biogeographical context, and a unique successional sequence leading to a single climax community [37]. However, the proposed restoration actions depend on current land use and other landscape characteristics. For instance, if the headwaters have fertile soils, the ideal land use would be agriculture to fully exploit these areas, while also considering the necessity of adopting sustainable management practices and landscape features that can benefit biodiversity, water, and soil conservation, such as hedges, to provide habitat corridor and other ecological function, such as reducing soil erosion and improve water infiltration. Conversely, if the current landscape consists of pastureland used for grazing—commonly practised in highland commons—these practices should not be overlooked. Therefore, headwater systems are compatible with species from natural potential vegetation, ranging from shrubs to forests, as well as pasture or agricultural landscapes. The potential land uses in the headwater system follow the principles outlined in the materials and methods section.

By comparing current land use (Land Use and Land Cover Map of Mainland Portugal 2018) with the potential land use envisioned in headwater systems, in GIS, it is possible to identify areas where land use is compatible with conservation goals and those in conflict, which require restoration efforts. The results indicate that 34% of the headwater systems currently exhibit land use practices that align with the guiding principles of the proposed land use strategy. The results also indicate that restoration hotspots encompass 58% of the Headwater Systems and include several subsystems (Figures 4 and 5): restoring coastal landscapes (0.9%), restoring forest landscapes (46%), and restoring agricultural landscapes (11.5%).

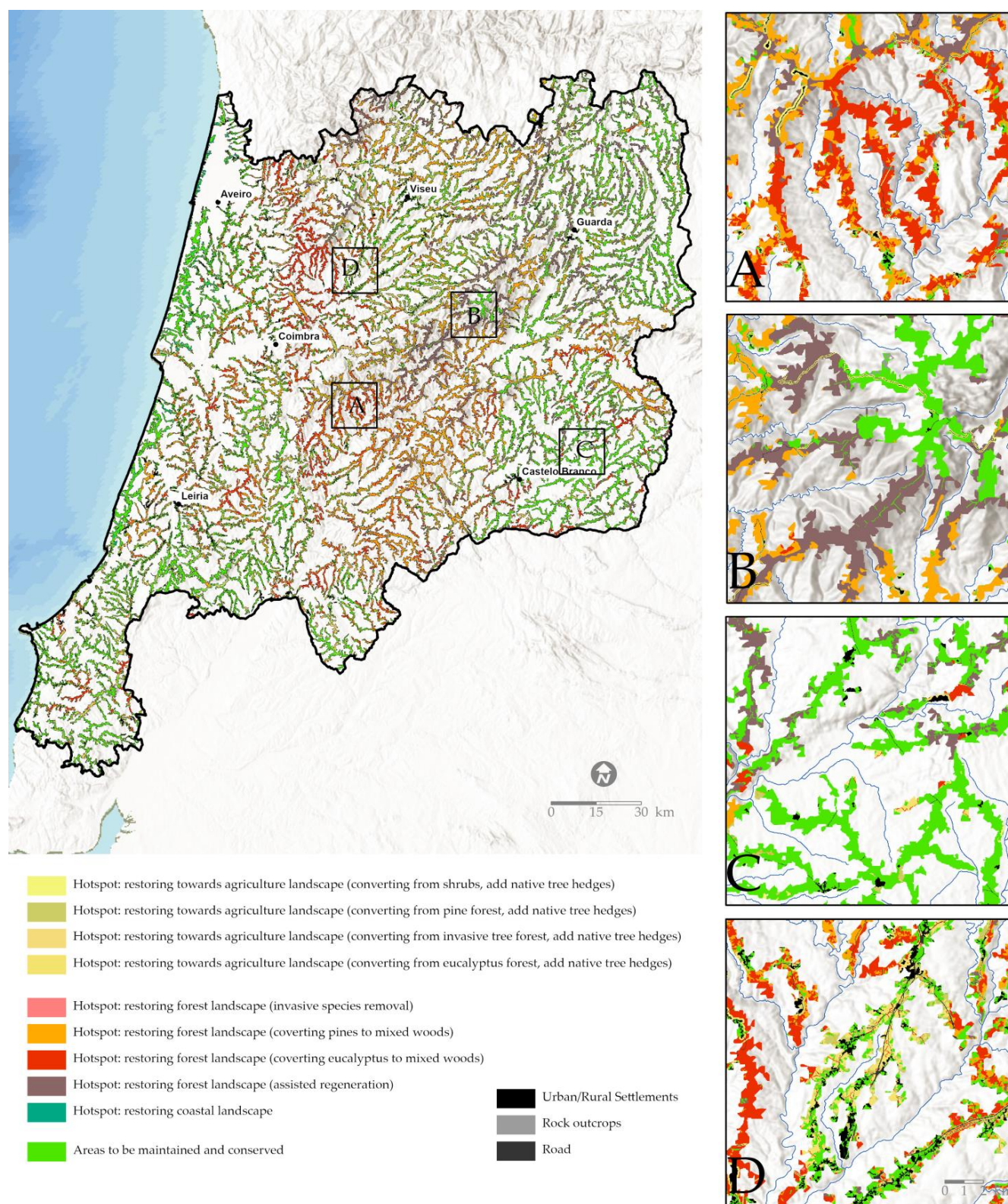


Figure 4. (A–D) Hotspots for Restoring Headwater Systems.

The hotspot for restoring the agricultural landscape comprises areas in headwater systems that have potential for agriculture, either due to soil characteristics or proximity to settlements. This hotspot typology includes conversions from shrubs (1.8%), maritime pine forest (5.3%), eucalyptus forest (4.3%), and invasive trees such as *Acacia* sp. (0–0.1%).



Figure 5. Actions percentage in the Headwater system areas. (Light green: areas that require no changes; blue: restoration in coastal landscapes; dark green: restoration in forest landscapes; dark yellow: restoration in agricultural landscapes; grey and black: other areas not subject to restoration).

The hotspot for restoring forest landscapes involves transforming forest composition and integrating species from potential natural vegetation, as the native vegetation that would be most likely to exist in the absence of human activities. This change should be implemented progressively, ideally through close-to-nature silviculture. By comparing the proposed land use with the current land use, the data indicate that 17.9% of the area should be converted from maritime pine, 13.1% from eucalyptus, and 14.9% should undergo assisted natural regeneration, following the successional sequence from existing shrubland.

The coastal landscape includes only 0.9% restoration, but it is also essential to diversify ecological systems and contribute to equilibrium in coastal morphologies.

The target restoration of the total hotspot is 439,822 ha, representing 16% of the Central Region.

In the Natura 2000 areas (Table 4), data show that about 44% of the headwater system areas have current land uses aligned with those identified in the guiding principles of the proposed land use strategy. Thus, they represent land uses that should be maintained and conserved; 45% should be progressively transformed into a biodiverse forest landscape with mixed woods from natural vegetation series, 5.6% is compatible with agricultural landscapes, and 2.1% is located along the coastal area where specific restoration should be targeted.

Table 4. Restoration actions in the headwater systems of the Natura 2000 sites (SAC), area, and percentage.

Restoration Actions in the Headwater Systems of the Natura 2000 Sites (SAC)	Area (ha)	% Concerning Total Headwaters Area in SAC
Areas to be maintained and conserved	45,285	43.6
Hotspot: restoring forest landscape (converting eucalyptus to mixed woods)	2805	2.7
Hotspot: restoring forest landscape (assisted regeneration)	25,072	24.1

Table 4. Cont.

Restoration Actions in the Headwater Systems of the Natura 2000 Sites (SAC)	Area (ha)	% Concerning Total Headwaters Area in SAC
Hotspot: restoring forest landscape (converting pines to mixed woods)	18,912	18.2
Hotspot: restoring towards agriculture landscape (converting from eucalyptus forest, adding native tree hedges)	1406	1.4
Hotspot: restoring towards agriculture landscape (converting from shrubs, adding native tree hedges)	1510	1.5
Hotspot: restoring towards agriculture landscape (converting from pine forest, adding native tree hedges)	2859	2.8
Hotspot: restoring towards an agriculture landscape (converting from invasive tree forest, adding native tree hedges)	73	0.1
Hotspot: restoring the coastal landscape	2185	2.1

3.3. Connectivity Assessment Between Headwater Systems and Natura 2000 Sites

The Cost Connectivity Tool in ArcGIS Pro enabled the analysis of linkages between Natura 2000 sites through headwater systems using the graph theory. The spatial representation of these linkages is shown in Figure 6. The black lines represent the least-cost path that can be established between each Natura 2000 area through the Headwater system (HS) areas.

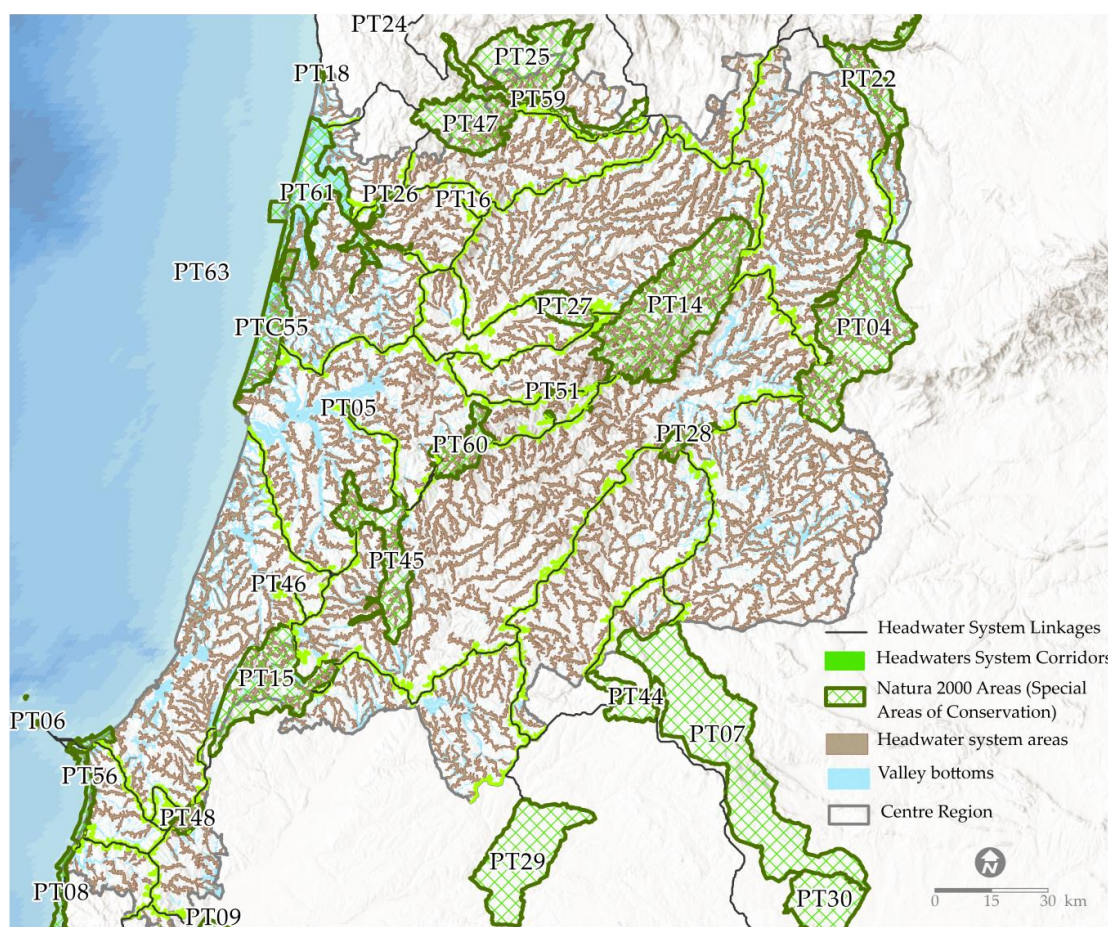


Figure 6. Linkages and corridors between Natura 2000 Sites through Headwater systems.

Linkages can be planned both within the Centre Region and between Natura 2000 sites in the Centre Region (internal connections) and between those in the northern or southern

areas (external connections). In total, there are 61 linkages: 13 external and 48 internal (Figure 7). Considering external linkages is particularly relevant, given that ecological connectivity transcends administrative boundaries, such as the limits of the Centre Region. Several key linkages originate in Special Areas of Conservation (SACs) within the Centre Region and extend into both northern and southern neighboring regions, highlighting the need for cross-regional coordination in connectivity planning. The average length of these linkages is 77 km. The internal linkages span 3206 km, while the external ones cover 1514 km. However, overlapping segments exist within this network.

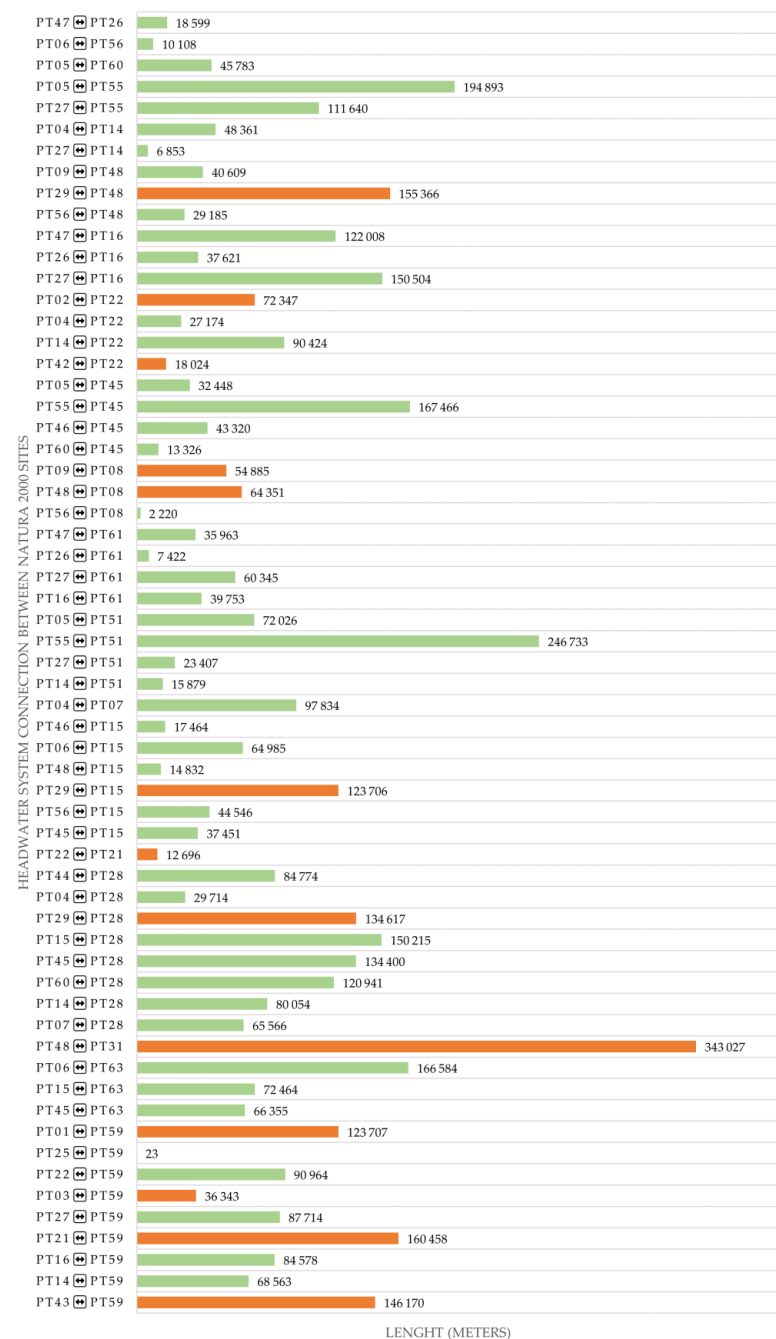


Figure 7. Length of the linkages between Natura 2000 Sites. The arrow symbol represents the linkage between two Natura 2000 sites; the green represents the linkages between Natura 2000 sites within the Centre Region, while the orange indicates linkages between Natura 2000 sites in the Centre Region and those outside.

Excluding the double-counting of overlapping segments, the total length of the network within the Centre Region is 1332 km. This linear network allows for the identification of HS areas capable of functioning as short-distance ecological corridors between SACs (Figure 6). Considering the results from Section 3.2, the mapped corridors in the Centre Region indicate that about 67% should have restoration actions (Table 5). The results reveal that approximately 33% of the features have suitable land uses and should be conserved, while 53% require restoration of forest landscapes, and 14% necessitate actions to restore agricultural landscapes.

Table 5. Restoration actions in the HS corridors between Natura 2000 sites.

Restoration Action in the HS Corridors Between Natura 2000 Sites	Area (ha)	Percentage
Hotspot: restoring forest landscape (converting pines to mixed woods)	19,852	18.8
Hotspot: restoring forest landscape (converting eucalyptus to mixed woods)	18,116	17.2
Hotspot: restoring forest landscape (assisted regeneration)	17,747	16.8
Hotspot: restoring forest landscape (deal with invasive trees)	204	0.2
Hotspot: restoring towards agriculture landscape (converting from eucalyptus forest, adding native tree hedges)	6359	6.0
Hotspot: restoring towards agriculture landscape (converting from pine forest, adding native tree hedges)	6216	5.9
Hotspot: restoring towards agriculture landscape (converting from shrubs, adding native tree hedges)	1931	1.8
Hotspot: restoring the coastal landscape	339	0.3

4. Discussion

The results underscore the critical role of headwater systems in enhancing ecological connectivity across the Centre Region of Portugal. Integrating these areas into green infrastructure planning strengthens ecological networks by supporting key ecological processes necessary for the sustained delivery of a wide range of ecosystem services [38], while also advancing biodiversity conservation beyond the scope of the Natura 2000 framework. The analysis reveals substantial land-use transformations over the past 70 years, underscoring the need for targeted restoration strategies aligning with environmental and socio-economic objectives. These findings are consistent with previous research on the importance of riparian corridors and headwater ecosystems in promoting landscape connectivity and biodiversity conservation [39], reinforcing the imperative to incorporate them into regional planning frameworks.

4.1. Land Use Dynamics in Headwater Systems

Land use changes observed in the study area—namely the expansion of eucalyptus plantations and agricultural abandonment—are not solely ecological phenomena but are also deeply rooted in socio-economic dynamics. This shift is mainly attributable to socio-economic drivers, particularly the economic incentives introduced through large-scale reforestation programs in the 1960s, which promoted monocultures of fast-growing timber species [40]. While these initiatives contributed to job creation in the forestry sector, they coincided with a decline in traditional agricultural activity and rural depopulation. Quantitative studies in Southern Europe have demonstrated strong correlations between rural depopulation, reduced agricultural profitability, ageing farming populations, and the transition toward less intensive or industrial land uses [41]. For example, econometric models have shown that municipalities with declining population densities and low agricultural incomes are more likely to experience forest expansion or plantation forestry [42]. Although our study did not include a detailed socio-economic model, we recognise that integrating such variables—such as census trends, land ownership fragmentation, CAP

subsidy patterns, and rural labour dynamics—would add depth to our understanding of land use trajectories. We therefore identify this integration as a critical next step for aligning ecological priorities with socially viable restoration strategies.

These land-use dynamics—driven by economic policy, demographic shifts, and land management practices—have contributed to increased landscape fragmentation, greater wildfire risk, and loss of biodiversity [43,44]. Similar patterns have been documented in other Mediterranean regions, where afforestation with fast-growing exotic species has led to ecological degradation and reduced resilience [45]. The ongoing decline of *Pinus pinaster* is primarily attributed to the increased frequency of rural fires and the abandonment of agricultural land, which together contribute to changes in vegetation cover and further exacerbate ecosystem vulnerability. The reduction of agricultural areas is particularly concerning, as it reflects broader processes of rural depopulation, leading to unmanaged landscapes and heightened exposure to fire and other disturbances. These findings reinforce the urgency of proactive land-use planning that integrates ecological restoration with sustainable rural development.

In recent years, forest value has been gradually redefined to encompass more diverse systems that include not only wood production but also non-wood forest products [46] and the broader range of ecosystem services they provide [47]. Headwater systems represent a strategic entry point for driving this transition, with the potential to diversify the wider landscape matrix progressively.

Future research is needed to empirically test these socio-economic and policy-related factors to deepen our understanding of the drivers of land-use change and their implications for landscape restoration and management.

4.2. Restoration in Headwater Systems

The identification of restoration hotspots provides a robust foundation for landscape-scale interventions aimed at enhancing ecosystem services and ecological connectivity. The proposed restoration scenarios are informed by natural vegetation succession dynamics and advocate for mixed woodlands, sustainable agricultural systems, and fire-resilient landscapes. Notably, 58% of headwater systems in the study area require some form of restoration, highlighting the urgency of implementing site-specific measures. These findings are consistent with previous studies demonstrating that the restoration of riparian and headwater ecosystems plays a pivotal role in regional biodiversity conservation and climate change adaptation strategies [48,49]. The classification of the landscape into agricultural, forest, and coastal restoration zones offers a structured approach to addressing diverse ecological conditions and socio-economic realities. This framework not only enhances the effectiveness of restoration efforts but also provides a transferable model for other Mediterranean regions facing similar environmental pressures and land-use conflicts.

Nonetheless, implementing restoration in headwater systems is often constrained by significant socio-economic barriers [50]. One of the primary challenges is the limited financial capacity of local landowners and municipalities, which hinders investment in restoration activities, especially when short-term economic returns are uncertain. Additionally, rural depopulation and land abandonment result in a lack of human capital and institutional capacity to sustain long-term restoration efforts. Competing land uses—such as commercial forestry—can also obstruct restoration, as they tend to offer more immediate economic benefits. Furthermore, low awareness of the ecological importance of headwater areas can lead to insufficient community engagement and weak policy prioritisation. Overcoming these challenges requires integrated policy support, financial incentives, and participatory governance models that align ecological objectives with local development goals. Future research should explore how stakeholder engagement can enhance the under-

standing of local perspectives, foster long-term support, and ensure the social feasibility of restoration efforts, particularly in assessing whether identified restoration hotspots align high restoration feasibility with socio-environmental benefits.

The connectivity assessment performed demonstrates that headwater systems can function as effective ecological corridors, linking isolated Natura 2000 sites. Identifying 61 internal and external connections provides a valuable basis for strategic planning aimed at increasing habitat permeability and facilitating species movement. After accounting for overlapping segments, the total network length suggests a significant opportunity for landscape-scale restoration to strengthen ecological connectivity across the region [51]. These findings align with existing connectivity models that emphasise the importance of continuous and well-connected ecosystems for maintaining biodiversity and ecosystem resilience.

4.3. From Science to Policy: Bridging Restoration and Governance

Overall, the results support the objectives of the Portuguese National Programme for Spatial Planning Policy (PNPOT) [32] and the EU Biodiversity Strategy for 2030 [4]. However, existing policies often lack spatial specificity in defining priority areas for ecological connectivity at the regional scale. The outcomes of this study indicate that headwater systems should be explicitly integrated into national and regional green infrastructure strategies. Moreover, the Portuguese Fundamental Network for Nature Conservation would benefit from an expanded framework that recognises headwater systems as critical components of ecological continuity. Previous policy assessments have underscored the need for more targeted and regionally adapted measures to meet connectivity and biodiversity goals [52] effectively. In this context, incorporating headwater systems into planning and policy frameworks may offer a concrete step toward bridging current implementation gaps and enhancing landscape ecological resilience.

The identification of restoration hotspots in headwater systems offers actionable insights for spatial planning and policy implementation. These findings can support the prioritisation of areas for ecological restoration within regional and national strategies, such as river basin management plans, biodiversity action plans, nature restoration plans, and agri-environmental schemes that offer funding and incentives for landowners under the Common Agricultural Policy (CAP). Policymakers can use these spatial outputs to allocate restoration funding more efficiently, particularly in catchments where ecological returns are likely to be highest.

To enhance the practical application of the identified restoration hotspots, it is crucial to consider appropriate restoration techniques adapted to the ecological conditions of Mediterranean landscapes. Depending on site degradation and land-use history, passive restoration (natural regeneration) may be viable in areas with nearby native seed sources and minimal disturbance [53]. In more degraded areas, active methods are often required, including afforestation using container-grown native broadleaved species, direct seeding, and soil preparation techniques to reduce compaction and increase water infiltration [54,55]. Selecting drought-tolerant native species and using mulch or nurse plants can further improve establishment success and long-term resilience. Integrating these techniques into hotspot areas may optimise restoration outcomes, particularly in headwater systems where vegetation recovery is closely linked to water regulation and erosion control.

Managing trade-offs with other land uses requires participatory planning processes that involve stakeholders from agriculture, forestry, conservation, and local communities, enabling the negotiation of compromises and co-benefits. Adaptive management approaches that monitor ecological and socio-economic outcomes can further help balance competing priorities and adjust interventions over time.

4.4. Study Limitations

As with any spatial modelling approach, this study is subject to inherent limitations related to data availability, resolution, and modelling assumptions. The spatial data used—including land use/land cover classifications and hierarchical river basin information—may contain classification errors and variations in spatial resolution. Consequently, the reported percentages and spatial prioritisation outputs should be interpreted as indicative rather than precise values.

The connectivity analysis was deliberately focused on headwater systems, using a least-cost path approach tailored to these specific ecological units. While this focus highlights the critical role of headwaters in regional connectivity, it may overlook alternative connectivity pathways beyond these areas—such as valley bottoms, riparian zones, or semi-natural agricultural mosaics—that also contribute to ecological resilience. Therefore, the centrality of headwater systems in our findings must be understood within the context of this methodological framing.

Moreover, although the study provides a structural assessment of connectivity—delineating 61 potential corridors with an average length of 77 km—it does not evaluate functional connectivity, such as species movement or habitat suitability. Addressing functional aspects typically requires species-specific ecological resistance surfaces and distribution models, which demand detailed ecological data that were beyond the scope of this study. Future research should integrate these components to inform conservation planning and corridor effectiveness better.

Another limitation concerns the scope of the restoration prioritisation. While our approach is grounded in ecological modelling and biophysical indicators, effective ecological restoration also depends on historical land-use legacies, social acceptance, and institutional feasibility. The identification of restoration hotspots based on potential should be seen as a preliminary step in a broader, iterative process that includes validation through stakeholder engagement and integration of local ecological knowledge.

Additionally, this study does not include a cost–benefit assessment of restoration scenarios. The decision-making process also requires consideration of direct implementation costs, opportunity costs, and long-term socio-ecological benefits such as biodiversity recovery, water regulation, and carbon sequestration. Incorporating spatial economic data and ecosystem service valuation frameworks in future studies will be crucial to ensure that proposed actions are not only ecologically sound but also financially and socially viable.

5. Conclusions

This study reinforces the importance of headwater systems as key components of green infrastructure, capable of enhancing landscape connectivity and ecological resilience. By integrating these areas into spatial planning frameworks, it is possible to create a more cohesive and functional ecological network that supports biodiversity, mitigates climate change impacts, and promotes sustainable land-use practices. Accordingly, in the Centre Region, 58% of the Headwaters System needs restoration, even in Natura 2000 areas, where restoration is required in 45% of the HS. The study also showed the possibility of establishing 61 linkages and corridors between Natura 2000 areas through Headwaters.

The results call for a stronger policy emphasis on headwater system restoration, ensuring that these areas contribute effectively to broader conservation and sustainability goals. The integration of findings from this study with broader ecological and policy discussions highlights the urgent need for multi-scale approaches that align local restoration efforts with national and EU-level conservation strategies. Despite the regional specificity of Portugal's Central Region, Headwater Systems represent key green infrastructure with

the potential to enhance connectivity between Natura 2000 sites, while also contributing to greater landscape diversity, risk reduction, and the enhancement of ecosystem services.

From a management perspective, the mapped restoration hotspots can guide the design and implementation of targeted interventions in headwater landscapes. Land managers and local authorities could use these outputs to coordinate restoration actions across multiple landholdings. These prioritising measures enhance connectivity and support key ecosystem services such as water quality regulation and flood mitigation. For example, restoration efforts in agricultural headwaters could include the establishment of contour hedgerows, sediment traps, or exclusion fencing to reduce livestock access to streams. Additionally, engagement with local communities and stakeholders is essential to ensure that restoration strategies are adapted to the socio-ecological realities of each area, increasing their feasibility and long-term success.

Studies on governance models and incentive structures for sustainable land management could provide valuable insights into how restoration efforts can be effectively implemented at both local and regional scales. Furthermore, research into the hydrological impacts of headwater restoration on downstream water availability and quality could inform integrated watershed management strategies.

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Data Availability Statement: The datasets presented in this article are not readily available because the data are part of an ongoing study. Requests to access the datasets should be directed to author.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GI	Green Infrastructure
EU	European Union
PNPOT	National Spatial Planning Policy
SNAC	National System for Classified Areas
RNAP	National Protected Areas Network
REN	National Ecological Reserve
REN	National Agriculture
DPH	Water Public Domain
REOT	Report on the State of Spatial Planning
SAC	Special Areas of Conservation from Natura 2000
ISA	School of Agriculture from the University of Lisbon
ICNF	Institute for Nature Conservation and Forests from Portugal
DGT	Directorate-General for Territory from Portugal
A	Agriculture
AFS	Agro-forest system
CF	Chestnut forest
COF	Cork oak forest
EF	Eucalyptus forest
IF	Invasive Forest
OBF	Other broadleaved forest
OCF	Other conifers forest
OOF	Other oak forest
P	Pastures

PPeF	Pinus Pinea forest
PPF	Pinus pinaster forest
RO	Rock Outcrops
S	Shrubs
SV	Sparse vegetation;
URS	Urban/Rural Settlements
W	Water

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