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ForestConnect

FOREST CONNECT

OUTPUT 2.2.2

Guidelines on Preserving Ecosystems and Related Services in Eco-connectivity Areas for the Benefit of Large Carnivores and Local People

June 2026

Output 2.2.2 Guidelines on preserving ecosystems and related services in eco-connectivity areas for the benefit of large carnivores and local people

Elaborated in the framework of Specific Objective 2 “Heterogeneity, connectivity and climate resilience of large carnivores’ forests is improved”, Activity 2.3 “ Develop guidelines on preserving ecosystems and related services in relevant ecological connectivity areas and assess the role of ecological corridors in the local economies”

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ForestConnect Project “Towards a Climate-smart Forest Connectivity for Large Carnivores in the Balkan- Carpathian-Dinaric Region”, Interreg Danube Region Programme, DRP0200359

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Contents

I. About the ForestConnect project

ForestConnect "Towards a Climate-smart Forest Connectivity for Large Carnivores in the Balkan-Carpathian-Dinaric Region" is a project financed by the Interreg Danube Region Programme running from January 2024 to June 2026. The project focuses on protecting, preserving, and enhancing ecological corridors for large carnivores across six countries of Eastern and Southeastern Europe. Unsustainable management practices, infrastructure developments, and the effects of climate change pose pressures on ecosystems. Given the transboundary nature of wildlife movement, coordinated efforts are essential to guarantee provision of the habitat and ecological needs of large carnivores and their prey. ForestConnect addresses these needs by developing and integrating innovative tools and technologies for transnational monitoring of large carnivores, including mapping safe corridors under various climate change scenarios. ForestConnect proposes practical, climate-resilient measures, engaging local communities and filling critical knowledge gaps. Through capacity building, cooperation, and awareness raising campaigns, ForestConnect provides resources and actionable strategies intended to be implemented by protected area managers and stakeholders, ensuring the durability, transferability, and uptake of its results. These efforts contribute to the long-term conservation of large carnivores and the health of ecosystems across the Danube region.

Implementation note:
Since 2021 part of the project region – Ukraine – is affected by another type of disaster – the war. The natural habitats in the country are not spared by the adverse effects of this terrible situation. The national forestry authority of Ukraine stated that the implementation of the current guidelines cannot be prioritized outside of the protected areas in the current situation due to supposed complications and economic losses.

II. Overall purpose of the guidelines

Eco-connectivity and ecosystem services as a basis for landscape conservation

This document serves as a **technical and policy guide** derived from the ForestConnect project's experience in ecological connectivity and ecosystem-service assessment — used as a tool to preserve and strengthen connectivity across landscapes. It provides an **overarching framework** to:

1. Support **decision-makers** in integrating **connectivity considerations** into sectoral policies and spatial planning, including **forestry, transport, and biodiversity management at national and transnational scales.** It aims to guide both **national authorities, conventions, and policy platforms.**
2. Assist **conservation practitioners** in addressing management challenges related to improving the connectivity of large carnivores (LCs) through the lens of **preserved and healthy ecosystem services**. It aims to guide practitioners in managing **critical eco-connectivity areas** as **multifunctional landscapes** where **ecosystem services, local livelihoods, and large carnivore conservation** reinforce one another rather than compete.

Ecosystem services—e.g., supporting like habitat quality for cover and breeding, nutrient cycling for prey productivity, and primary production for vegetation vigor—underpin LC corridors by preserving forest structure, hydrological balance, and prey base resilience. These enable species movement and population viability amid fragmentation. Without them, corridors structure and permeability degrade under climate and human pressures, forcing LCs into human-dominated areas, isolating populations, eroding ecosystem function, and increasing conflicts like livestock depredation or encounters near communities.

Viewing LCs connectivity through the lens of preserved and healthy ecosystems and related services ties ecological needs (e.g., dispersal) to socioeconomic dimensions, such as timber production, regulation of species populations, or tourism revenue—foster multi-stakeholder policies for permeable landscapes that balance conservation with rural livelihoods, which lies at the core of ForestConnect.

The current Guidelines are based upon:

- Structural ForestConnect pilot actions implemented around connectivity networks;
- Spatial modelling and data analysis tools piloted in ForestConnect;
- Strategic Action Plan with Adaptation Actions and Climate Resilience-Enhancing Forest Management Practices for Protected Areas (ForestConnect Output 3.1 to be found on ForestConnect Internet page, Library Section)
- Stakeholder engagement (local communities, forestry, NGOs).

This guideline builds on the D.2.3.2 Regional report combining national assessments of ecosystem services (to be found on ForestConnect Internet page, Library Section) that addresses the pressing need for protecting and sustaining ecological corridors critical to the survival of large carnivores across the Carpathians, Balkans, and Dinarides. It describes how ecosystem services directly support ecological corridors by providing essential services like habitat quality and prey availability for targeted actions ensuring immediate permeability and conflict reduction.

III. Conceptual Framework for Climate-Resilient Ecological Connectivity

There is a reciprocal relationship between ecological connectivity and ecosystem services: targeted connectivity measures support ecosystem functions and the delivery of ecosystem services, while intact ecosystem processes and landscape functionality facilitate broader ecological connectivity.

Contemporary conservation planning is often framed around two complementary but distinct paradigms: land-sparing and land-sharing (Fischer et al. 2014)**.**

- The **land-sparing approach** is based on the spatial separation of intensive human land use and biodiversity conservation, concentrating economic activities in certain areas while preserving natural values elsewhere.
- In contrast, **land-sharing** promotes the integration of biodiversity conservation within multifunctional landscapes, where human activities such as agriculture, forestry, or infrastructure coexist with ecological functions and species persistence.

While these concepts originated in agricultural and biodiversity research, they have become increasingly relevant for spatial planning, infrastructure development, and landscape-scale conservation strategies more broadly.

When ecological connectivity is addressed through the lens of an **ecological security pattern (ESP),** the underlying logic aligns closely with a land-sparing perspective. The concept of ESP builds upon earlier frameworks such as landscape ecology, ecological networks, and habitat connectivity, shifting from site-based conservation toward a spatially strategic and planning-oriented approach that prioritizes critical ecological structures within multifunctional landscapes.

ESPs are typically structured around clearly defined core or source areas—often protected areas with high ecological value—linked through ecological corridors that facilitate species movement, gene flow, and ecological processes. In this framework, the landscape is hierarchically organized: core areas serve as biodiversity reservoirs, while corridors and stepping-stone habitats mitigate fragmentation (Gong et al., 2025). Importantly, these corridors are zones with differentiated land-use and management regimes, designed to maintain permeability while allowing certain forms of human activity. This differentiated management concept is central to many ecological network and connectivity models applied across Europe.

At the same time, **European conservation policy and practice increasingly reflect a shift toward land-sharing approaches, particularly outside formally protected areas**. This trend is evident in the broader implementation of the EU Biodiversity Strategy for 2030 and is reinforced by recent interpretative developments under EU nature legislation. A key example is the 2026 European Commission Guidance on the implementation of Articles 5 and 9 of the Birds Directive, which explicitly clarifies that the general system of bird protection applies across the entire territory of Member States, not only within Natura 2000 sites or designated ecological corridors. By emphasizing that preventive measures must be considered already at the design stage of plans and projects—and that protection obligations extend to any landscapes used by birds for breeding, resting, or migration—the guidance implicitly supports a land-sharing logic. Biodiversity conservation is no longer confined to isolated protected cores but becomes a shared responsibility across the wider managed landscape.

This evolving policy context has important implications for how ecological connectivity should be conceptualized and operationalized. Connectivity should not be treated solely as a property of protected-area networks or mapped corridors, but as a functional attribute of the entire landscape, influenced by 1) land-use intensity, 2) infrastructure density, and 3) management practices. From this perspective, land-sparing and land-sharing are not mutually exclusive; rather, they form a continuum. Core protected areas and strategic corridors remain essential for conserving habitat specialists and ensuring long-term ecological resilience, while a permeable matrix of shared landscapes enhances everyday connectivity and reduces cumulative fragmentation effects.

Recent European research on large carnivores consistently shows that functional connectivity increasingly depends on coexistence within human-dominated landscapes rather than on strictly protected cores alone (van den Bosch et al., 2025). Studies at the European scale show that, although there is a large amount of suitable habitat for brown bears, connectivity between these areas is still limited. Agriculture and human development act as the main barriers to movement, especially outside protected areas. Similar patterns have been documented for wolves and other large carnivores, whose recovery and dispersal largely occur in shared, multifunctional landscapes where management, tolerance, and landscape permeability are decisive. Accordingly, recent European connectivity frameworks emphasize that maintaining ecological flows requires going beyond designated corridors and integrating biodiversity considerations into the wider landscape matrix. **Together, these findings support a shift toward land-sharing approaches to connectivity, in which coexistence and differentiated management in everyday landscapes complement land-sparing measures focused on area-base solutions. We believe,** this approach may be more appropriate as a first option in the context of climate changes that remain partially uncertain or unpredictable.

BOX 1: CONCEPTS

land sharing = co-existence model = multifunctional landscape

(goggle maps image – example from Bulgaria)

land sparing = separation model = specific land function allocation

(goggle maps image – example from Slovakia)

This conceptual framework has effect on the formulation of the connectivity cases in chapter VI.

Case 1 High-permeability landscapes (low fragmentation) align with land-sharing strategies.

Case 2: Low-permeability landscapes (high fragmentation) align most strongly with the *land-sparing* paradigm and the Ecological Security Pattern (ESP) approach.

Case 3 Zero-permeability / Impermeable landscapes - corresponds most strongly with the Ecological Security Pattern (ESP) and the land-sparing paradigm

IV.onnectivity in the context of climate change

Climate-driven shifts, forest heterogeneity, and ecosystem services in Europe

Climate change is increasingly reshaping forest ecosystems across Europe, acting as a powerful driver of habitat and species range shifts while simultaneously intensifying landscape fragmentation. Rising temperatures, altered precipitation regimes, and more frequent extreme events are modifying ecological dynamics at multiple spatial and temporal scales. Changes are often faster than species and habitats can naturally adapt. One of the most visible manifestations of this process is the rapid escalation of forest disturbances. Continental-scale assessments consistently show increasing impacts from wildfire, windthrow, and bark beetle outbreaks across all climate scenarios, with the disturbed forest area potentially doubling by the end of the century under high-warming pathways.

The ecological response to climate change is heterogeneous across Europe, reflecting strong regional contrasts in climatic limitations. In temperature-limited regions, such as northern Europe and higher elevations, moderate warming can initially enhance forest productivity, with species like *Pinus sylvestris* showing growth gains where moisture remains sufficient. In contrast, water-limited regions—particularly southern, eastern, and lowland areas—are already experiencing declining growth, increased drought stress, and greater susceptibility to heat-related mortality and biotic agents. These divergent responses are consistently reported in recent pan-European modelling and empirical studies, highlighting that future forest trajectories will not be uniform. Spatially differentiated according to climatic thresholds and site conditions will be manifest.

As climate stress intensify, shifts in forest species composition and habitat suitability are becoming increasingly evident. Several continental and regional studies document northward and upward shifts of suitable climate for dominant European tree species, accompanied by contractions at their southern and lower-elevation margins. For example, *Picea abies* is projected to become increasingly vulnerable to water stress across warmer and drier parts of its range, while *Pinus sylvestris* generally performs better under warming conditions in northern Europe. Similar patterns are emerging across temperate broadleaves and conifers, indicating that future forests are likely to differ substantially in composition from historical reference states.

Climatic range shifts do not occur in isolation but interact with disturbance regimes and landscape structure, accelerating fragmentation even within protected areas. Old-growth forests, often assumed to be climate refugia, are not immune: modelling in mountain regions such as the Alps shows projected declines of over 20% in old-growth extent by mid- to late-century, with remaining patches becoming smaller and less cohesive. These trends signal emerging fragmentation processes driven by climate impacts rather than direct land-use change. Comparable signals are reported from the Carpathians, where altered temperature and precipitation regimes are linked to changes in species composition, upward treeline shifts, and reduced space for alpine and subalpine habitats.

Against this backdrop of accelerating areal shifts and disturbance-driven fragmentation, the maintenance of habitat heterogeneity emerges as a critical adaptation strategy. Recent European-scale analyses demonstrate that structurally and compositionally heterogeneous forest landscapes are more resilient to climate-driven disturbances. By diversifying age classes, species composition, and stand structures, heterogeneous landscapes reduce the synchronicity of disturbance impacts, limit large-scale biomass losses, and buffer against cascading failures. Quantitative assessments suggest that increasing ecosystem heterogeneity could reduce climate-driven biomass losses by nearly one-fifth at the European level, making it one of the most effective levers available within current adaptation portfolios.

The implications for ecosystem services are profound. Forests underpin a wide range of services that are directly affected by climate-induced shifts, including carbon sequestration, local and regional climate regulation, water regulation, habitat provision, and disturbance mitigation. Intensifying disturbances threaten carbon storage both through direct biomass loss and through increased variability of carbon sinks over time, undermining the reliability of forest-based mitigation. At the same time, changes in species composition and stand structure can alter microclimatic regulation and water balance, with knock-on effects for downstream ecosystems and human livelihoods. Maintaining heterogeneous forests supports the continuity of these services by stabilizing ecosystem functioning under variable and uncertain future conditions, rather than maximizing a single output such as timber production or short-term carbon uptake.

In this context, habitat heterogeneity should not be viewed merely as a silvicultural option but as a strategy to accommodate inevitable range shifts while sustaining ecosystem services at landscape and regional scales. By providing a mosaic of microclimates, soil conditions, and structural niches, heterogeneous landscapes increase the likelihood that species can persist locally or shift incrementally without crossing ecological thresholds. This approach aligns with emerging European policy and scientific frameworks that recognize climate-driven dynamics as a central organizing principle for future forest planning, emphasizing resilience, functional diversity, and landscape-scale integration over static notions of historical stability.

V. Uncertainty of climate change impacts on ecosystem service stability

Uncertainty, climate change, and the primacy of structural connectivity

Uncertainty regarding the magnitude, timing, and spatial extent of climate change impacts on habitats, species distributions, and ecosystem functions represents one of the central risks for long-term ecological connectivity planning. Climate projections indicate increasing temperatures, altered precipitation regimes, and more frequent extreme events, yet the ecological consequences of these drivers remain highly variable across regions, species, and landscape contexts. This uncertainty is amplified by interacting stressors, including land-use types, soils, disturbance regimes, and biotic agents, which together shape ecological responses in ways that are difficult to predict at fine spatial scales or over long time periods. As a result, assumptions about future functional connectivity (actual movement of organisms or ecological flows through the landscape) are uncertain, species-specific, and temporally contingent.

Within this context, emphasising the strategic importance of structural connectivity as a more robust and precautionary planning foundation might be effective. Structural connectivity refers to the physical arrangement and continuity of natural and semi-natural landscape elements that shape the spatial configuration of the matrix. Under stable environmental conditions, is expected that functional connectivity to be reasonably modelled based on ESP for example. Under rapid climate change, however, species responses are increasingly decoupled from known behavioural patterns, limiting the reliability of functional interpretations or expectations.

In landscapes experiencing climate-driven habitat and species range shifts, structural connectivity inherently carries functional potential. Any existing physical connection between habitats—whether currently used or not—may become functionally relevant as species disperse in response to changing climate, altered disturbance regimes, or different ecological gradients. This principle is particularly important under climate uncertainty, where future movement routes cannot be confidently predicted and where species may traverse landscapes in directions, at speeds, or through habitat types that differ markedly from past observations. Consequently, structural connections should not be considered ecologically irrelevant simply because their present-day functional use cannot be demonstrated. They should be recognized as latent pathways that may support future movements and ecological processes and therefore be maintained or enhanced as part of adaptive connectivity planning.

From this perspective, structural connectivity is closely aligned with the concept of landscape permeability. Where structural connectivity exists, the landscape offers lower resistance to movement, facilitating the dispersal of individuals, the exchange of genetic material, and the spatial coupling of ecological processes. Permeability is increasingly recognized as a critical property of landscapes facing climate change, not only for mobile species but also for ecological flows related to disturbance recovery, succession, and ecosystem functioning. Importantly, permeability operates at broader spatial scales than individual ecological corridors, emerging from the cumulative effect of multiple landscape elements rather than from discrete, linear features alone. Thus, permeability is most relevant at the level of ecological connectivity across the landscape matrix. Conversely, identifying existing or planned physical barriers is equally important, as it allows the anticipation, avoidance, or mitigation of future fragmentation.

Forests play a central role in this framework, as they constitute the dominant habitat type underpinning ecological connectivity for large carnivores. However, forest responses to climate change illustrate clearly why structural approaches are necessary. While projections broadly agree on the direction of change, the magnitude of impacts varies on climate scenarios, soil conditions, management history, and the interaction of disturbance agents (drought, wind, fire, and bark beetles).

Rising climatic variability and interacting disturbances are already affecting forest resilience and threatening the continuity and reliability of ecosystem services, including climate regulation, habitat provision, and disturbance buffering. While boreal and temperature-limited forests may experience transient gains in productivity or resilience under moderate warming, temperate and water-limited forests increasingly exhibit signs of declining resilience and critical slowing down. Even where datasets are revised or corrected, regional amplitudes may shift but the conclusions regarding increasing vulnerability and spatial heterogeneity persist.

BOX 2: TRIGGERS

Climate change uncertainty => Habitats shifts and species shifts

In that circumstances recommendation is to focus on Structural connectivity as latent pathways that may support future movements and ecological processes and therefore be maintained or enhanced as part of adaptive connectivity planning.

Structural connectivity inherently carries functional potential. Any existing physical connection between habitats (whether currently used or not) may become functionally relevant as species disperse in response to changing climate.

In this context of uneven responses, **focusing on structural connectivity** and landscape permeability provides a precautionary and adaptive basis for sustaining ecological connectivity and the ecosystem services it supports. By preserving and enhancing the physical connectedness of landscapes, these guidelines seek to keep future pathways open for species movements and ecological processes that cannot yet be anticipated, thereby increasing the capacity of ecosystems to reorganize and continue delivering essential services under ongoing climate change.

VI.Ecosystem services provided by connectivity

To illustrate ecosystem services supported by forest connectivity, including the role of large carnivores, examples are drawn from three regions—the Balkans, the Carpathians, and the Dinaric Mountains. These examples show how connected forest landscapes support biodiversity conservation, climate regulation, and socio-economic resilience across different ecological and management contexts.

When identifying and evaluating ecosystem services related to connectivity, the analysis goes beyond the boundaries of ecological corridors. The benefits of connectivity extend well beyond narrow areas that allow animal movement, such as designated corridors.

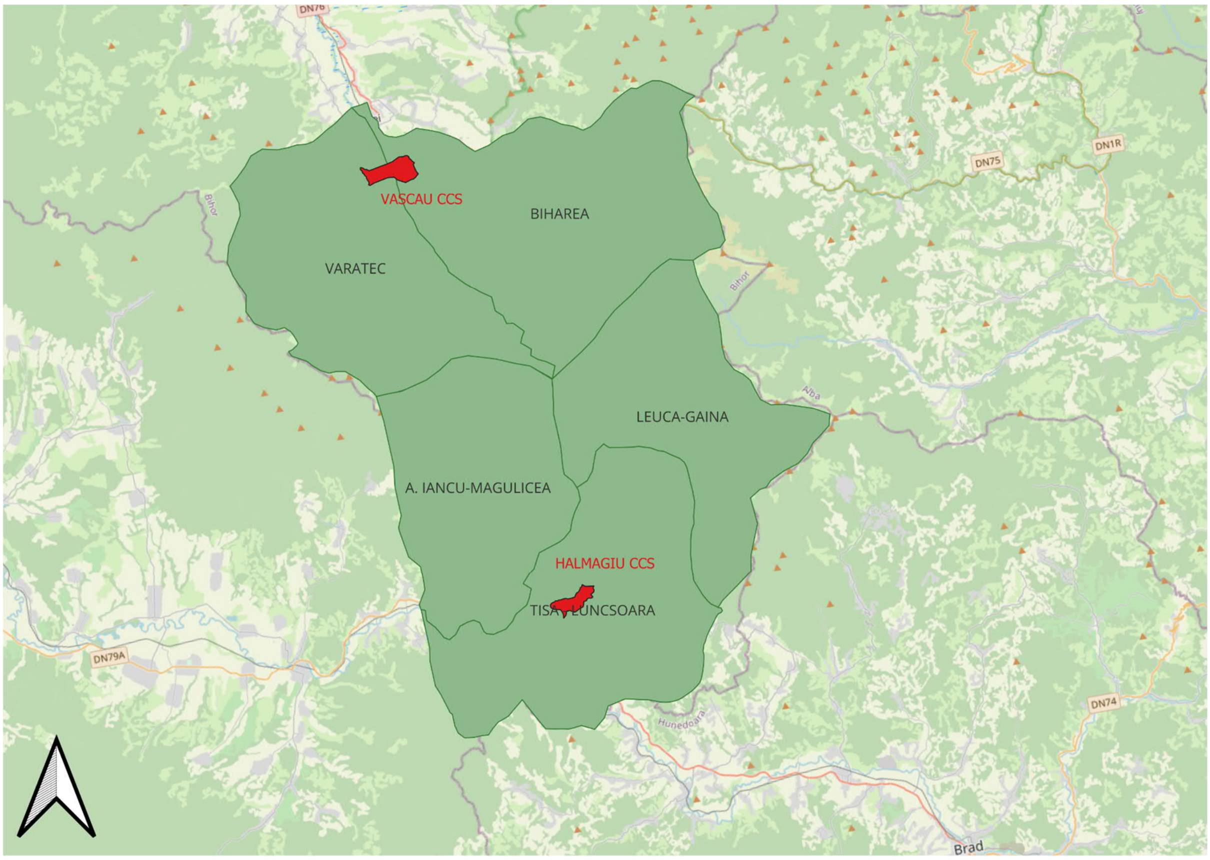

Figure 1. Administrative boundaries of ES valuation in Romania case study (Halmagiu Area example)

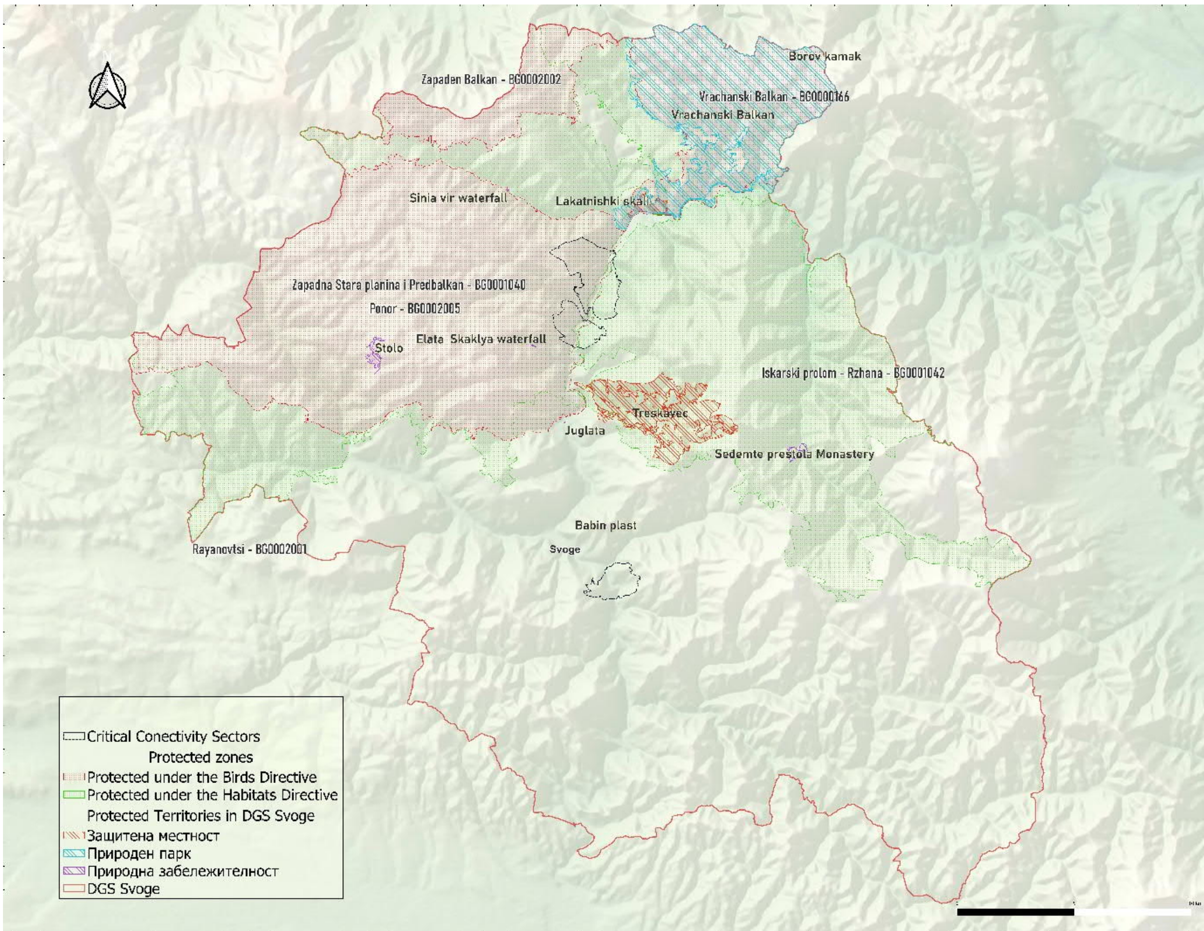

Figure 2. Administrative boundaries of ES valuation in Bulgaria case study (Svoge State Forestry Management Unit)

To clarify this approach, a comparison can be made with protected areas (PAs). Protected areas are site-based conservation measures, designated to maintain or improve specific habitats, species, or landscape features within clearly defined boundaries. In this case, it is reasonable to assess ecosystem services primarily within the boundaries of the protected area itself.

In contrast, the ecosystem services associated with connectivity are most clearly expressed in surrounding and neighbouring areas, where landscape permeability supports ecological processes, species movements, and broader environmental benefits.

Within the ForestConnect project (Deliverable D.2.3.2), ecosystem services linked to ecological connectivity were identified and monetarily assessed only where sufficient data were available in Romania, Bulgaria, and Montenegro. Consequently, the valuation covers a **partial set** of services and differs between countries. For several important services, national data were lacking; in such cases, illustrative examples from Spain, Portugal, and New Zealand were included to demonstrate the broader relevance of these services, without serving as benchmarks or comparison points.

The ecosystem services linked to connectivity that were identified cover all main categories: provisioning, regulating and maintenance, and cultural services (Table1). Provisioning services include wild animals used for food and the trophy value of wildlife. Regulating and maintenance services include disease control, regulation of species populations, maintenance of nursery habitats and populations, and control of invasive species. Cultural services include experiential use and aesthetic values.

Table 1: Ecosystem Services correlated with large carnivores' ecological roles and habitat connectivity

Section	Division	Class	Example specific to large carnivores	Suggested monetary valuation method
Provisioning	Biomass provisioning	Wild animals for food	Dispersal of large mammals through corridors supports sustainable hunting (e.g., deer, wild boar)	Market price (value of game)
Provisioning	Biomass provisioning	Trophy value from wild animals	Corridors support healthy populations of large mammals, enhancing trophy quality for sustainable hunting	Market price / Contingent valuation (trophy tourism value)
Regulation & Maintenance	Lifecycle maintenance, habitat and gene pool protection	Maintaining nursery populations and habitats	Corridors as dispersal routes for juvenile wolves or lynx	Avoided cost (costs of relocation or reintroduction)
Regulation & Maintenance	Pest and disease control	Control of invasive species	Presence of wolves reduces overpopulated wild boar or herbivore populations	Avoided cost (costs of pest control)
Regulation & Maintenance	Pest and disease control	Disease control	Large carnivores remove sick individuals, contributing to disease control (e.g., African swine fever)	Avoided cost (veterinary and biosecurity costs)

Regulation & Maintenance	Lifecycle maintenance, habitat and gene pool protection	Regulation of species populations	Large carnivores regulate herbivore populations, allowing forest regeneration	Benefit transfer (value of forest regeneration)
Cultural	Physical and experiential interactions	Experiential use	Observation of tracks or behavior of carnivores during ecological hikes	Willingness to pay
Cultural	Spiritual, symbolic and other interactions	Aesthetic value	Symbolic value of bear or wolf presence in natural landscapes	Willingness to pay

The monetary values presented for these services in Table 2 should not be interpreted as harmonized or directly comparable across countries. Instead, they provide **order-of-magnitude indications** of the relative scale of different services within each national context. Their purpose is to highlight the types of benefits that connectivity supports and to illustrate the potential costs that arise when ecological functions are degraded or lost.

Table 2: Ecosystem services monetary valuated in ForestConnect project

ES type	**Romania ES value (EUR/year)**	**Bulgaria ES value (EUR/year)**	**Montenegro ES value (EUR/year)**	***Example*** **(Spain-Portugal; New Zealand) (EUR/year)**
Wild animals for food	334,401.75	29,797		
Trophy value from wild animals	237,250.00			
Disease control		1,542		
Regulation of species populations	10,354,420.85			
Maintaining nursery populations and habitats		71,933		5,183,083.37
Control of invasive species				40,000,000
Experiential use		57,709	15,164,228.96	
Aesthetic value		298,592	16,031,955.95	

Furthermore, Deliverable D.2.3.2 imagined 3 different scenarios to understand better the relation between connectivity, ecosystem services and costs of connectivity maintenance.

Under the "business-as-usual" scenario, the ecosystem services assessment reflected the current state of connectivity and the services provided under present conditions. It was assumed that wildlife can move between core areas to a sufficient extent and that connectivity-related ecosystem services are delivered.

The "conservation-oriented" scenario explored a situation in which all land within ecological corridors is restored to a favourable condition for large carnivores, for example forest land. This scenario may also test the designation of a protected regime over these sectors. Restoration and protection costs, including potential compensation, were estimated for each critical connectivity sector.

The third case, the "development-oriented" scenario, assumes that corridor permeability is disrupted by infrastructure development, leading to the loss of ecosystem services generated by connectivity. In this case, it is appropriate to underline the cost of restoring ecological connectivity, for example through the construction of wildlife overpasses or ecoducts.

BOX 3: CONNECTIVITY COSTS

Increasing fragmentation raises the cost of maintaining the same level of ecosystem service delivery

- business-as-usual" scenario – baseline scenario
- "conservation-oriented" – costs for restoration, protection, compensations, management etc.
- "development-oriented" scenario – costs for construction of wildlife overpasses or ecoducts (infrastructure)

Foundation of the connectivity solutions that we propose further – chapter VII

Together, these scenarios illustrate how increasing fragmentation raises the cost and complexity of maintaining the same level of ecosystem service delivery, even though the benefits of connectivity remain comparable across all landscape types. This pragmatic understanding is the foundation of the large-scale (landscape-level) connectivity solutions that we propose further in Chapter VI.

The results can be interpreted as follows: ecosystem services become most visible and quantifiable when ecosystems are altered or degraded. In practice, this reflects the way of monetary valuation methods that are commonly applied, as they are often based on the calculation of avoided or replacement costs for regulating and maintenance services. As a result, when ecological connectivity is intact and functions properly, the associated services tend to be overlooked, simply because no direct costs are incurred.

The presence of large carnivores generates a wide range of ecosystem services, including provisioning services, regulation of herbivore populations, pest and disease control, limitation of invasive species, maintenance of life cycles, and protection of habitats and genetic diversity. When large carnivore populations are able to perform their ecological functions within a permeable landscape that allows sufficient space for movement and dispersal, these ecosystem services are effectively provided “for free”.

As pressure on large carnivores’ movement increases and their ecological functions become constrained, costs begin to emerge in order to compensate for the resulting loss of services. Based on Deliverable D.2.3.2, it was estimated that EUR 10,354,420.85 per year would be required in the Romanian pilot sites only (25,782 ha) to artificially regenerate forest areas if large carnivores no longer regulated ungulate populations. Similarly, for the Bulgarian pilot site, an estimated EUR 71,933 per year would be needed solely for management actions related to bear relocation to ensure genetic exchange between isolated populations.

In more extreme situations, where large carnivore populations are absent, the associated costs increase substantially. The case of the Iberian lynx in Spain and Portugal illustrates this situation: between 2006 and 2025, a total of EUR 98,478,584 was invested through the LIFE programme alone to re-establish a viable population, and this process is still ongoing. Another illustrative example is New Zealand, where the absence of apex predators has led to very high annual management costs to control invasive species, currently estimated at EUR 40–60 million per year. This expenditure reflects the economic value of the regulating ecosystem services that are missing in the absence of top predators.

When area-based conservation approaches are applied to protect connectivity, such as the designation of ecological corridors, certain costs are unavoidable. These might include costs for restoring habitats to a favourable state (or afforestation) and compensation for landowners where land-use restrictions are introduced to support connectivity objectives. For the Romanian pilot sites alone, restoring 687 ha of forest through afforestation is estimated to cost EUR 7,805,130.66, while land-use restrictions affecting 1,310 ha of critical connectivity sectors could generate compensation costs of approximately EUR 195,190 per year.

In the most extreme situation, where landscape permeability is severely reduced or absent, maintaining the ecosystem services provided by large carnivores requires substantial infrastructure investments. In such cases, ecological connectivity restoration measures, such as wildlife overpasses, become necessary. For example, the estimated cost of constructing a single ecoduct (wildlife overpass) is approximately EUR 6 million.

Based on the evidence above, at least three distinct landscape situations can be identified, each requiring a different approach to connectivity: (i) low-fragmentation landscapes, (ii) highly fragmented landscapes, and (iii) largely impermeable landscapes.

VII. Recommended solutions for preserved eco-connectivity

Below we discus and compare three connectivity contexts, each reflecting a different degree of landscape fragmentation. Thus, the proposed solutions are based on the condition regarding landscape permeability. Depending on that, a prioritisation of the solutions can be made. Here we present high level solutions upon connectivity in the context of climatic change which have to be blended with low scale solutions that improve habitat conditions at site level. All proposed solutions rely on digital tools from ForestConnect project that were already piloted during implementation. Here we integrated and propose a broader framework to approach connectivity, considering climate change also.

All cases assume that ecosystem services provided by connectivity are equal—meaning that, wherever functional connectivity exists, it delivers similar ecological and socio-economic benefits.

The difference lies in the cost and effort required to achieve or maintain that connectivity. As fragmentation increases, restoring or creating permeability becomes more expensive and localized.

We believe this framing will help **advocacy and policy discussions**, as decision-makers can see that connectivity always brings comparable benefits, but the investment needed depends on the landscape's fragmentation level.

The main variable across the three cases is landscape permeability, which ranges from **high to zero**. Permeability determines the degree of structural and functional connectivity and directly influences the scale, cost, and type of management intervention required.

Case 1: High-permeability landscapes (low fragmentation)

This section presents the first connectivity case, which applies to landscapes with high permeability and low levels of fragmentation. In this context, structural and functional connectivity already exists across large areas, allowing ecological processes and species movement to occur with limited restriction. As discussed earlier in this guidance, ecosystem services provided by connectivity can be assumed to be comparable wherever functional connectivity is present. The key difference between cases is therefore not the type of benefits delivered, but the cost and effort required to maintain or restore connectivity.

In high-permeability landscapes, the primary objective is to maintain existing ecological flows by ensuring that **landscape permeability is preserved as a "first line of defence"**. This does not imply avoiding land-use change or development, but rather integrating permeability requirements from the outset of planning and design. In practice, this means that new land uses and developments should be conceived and implemented in ways that retain structural connections and avoid generating unnecessary barriers. Under climate uncertainty, this preventive and **anticipatory approach** is especially important, as future species movements and habitat use cannot be predicted with confidence.

For infrastructure development, this integrated view of permeability is crucial. Connectivity concerns are often raised only at later planning stages, typically when projects intersect protected areas or identified ecological corridors. However, current ecological evidence and EU policy guidance indicate that connectivity should be considered from the earliest stages of planning, regardless of whether formal conservation designations or mapped migration routes exist. Linear infrastructure such as roads, railways, pipelines, or energy corridors can significantly reduce connectivity by creating barriers, increasing mortality, and fragmenting habitats.

An early and proactive approach allows planners and developers to assess connectivity risks before design options become limited. This may include avoiding sensitive alignments, incorporating permeable design solutions, maintaining open landscape structures, or adjusting construction and operational practices. Such measures should be justified not only where protected areas are present, but through the broader obligation, as a planning routine, to prevent the degradation of ecological functions across the wider landscape.

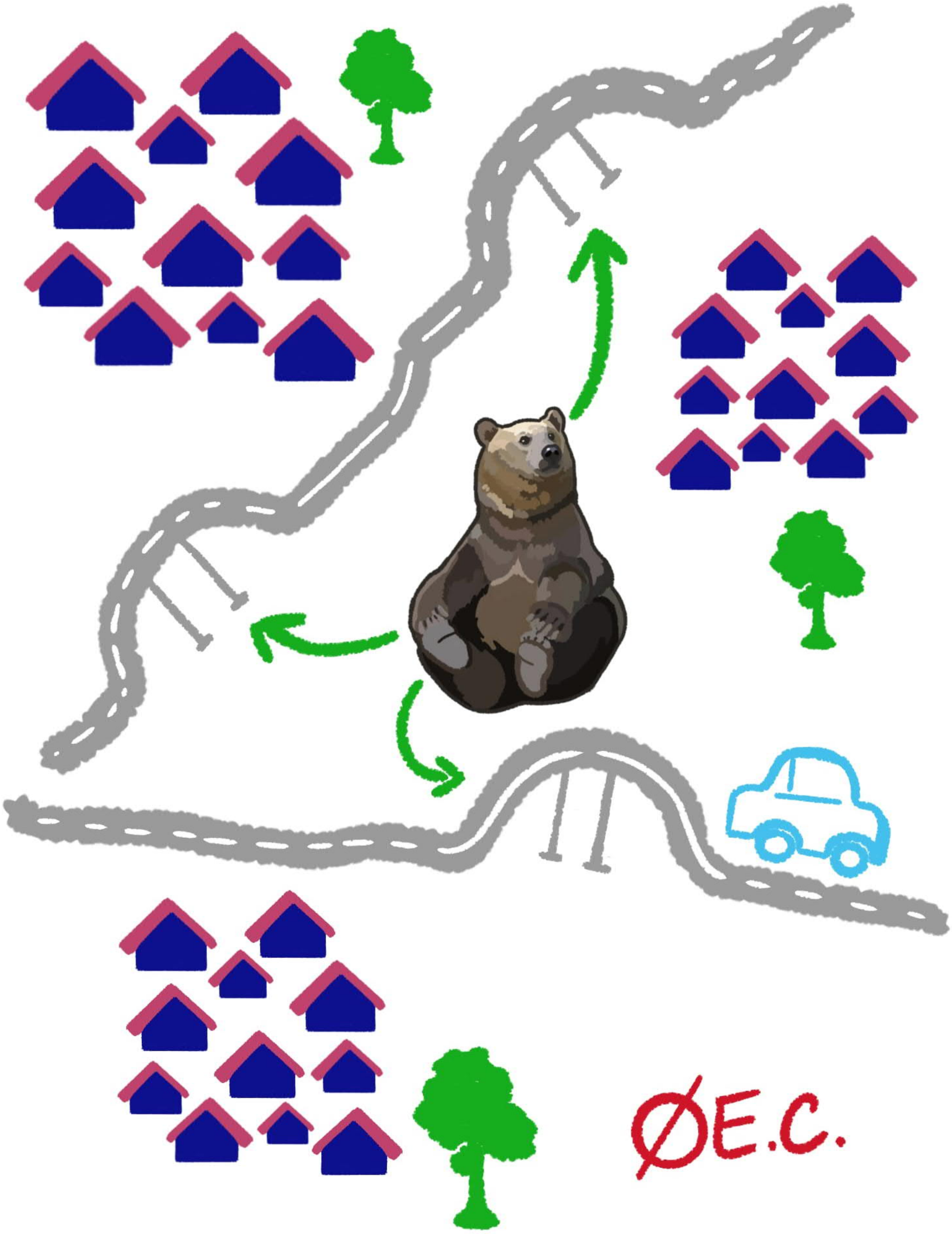

Figure.: Case 1- High-permeability landscapes (low fragmentation)

In high-permeability landscapes, connectivity should be maintained primarily through integration, not through strict spatial designation or large-scale restoration. This approach aligns with hybrid land-sharing and land-sparing strategies: while protected areas and ecological cores remain essential, their effectiveness depends largely on how the surrounding matrix is planned and managed. Maintaining permeability in the wider landscape ensures that connectivity-based ecosystem services continue to be delivered at low cost, with no need for heavy interventions.

The effectiveness of this situation is further strengthened by maintaining habitat heterogeneity and creating micro-refugia. Diverse habitat structures provide a wider range of microclimatic conditions, support ecological resilience, and increase the adaptive capacity of species and ecosystems under climate change. In this way, preserving permeability and heterogeneity together helps keep future ecological pathways open, even as environmental conditions change.

Main solutions in high-permeability landscapes

- **Integrate connectivity and permeability principles into spatial planning and infrastructure development,** ensuring that new transport, energy, or urban projects adopt permeable design solutions from the earliest planning stages, even in the absence of explicit ecological constraints (e.g. known large carnivore presence or mapped migration routes).
- **Avoid new sources of impermeabilization**, such as continuous fencing, large sealed surfaces, or linear barriers without crossing options, especially in currently open and lightly fragmented landscapes.
- **Apply preventive measures as a priority**, as prevention is significantly more cost-effective than later restoration or mitigation. Early design choices can often maintain connectivity without additional costs or with minimal adjustments.
- **Preserve landscape permeability as a landscape-level objective**, rather than relying only on site-based or corridor-based measures. Connectivity should be maintained through the overall structure of the landscape matrix.
- **Maintain and enhance connectivity-based ecosystem services** at low cost, and explicitly recognize these benefits in regional and sectoral planning documents.
- **Use land-use planning tools to support permeability**, such as green infrastructure planning, zoning that avoids barrier concentration, and coordination between transport, urban, and environmental planning sectors.
- **Maintain habitat heterogeneity and promote micro-refugia**, through mixed land-use patterns, diverse forest structure, riparian buffers, and small natural elements, which increase ecological resilience and adaptive capacity under climate change (ForestConnect pilot field actions described in detail in Output 2.1.1 and Output 2.2.2 and Guidelines for management of mosaic habitats, Output 2.2.1 – to be found in the library section of ForestConnect internet page)
- **Monitor early warning signals of fragmentation**, including traffic intensity, fence expansion, land-use change, and human–wildlife conflicts, to detect emerging risks before connectivity is significantly reduced.

Case 2: Low-permeability landscapes (high fragmentation)

This situation applies to landscapes where fragmentation is pronounced and overall permeability has been reduced, but where structural and functional connectivity has not been fully lost. In such contexts, ecological flows still occur, although they are weakened and increasingly vulnerable. As a result, the conservation objective shifts from pure prevention toward a combination of targeted restoration and active management, aimed at reinforcing connectivity and maintaining ecosystem service delivery.

In low-permeability landscapes, connectivity can no longer be ensured across the entire landscape matrix. Instead, it must be **supported through specific, spatially focused interventions** in areas that remain critical for movement between habitat patches. This makes area-based solutions both necessary and appropriate.

The core measure under this case is the identification and designation of ecological corridors that maintain or restore movement between core habitat areas. These corridors represent parts of the landscape where permeability is deliberately prioritized in order to compensate for surrounding fragmentation. Their role is not only to support current movements, but also to retain future functional potential under climate-driven habitat and species shifts.

Given the uncertainty associated with climate change, this case places particular emphasis on structural connectivity. Physical connections between habitat patches should be secured even where present-day functional use is limited or intermittent. Structural corridors may become functionally important at any time, as species redistribute, recolonize, or adjust their movement behaviour in response to changing environmental conditions.

Because ecological corridors are area-based solutions, their designation usually entails adjustments to land-use rules within corridor boundaries. These adjustments may include habitat restoration, restrictions on land-use intensification, or changes in management practices to maintain permeability and ecological function. Consequently, this case implies higher management and compensation costs than in high-permeability landscapes, reflecting the need for active interventions.

At the same time, permeability objectives should remain integrated into spatial and infrastructure planning, ensuring that restoration actions within corridors are not undermined by new developments and that existing uses are adapted. Adaptive management plays a key role, combining ecological monitoring with socio-economic incentives to align connectivity objectives with local land-use practices and stakeholder interests.

Under this context, connectivity-based ecosystem services continue to be delivered, but at a higher cost. These costs reflect the investments required for restoration, management, and compensation, as documented in Deliverable D.2.3.2. However, they remain substantially lower than the costs associated with restoring connectivity once landscapes become fully impermeable.

The effectiveness of ecological corridors in fragmented landscapes is further enhanced by maintaining habitat heterogeneity and creating micro-refugia. Diverse habitat structures within corridors increase resilience, support species persistence, and improve the ability of ecosystems to cope with increasing climatic variability.

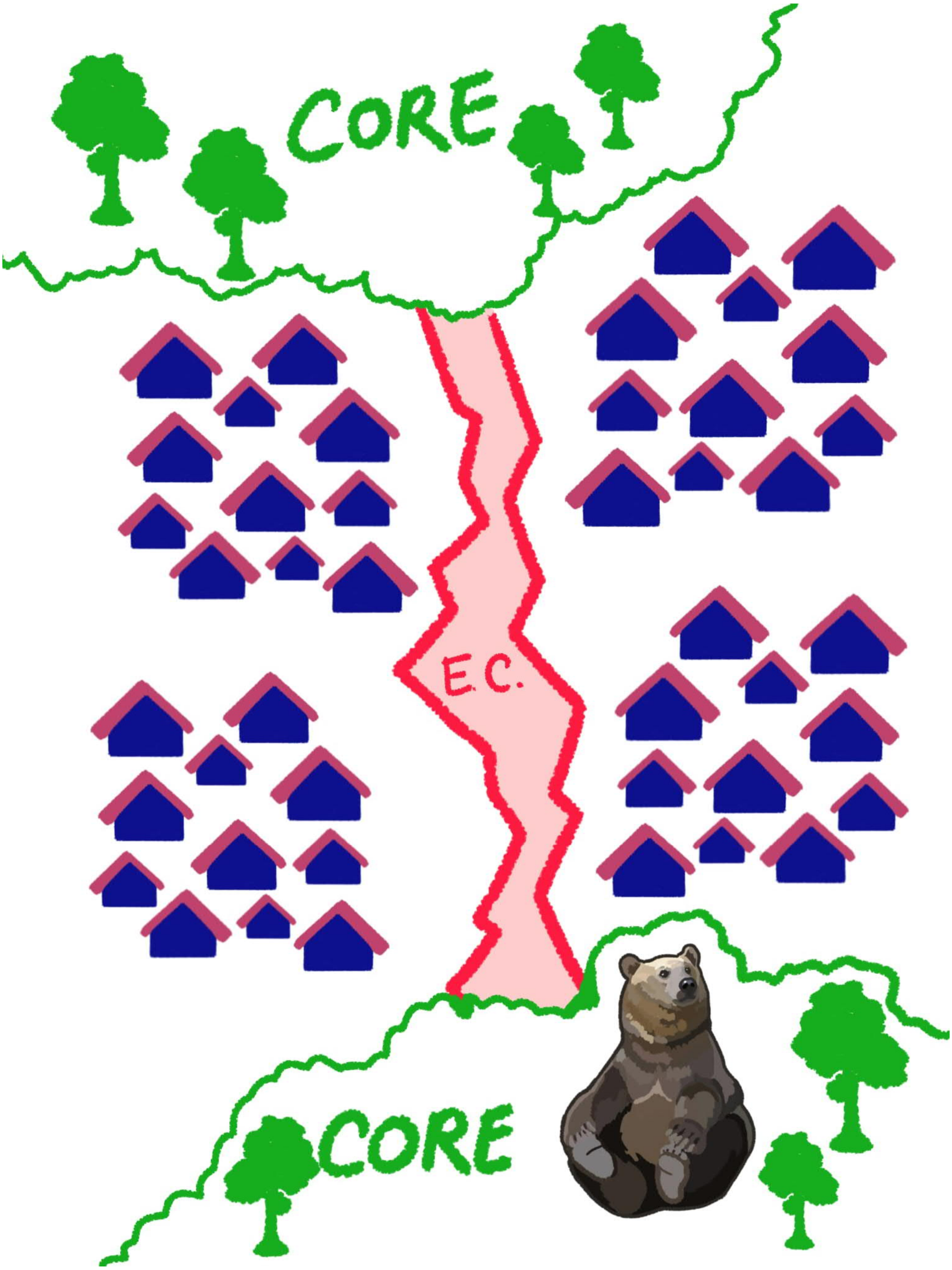

Figure 4. Case 2 - Low-permeability landscapes (high fragmentation)

Main solutions in low-permeability landscapes

- **Identify and designate ecological corridors** that maintain or restore movement between core habitat areas.
- **Prioritize structural connectivity under climatic uncertainty**, recognising that physical connections may enable future functional connectivity.
- **Apply area-based land-use rules within corridors and buffer zones** to maintain permeability and ecological function.
- **Integrate corridor restoration with spatial and infrastructure planning** to ensure coherence with ongoing development.
- **Implement adaptive management approaches** that combine ecological monitoring with socio-economic incentives.
- **Maintain connectivity-based ecosystem services at manageable (but higher) costs** through active restoration and management.
- **Enhance corridor performance** through habitat heterogeneity and micro-refugia creation (ForestConnect pilot field actions are described in detail in Output 2.1.1 and Output 2.2.2 and Guidelines for management of mosaic habitats, Output 2.2.1 – to be found in the library section of ForestConnect internet page)

Case 3: Zero-permeability landscapes (impermeable / fully fragmented)

In landscapes with low **or near-zero permeability**, ecological connectivity is completely disrupted. The conservation goal is **to restore connectivity where physical barriers block any dispersal of large carnivores (LCs) and other species**. This situation focuses on **site-specific interventions** that rebuild ecological flow through engineered or ecological solutions.

Main solutions for zero-permeability landscapes

- **Restore connectivity** by removing or mitigating barriers that prevent species movement, prioritizing sites where dispersal routes are fully blocked.
- **Construct wildlife passage infrastructure** - such as overpasses, underpasses, and culverts - to re-establish movement corridors across impermeable zones.
- **Apply site-based solutions** tailored to local conditions, combining engineering design with ecological restoration to ensure long-term functionality.
- **Implement in impermeable landscapes**, where fragmentation is extreme and natural permeability cannot be recovered without direct intervention.
- **Provide connectivity-based ecosystem services** - including habitat continuity, genetic exchange, and water flow regulation - at the **highest cost**, reflecting the intensity of physical restoration required (see Table and conclusions of *D.2.3.2 "Regional report combining national assessments of ecosystem services"* to be found in the library section of ForestConnect internet page).
- **Enhance effectiveness** through complementary measures such as **habitat heterogeneity and microrefugia creation**, which support recolonization and resilience once structural connectivity is re-established. ForestConnect pilot field actions are described in detail in Output 2.1.1 and Output 2.2.2 and Guidelines for

management of mosaic habitats, Output 2.2.1 – to be found in the library section of ForestConnect internet page.

Figure 5. Case 3 - Zero permeability landscapes

BOX 4: SOLUTIONS

1st case - Permeability Conservation

- Keep landscape permeable = avoid impermeabilization
- Connectivity based ES are provided at low costs
- **Adoption** - integrate permeability solutions as a routine when planning and develop transportation infrastructure or urban spaces without the existence of any factual ecological constrains
- Landscape level solution
- Solution is enhanced / complemented by increased habitats heterogeneity and microrefugia creation

2nd case - Low-permeability landscapes (high fragmentation)

- Keep permeable certain critical connectivity areas
- It provides connectivity-based ES at higher cost
- **Adoption** - Identify and designate EC (connectivity networks)
- Structural connectivity should be stressed. It might activate functional connectivity at any time.
- Area based solution – it changes some rules of land use on its territory
- Solution is enhanced / complemented by increased habitats heterogeneity and microrefugia creation in/near connectivity features

3rd case - Zero **permeability landscapes (impermeable / fully fragmented)**

- Restore connectivity where barriers block any dispersal of LCs
- **Adoption** – building wildlife passage infrastructure
- Is site specific solution
- It provides connectivity-based Ecosystem Services at highest costs
- Solution is enhanced / complemented by increased habitats heterogeneity and microrefugia creation in/near created infrastructure

Why not identify and designate directly EC (skip the 1st case)?

- It reduces the value of the wider landscape!
- Will increase development and intensity outside designated EC!
- Limits future flexibility under climate change pressure!
- Will stay the only solution for dispersion in future!

VIII. ForestConnect Tools for Implementing Solutions and Adaptative Management - Decision Support System

These tools support the prioritisation and spatial application of the connectivity solutions presented in the previous chapter.

Effective connectivity planning increasingly relies on **digital and analytical tools** that enhance decision-making, transparency, and adaptive management. These tools allow planners and policymakers to visualize fragmentation, simulate ecological flows, and test restoration scenarios under changing climatic and socio-economic conditions.

Key instruments and their roles

- **Fragmentation Indexes (e.g., Continuum Suitability Index)** - Quantitative metrics that measure the degree of landscape fragmentation and habitat suitability. They help identify priority areas for intervention, track progress over time, and compare alternative planning scenarios.
- **Digital Twin (fed with online data)** (ForestConnect Output 1.2.2) A dynamic, data-driven model of the landscape that integrates real-time environmental, climatic, and land-use information. It enables scenario testing, early-warning analysis, and continuous monitoring of connectivity performance.
- **Online Viewer** (ForestConnect Output 1.1.3) - An interactive platform for visualizing connectivity networks, ecological corridors, and permeability layers. It supports stakeholder engagement and spatial planning by making complex data accessible to non-technical audiences. It enables interactive visualization of spatial layers such as human–wildlife conflict hotspots, connectivity modelling outputs, and habitat suitability data. Hot Spots of Conflicts Map is a spatial layer of Online Viewer identifying areas where ecological connectivity intersects with competing land-use interests (e.g., transport corridors, energy infrastructure, or urban expansion). It is particularly relevant for **medium- and low-permeability cases**, where restoration or mitigation measures must balance ecological and socio-economic priorities. The map supports **conflict-sensitive planning**, guiding decision-makers toward solutions that minimize trade-offs and optimize ecosystem service outcomes.
- **Strategic Action Plan with Adaptation Actions and Climate Resilience-Enhancing Forest Management Practices for Protected Areas** (ForestConnect Output 3.1).
- **Guidelines on management of transnational mosaic habitats along forest corridors** (ForestConnect Output 2.2.1). The ForestConnect outputs can be found in the library section of the ForestConnect Internet page.

Digital Twin for Ecological Connectivity

The Digital Twin represents an advanced decision-support tool that integrates multiple datasets into a dynamic representation of the landscape. In the context of ecological connectivity, it functions as a continuously updated model of the territory, combining spatial and environmental data to support planning and management decisions.

In practice, the Digital Twin integrates information on landscape structure and ecological processes, including barriers such as roads, railways, fences, settlements, and energy infrastructure, as well as habitat characteristics, land use, and natural features. It also incorporates data on species presence and distribution, particularly for large carnivores, together with landscape permeability layers and, where available, regularly updated environmental data.

By combining these datasets, the Digital Twin enables a system-level understanding of the landscape. Instead of analysing isolated elements, it allows connectivity to be assessed as a continuous and dynamic process across the territory.

Role under climate uncertainty

Under climate change, one of the main constraints for connectivity planning is uncertainty. It is not possible to predict with precision where species will move in the future or which areas will become critical for ecological processes. As a result, planning approaches based only on existing corridors or known migration routes are not sufficient.

The Digital Twin supports a forward-looking approach by allowing planners to assess not only current conditions, but also potential future developments. It makes it possible to identify areas where barriers reduce permeability, detect potential movement pathways even where current use is not confirmed, and simulate how connectivity may change under different cases, including infrastructure development, land-use change, or habitat restoration.

Focus on barriers and species

For practical implementation, the Digital Twin should focus primarily at least on two key elements: barriers and species distribution.

Barriers to movement include transport infrastructure, energy corridors, urban expansion, and fencing. These are the main drivers of connectivity loss and fragmentation. At the same time, information on species presence and distribution - particularly for large carnivores - helps define where connectivity is most relevant. This includes current occurrence areas, core habitats, and potential expansion zones.

Together, these elements allow the identification of areas where connectivity is at risk and where interventions are most needed.

Practical applications

Even when implemented at pilot level, the Digital Twin can serve as a powerful tool for prioritizing interventions across different sectors.

In spatial planning, it helps identify areas where development may reduce connectivity and supports the early integration of permeability requirements into land-use decisions. In infrastructure planning, it highlights where linear infrastructure intersects potential movement areas and allows prioritization of avoidance or mitigation measures. In restoration planning, it identifies key bottlenecks where targeted interventions can restore connectivity, ensuring that investments are directed to areas with the highest strategic value.

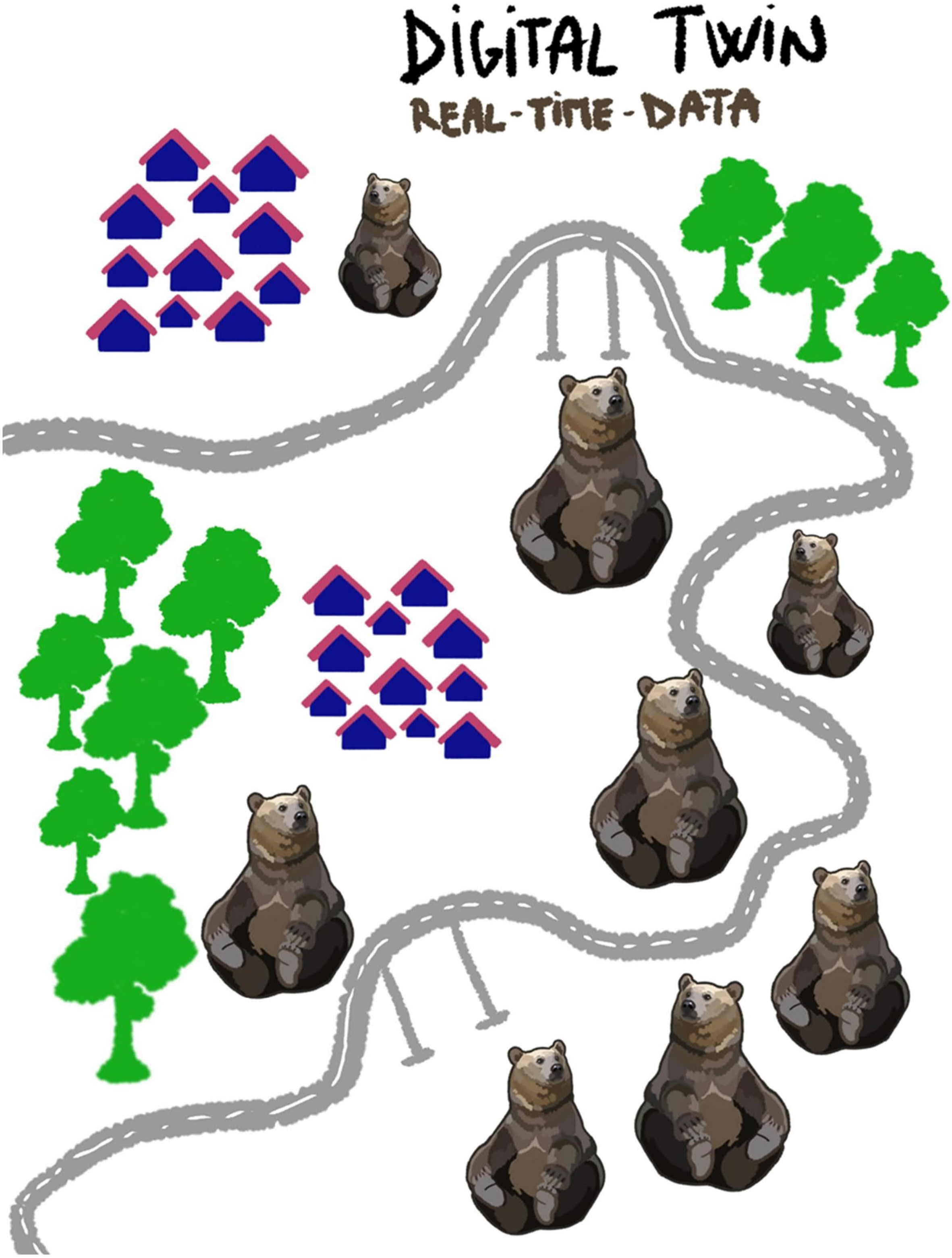

Figure 6. The digital twin helps prioritizing interventions across different sectors

Overall, the Digital Twin supports better decisions at earlier stages, reducing long-term costs and avoiding ineffective or poorly targeted measures.

Key added value of the Digital Twin

The value of the Digital Twin lies not only in mapping connectivity, but in supporting the prioritization of interventions under uncertainty. It provides a practical basis for applying different connectivity solutions depending on landscape conditions, from prevention in high-permeability landscapes, to management and corridor designation in fragmented areas, and restoration in severely impermeable contexts.

Below we have key example of few features that Digital Twin may exhibit over connectivity as they were explored during ForestConnect digital tools piloting.

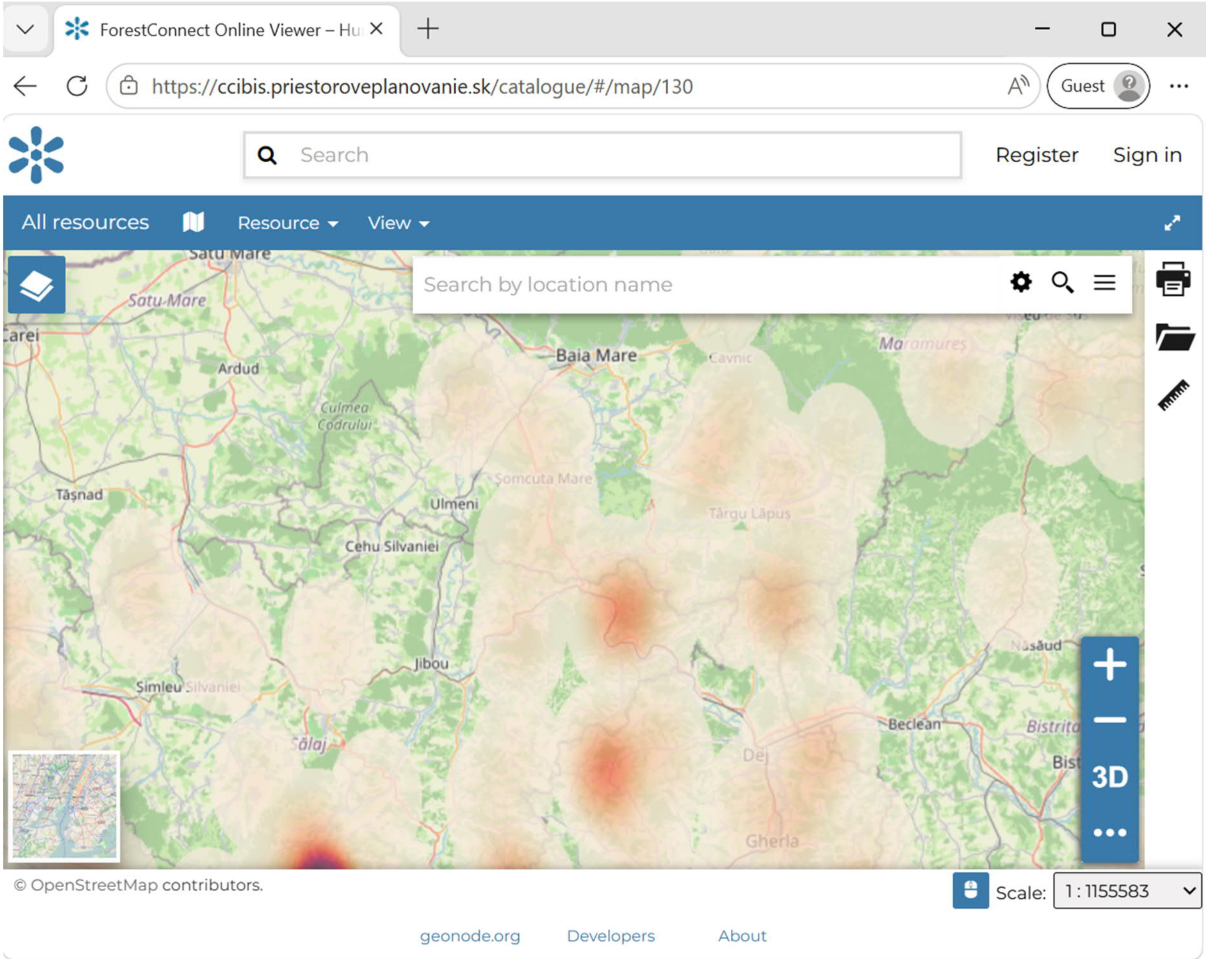

Figure 7. Human–wildlife conflict is visualised as a heatmap, where areas with higher intensity (i.e. more events) are shown in stronger colours and lower intensity areas in lighter shades. The heatmap represents the number of conflict events recorded over a five-year period (2020–2025). These include damage to beehives, livestock, poultry, crops, orchards, and structures such as greenhouses and fences.

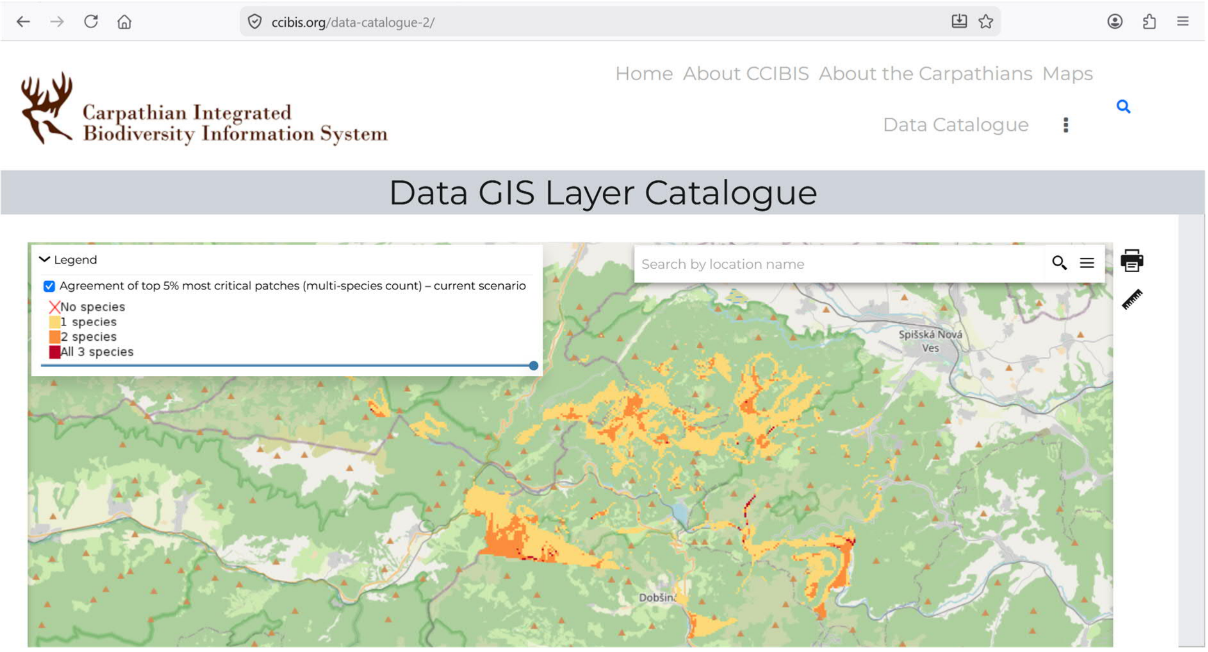

Figure 8. Multi-species raster showing the number of large-carnivore species (grey wolf, Eurasian lynx, brown bear) whose top 5% most critical connectivity patches overlap each pixel in Slovenský Národný Park (Slovakia), considering the current (baseline) scenario of climatic variables.

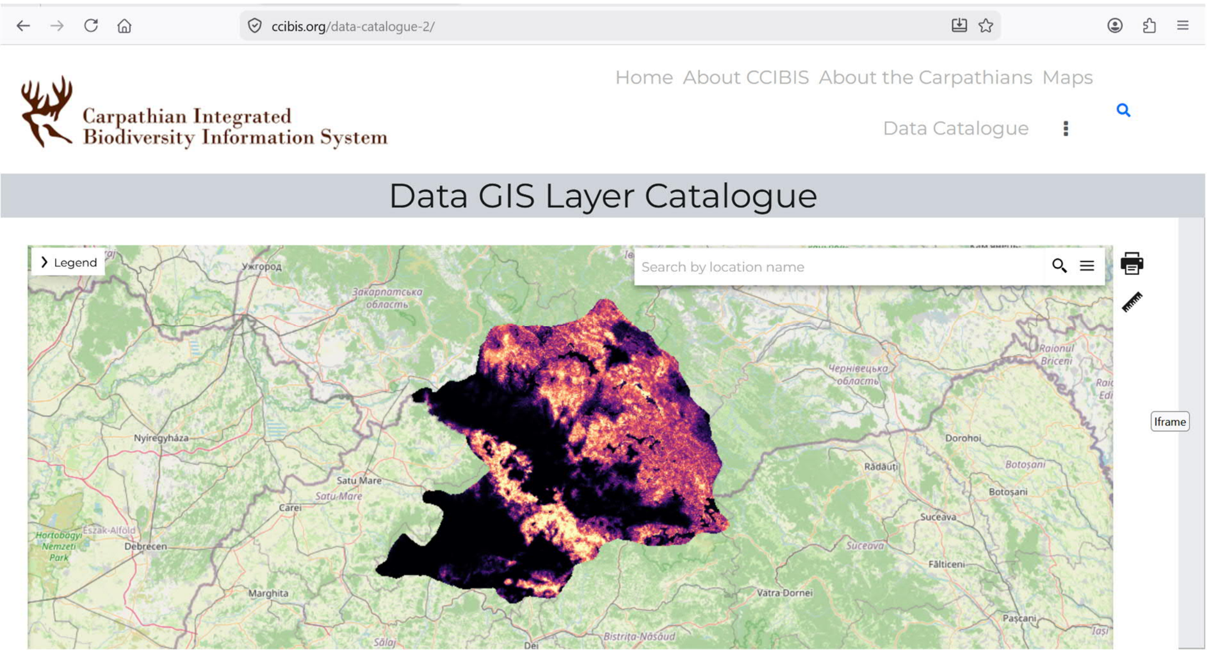

Figure 9. Connectivity model output, standardized to a 1-100 scale, for Ursus arctos (Brown bear) in Transboundary Maramureș (Romania – Ukraine), considering the present scenario of climatic variables. Computed in Circuitscape

Online Viewer and Conflict Mapping

The Online Viewer complements the Digital Twin is meant to provide an accessible interface for the visualization of complex spatial data. It supports planners, stakeholders, and decision-makers by translating technical analyses into formats that are easier to understand and use in real planning processes.

The platform enables the visualization of connectivity networks, ecological corridors, landscape permeability, habitat suitability, and modelling results. It also integrates layers that reflect interactions between ecological and socio-economic systems.

Human–wildlife conflict hotspots

A key component of the Online Viewer is the human–wildlife conflict hotspots layer. This identifies areas where ecological connectivity overlaps with competing land-use interests, such as transport infrastructure, energy developments, urban expansion, or agricultural activities.

These locations often correspond to areas with increased wildlife mortality, higher levels of conflict, or strong pressure on connectivity. They are particularly relevant in medium- and low-permeability landscapes, where ecological and socio-economic priorities must be balanced.

Role in planning and decision-making

The conflict mapping function supports more informed and balanced decisions by highlighting where trade-offs are strongest. It allows planners to identify where mitigation measures are necessary, where restoration should be prioritized, or where alternative solutions may reduce conflicts.

Practical value

The Online Viewer supports spatial planning processes, stakeholder engagement, and transparent communication of connectivity issues. It helps translate ecological connectivity from an abstract concept into a spatially explicit and measurable planning element, making it easier to integrate into policy and practice.

Combined role of the tools

Together, the Digital Twin and the Online Viewer provide a practical framework for applying connectivity solutions across different landscape conditions.

The Digital Twin supports analysis, simulation, and prioritization, while the Online Viewer supports visualization, communication, and implementation. Combined, they enable a shift from reactive to proactive and adaptive planning, ensuring that connectivity is considered early and integrated into real decision-making processes.

BOX 5: Decision Support System

- Connectivity Digital Twin
- Online Viewer
- Guidelines on management of transnational mosaic habitats along forest corridors
- Strategic Action Plan with Adaptation Actions and Climate Resilience-Enhancing Forest Management Practices for Protected Areas

Combined role of the tools

- Dynamic, data driven model of the landscape
- Prioritizing interventions across different sectors under uncertainty
- Supports a forward-looking approach
- Continuous and integrated connectivity analysis

Linking Digital Tools to Connectivity Cases

The Digital Twin and the Online Viewer are designed to support the selection and application of connectivity solutions under different landscape conditions. Their role is not only to provide data, but to guide decisions on which type of intervention is needed, where, and at what scale.

Each of the three connectivity cases presented in this guidance corresponds to a different level of landscape permeability and requires a different type of response. The tools help identify these conditions and support appropriate action.

Case 1 – High-permeability landscapes (Low fragmentation – prevention approach)

In landscapes where permeability is still high, the main objective is to avoid new fragmentation.

In this case, the Digital Twin is used to:

- identify existing barriers and emerging pressures (e.g. planned infrastructure, land-use change),
- detect early signs of permeability loss,
- highlight areas where development have to be mitigated to preserve existing ecological flows.

The Online Viewer supports:

- visualization of the current connectivity status,
- communication with planners and stakeholders,
- integration of permeability considerations into spatial planning processes.

In this case, the tools are mainly used in a preventive role, helping to ensure that connectivity is maintained before problems appear.

Case 2 – Medium-permeability landscapes (High fragmentation – management and corridor approach)

In fragmented landscapes, connectivity exists but is weakened and requires targeted spatial interventions.

Here, the Digital Twin plays a key role in:

- identifying critical connectivity areas and bottlenecks,
- supporting the delineation of ecological corridors,
- analysing how species presence overlaps with barriers and land-use pressures,
- testing how different corridor configurations improve connectivity.

The Online Viewer supports:

- visualization of corridor networks and priority areas,
- identification of human–wildlife conflict zones,
- communication with stakeholders regarding land-use adjustments and restrictions.

In this context, the tools support prioritization and spatial targeting, ensuring that investments and management efforts focus on the most critical areas.

Case 3 – Low or no permeability landscapes (Severely fragmented – restoration approach)

In landscapes where permeability is largely lost, connectivity can only be restored through site-specific interventions, such as wildlife passages.

In this case, the Digital Twin is essential for:

- identifying exact barrier locations that block movement,
- determining where restoration measures (e.g. ecoducts) are most effective,
- assessing the impact of infrastructure on species movement.

The Online Viewer supports:

- visualization of conflict hotspots and barrier impacts,
- communication of the need for costly interventions,
- supporting decision-making by showing trade-offs between development and ecological restoration.

In this case, the tools are used for precision planning and justification of high-cost measures, ensuring that interventions are well targeted and effective.

Overall role of the tools

Across all situations, the Digital Twin and the Online Viewer provide a common decision-support framework:

1. The Digital Twin supports analysis, simulation, and prioritization.
2. The Online Viewer supports visualization, communication, and implementation.
3. Together, they allow decision-makers to move from a reactive approach to a proactive and adaptive planning process, where connectivity is considered early and managed efficiently across different landscape conditions.

The Connectivity Decision Support System provides a structured and practical approach for integrating ecological connectivity into planning processes. By combining analytical capacity with accessible visualization, it enables informed, transparent, and adaptive decisions, ensuring that connectivity is maintained, managed, or restored in the most effective way under different landscape conditions.

IX. Transferability and upscaling

The proposed connectivity solutions are designed to be easily transferred and progressively scaled across different regions by following a structured, stepwise approach and ensuring the involvement of relevant stakeholders.

Implementation should primarily be led by public authorities responsible for spatial planning and infrastructure development, including those in charge of planning, permitting, and approving linear infrastructure (transport, energy, utilities) and urban development. Protected area administrations play a key role, particularly in fragmented landscapes, while infrastructure developers and investors are essential for integrating connectivity measures into project design and delivery.

Effective application of the solutions relies on continuous data input from multiple stakeholders. Foresters, hunters and game managers, environmental NGOs, and citizens (through citizen science applications) contribute valuable information on habitats, species presence, movement patterns, and barriers. This ensures that connectivity data is regularly updated and that the approach can be applied in new areas without requiring extensive baseline studies.

To enable transferability, landscapes should first be classified according to their permeability level (permeable, fragmented, or impermeable). The solutions can then be applied in a modular way, depending on this classification. In permeable landscapes, measures should be integrated into standard planning rules, ensuring low-cost and widespread application. In fragmented landscapes, Ecological Connectivity (EC) networks should be identified and incorporated into spatial planning instruments. In impermeable landscapes, targeted, site-specific interventions (e.g. wildlife crossings) should be implemented to restore connectivity.

In all cases, complementary measures, such as enhancing habitat heterogeneity and creating microrefugia, should be incorporated, as they are low-risk and widely applicable.

Upscaling should follow a progressive pathway:

1. Apply permeability measures broadly to maintain overall landscape functionality;
2. Identify and secure priority connectivity areas and integrate them into regional planning;
3. Implement targeted restoration measures in key bottlenecks.

This approach supports scaling from site level to landscape level and further to cross-border coordination, ensuring coherence across administrative boundaries.

By following this structured process, connectivity solutions can be consistently replicated and expanded, supporting long-term, integrated landscape management.

BOX 6: Transferability of the solutions

Target stakeholders:

- Authorities that regulate or permitting linear infrastructure planning, development and approval
- Authorities that regulate or permitting urban planning, development and approval
- Protected areas administrations
- infrastructure developers and investors

Key stakeholders for information input:

- Foresters
- Hunters
- Environmental NGO's
- Citizens (Citizen Science app)

Operate, data feeding and maintaining Digital Support Systems

- Requires institutional ownership at transnational or regional level (e.g. Carpathian Convention or similar governance structures)

Transferability mechanism:

- Case 1 - integrated directly into standard planning rules (low-cost, easy replication)
- Case 2 - requires designation of Ecological Connectivity (EC) networks within spatial plans
- Case 3 - implemented through project-based interventions (engineering solutions)
- Complementary measures (habitat heterogeneity, microrefugia) are universally applicable, ensuring easy transfer across regions

The transnational added value for the Danube region derives from the need to manage connectivity across a structurally and functionally heterogeneous macro-region, where natural landscapes, land-use intensity, and barrier density vary significantly between countries. This is particularly critical for large carnivores, whose populations are unevenly distributed and depend on long-distance, cross-border dispersal.

By applying a shared three-case framework, the approach allows countries with different landscape conditions, from relatively intact Carpathian cores to heavily fragmented lowlands, to implement context-specific measures while contributing to a coherent cross-border connectivity system. This avoids situations in which connectivity is maintained in source areas but lost in adjacent countries, effectively breaking dispersal pathways at national borders.

In this sense, the added value is operational: it enables alignment between areas that primarily conserve permeability (source and core habitats) and those that must actively secure or restore connectivity (corridors and bottlenecks), ensuring that ecological flows are maintained at the scale required by wide-ranging species.

X. Conclusions

This guidance highlights that maintaining ecological connectivity under current and future conditions requires a progressive, landscape-based approach, adapted to different levels of fragmentation and uncertainty. Three main types of solutions are identified, forming a continuum of intervention depending on the state of landscape permeability.

At one end of this continuum, permeability conservation represents the most efficient and cost-effective approach. In landscapes where connectivity is still intact, the priority should be preventive. This means integrating connectivity requirements directly into spatial planning and infrastructure development, ensuring that new barriers are avoided from the outset. In such contexts, connectivity does not need to be "planned" as a separate objective, but rather preserved as an inherent property of the landscape.

As fragmentation increases, connectivity networks, based on the designation of ecological corridors, become necessary. These solutions are more specific and spatially targeted, as they focus on maintaining key connections between habitat areas where movement is already constrained. While effective, they require active management, land-use adjustments, and, in many cases, compensation mechanisms. They therefore involve higher costs than preventive approaches, but remain essential for maintaining ecosystem services in fragmented landscapes.

In highly fragmented or impermeable landscapes, connectivity restoration becomes the only viable option. This includes site-specific interventions, such as wildlife crossings or ecoducts, aimed at repairing broken connections. These solutions are costly and technically complex, and they highlight the long-term consequences of failing to integrate connectivity considerations at earlier stages of development.

Across all cases, a central message of this guidance is that planning should focus primarily on landscape permeability and barriers, rather than relying only on current species presence, biodiversity "hotspots", or protected area boundaries. Connectivity must be treated as a structural property of the landscape, not as a reactive response to observed ecological constraints. In this respect, structural connectivity should be seen as a precondition and a reserve for future functional connectivity, especially under climate uncertainty.

A key risk identified is the persistence of a "separation model", where unprotected landscapes are treated as areas available for development without sufficient consideration of connectivity. This can lead to accelerated fragmentation through infrastructure expansion and urban growth that fails to integrate permeability, ultimately increasing future costs and reducing ecosystem resilience.

To address these challenges, the development and adoption of a Connectivity Digital Twin, complemented by an Online Viewer, are essential. Together, these tools form a practical decision-support system that enables better prioritization of interventions, early identification of risks, and more transparent planning processes. They allow connectivity to be addressed proactively, rather than reactively, and to be integrated across sectors and spatial scales.

At the same time, current practice still faces important limitations. Existing approaches to connectivity assessment are often based on land cover and expert judgement, with a strong focus on linking protected areas or specific habitat types. While these methods provide useful initial guidance, they are often static and do not fully capture the dynamic nature of ecological processes. In addition, monitoring of effectiveness remains limited, and significant data gaps persist, particularly regarding species movement and dispersal.

These limitations reinforce the need for a more integrated and adaptive approach, where connectivity is continuously assessed, monitored, and adjusted over time. In this context, the proposed framework supports a shift from isolated and reactive interventions toward a coherent, forward-looking model, where prevention, management, and restoration are applied in a complementary way.

Ultimately, the most effective strategy is not to rely on costly restoration measures, but to maintain landscape permeability wherever possible, keeping future options open in the face of uncertainty and ensuring the continued delivery of ecosystem services at the lowest possible cost.

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