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PlanToConnect

Standardized protocol of GBI network design

Guidelines for implementing Green and Blue Infrastructure (GBI) networks for spatial planners

V2.2

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Guidelines for Implementing Green and Blue Infrastructure (GBI) networks for spatial planners

Standardized protocol of GBI connectivity networks

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1 Purpose and scope

This protocol provides a framework for designing Green-Blue Infrastructure (GBI) networks in the Alpine region as part of the PlanToConnect project. It offers practical guidance for spatial planners, environmental managers, and policymakers on embedding ecological connectivity effectively into land-use policies and regional development strategies.

Guiding principles

The design and implementation of Green and Blue Infrastructure (GBI) networks should be guided by the following key principles:

- **Ecosystem-based approach:** Conserving entire ecosystems and their functions rather than individual species.
- **Multi-purpose use:** Serving ecological, social, and economic goal
- **Sustainability:** Promoting biodiversity, ecosystem health, and climate resilience sustainable land-use planning
- **Anti-fragility:** Encourage strategies that not only withstand disturbances but improve through them, fostering systems that benefit from variability and stress.
- **Cohesion and life quality:** Enhancing life quality by integrating GBIs into sustainable urban and regional development policies.
- **Transboundary planning:** Ensuring ecological connectivity planning across political boundaries through a consideration of natural ecosystems and collaborative mechanisms (see D.1.4.2 – Guidelines for Implementing GBI Networks).

While actual implementation involves specific actions like habitat restoration and barrier removal, this document specifically addresses the strategic design stage — covering conceptual planning, essential for creating effective connectivity frameworks. For detailed technical instructions regarding defragmentation techniques, policy integration, and stakeholder engagement, see D1.4.2.

Overview of the GBI design process:

1) Data collection	Collect land use, biodiversity, infrastructure and ecosystem services data
2) Definition of core areas and corridors	Identify protected areas, biodiversity hotspots, permeable areas, least-cost-paths, etc.
3) Barrier identification	Locate roads, urban clusters, fences, dams, etc.
4) Prioritization	Score and phase corridors based on urgency and feasibility
5) Implementation	Execute measures like protection in spatial plans, restoration of connecting green infrastructure elements, defragmentation, etc.

Figure 1: A step-by-step visualisation of the GBI design process, starting with data collection and ending with implementation.

This structured approach ensures that ecological connectivity planning is grounded in spatial evidence, stakeholder engagement, and policy alignment across all implementation levels.

2 GBI networks in the Alpine region

Ecological connectivity in the Alpine region is underpinned by key European Union policy frameworks, including:

- The Natura 2000 Network (Articles 3, 6, and 10 of the Habitat Directive).
- Other Effective Area-Based Conservation Measures (OECMs).
- The EU Green and Blue Infrastructure Strategy.
- The Trans-European Network for Nature (TEN-N).
- EU nature restoration law

Ecological connectivity became increasingly important in the context of the ongoing landscape fragmentation and biodiversity loss in Europe. The EU's Green Infrastructure Strategy therefore aims at developing a strategically planned network of natural and semi-natural areas. This network should enhance ecosystem services (ESS) and connects protected areas (PAs), thereby supporting multifunctional landscapes (Hermoso et al., 2020). The European Commission defines Green Infrastructure (GI) as "*strategically planned networks of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services. It incorporates green spaces (or blue if aquatic ecosystems are concerned) and other physical features in terrestrial (including coastal) and marine areas. On land, GI is present in rural and urban settings."* (European Commission 2013 & 2021). This network of green (land) and blue (water) spaces can improve environmental conditions […] and enhances biodiversity. The Natura 2000 network constitutes the backbone of the EU green infrastructure (EC 2021).

Key principles related to Green Infrastructure are:

- Connectivity
- Ecosystem services
- Spatial planning
- Nature capital
- Nature-based solutions
- Ecological functionality
- Multifunctionality
- Nature conservation
- Landscape ecology
- Landscape management
- Transcalarity

Among these principles, spatial planning and connectivity are one of the most important, along with multi-functionality. The social and ecological benefits of GBI depend to a large degree on ecological connectivity (Moreira et al. 2024), because it is "the unimpeded movement of species and the flow of natural processes that sustain life on Earth" (UNEP - CMS, 2020).

Ecological networks across the entire Alpine range are crucial for meeting European pledges for 2030, as biodiversity is endangered by changes in land use, urbanization, fragmentation, and man-made barriers.

Ecological connectivity:

According to Worboys et al. (Connectivity conservation management: a global guide, 2010), there are four types of connectivity: landscape connectivity, habitat connectivity, ecological connectivity, and evolutionary process connectivity. Landscape connectivity refers to vegetation patterns within a landscape, habitat connectivity relates to suitable habitats for specific species, ecological connectivity relates to ecological processes across scales, and evolutionary process connectivity identifies species movement.

- Facilitates species movements (feeding, breeding, escaping).
- Sustains ecosystem services (e.g., water purification, erosion control).
- Enables climate adaptation, vital in mountainous environments where fragmentation rapidly isolates populations.
- Maintains genetic diversity for wildlife.

In the Alpine region, steep gradients, changing climates, and intensive land uses complicate connectivity, but large tracts of semi-natural habitats remain. Linking these areas via GBI networks can:

- Foster biodiversity by supporting species' genetic exchange.
- Provide ecosystem services like flood mitigation and soil stabilization.
- Build climate resilience through better ecological adaptability

Classification framework

To support strategic GBI planning, landscape elements can be categorized according to their ecosystem type, land use intensity, and ecological functionality. This simplified classification supports spatial planners to understand principles for protection, restoration, or sustainable management of existing or potential ecological networks.

Ecosystem types:

- Terrestrial (forests, grasslands, alpine meadows, agricultural fields).
- Aquatic (rivers, streams, lakes, wetlands).
- Urban (green roofs, parks, urban waterways, road verges).

Land use intensity:

- Low - intensity use areas (extensive agriculture, silviculture).
- Medium - intensity use areas (intensive agriculture, managed forests).
- High - intensity use areas (urban centers, industrial zones).

Ecological functionality:

- High-functionality areas: intact ecosystems with high biodiversity.
- Medium-functionality areas: areas that retain some ecological function but are impacted by human activities.
- Low-functionality areas: heavily degraded but with restoration potential.

Effective ecological connectivity requires proactive integration into spatial and sectoral planning processes—well before major infrastructure or land-use changes occur. In the Alpine context, where topographical constraints and development pressures converge, early planning must adopt a cross-sectoral and multi-level approach, combining ecological insights with governance tools.

Key principles for early-stage planning include:

Integrated and multi-scale planning

- Align spatial planning efforts across local, regional, national, and transnational levels
- Ensure ecological connectivity is addressed consistently beyond administrative boundaries
- Identify, designate and safeguard key ecological corridors and core areas (e.g., corridors with macro-regional importance, Natura 2000 sites, SACAs).

Green and Blue Infrastructure (GBI) integration

- Design permeable landscapes, especially in urban contexts, through green belts, green roofs, and vegetated riverbanks
- Preserve and restore wildlife corridors and water-based networks
- Apply nature-based solutions such as reforestation, riparian buffer zones, and wetland restoration

Infrastructure planning with ecological considerations

(See guidelines on integration of GBI networks into planning, D1.4.2)

- Integrate wildlife crossings, eco-ducts, and fish passages into transport and energy projects
- Minimize the ecological footprint of renewable energy facilities (hydropower, wind, solar)

Smart land use regulations and incentives

(See guidelines on integration of GBI networks into planning, D1.4.2)

- Establish eco-sensitive zoning to prevent fragmentation in key areas
- Provide incentives for landowners to adopt biodiversity-friendly practices

- Introduce compensation schemes (e.g., habitat banking) for unavoidable impacts on connectivity

Stakeholder engagement and governance

(See guidelines on integration of GBI networks into planning, D1.4.2)

- Foster participatory planning involving municipalities, landowners, NGOs, and conservation experts
- Promote cross-sectoral collaboration between planners, ecologists, and policymakers
- Apply soft planning tools, such as landscape agreements or voluntary cooperation models

Informed and adaptive decision-making

(See guidelines on integration of GBI networks into planning, D1.4.2)

- Use spatial analysis tools (e.g., GIS, remote sensing) to identify connectivity gaps and corridors
- Implement long-term biodiversity monitoring
- Plan using scenario-based models that anticipate land-use change and climate impacts

By embedding these principles early in the planning cycle, Alpine regions can proactively safeguard ecological networks while balancing development and conservation needs.

3 Key elements and challenges (on Alpine Space level)

3.1 Ecological networks

Ecological networks are composed by core areas characterized by large, undisturbed habitats and landscape elements that connect them:

- **Core areas**:
  Core areas can be referred to specific species large, undisturbed habitats.
  From a structural point of view, core areas can represent areas with permeable landscape features, natural land cover and low influence of anthropogenic pressures. Often, protected areas represent core areas from a structural point of view.
- **Connecting elements (corridors)**: Connecting landscape elements are the connective "tissue", linking core areas, and can have various characters (see Figure 2 below):
  - linear corridors (e.g. narrow landscape strips within anthropized landscapes, green elements along rivers or roads, hedgerows in agricultural context),
  - buffer zones (e.g. around protected areas),
  - sustainable use areas (e.g. extensive agricultural areas), or
  - stepping stones (e.g. smaller forest patches, series of water ponds).

The GBI concept provide a more detailed classification of the landscape elements, starting from six main elements and breaking them down to a high level of detail, e.g., urban green belts, agroforestry buffers, etc. (see section 3.3 - "GBI elements").

Although protected areas often overlap with core areas, they are not considered as landscape patterns but as additional elements of the GBI network, representing normative conservation zones:

For a detailed collection of protected areas in the Alpine Space and their protection status, please visit the JECAMI platform:
https://www.jecami.eu/static/mapViewer/docu/docu_env_eusalp.pdf.

Additionally, to the mentioned elements, for the Alpine area including the EUSALP space numerous simulations and maps have been produced, identifying other areas of biodiversity value, which can be used for planning at an alps-wide scale (see Alpine Nature 2030, 2016 / Alpine Parks 2030; 2023 / Atlas ALBPIONET2030, 2019). The JECAMI data base is gathering numerous maps and alps-wide scenarios of ecological connectivity from former and current projects (www.jecami.eu).

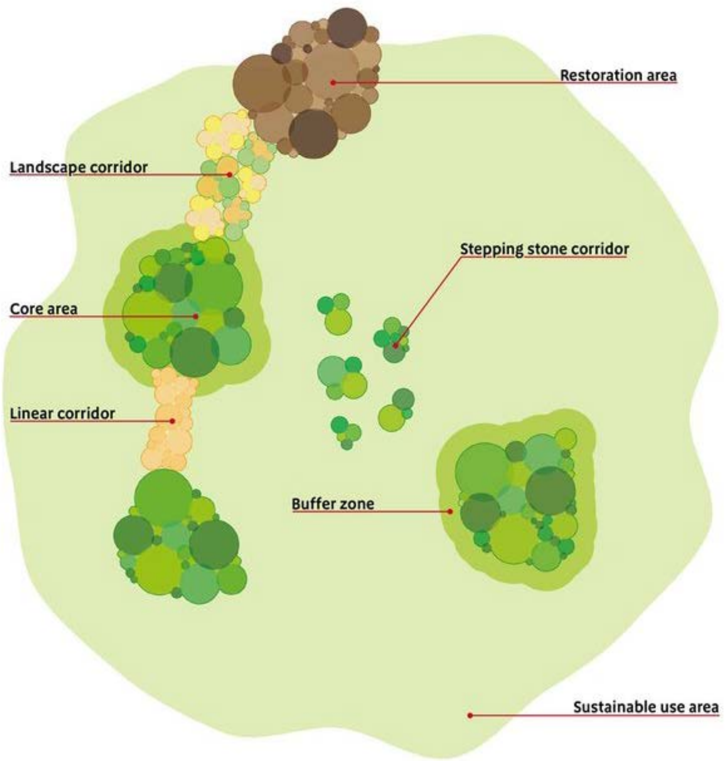

Figure 2: The components of ecological networks by Lawton et al. (2010)

3.2 Challenges and opportunities

Alpine Green and Blue Infrastructure (GBI) planning faces a unique set of geographical and socio-economic challenges:

- Rugged topography: Steep slopes, deep valleys.
- Existing anthropogenic infrastructure: Urban Sprawl & transport infrastructure, especially in the alpine valley bottoms created landscape and habitat fragmentation, specifically by settlement development, highways, railways, hydropower installations, transmission infrastructure.
- Existing anthropogenic land use by intensive agriculture: e.g. conversion of semi-natural areas into intensively used areas.
- Upcoming risks for connectivity: Renewable Energy infrastructure, especially by wind power and solar power installations.
- Transnational dimensions: Ecosystems cross administrative borders, requiring collaborative frameworks (e.g., Alpine Convention).

The impact of infrastructure development on structural and functional connectivity varies depending on the type of infrastructure and the extent of mitigation measures. High impacts on structural and functional connectivity are assigned to hydroelectric reservoirs due to related large land take and barrier/fragmentation effects. Run-off river power plants have a high impact on functional connectivity due to their barrier/fragmentation effects in the water body, while their impact on structural connectivity is rather low due to minimal land take. A similar differentiation can be applied to wind power and ground-mounted solar power. While their impact on structural connectivity is considered rather low due to low levels of land take/soil sealing, they can have a partly high impact on functional connectivity due to collision risks for birds and bats and fragmentation effects of fenced solar panels for large mammals. For bioenergy plants, the effects on ecological connectivity strongly depend not on the infrastructure itself, but on land use changes related to biomass production.

Road and railway infrastructure have high impacts on structural as well as functional connectivity through their large land take and barrier effects, mortality and emission impact due to traffic. Similarly, settlement development is having a high impact on structural and functional connectivity through its large share of overall land take. Summarising, transport infrastructure and settlement development are considered to have the most negative impacts on connectivity among the infrastructures analysed.

Urban sprawl and infrastructure development have significant impacts in ecological connectivity. These transformations increase the landscape fragmentation, reduce the quality of wildlife habitats and create barriers to wildlife movement. These anthropogenic pressures are intensified by the presence of higher population concentrations which lead to an increase on resources demand and widespread of artificialization. (Forman R., 2008)

The Alps represent some peculiarities in its urban development patterns, and because of their geographical position, that create specific problems for ecological connectivity:

- Linear infrastructure development of Inner-alpine valleys: A characteristic problem in the inner Alpine valleys are the infrastructural expansions and agricultural land uses, which are developing along the linear valley bottoms, due to the special topography. For this reason, these expansions tend to create linear barriers, interrupting habitat connections between mountain slopes.
- A second characteristic problem is that the Alps are at risk to become a biological island, because anthropogenic infrastructure is strongly developing in the outer Alpine Space. It is creating a belt of infrastructure barriers around the inner Alpine Space, interrupting ecological connections between the Alps and other mountain ranges. The Alps, located at the core of Europe would have a high potential for such macro-connections.
- Many national boundaries were drawn Along the mountain ridges in the Alps, for which reason the transnational dimension of ecological connectivity became crucial. Therefore, ecological connectivity planning requires collaborative frameworks.

The Alpine region biodiversity hotspots are being constantly threatened, on the valley area, the increasing infrastructure developments, the impacts of overtourism and the future demands regarding the use of the land and natural resources (e.g. renewable energies) within the region are key challenges to address when elaborating the design of the ecological network for the region. (Perrin, Berthrand, & Kohler, 2019)

Among renewable energies, hydropower is associated with the most negative impacts on connectivity, while wind power is seen as having the least negative impacts.

For all sectors analysed, impacts on the environment and in particular on connectivity can be reduced through appropriate avoidance and mitigation measures.

The Alps have a potential for the expansion of renewable energies due to their natural resources of water, biomass as well intensive solar radiation. For hydropower, most potential is already utilised and additional capacities, particularly for small hydropower projects feature a disproportionately negative balance of ecosystem impacts in relation to energy generation. Compared to high-yield locations across Europe, the wind power potential in the Alps is average. Solar energy potentials are particularly seen for areas in the southern Alps, with valley exposed to the south and more intensive solar radiation. Topographical conditions impede the accessibility of sites for renewable energy production in the Alps and access infrastructure therefore needs to be taken into consideration when assessing the overall impact of renewable energies on ecological connectivity.

Yet the Alpine region’s rich conservation history, advanced spatial modelling, and diverse communities create opportunities for a well-connected, resilient landscape.

Regarding infrastructural developments, opportunities lie in the application of appropriate avoidance and mitigation measures. Ideally, ecological connectivity concepts and hotspots are already taken into consideration at early stages of infrastructure planning processes. But also, for existing infrastructure, data is available on connectivity gaps and needs for action that can be used as an orientation on where connectivity retrofitting is most effective. Transportation corridors can have a significant potential for habitat connectivity, especially for generalist and specialised open grassland species, which favour early to mid-successional habitats. Verges, for example can provide a vital resource for landscape scale habitat connectivity and biodiversity by functioning as both connecting corridors and remnant habitat.

For wind power facilities, suitable measures can mitigate bird and bat mortality. Ground-mounted solar panels as well as for transmission lines not only represent risks but can also create opportunities for improving ecological connectivity under the precondition of connectivity-oriented design and location. These opportunities include high-diversity grassland due to extensive grazing schemes and the exclusion of other infrastructural developments or intensive land uses on the respective locations.

3.3 GBI elements

Green and Blue Infrastructure (GBI) refers to a network of natural and semi-natural areas, features, and green spaces in rural and urban, terrestrial, freshwater, coastal, and marine areas. These elements work together to:

- Contribute to biodiversity conservation
- Enhance ecosystem health and resilience
- Provide benefits to human populations through the maintenance and enhancement of ecosystem services

GBI is an alternative to traditional grey infrastructure, promoting sustainable land-use management and ecological connectivity.

GBI Category	Subtypes / Features	Typical examples
1. Core areas	Natural and semi-natural ecosystems with high biodiversity value	Alpine pastures, dry meadows, natural forests, bogs, floodplains, lakes, rivers, coastal wetlands
2. Restoration zones	Previously degraded or abandoned areas with ecological restoration potential	Reforested quarries, rewetted fens, revitalized floodplains, former farmland
3. Anthropogenic use zones	Agricultural or forestry landscapes with retained ecological function	High Nature Value (HNV) farmland, protection forests, extensive pastures
4. Urban & peri-urban green areas	Vegetated areas within or around cities that provide ecological and social benefits	Green paths, street trees, allotments, green roofs, urban parks
5. Natural connectivity features	Structural elements that support species movement and landscape continuity	Hedgerows, field margins, ponds, small woodlands, riparian vegetation
6. Artificial connectivity features	Engineered interventions to mitigate fragmentation and restore connectivity	Wildlife overpasses, amphibian tunnels, fish ladders, greened roadside verges

Table 1: GBI categories with subtypes and typical examples

(modified according to Benett et al. 2011)

Core areas

Subtypes / Elements	Function	Examples
Extensive agricultural landscapes	High biodiversity, low disturbance	Pastures, dry meadows, orchard meadows
Extensive forest landscapes	Habitat stability, ecosystem services	Natural forests, brushwood
Shorelines & coastal zones	Interface habitats, climate buffer	Lagoons, beaches, marine habitats
Wetlands (large-scale)	Water retention, carbon storage	Bogs, fens, marshes
Riverine landscapes	Natural corridors, flood mitigation	Rivers, creeks, floodplains
Pristine mountain areas	Climate refugia, species reservoirs	Alpine pastures, wastelands, glaciers
Still waters	Biodiversity hotspots, water regulation	Lakes, ponds

Table 2: Types, functions and examples of core areas

Restoration zones

Subtypes / Elements	Function	Examples
Restored agro/forest areas	Recovery of degraded land	Abandoned farmland, reforested sites
Restored riverine systems	Hydrological restoration	Revitalized watercourses
Restored wetlands	Biodiversity return, flood control	Rewetted fens, restored bogs
Restored industrial sites	Land recycling, habitat reintroduction	Disused quarries, brownfields

Table 3: Types, functions and examples of restoration zones

Anthropogenic use zones

Subtypes / Elements	Function	Examples
Extensive agriculture	Ecological function within land use	HNV farmland, orchards
Sustainable forests	Protection & multi-use	Watershed forests, avalanche protection
Functional riparian areas	Mixed-use corridors	Managed riverbanks, buffer strips
Intensive agriculture	Economic focus, low ecological value	Cropland, intensive pastures
Intensive forests	High disturbance, limited function	Plantations, deforested zones

Table 4: Types, functions and examples of anthropogenic use zones

Urban & peri-urban green areas

Subtypes / Elements	Function	Examples
Greenways (linear)	Connectivity, cooling	Tree-lined streets, cycle paths, green ditches
Greenbelts (area-based)	Urban-rural transition, buffer	Allotments, storm ponds, orchards
Metropolitan Park systems	Recreation, ecosystem services	Urban parks, cemeteries, green roofs

Table 5: Types, functions and examples of urban and peri-urban green areas

Natural connectivity features

Subtypes / Elements	Function	Examples
Multifunctional landscapes	Transition zones, biodiversity	Hedgerows, stone walls, small woodlands
Riparian corridors	Movement pathways	Riparian strips, riverbank vegetation

Table 6: Types, functions and examples of natural connectivity features

Artificial connectivity features

Subtypes / Elements	Function	Examples
Migration corridors	Safe passage for wildlife	Green bridges, amphibian tunnels
River continuum elements	Aquatic species movement	Fish ladders, bypass channels
Infrastructure green zones	Linear mitigation spaces	Roadside verges, powerline corridors

Table 7: Types, functions and examples of artificial connectivity features

4 Strategic framework for designing GBI networks

Designing Green-Blue Infrastructure (GBI) networks in the Alpine region entails navigating a rugged topography of steep mountains and deep valleys, along with considerable human pressures such as urban sprawl, infrastructure development (highways and railways), and intensive agriculture. These forces often fragment habitats and disrupt species movement. Yet the Alpine Space also holds substantial potential: natural and semi-natural areas remain widespread, providing a strong basis for connectivity if they are managed and linked effectively. Moreover, decades of conservation efforts, reinforced by transnational initiatives like the Alpine Convention, offer a collaborative framework for strengthening ecological connectivity.

Strategic implementation doesn't mean to focus on as many connected areas as possible but to proceed by priorities – to link habitats and to reduce fragmentation of natural areas where they have an ecologically spoken strategic signification such as "the last connection" of a very fragmentated space, a strategic link between two mountain ranges or a link between aquatic systems and interdepend habitats surrounding them. This approach needs to be done at all levels from the local to the international or inter-massif one.

A Strategic Framework for Designing Green and Blue Infrastructure Networks through Ecosystem Services can provide a structured approach for designing ecological networks that leverage ecosystem services to enhance ecological connectivity, biodiversity, and climate resilience while supporting socio-economic development.

By adopting this ecosystem service-based strategic framework, planners can create functional, resilient, and transboundary GBI networks that integrate nature, economy, and society in a sustainable manner.

1. Vision and objectives

A general vision based on the GBI concept is to create an anti-fragile, multifunctional, and interconnected Green and Blue Infrastructure network that enhances biodiversity, supports ecosystem services, and integrates sustainable land-use practices across different spatial scales. Core objectives of the development of a GBI networks can entail:

- Enhance ecological connectivity by integrating protected areas, habitats, and corridors.
- Support climate resilience through flood control, carbon sequestration, and microclimate regulation.
- Improve water management by restoring natural hydrological cycles and reducing flood risks.
- Promote socio-economic benefits through sustainable agriculture, forestry, and tourism.
- Foster multi-level governance and stakeholder engagement for cross-sectoral and transboundary coordination.

2. Ecosystem services as a planning framework

Ecosystem services provide a base for designing GBI by linking ecological functions with human benefits. The approach should enhance ecosystem service performances through a multifunctional perspective. The framework focuses on four key service categories:

- Provisioning Services (Material benefits provided by nature)
- Sustainable agriculture and forestry
- Freshwater supply from natural reservoirs
- Renewable energy potential (e.g., hydropower, biomass)

- Regulating Services (Processes that maintain environmental stability)
- Carbon sequestration (forests, peatlands)
- Water filtration and quality improvement (wetlands, riparian zones)
- Air purification (urban green spaces, forests)
- Natural flood and erosion control (coastal wetlands, riverbanks)

- Supporting Services (Underlying ecological processes)
- Habitat provision for biodiversity
- Pollination for agriculture and forestry
- Soil formation and nutrient cycling

- Cultural Services (Non-material benefits to society)
- Recreation and ecotourism (trails, green spaces)
- Aesthetic and landscape value
- Cultural heritage linked to natural areas

3. Strategic design principles

To integrate ecosystem services into GBI networks, planning should tail key design values:

a. Multi-scale and cross-border Integration
Since ecosystems span administrative boundaries, transnational planning efforts are indispensable in maintaining ecological connectivity across the Alps. Existing frameworks such as the Alpine Convention and the EU Green Infrastructure Strategy provide guidelines for harmonizing national and regional approaches. Joint projects can align cross-border corridors, ensuring large herbivores, migratory birds, and other species can move freely through contiguous habitats.

- Connect local, regional, and transnational ecological networks (e.g., Natura2000, Emerald Network).
- Strengthen cross-border planning to maintain transnational ecological corridors.

- Align harmonized GBI networks with national, transnational (EUSALP, Alpine Convention) and EU policies already within the planning process.

b. Nature-Based Solutions (NBS) and landscape resilience

- Restore natural water retention areas (e.g., wetlands) for climate adaptation.
- Increase urban green spaces (green roofs, tree corridors) for heat mitigation.
- Rewild degraded areas to enhance biodiversity and ecosystem services.
- The integration of NBS solutions should be considered as a driver for restoring ecological connectivity. The assessment of restoration needs via advanced spatial models is favourable.

c. Multi-Functionality and Land-Use Integration

- Design GBI networks with multiple functions (biodiversity, recreation, flood protection).
- Implement eco-sensitive zoning to integrate green areas into urban and rural planning.
- Promote agroecological practices that balance food production and ecosystem conservation.

d. Sustainable Infrastructure Development
In general, for strengthening connectivity, corridor planning should be aligned with transport, agriculture, and urban expansions:

- Incorporate wildlife-friendly transport infrastructure (green bridges, underpasses).
- Ensure low-impact energy projects (e.g., fish-friendly hydropower, biodiversity-conscious wind farms).
- Develop permeable urban landscapes (bioswales, green streets) for water management.

Uniting the above elements, a **structured, data-driven** approach can weave ecological connectivity into **spatial planning**, **policy frameworks**, and **land-use decisions** (see D1.4.2)

e. Participatory planning, cultivating public participation and awareness rising
Local communities and stakeholders play a crucial role in shaping GBI networks from which also the local population can benefit, and in creating acceptance for GBI measures. Early engagement allows planners to gather local insights, identify conservation priorities that resonate with community values, and communicate the benefits of connectivity in accessible ways, using participatory mapping, public consultations, or visual communication tools. This inclusive process not only fosters

goodwill but also ensures that GBI designs reflect on-the-ground realities and cultural landscapes. It helps also to visualize the values of green areas and make them visible.

f. Fostering interdisciplinary collaboration
Effective connectivity design depends on the shared expertise of spatial planners, conservation biologists, and ecological experts. These experts should find a common language when designing ecological networks and overcome the problem that spatial planners try to find a pragmatic way to define ecological networks, while wildlife biologists and ecologists try to be very precise in analysing the complexity of natural systems (Battisti 2004).
Multi-level expert panels encompassing local, regional, and international authorities, can facilitate knowledge exchange and coherent policy alignment. Such panels are vital when balancing technical data (for example, from connectivity models) with legal and social dimensions, particularly in areas where industrial or urban expansion may conflict with wildlife needs.
Panels at higher, international levels encompass for example, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Panels that can be used at national levels are e.g. the ÖROK in Austria or the panel regarding upgrading guidelines for ecological connectivity form ISPRA in Italy. Planning processes at lower level should be used for the creation and validation of plans or models on ecological networks at local level and should be elaborated in collaboration between planners and biologists.

4. Implementation and action plans

To operationalize the framework, a phased action plan is needed:

Phase 1: Assessment and mapping

- Identify key ecosystem services and ecological connectivity needs using GIS and spatial analysis. (see section 5 - GBI design checklist).
- Conduct stakeholder consultations to define priorities.
- Assess policy frameworks to align GBI planning with existing regulations.

Phase 2: Strategic planning and design

- Develop a trans-scalar GBI network integrating ecological, hydrological, and land-use systems.
- Establish eco-sensitive land-use zoning to prevent fragmentation.
- Prioritize nature-based solutions for flood prevention, carbon storage, and biodiversity conservation.

Phase 3: Implementation and governance

- Engage local communities, landowners, and stakeholders in decision-making.
- Implement pilot projects to test ecological corridors and green spaces.
- Foster cross-border cooperation for transnational corridors.
- Integrate GBI planning into local and regional policies.
- Establish public-private partnerships to fund GBI initiatives.
- Use adaptive management based on ongoing monitoring and evaluation.

Phase 4: Monitoring and adaptive management

- Establish long-term monitoring using ecological indicators.
- Adjust policies based on ecosystem performance and climate change scenarios.
- Promote knowledge exchange among Alpine stakeholders.

5. Expected outcomes

- Enhanced biodiversity and ecological resilience through well-connected habitats.
- Improved water and climate regulation with sustainable hydrological management.
- Increased socio-economic benefits from eco-tourism, recreation, and sustainable land use.
- Stronger cross-border governance and policy coherence.
- More sustainable anthropogenic infrastructure with minimal environmental impact.

5 GBI Design Checklist (conceptual stage)

This checklist is meant as a guide for planners, policymakers, and developers to ensure the effective integration of Green and Blue Infrastructure (GBI) into spatial planning and land-use development, particularly in ecologically sensitive regions like the Alpine space. It starts from a concept of a multifunctional, multiscale, antifragile approach to the design of GBI networks. By systematically applying this checklist, planners and decision-makers can enhance ecological connectivity, climate resilience, and sustainable development while ensuring that Green and Blue Infrastructure remains a core component of spatial planning.

Detailed methodological instructions on using specific GIS tools and modelling techniques are explained in section 6 - Technical Methodologies and Tools for GBI networks.

This conceptual checklist should ensure that planners consider some critical aspects of connectivity before moving into detailed technical steps. For implementation-specific instructions (e.g., barrier removal methods, restoration techniques), see D1.4.2.

5.1 The checklist

In the checklist, following elements should be considered:

1. Strategic planning and policy alignment
   - Align with national, regional, and transnational ecological connectivity strategies (e.g., Natura2000, EUSALP, Alpine Convention).
   - Ensure coherence with local land-use and spatial planning policies.
   - Incorporate GBI planning early in development processes rather than as a mitigation measure.
   - Facilitate cross-border cooperation for transnational ecological corridors.

2. Ecological connectivity and biodiversity preservation
   - Identify and map critical habitats, ecological corridors, and connectivity areas (e.g., Strategic Alpine Connectivity Areas - SACAs).
   - Avoid fragmentation of natural habitats by maintaining continuous ecological corridors.
   - Promote nature-based solutions such as rewilding and habitat restoration.
   - Implement buffer zones around sensitive ecosystems.

3. Climate adaptation and water management

Integrate climate change aspects to consider long-term land cover changes:

- Integrate natural water retention measures (e.g., wetlands, floodplains) to manage stormwater and prevent flooding.
- Restore and protect riparian zones and natural river morphology.
- Design urban drainage systems to include permeable surfaces, bioswales, and rain gardens.
- Enhance resilience to climate change by incorporating drought-resistant vegetation and sustainable irrigation practices.

4. Sustainable land use and development
   - Implement eco-sensitive zoning to protect key GBI networks.
   - Minimize soil sealing and encourage green infrastructure in urban areas (e.g., green roofs, vertical gardens).
   - Encourage mixed land use that integrates nature within residential, commercial, and industrial developments.
   - Incentivize sustainable agricultural and forestry practices that support biodiversity.

5. Infrastructure and mobility integration
   - Incorporate wildlife crossings (overpasses, underpasses) in road and rail projects.
   - Avoid barrier effects from transport infrastructure by maintaining permeability for species movement.
   - Promote sustainable transport corridors (e.g., greenways, cycling and walking paths).
   - Design energy infrastructure (hydropower, wind farms) to minimize impact on ecological connectivity.

6. Stakeholder engagement and governance
   - Ensure participatory planning by involving local communities, landowners, and conservation groups.
   - Foster multi-level governance, connecting local, regional, and transnational actors.
   - Encourage public-private partnerships to support GBI projects.
   - Implement soft planning tools such as voluntary agreements and financial incentives.

7. Monitoring, evaluation and adaptive management
   - Establish a long-term monitoring framework to assess GBI performance.
   - Use GIS mapping and remote sensing to track habitat changes and corridor effectiveness.
   - Integrate adaptive management strategies to refine approaches based on new data.
   - Set clear ecological and socio-economic indicators to measure success.

5.2 Important steps to consider in the GBI design process

Data Collection (Conceptual Stage)

Collect relevant data on land use, biodiversity hotspots, protected areas, agroecological infrastructures and human infrastructures.

The process begins with comprehensive data collection. High-resolution land-use and land-cover datasets, for example the EUSALP LULC 2020 dataset (5×5 m resolution), capture the detailed mosaic of forests, meadows, and built-up areas across the Alps. This dataset, together with information from Natura 2000, the WDPA, and national protected area catalogues, allows planners to accurately identify existing core areas and map the current state of ecological networks.

Ecosystem services approach: It is recommended to make a selection of ecosystem services which are useful for defining a strategic knowledge base for the GBI project (such as habitat quality, stormwater retention, nutrient retention, sediment retention, etc.). The collection of input datasets must be based on the chosen models (data related to land use, hydrogeological and lithological characteristics, vegetation quality, etc.).

Analysis of ecological connectivity: Defining Core Areas and Corridors

The next phase involves identifying and delineating core areas and ecological corridors. Core areas represent high-value conservation zones with stable populations, while corridors serve as the critical links between them. GIS models help determine potential routes that facilitate species movement and reduce isolation.
Gap Analysis: Identify gaps in connectivity across the Alpine region by assessing the current status of GBI and ecological networks. This could involve satellite imaging, GIS mapping, and data collection on species movement.
Climate Resilience and Antifragility: Evaluate how the identified ecological networks contribute to resilience against climate change, such as providing refugia for species shifting due to changing temperatures.

The SACA approach applied within the PlanToConnect project:

The Strategic Alpine Connectivity Areas (SACA) approach offers a useful lens through which to view the questions of ecological connectivity and protected areas. All Alpine and EUSALP areas have been analysed regarding their potential for ecological connectivity and assigned to one of three categories according to the status of their ecological connectivity and to the type of action required. For the

EUSALP area it can be illustrated, at a pan-Alpine level, where to prioritise conservation action, restoration activities or planning for more important ad-hoc measures.

Based on expert knowledge, the main barriers to ecological connectivity in and around the Alps have been defined based on the Strategic Alpine Connectivity Areas (SACA) analysis. These barriers represent significant obstacles to the movement of flora and fauna. One can observe a concentration of barriers in the border zone between the Alpine Convention area and the EUSALP area. The isolation of the mountainous region of the Alps from the surroundings is therefore a fact that needs to be considered when discussing ecological connectivity in the European Alpine context.

Ecosystem services approach:

The analysis of the selected ecosystem models and their overlaid synthesis supports an interpretative assessment of the ecosystem capacity of the project area. This, combined with the analysis of other key territorial elements based on local and regional knowledge, leads to the identification of core areas on one hand and the vulnerable areas on the other, where restoration areas and potential ecological corridors are located.

Barrier Identification (High-Level)

Following data collection, a thorough barrier and fragmentation analysis is conducted using GIS-based tools mentioned in section 6 – Technical methodologies and tools for GBI networks. This step documents both natural barriers (e.g., rivers, steep ridges) and human-made obstacles (e.g., roads, railways, urban zones) while assessing their permeability for various species. In regions where traditional mitigation (like wildlife crossings) falls short, an active defragmentation strategy is necessary to restore connectivity.

Analyze how permeable different landscapes are to species movements, or from the landscape structure perspective, or from the perspective of ecosystem services (GBI), considering natural and anthropogenic barriers (Landscape Permeability Assessment). For all the three approaches, barrier identification can be conducted in a similar way The Identify roads, railways, dense urban clusters, intensive agricultural land uses (see D.1.2.1 - on most important anthropogenic pressures in the Alps), installations for energy production, hydraulic structures or other major impediments. Note where existing wildlife crossings or stepping-stone habitats might already exist.

For a more precise mapping on a more detailed level, fences, walls, road surrounding infrastructures, unintentional traps can be identified to enhance barrier identification and local continuity issues for terrestrial connectivity. For water continuity, dams, thresholds and riverbed infrastructures can be identified.

Figure 3: Reflecting insights from the expert workshop at the PlanToConnect Mid-term event in Obergurgl, Austria (2024), this protocol underscores several interconnected strategies for harnessing opportunities and overcoming persistent challenges.

Prioritizing interventions (strategic overview)

Interventions are prioritized based on ecological significance, connectivity potential, barrier impacts, and implementation feasibility. This targeted strategy ensures efficient resource allocation and defines both short-term and long-term conservation actions.

Potential corridors can be scored based on ecological impact, feasibility, and land-use conflicts. In the PlanToConnect project, linkages were prioritized according to the Eisenhover matrix by importance of the linkage and risk of getting lost. For “importance” of an ecological linkage, criteria for the network coherency at alpine level were used. For urgency, the risk of the linkage to get lost by anthropogenic interventions in the landscape was used. The aim is to develop a phased plan that targets the most critical linkages first.

We propose a simplified decision scheme, which is based on the location of ecological corridors in strategic zones (e.g. SACA1 or Natura 2000), level of fragmentation, future risks, feasibility of implementation, and transboundary significance. The final prioritization is derived from the number of criteria met.

	Guiding questions	No – low priority	Yes – high priority
Importance	The corridor is in a SACA1 or Natura 2000 buffer or it is connecting those core areas?	No – general ecological value	High ecological potential
	It is part of a transboundary or regional linkage?	No – Local relevance only	Yes – Strategic weight for the Alpine network
	There is a high habitat fragmentation or barrier density?	No – Low pressure	Yes – Strong restoration need
Urgency	Is the area of interest for anthropogenic infrastructure projects, which will be developed in future?	No – low current risk of getting lost	Yes – high current risk of getting lost
	Are land-use conflicts moderate to low?	No – considerations of alternatives	High feasibility

Table 8: Simplified decision scheme guiding planners in assessing and prioritizing ecological corridors

Implementation:

Protecting and improving core habitats:

Key biodiversity areas, which may include SACA1 zones, hold the highest conservation value and are often essential stepping stones for wide-ranging species. By formally incorporating these zones into local and regional land-use plans, policymakers can prevent further fragmentation. This approach preserves ecologically intact areas as the “backbone” of a wider network, safeguarding breeding grounds, feeding sites, and refuge habitats vital for wildlife survival.

Mitigation of barrier effects by enhancing existing corridors:

Where corridors already exist—along rivers, forest strips, or hedgerows—improving their ecological functionality may involve widening them, removing man-made barriers, and enhancing habitat quality (for instance, by diversifying vegetation). By integrating these corridors into municipal plans and protected area management strategies, local governments can strengthen connectivity at scales that directly affect human livelihoods, from farmland productivity to flood mitigation.

Restoring degraded areas to enhance connectivity:

Not all critical habitats are pristine; many have suffered from historical or ongoing degradation. In such cases, targeted restoration strategies can help re-establish connectivity between isolated habitats. Tools like Marxan enable planners to weigh cost-effectiveness and ecological gains, ensuring restoration actions yield substantial benefits while remaining financially feasible. By rehabilitating wetlands, replanted forests, or riverine corridors, these efforts bolster the overall resilience of local ecosystems.

6 Technical methodologies and tools for GBI networks

Effective GBI projects rely on data-driven GIS-based landscape analysis and science-based design, using modeling tools that help identify critical corridors, optimize restoration sites, and forecast landscape changes.

GIS-based tools (including the JECAMI platform, Linkage Mapper, or Marxan) make it possible to pinpoint optimal corridors, prioritize critical biodiversity areas, and gauge feasibility under varying land-use pressures. By integrating ecosystem service valuation into corridor design, stakeholders can more effectively justify investments in GBI infrastructure. Whether identifying undeveloped ecological corridors, such as SACA1 zones, or projecting the impact of new transport routes, data-driven models ensure that connectivity solutions are founded on robust spatial evidence.

Accurate and comprehensive data collection, coupled with advanced spatial analysis, forms the basis for effective GBI design. The PlanToConnect Mid-term Workshop (2024) stressed the need to differentiate between Alpine-wide approaches and site-specific strategies, ensuring that the selection of data sources and analytical tools is tailored to the scale of decision-making.

6.1 Analysis of GBI elements

Mapping ecosystem services (ES) is essential for integrating natural capital into spatial planning, conservation, and decision-making. Various methodologies and tools help quantify, model, and visualize these services across different scales. Below is a structured overview of key approaches. By integrating biophysical, socioeconomic, participatory, and GIS-based approaches, spatial planners, conservationists, and policymakers can effectively manage and enhance ecosystem services to support sustainable development.

Being a multiscale process involving also monitoring steps, it is important that datasets and knowledge bases are built in an homogeneous approach, possibly using the same semiology (at least, for the land use at different scales, with a more precise categorization than the Corine), using integrated legend structures (which start from the local and more defined level and arrives to the territorial scale, where detailed information is grouped).

The choice of technical methodologies and tools depends on:

- The scale of analysis (local, regional, or global).
- The type of ecosystem services (provisioning, regulating, cultural, or supporting).
- The available data (spatial, economic, participatory inputs).

A. **Methodologies for mapping Ecosystem Services**
B. Biophysical Approaches

These methods rely on ecological data, remote sensing, and GIS to analyze the distribution and function of ecosystems.

- Land Cover-Based Assessments: Uses land use/land cover (LULC) data to infer ecosystem service provision. A dataset which was commonly used in the PlanToConnect pilot site projects was the EUSALP LULC 2020 Dataset (5×5 m resolution): This high-resolution dataset offers detailed land-use/ land-cover information for the European Alps, surpassing the coarser CORINE Land Cover data and enabling refined connectivity planning. https://doi.org/10.6084/m9.figshare.c.6357056.v1
- Remote Sensing and GIS Mapping: Uses satellite imagery, LiDAR, and aerial photography to analyze vegetation, water bodies, and urban areas.
- Biodiversity and Habitat Models: Predict the presence of species and habitat quality, essential for regulating services.

C. Process-based ecological modeling

These models simulate ecosystem functions and services under different scenarios.

- Hydrological Models (e.g., SWAT, InVEST Water Yield Model): Assess water provisioning, flood regulation, and watershed services.
- Carbon Sequestration Models (e.g., InVEST Carbon Model): Estimate carbon storage and sequestration in forests and soils.
- Pollination and Habitat Models (e.g., LONS, Pollination InVEST Model): Analyze the role of landscapes in supporting pollinators.

D. Socioeconomic and valuation approaches

These methods link ecosystem services to human well-being and economic valuation.

- Benefit Transfer Method (BTM): Uses existing economic valuation data from similar ecosystems to estimate services.
- Revealed and Stated Preference Methods (e.g., Contingent Valuation, Travel Cost Method): Measure how people value nature through surveys and market behaviors.
- Ecosystem Accounting (e.g., SEEA EA): Integrates ecosystem services into national economic accounts.

E. Participatory and expert-based approaches

- Involves local knowledge, expert judgment, and stakeholder engagement in ecosystem services mapping.
- Participatory GIS (PGIS): Engages communities in mapping culturally significant landscapes.
- Expert-Based Scoring: Uses Delphi or multi-criteria analysis to rank ecosystem services importance in a given region.
- Scenario Planning: Engages stakeholders to evaluate how land-use changes impact ES provision.

2. Tools for mapping ecosystem services

Some spatial analysis tools and models have been settled to assess ecosystem services at various scales:

F. GIS-based tools

These tools are the basic instruments for spatial analysis, and therefore also for ecosystem functions and services:

- ArcGIS and QGIS: Used for ecosystem service mapping, spatial analysis, and overlaying different environmental datasets.
- Google Earth Engine (GEE): A cloud-based platform for large-scale geospatial analysis, often used for vegetation and water monitoring.

B. Comprehensive decisional models based on Multicriteria Analysis

These tools are meant to evaluate ecosystem services, based on GIS tools, and provide a decisional framework to integrate them using the Multicriteria Decision Analysis (MCDA) framework:

- Burkhard model: an easy-to-apply concept based on a matrix linking spatially explicit biophysical landscape units to ecological integrity, ecosystem service supply and demand.
- ONEforest framework: a Multi-Criteria Decision Support System (MCDSS) to provide information for decision-making to stakeholders by assessing SFM, synergies and trade-offs of FES, reliable wood supply, and stakeholder interests through indicators of social, economic, and environmental dimensions.

C. Ecosystem service models

These models help quantify and predict ecosystem services distribution.

- InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs): Models carbon sequestration, water supply, habitat quality, and other ecosystem services.
- ARIES (Artificial Intelligence for Ecosystem Services): Uses machine learning and Bayesian networks to assess ecosystem services supply, flow, and demand.
- ESII (Ecosystem Services Identification and Inventory Tool): A web-based tool for rapid ecosystem services assessments.

G. Hydrological and climate tools

These tools assess water-related services and climate resilience.

- SWAT (Soil and Water Assessment Tool): Models of water quantity and quality at watershed levels.
- WEAP (Water Evaluation and Planning System): Evaluates water allocation scenarios and ecosystem impacts.
- Climate Risk and Vulnerability Assessments (CRVA): GIS-based tools to analyze climate resilience of ecosystem services.

H. Biodiversity and habitat connectivity models

These tools assess ecological networks and species movement. Since these models are the forerunners for ecological network modelling, the following section will focus on them and provide more detailed information with experiences from the PlanToConnect pilot sites.

6.2 Tools for network design and connectivity models

At the pilot site or regional level, GBI design must account for specific ecological and land-use conditions. Tools that facilitate this, which were used in the PlanToConnect project include:

- **Invest:** to assess a wide range of ecosystem services from regional to local scale depending on the input precision
- **Linkage Mapper:** This GIS-based modelling tool simulates movement pathways and identifies barriers at a regional scale.
- **Graphab:** calculates the least cost path from one reservoir to another.
- **Circuitscape:** represents all the potential paths that can be taken.
- **Marxan:** Particularly useful for balancing ecological value against cost and feasibility, Marxan aids in prioritizing local restoration or conservation actions.

The JECAMI platform, created in former connectivity projects and further developed in PlanToConnect, is an interactive interface, with ecological connectivity analysis, that are based on the before mentioned tools, allowing rough regional connectivity assessments.

Linkage Mapper (Network design by least-cost-paths)

- Use case: Creates ecological networks by identifying the nearest core areas, and identifies wildlife corridors, and shortest linkages, by analyzing least-cost paths based on landscape "cost" surfaces. It also proposes corridor width and identifies potential bottlenecks.
- Model Calibration:
  - Data Collection: Assembling land-cover layers, species distribution data, disturbance distances to infrastructure and topographic data.
  - Parameter Setup: Creation of core areas (e.g. of habitats), that might be produced by habitat suitability maps or by a structural approach and define habitat resistance values.
- Outputs: Produce network and corridor maps highlighting priority connections for targeted species or within structural networks.

(McRae & Kavanagh, 2011)

Graphab (Least Cost Path approach)

- Use case: Shows the cheapest route relative to the cost units defined originally.
- Model calibration: Calculation of each cell depending on its weight.
- Outputs: It can be a first step to identify potential paths taken by species depending on their ecological preferences before a field survey, and can help decision making on prioritizing corridors.

Circuitscape / Omniscape (Electric circuit theory)

- Use case: Uses an electrical circuit model to assess overall landscape permeability, applying connectivity to a landscape matrix with an area-based approach, using core areas as sources for wildlife movements. It can be used on a pr
- Model calibration: Adjust cost/resistance values to reflect local species movement and terrain.
- Outputs: "Current flow" maps showing where ecological flows (or potential wildlife passages) are strongest and where ecological flows are lowest or nearly unpossible due to high resistances.

(McRae et al., 2008)

InVEST Software (ES modelling tool)

- Use case: Assess a wide range of ES models enabling visualization, analyses and overlaying

- Procedure/ model calibration:
  - Selection of a representative number of models (ex. Habitat quality, stormwater retention, pollination value, nutrient retention, sediment retention…) basing on the natural and morphological characteristics of the pilot region
  - Data Collection: depending on the selected model the database inputs vary including for instance land-cover layers, soil and subsoil characteristics, hydrologic data, cultural entities, pollination data…
  - Models launch and parameters setup
- Output: Several outputs depending on the model that spatialize qualitative and quantitative data

Marxan (Setting targets, cost layers, scenario analysis)

Marxan can be used for a variety of systematic conservation planning purposes. However, Marxan was primarily developed to find a selection of new protected areas. It identifies a set of areas that meet conservation goals at minimal "costs." The Marxan algorithm attempts to achieve the defined goal (e.g., a percentage of certain features in the landscape) with the smallest possible costs (or smallest possible area) for each indicator. Additionally, it helps evaluate how well each option meets conservation and socioeconomic objectives, thus facilitating the derivation of trade-offs. It can also be used to highlight places that appear in a large number of 37oluteions (calculated by the algorithm - "simulated annealing"), which can help set priorities for conservation measures. The application assumes there are too many considerations for the solution to be readily apparent. It serves as decision support software in a planning process, and it does not create a final protected area.
Therefore, Marxan is a component of a larger planning process. Costs and time required for the effective use of Marxan ultimately depend on expertise, data availability, data volume, data format, team size, and planning context. It is particularly essential to allocate time for analysis and thoughtful communication of the results.

- Use case: Systematic approach for prioritizing conservation or restoration areas based on ecological and socio-economic trade-offs.
- Targets calibration: e.g., ensuring that at least X% of each critical habitat type remains protected.
- Output: Scenarios to compare multiple land-use or budget options to find cost-effective solutions.

(Marxan, 2025)

Support for connectivity planning with JECAMI

- Use case: Landscape and spatial planners who are less familiar with ecological connectivity modelling can view the Web-GIS application for visualizing corridors and potential connectivity improvements for their study region. It is possible to retrieve visualization and data for ecological connectivity assessments for transboundary and regional scales. The platform is interlinked with a data repository, that provides geographic data for the entire Alpine potential ecological network and makes them available for download. We recommend especially consulting data regarding non-protected permeable areas (SACA1 not protected) and priority connectivity areas in and around the Alps. However, they must be completed by ecological connectivity assessments at regional to local scales (as shown in the PlanToConnect pilot sites).

- Key Feature: Integrates the PlanToConnect Alpine Structural Potential Ecological Network for scenario testing and finer planning decisions.
  Serving as a comprehensive Web GIS tool, JECAMI integrates multiple datasets and allows planners to visualize the Alpine-wide Structural Potential Ecological Network developed within the PlanToConnect project. At the macro-regional level, the PlanToConnect Structural Connectivity Model identifies potential ecological linkages across the Alps. https://www.jecami.eu/ptc/

7 Monitoring and policy feedback

A **common methodology** ensures consistent design, implementation, **long-term monitoring and policy feedback.** Monitoring regarding ecological connectivity should not only be reduced to functional connectivity but should also be applied to landscape elements (structural connectivity) and extended to policy instruments (see D.1.4.2 - Guide on procedural steps for integrating GBI networks into planning).

7.1 Setting connectivity targets and measurable indicators

Define **quantifiable goals** (e.g., reduce wildlife-vehicle collisions by a certain percentage, increase corridor usage by target species by a certain percentage) so progress can be monitored. Additionally, targets for the land use and landscape structure (coverage of landscape elements (forest patches, hedges, water bodies, grassland etc.) can be defined and monitored (e.g. minimum of 70 % covered by forest, 10 % hedges, 20 % open grassland, no increase of technical infrastructure).

Monitoring can be differentiated into assessing structural and functional connectivity:

Structural connectivity indicators:
By GIS-based monitoring and remote sensing, various indicators can be monitored: With the established approach of Strategic Alpine Connectivity Areas and the Continuum Suitability Index, a monitoring could be based on landscape elements like the identification of permeable landscapes (SACA1 areas) main barriers(SACA3 areas), their patch sizes, distances to nearest neighbours of SACA1 areas, presence of habitats within buffer zones (< 2.5 km), and network indicators like the centrality of linkages, number of bottlenecks, (see PlanToConnect Mapping report of priority connectivity areas D.1.1.1 and Keely et al., 2021). Data on pressures from infrastructure and anthropogenic land uses are now used by the European Environment Agency (EEA, 2023) for monitoring protected areas. Many of them may be useful for ecological network monitoring. The “PlanToConenct” project proposes an adopted standardized list of pressures for corridors and tried to apply it on ecological networks in pilot areas (D1.2.1).

Monitoring structural connectivity builds on the modelling of structural connectivity, e.g. as it is outlined in the PlanToConnect Mapping Report of Priority Connectivity Areas for Spatial Planning (D1.1.1). Such a monitoring assesses how structural connectivity elements have developed between monitoring intervals. This includes:

- The securing of structural connectivity elements and corridors through spatial planning and other comparably formal sectoral instruments

- The implementation of recommended measures with the objective of improving structural connectivity (e.g. have habitats been developed according to the recommended measures, e.g. extensification, rewetting, reforestation etc.). Relevant indicators are those that allow conclusions in regard to the development of habitat conditions, e.g. nutrient withdrawal on previously fertilised plots.
- The evolution of structural connectivity functions within the landscape over the course of time (have open spaces and habitats lost or gained structural connectivity functions due to external factors such as land use changes, changes in climatic conditions)

Part of the monitoring is to quantify how these aspects of structural connectivity have developed over time at the respective spatial level:

- What quantitative share of structural connectivity elements has been secured?
- To what extent have measures been implemented in quantitative terms and also in terms of coherently and continuously developing ecological corridors?

Setting and monitoring quantitative targets in respect to structural ecological connectivity can help to interpret the monitoring results and draw conclusions for future recalibration of policies and measures.

Functional connectivity indicators:
Functional connectivity can be monitored by indicators regarding e.g. species presence, patch occupancy, movements of migratory individuals, species population sizes, habitat quality and suitability or species diversity in patches over time. (See PlanToConnect pilot sites South Tyrol, South Lake Annecy, Illertal, and Keely et al., 2021).

Monitoring functional connectivity focusses on the assessment of whether species or species groups are able to reach core areas using identified corridors (Sedy et al. 2022:43). Area-wide monitoring of functional connectivity is practically not feasible, so the spatial focus of monitoring functional connectivity should be placed on bottleneck situations of relevant corridors (over- and underpasses, grey infrastructure-related bottlenecks) and the permeability they allow over the course of time. Suitable indicator species need to be identified whose habitat requirements are sufficiently known and whose occurrence can be correlated with specific habitat conditions (ibid). Habitats surrounding bottleneck areas need to be selected to be able to identify specific indicator species.

Depending on the type of corridor and habitat, appropriate animal groups and efficient survey methods need to be selected. Animal groups feature different action radius and consequently use of connectivity elements. Monitoring functional connectivity with indicator species of large carnivores or large resp. medium sized mammals encompasses two approaches: Photo traps and field monitoring. The timing and timespan of monitoring depends on the selected methodology and indicator species (see table cf. Sedy et al. 2022:46 ff).

Indicator species groups (examples)	Recording methods	Duration and frequency
Large and medium sized mammals, including large carnivores	Camera traps and field monitoring, observation of road kills near crossing aids	1 year, with 3 visits in winter and 3 in summer
Small mammals	Near-ground camera traps, track traps, live traps, Observation of road kills near crossing aids	Continuous recording from June to August Evidence collection throughout the year
Amphibians and reptiles	Observation of road kills near crossing aids, artificial hiding places, fences and pitfall traps, acoustic detectors, camera traps, electrofishing surveys	Depending on the method: Monthly between March-October, twice within 14 days in spring, early summer

Table 9: Monitoring methods for functional connectivity

Appropriate monitoring sites can be determined based on the bottlenecks identified in the modelling of connectivity linkages between core areas, with supplementary knowledge provided by local experts. Monitoring sites for photo traps should be established in source and target areas of umbrella species, corridor segments where modelling suggests high connectivity, corridor segments where modelling suggests impacts/disruptions of connectivity and bottleneck segments of corridors (see Sedy et al. 2022:46 ff).

Alternatively, monitoring can also be based on threats in terms of regularly screening of regional/local development plans and exchange with spatial planning bodies. There, projects with a high probability to compromise the connectivity goals, could be detected. This approach could be used in highly dynamic areas. It would allow to act in advance, when threats arise, and projects are still in a pre-planning phase.

Monitoring Green and Blue Infrastructure and ecosystem services

With additional ecosystem services indicators, e.g. pollination, seed dispersal, or water regulation, the monitoring on a more comprehensive analysis on GBI elements can be gained (see PlanToConnect pilot site study of the Province of Sondrio and Caorle Wetlands).

Monitoring green and blue infrastructure (GBI) based on the ecosystem- service approach requires tracking key indicators to assess the health, function, and impact of GBI:

- Biodiversity Indicators: Species richness, habitat connectivity, and presence of indicator species.

- Water Quality and Hydrological Indicators: pH levels, dissolved oxygen, water flow, and wetland retention.
- Carbon Sequestration and Air Quality: Vegetation cover, CO_2 absorption rates, and particulate matter reduction.
- Land Use and Landscape Connectivity: Changes in land cover, urban expansion, and green space fragmentation.
- Climate Resilience and Extreme Weather Events: Impact of GBI on flood mitigation, heat reduction, and drought resilience.
- Social and Economic Benefits: Recreational use, property value increase, and community well-being.

7.2 Tools and Techniques for Monitoring

Remote Sensing: Drones, satellite imagery to monitor vegetation changes and land-use shifts.

The comparison of selected corridor areas over time allows for tracking changes in corridors in terms of structural and functional connectivity. Via screening of satellite images, rapid developments can be detected without going into the field.

Remote sensing offers a range of effective tools for monitoring ecological corridors, depending on the corridor's size, structure, and the required level of detail. For large-scale corridors, Sentinel-2 satellite imagery, with its 10 m spatial resolution and 5-day revisit cycle, provides a reliable basis for vegetation monitoring and land cover mapping. Through NDVI (Normalized Difference Vegetation Index) time series, it is possible to assess vegetation health and detect changes over time, such as encroachment by shrubs, seasonal dynamics, or the effects of management interventions.

For smaller, narrow, or more structurally complex corridors, like hedgerows, riparian strips, or wildlife passages, higher-resolution data is needed. UAV (drone) imagery and aerial orthophotos enable fine-scale mapping of corridor width, continuity, and fragmentation, using object-based classification methods. Multispectral drone sensors can complement this with NDVI analysis, and targeted manual field validation ensures accuracy in sensitive areas.

To capture vertical vegetation structure, such as tree height, canopy density, or understory complexity, LiDAR (Light Detection and Ranging) is the most precise method, delivering detailed 3D information. In summary, the choice of remote sensing method should be based on the scale and ecological characteristics of the corridor: coarse-resolution satellite data is efficient for broad patterns, while drones and LiDAR are essential for detailed, site-specific assessments.

Field data:

Telemetry, mark-recapture, or camera traps to confirm wildlife presence and movement.

For the generation of exact data (e.g. on vegetation changes or zoological questions (absence/presence of wildlife like traces) field data are very valuable for monitoring the corridor functionality. Collection of field data complements the remote sensing tools and is especially used for terrestrial verification of remote sensing data or for monitoring wildlife movements. However, the collection of field data requires resources to give valid information beyond random finds.

Good planning and careful sampling are key to generating statistically sound and comparable data in a changing environment. Therefore, fixed habitat plots, or wildlife transects are used to provide comparable data. Depending on the habitats and species, these plots and transects are different in size and in the parameters taken.

Such parameters within the plots are, for example, the vegetation coverage per vegetation layer (litter, mosses, herbal layer, shrubs, trees), the species found, the soul conditions, and the average height.

Depending on the question they can be set in the landscape based on qualitative criteria (e.g. on forest edges to measure the increase of forest into grassland in a gradient) or in a regular grid (e.g. every 100/1000 m). The latter approach is used for large areas.

For the monitoring of species movement, camera traps are set along transects and along wildlife pads and placed there for a certain time. The photos are analyzed either individually or with the help of artificial intelligence such as DeepFaune from CNRS.

Additionally, radio collars are used to detect animal movement.

Field data can also be generated via citizen science in terms of collaboration with those people who are regularly in the forest, like foresters or hunters. Via notified apps they could also be able to contribute their observations into a structured system. Examples are I-naturalist or (bird net or ornitho-platform).

Field data on road collisions are a good indicator of a disturbed corridor path and can gather data about a large range of different species.

Tools and techniques to monitor GBI performance:

Despite the already mentioned remote sensing techniques and satellite images, that can detect land-use changes to analyse ecosystem health, various technologies and participatory methods can be used to monitor GBI performance:

- IoT and Smart Sensors: Real-time monitoring of air quality, water flow, and soil moisture.
- Citizen Science and Participatory Mapping: Engaging communities in data collection (e.g., biodiversity surveys, crowd-sourced water quality testing).
- Ecological Modeling: Predictive models like InVEST, SWAT, and ARIES assess ecosystem service dynamics.

8 Conclusion

This protocol provides the conceptual and strategic roadmap for designing GBI networks in the Alpine region. By:

- Addressing multi-level governance and policy frameworks,
- Promoting cross-border cooperation and European policy alignment,
- Emphasizing robust data and stakeholder engagement, planners can embed ecological connectivity into land-use strategies and long-term planning.

Realizing robust GBI networks calls for integration into policy:

- Institutionalizing GBI principles in zoning and land-use laws.
- Ensuring stable funding (EU grants, national biodiversity funds) for corridor maintenance.
- Aligning efforts across sectors (nature – and landscape protection, transport infrastructure planning, adaptation of agricultural practices, urban development) and across borders.
- Monitoring corridor effectiveness with GIS-based tools and adaptive management strategies.
- Inform and raise awareness among policy makers.

While this document outlines the why and what of GBI networks, and detailed GIS analyses, D1.4.2 offers step-by-step technical guidance on implementation details, like barrier removal, habitat restoration, and ongoing monitoring procedures. These two documents together form an end-to-end framework—from conceptual design to on-the-ground implementation, ensuring ecological connectivity remains a cornerstone of sustainable land management in the Alpine region.

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PlanToConnect

Mainstreaming ecological connectivity in spatial planning systems of the Alpine Space

Project partners:

Urban Planning Institute of the Republic of Slovenia (SI)
Veneto Region (IT)
ALPARC – the Network of Alpine Protected Areas (FR)
Asters, organisation for the conservation of natural areas in Upper Savoy (FR)
Eurac Research (IT)
ifuplan - Institute for Environmental Planning and Spatial Development (DE)
University of Würzburg (DE)
Salzburg Institute for Regional Planning and Housing (AT)
E.C.O. Institute of Ecology Ltd. (AT)
Fondazione Politecnico di Milano (IT)

Standardized protocol of GBI network design
Guidelines for implementing Green and Blue Infrastructure (GBI) networks for spatial planners

Reference in AF D1.4.1 Standardized protocol of GBI connectivity networks

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