Towards Harmonised Biodiversity Indicators: Insights from a Biodiversa+ Workshop on Connectivity

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What is Biodiversa+

The European Biodiversity Partnership, Biodiversa+, supports excellent research on biodiversity with an impact for policy and society. Connecting science, policy and practice for transformative change, Biodiversa+ is part of the European Biodiversity Strategy for 2030 that aims to put Europe's biodiversity on a path to recovery by 2030. Co-funded by the European Commission, Biodiversa+ gathers partners from research funding, programming and environmental policy actors in European and associated countries to work on 5 main objectives:

1. plan and support research and innovation on biodiversity through a shared strategy, annual joint calls for research projects and capacity building activities;

2. set up a network of harmonised schemes to improve monitoring of biodiversity and ecosystem services across Europe;

3. contribute to high-end knowledge for deploying Nature-based Solutions and valuation of biodiversity in the private sector;

4. ensure efficient science-based support for policy-making and implementation in Europe;

5. strengthen the relevance and impact of pan-European research on biodiversity in a global context.

More information at: https://www.biodiversa.eu/

Table of contents

   www.biodiversa.eu

Main acronyms and definitions used in the report

CBD	Convention on Biological Diversity
DOPA	Digital Observatory for Protected Areas
EAP	Environment Action Programme
EBVs	Essential Biodiversity Variables
EEA	European Environmental Agency
EU	European Union
EUDR	EU Regulation on deforestation and forest degradation
EUFO	EU Observatory on deforestation and forest degradation
FAD	Forest Area Density
FMR	Forest Monitoring Regulation
JRC	European Commission Joint Research Centre
GEOBON	Group on Earth Observation Biodiversity Observation Network
K-M GBF	Kunming-Montreal Global Biodiversity Framework
MSFD	Marine Strategy Framework Directive
NRR	Nature Restoration Regulation
OECM	Other Effective area-based Conservation Measures
PA	Protected Area
PARC	Protected Area Connectedness Index
ProtConn	Protected Area Connectivity
UN	United Nations
WFD	Water Framework Directive

Executive summary

This report presents the outcomes of an online Biodiversa+ workshop held on 27 March 2025 focused on the harmonization and development of biodiversity connectivity indicators, essential tools for monitoring habitat condition and guiding conservation policy at global, European, and national levels. Connectivity indicators, ranging from graph-based metrics of protected area networks to structural measures like forest area density and functional indices based on species population size, are increasingly used to assess ecosystem health and track progress toward restoration targets under the EU Biodiversity Strategy 2030 and the Kunming-Montreal Global Biodiversity Framework. Despite their importance, significant challenges remain, including the multitude of assessment schemes, uneven capacity, limited data availability and/or data of good accuracy/quality, and gaps in integrating ecological complexity into indicator design. The workshop emphasized the need for capacity building, improved data availability and accuracy/quality, and stronger science-policy collaboration to ensure indicators are relevant, trusted, and widely adopted. A multi-scale, multi-indicator approach rooted in ecological understanding and aligned with policy priorities is promoted for advancing biodiversity connectivity monitoring and supporting nature restoration goals across Europe. While structural measures such as Forest Area Density can play a role in broad EU-wide assessments, they represent only one of several possible starting points for EU-wide accounting. At the same time, network-based indicators grounded in ecological theory are emerging as powerful tools for local and regional planning, and future work should explore their aggregation for broader reporting. Balancing these approaches will allow monitoring to remain both feasible today and scientifically robust tomorrow. Biodiversa+ is well placed to support these efforts by fostering networks for knowledge exchange, promoting open tools and data platforms, and engaging national stakeholders in indicator development.

Introduction

Biodiversity monitoring data play a central role in shaping effective public policies. By translating complex environmental data into actionable indicators, decision-makers can track progress, identify gaps, and prioritize actions. In Europe, directives such as the Birds-[1] and Habitats Directives[2], the Marine Strategy Framework Directive[3] (MSFD), the Water Framework Directive[4] (WFD), the proposed EU Forest Monitoring Regulation[5] (FMR), the EU environment action programme to 2030 (8EAP)[6], and the Nature Restoration Regulation[7] (NRR) incorporate a range of biodiversity indicators. Also, globally, the Convention on Biological Diversity's (CBD) Kunming-Montreal Global Biodiversity Framework (K-M GBF) recently has adopted a set of indicators.

An overview of European and global indicators, complemented by a survey to ministries of environment, environmental protection agencies and other relevant partners of Biodiversa+, highlighted the need for harmonization and development for these indicators (Naeslund et al 2023). This need is particularly critical for indicators connected to habitats and ecosystems, where questions of habitat quality, extent and connectivity have got new actuality with the goals in the EU Biodiversity Strategy for 2030[8] of establishing a functional network of protected areas and the EU nature restoration regulation[9].

On 27 March 2025, Biodiversa+ held the workshop "Integrating satellite remote sensing and emerging technologies to improve habitat connectivity indicators" to strengthen collaboration and share best practices. Participants discussed policy-relevant connectivity indicators, core metrics, modelling approaches, software tools, and novel technologies used to collect data. This report presents the outcomes from the workshop and discusses future needs for indicator harmonisation and development.

Background and showcases

Indicators of habitat condition, extent and connectivity help policymakers interpret complex landscape patterns and make evidence-based decisions about protection, restoration and ecological network design. A landscape perspective is essential because connectivity has both structural and functional dimensions, where structural connectivity describes the physical arrangement and aggregation of habitat,

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[1] Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds (Codified version): Conservation of wild birds | EUR-Lex

[2] Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora: Directive - 92/43 - EN - Habitats Directive - EUR-Lex

[3] Strategy for the marine environment: https://eur-lex.europa.eu/EN/legal-content/summary/strategy-for-the-marine-environment.html

[4] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy: https://eur-lex.europa.eu/eli/dir/2000/60/oj/eng

[5] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on a monitoring framework for resilient European forests: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52023PC0728

[6] EU environment action programme to 2030: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=legissum:4591047

[7] Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869 (Text with EEA relevance): https://eur-lex.europa.eu/eli/reg/2024/1991/oj/eng

[8] EU biodiversity strategy for 2030: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=legissum:4459196

[9] EU Nature restoration Regulation https://eur-lex.europa.eu/eli/reg/2024/1991/oj/eng

and functional connectivity reflects the real capacity of organisms to move across landscapes given their traits and the permeability (or resistance) of the intervening matrix. While these dimensions are often correlated, barriers can cause ecological (functional) distance to increase much faster than geographic distance, which is why policy monitoring must be explicit about what is being measured and how.

Connectivity metrics and indicators used in policy & showcases discussed

At the global scale, the Kunming-Montreal Global Biodiversity Framework (K-M GBF) use two connectivity indicators discussed at the workshop, Protected Connected Land (ProtConn, DOPA 2023) and the Protected Area Representativeness and Connectedness Index (PARC[10]) to support target 3 (30% conserved and well-connected by 2030). ProtConn reflects structural connectivity, while PARC emphasizes functional connectivity informed by biodiversity patterns. ProtConn is also used to assess Europe's protected-area connectedness (e.g., role of Natura 2000) and for aligning EU targets with CBD commitments.

Within the European Union, several structural connectivity metrics and indicators have been implemented. Key examples during the workshop were the Forest Area Density (FAD) metric and the Natural Area Connectivity indicator that build on the same metric as FAD. FAD was developed by the JRC for the UN-FAO and the EU's 8EAP, FMR, and NRR, and calculates the proportion of forest within a predefined moving window area[11]. FAD provides a measure of forest cover agglomeration and supports monitoring under the EU NRR. The metric is correlated with the amount of forest in a given area. The metric also supports the EU Regulation on deforestation and forest degradation[12] (EUDR), with forest connectivity assessed and reported for 260 reporting units, accessible in the EU Observatory on deforestation and forest degradation[13] (EUFO). The Natural Area Connectivity Indicator uses the same metric applied to generic natural land cover, reclassifies land cover into natural versus non-natural categories and is assessed in a 50 km^2 local neighbourhood when using global land cover This indicator it is used to assess the EU biodiversity strategy target 1 on achieving a coherent network of protected areas (Robuchon et al. 2024).

From metrics to models

During the workshop, various model approaches used for policy were also presented and discussed. Beyond structural metrics, connectivity can also be described in different 'spaces.' Metrics such as Forest Area Density (FAD) measure how habitat is aggregated in Euclidean space, i.e. in terms of geographic distance and area. By contrast, network-based approaches such as circuit theory or metapopulation capacity assess connectivity in topological space, where distances are defined by ecological resistance and/or dispersal pathways. While Euclidean and topological distances are generally positively correlated, the presence of barriers and obstacles can cause ecological distance to increase much more rapidly than geographic distance. This conceptual distinction underpins the methodological differences between structural measures like FAD and network-based models.

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[10] PARC Metadata Factsheet UN WCMS: https://gbf-indicators.org/metadata/other/A-5-C

[11] Quantifying Forest Connectivity/Fragmentation: https://ies-ows.jrc.ec.europa.eu/gtb/GTB/psheets/GTB-Fragmentation-FADFOS.pdf

[12] Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010 (Text with EEA relevance): https://eur-lex.europa.eu/eli/reg/2023/1115/oj/eng

[13] EU observatory on deforestation and forest degradation: https://forest-observatory.ec.europa.eu/forest/gfa

Network-based and resistance models have been used to assess connectivity across Europe. The Natura 2000 Connectivity Project by the JRC applied graph-based modelling to evaluate the connectivity of Natura 2000 forest sites across EU countries (Estreguil et al. 2013). At national and local levels, countries often use GIS tools to design and visualize ecological networks for conservation planning, e.g. maps showing how natural areas and protected sites link together. These networks can be analysed using graph and circuit theories to produce connectivity indices (e.g. area-weighted Probability of Connectivity) and to identify key corridors and pinch points. EU-funded projects within programmes such as LIFE and INTERREG have employed circuit theory and least-cost resistance models to map critical connectivity features, directly addressing issues of matrix permeability and dispersal distance.

Advanced functional models with the capacity to create species-specific models also contribute significantly to understanding habitat connectivity, e.g. the Landscape ecological Analysis and Rules for the Configuration of Habitat (LARCH-SCAN) and Connected Habitat Approach (CHA), that were presented during the workshop. LARCH-SCAN creates species-specific landscape models by evaluating species ecological networks based on habitat quality and suitability, patch area, inter-patch distances, and matrix permeability (Groot Bruinderink et al., 2003, Verboom & Pouwels, 2004, Verboom et al., 2001). LARCH-SCAN is proposed as potential future RS-enabled Essential Biodiversity Variables (EBV) for Fragmentation (ESA, FRAG)[14].

The Connected Habitat Approach (CHA) combines habitat suitability models with network analysis to estimate both the amount of functional habitat and its connectivity across different spatial scales. While not species-specific by default, CHA can be adapted for individual species by incorporating their habitat and dispersal parameters. The approach is based on metapopulation theory and uses concepts such as metapopulation capacity (the ability of a habitat network to support a species) and equivalent connected habitat (the total habitat available when connectivity is considered) (Van Moorter et al. 2023a). The CHA supports land-use planning, conservation, restoration, and forecasting the impacts of infrastructure and policy changes (Dorber et al. 2023).

Tools and softwares

A wide range of tools is available to support the analysis and implementation of habitat connectivity indicators, serving both technical users and practitioners with limited GIS experience. One valuable resource is the Conservation Corridor's Program and Tools summary[15], which provides a curated list of software platforms, guidance documents, and technical manuals for connectivity planning, e.g. GuidosToolbox (Vogt and Riitters 2017, Guidos Toolbox 2025) that can be used for FAD and Conefor (Saura and Pascual-Hortal 2007) used for ProtConn. ConScape is a Julia-based software library that was presented during the workshop and is designed to compute habitat connectivity metrics for large areas, including movement corridors, i.e. pinch points and bottlenecks (Van Moorter et al. 2023b). It implements a range of movement algorithms from optimal/least-cost to random walk, in addition to the full continuum represented by randomized shortest paths framework to allow for a more realistic representation of movement processes. For those working in R (R Core Team 2025[16]), a rapidly expanding number of open-source packages enables the exploration of spatial statistics, species distribution modelling, landscape genetics, and connectivity metrics.

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[14] ESA European space agency, earth observation for science. FRAG Remote Sensing-enabled EBV for Fragmentation https://eo4society.esa.int/wp-content/uploads/2021/01/GlobDiversity_Frag_Brochure_final.pdf

[15] Conservation Corridor Programs and Tools: Programs and Tools - Conservation Corridor

[16] R Core Team (2025). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

A summary table (Table 1) outlines key connectivity metrics, indicators and model approaches that were discussed during the workshop, their conceptual bases, and their relevance to policy.

Table 1

Name	Category	Fragmentation Dimension(s)	Method / Concept	Policy Use / Framework
Protected Connected Land (ProtConn)	Indicator, Structural	Area, Distance	graph/network analysis	CBD Kunming-Montreal GBF Target 3, EU reporting
Protected Area Representativeness & Connectedness (PARC)	Indicator, composite functional	Area, Distance	Composite of protected areas representativeness + connectivity, species turnover models; environmental similarity	CBD Kunming-Montreal GBF Target 3
Forest Area Density (FAD), Forest connectivity	Metric, Structural indicator	Focal area within local neighbourhood	Structural, degree in connectivity within forest habitat	EU: FMR, NRR, 8EAP, ForestEurope, Global: UN-FAO
Natural Area Connectivity (FAD-based)	Metric, Structural	Focal area within local neighbourhood	Structural, degree in connectivity within natural habitat	EU biodiversity strategy target 1 coherent network of protected areas
Natura 2000 Connectivity	Model approach, structural	Area, Distance, Matrix permeability	Graph & least-cost model (habitat resistance)	Natura 2000 coherence, EU Green infrastructure planning, Art. 10 habitats directive
CHA (Connected Habitat Approach)	Model approach, functional	Quality, Distance, matrix permeability	(Species-based) landscape network models / resistance modelling	Used for national Green Infrastructure planning, restoration planning, and cumulative impact assessment
LARCH-SCAN	Model approach, functional	Patch-area, Quality, Distance, Matrix permeability	Species-based landscape models / resistance modelling	Used in ESA GlobDiversity, national restoration planning (NRR)

Reflections from the workshop

Policy needs and current applications

Participants of the Biodiversa+ workshop explored policy needs and current applications of biodiversity connectivity indicators. They also addressed the necessity for harmonized implementation of policy-relevant indicators, data requirements, and the potential role of emerging technologies.

Participants shared diverse experiences on how connectivity indicators are currently being applied, or are planned to be applied, across multiple contexts and scales. Connectivity theory informs species-specific management plans by identifying critical habitat links, and it plays an important role in local and regional spatial planning, particularly for designing green infrastructure networks. One example is the network-based CHA, which guides sustainable land planning for wild reindeer in Norway, supporting cumulative impact assessment, scenario analysis, and zonation. The CHA also informs municipal multi-species green infrastructure planning (Panzacchi et al. 2024) and ecosystem accounting (Bjørkvoll et al. 2025).

Connectivity indicators and theories are also used to monitor dynamic environmental processes and pressures, such as land-use change and shifting landscapes (for example in delta regions), and for tracking wildfires. National governments are also increasingly considering connectivity indicators to meet obligations under the NRR, which requires restoring functional ecosystems by 2030, for instance improving connectivity of rivers and adjoining floodplains (art. 9) and forest connectivity (art. 12).

Conceptual and indicator-design challenges

Despite broad recognition of their value, several bottlenecks hinder the use of connectivity indicators. A central challenge lies in defining ecological connectivity in a way that is both meaningful and actionable. Participants emphasized that no single indicator can fully capture the complexity of ecological connectivity, as different species and ecosystems require tailored approaches. Biological factors such as dispersal distances, from local movements to continental migrations set the scope for meaningful assessments. At the same time, the scale and resolution of input data must match the intended purpose. Clarity about the question being asked and the scale at which the indicator operates is therefore essential to avoid misinterpretation.

A common example is the use of forest cover as a proxy for connectivity. While often treated as a positive biodiversity indicator, relying on forest cover alone at broad scales may mislead decision-making and threaten semi-natural open habitats (e.g., grasslands) that depend on active management. To improve relevance, indicators should capture ecologically significant features and ideally combine multiple measures.

Data limitations and their implications

Data availability on appropriate spatial and temporal scales often sets hard limits. Satellite remote sensing may overlook small-scale but ecologically important features such as stone walls or water elements in agricultural landscapes. Marine applications can be even more challenging: water-quality assessment requires sub-surface measurements (below 3 m) that are difficult to obtain remotely, and cloud cover further complicates monitoring in some regions.

The Copernicus program is gradually filling this data gap with high resolution data at 10 and 20 m resolution that hold promise for closing these gaps and assessing functional connectivity more effectively. However, the workshop underscored that the quality, compatibility, and temporal consistency of input data are decisive factors. Historical gaps, irregular update cycles, and inconsistent resolutions make long-term monitoring difficult.

A recurring issue in the discussions was that this mismatch between the scale of available data and the requirements of national policy frameworks were problematic. While the NRR mandates the development of national restoration plans, the data required for effectively setting ecological baselines and planning is often only available at coarse or generalized scales that fail to detect habitats or habitat features of conservation interest. Variability in country area and governance further complicate uniform EU-wide implementation.

Science-policy interface and scale mismatches

Challenges of this kind highlight weaknesses in the science–policy interface. EU-wide assessments often rely on datasets lacking local or regional calibration, undermining their credibility and practical usefulness. Connectivity, by its nature, varies across scales and species, and depends on numerous land-cover attributes that are rarely available at multiple spatial and temporal levels. As a result, upscaling from local to continental assessments is therefore fraught with difficulty. Though, strengthening the involvement of national experts and stakeholders in developing indicators and validating the indicators at local scales (ideally using local/regional/national data both for developing and validating), were highlighted as essential for building trust, transparency, and policy relevance.

Scale mismatches also reveal an important conceptual issue: the choice of space in which connectivity is measured. At aggregated scales such as country or EU reporting, structural (Euclidean-based) and functional (network-based) connectivity metrics often yield similar patterns because ecological and geographic distances are correlated at broad scales. At local and regional planning scales, however, the choice of space becomes more consequential. Linear infrastructures (e.g. roads, powerlines), rivers, or fjords can create sharp divergences between Euclidean and topological connectivity, with strong implications for zoning, restoration, and infrastructure development. In such cases, relying only on Euclidean indicators risks masking ecological barriers, whereas network-based approaches can reveal the true functional continuity of landscapes.

Methodological fragmentation

A further layer of complexity arises from the diversity of tools and software used across countries and institutions. While this variety allows practitioners to select context-appropriate methods, it complicates efforts to harmonize and compare commonly used indicators at national, European, and global levels.

This fragmentation is compounded by limited understanding of the network science principles that underpin much of connectivity science. Relationships among methods, for instance circuit theory as part of network theory, are often poorly communicated, giving the impression of greater methodological divergence than actually exists. Frameworks such as the CHA explicitly ground connectivity assessment in network theory, making the relationship between circuit theory, graph indices, and metapopulation models more transparent.

Resource constraints

Even when datasets exist, they may be difficult to access, interpret, or integrate into workflows without sufficient technical expertise. Limited human and financial capacity was identified as a major barrier, especially for regional authorities that must balance multiple responsibilities with small teams.

Advanced modelling approaches—such as graph-based metrics, circuit theory, or machine-learning-enhanced habitat maps—often require specialized skills that are not evenly distributed across institutions. This can lead to reliance on short-term projects or external consultants, reducing continuity when funding ends or staff change.

Financial limitations also restrict investment in high-resolution data, computational infrastructure, and sustained monitoring programmes. Although open datasets like Copernicus offer valuable opportunities, many institutions lack the resources to process large datasets or maintain the IT systems needed. As a result, promising technological advances remain underused.

Finally, resource constraints hinder cross-sector coordination, as effective collaboration among conservation agencies, planners, and data providers requires time and stable support. Without this, even well-designed indicators may struggle to achieve their intended policy impact.

Looking forward: opportunities and needs

Participants highlighted that several emerging techniques have the potential to significantly improve the way connectivity is measured and monitored. High-resolution satellite imagery, drone-based mapping, and airborne lidar can reveal fine-scale structures, such as vegetation height, small watercourses, or linear barriers that satellite datasets often miss. Though participants particularly highlighted and advocated for approaches that better integrate remote sensing with in-situ field data. And also using an iterative process where in-situ field data is used for building indicators and to validate the results.

Participants also noted that increasing access to machine learning and high-performance computing can help process large datasets and support more demanding models. Realizing this potential, however, requires standardized workflows, open-access data repositories, and investments in computational infrastructure that allows practitioners to work with increasingly large and complex datasets. The growing availability of high-performance computing within governments and research institutions is promising, but many authorities still need support to operationalize these tools and translate them into management-ready products.

Finally, participants noted that while connectivity science has developed considerably since the 1990s, decision-makers often need to act in the present. In practice, this means balancing innovative methods with more established approaches that can already support timely and informed management. Strengthening capacity building, improving communication between scientists and practitioners, and fostering interdisciplinary collaboration were highlighted as essential steps for ensuring that advances in connectivity science deliver tangible benefits for conservation and spatial planning.

Discussion and future needs

The Biodiversa+ workshop highlighted the growing importance and complexity of connectivity indicators in biodiversity monitoring and policy implementation. As biodiversity policies evolve to address more

ambitious targets, such as those outlined in the EU Biodiversity Strategy for 2030 and the K-M GBF, the need for reliable, harmonised, and policy-relevant indicators becomes ever more pressing.

The workshop discussions revealed that the current landscape of connectivity indicators remains fragmented, both in terms of methodological consistency and institutional uptake. This fragmentation reflects the fact that ecological connectivity cannot be captured by a single metric, as different species, spatial scales, and management objectives require different approaches. For this reason, the scientific community has developed various assessment schemes to address specific aspects of connectivity that are deemed relevant at a given scale, for a given species, a specific land management or policy planning purpose. While this does not make progress towards a balanced set of harmonized high-quality, policy-relevant and widely accepted connectivity indicators impossible, it mandates a significant and sustained effort to achieve progress.

Participants emphasized that while many countries and agencies have begun to adopt or explore connectivity indicators, there is a striking variability in how these indicators are defined, calculated, and interpreted. This variability is in part due to the diversity of ecosystems, species, and policy priorities across jurisdictions, but it also reflects a lack of harmonised guidelines and/or coordinated capacity-building.

There is especially a policy demand for coordinated capacity building for the use and interpretation at country/regional/local levels of key indicators already embedded in European and global frameworks such as the Forest Area Density (FAD), the Natural Areas Connectivity index, and Protected Connected land (ProtConn). To support local, regional and cross-border ecosystem management and ensure coherent reporting under shared biodiversity goals, it is essential to develop shared methodologies and standards, supported by clearly documented workflows and open-source tools. Moreover, the science-policy interface was repeatedly identified as a bottleneck. Indicators developed at EU or global levels sometimes lack ecological realism or policy relevance at national or local levels. On the other hand, indicators that are relevant at local level may well be irrelevant at continental level. Ensuring the involvement of national experts, planners, and practitioners from the earliest stages of indicator development at EU or global level is critical for fostering ownership, trust, and usability. Strengthening this interface through participatory co-design and structured feedback loops will ensure indicators better reflect the real-world conditions and management realities faced by countries. Ultimately, this will enhance not only their ecological validity but also their possible policy relevance across scales and dimensions of connectivity.

A further consideration for future indicator development is methodological consistency across scales. Structural measures such as FAD may be sufficient for aggregated accounting at EU or national levels, while network-based measures provide greater ecological realism at local scales. Yet there is added value in applying the same family of metrics consistently across scales. Network-based indicators can be calculated locally and aggregated upwards, creating a single conceptual framework that serves both accounting and planning purposes (Zetterberg et al. 2010). While this represents a promising direction, it is also important to acknowledge practical considerations. Structural measures such as FAD remain widely used because they are computationally efficient and operationally mature (e.g. Vogt and Caudullo 2025). Network-based approaches, though conceptually powerful, are still evolving in terms of computational feasibility and ease of implementation (e.g. Hughes et al. 2023, Van Moorter et al. 2023b). In this sense, FAD can serve as a pragmatic baseline indicator today, while network-based methods represent the trajectory of future innovation.

A fundamental limitation to indicator implementation is access to timely, high-resolution, and ecologically relevant data of adequate and well-documented quality. Several workshop participants reported that current available EU-level connectivity datasets are too coarse or are not representative to inform national

restoration plans or design or to capture fine-scale habitat features that are critical for functional connectivity. Moreover, key ecological structures, such as hedgerows, stone walls, small ponds, or semi-natural field margins, are often only visible in very high resolution remote sensing datasets but play disproportionately large roles in maintaining connectivity in agricultural landscapes. Thus, there is a strong need to complement connectivity datasets with higher resolution remote sensing datasets (lidar, aerial images, drones) and ground truth, in-situ data sources, such as national forest inventories, or species monitoring records. Emerging technologies, such as machine learning models trained on integrated satellite and field data, hold promise for improving the ecological realism of indicators. However, realizing these gains requires investment in open-access data infrastructures with capacity to manage large datasets, transparent model training processes, human resources, and ongoing data stewardship.

In addition, methodological transparency and accessibility are essential. Many tools used for connectivity analysis (like Conefor, ConScape, GuidosToolbox) require specialized expertise and are often applied in project-specific contexts. Participants also called for capacity building in using appropriate existing "toolboxes" or repositories for indicator applications such as those available for the K-M GBF[17], or BON in a Box (GEO BON 2025, Griffithet al 2025). BON in a Box is an open, web-based platform that provides ready-to-use workflows for producing biodiversity indicators, helping users move from raw data to standardized metrics in a transparent and repeatable way. Promoting user-friendly platforms, shared repositories, and documented workflows will help democratize access to these tools and build capacity across countries and institutions. This would support both newcomers and experienced users in applying appropriate methods for their ecological and policy context, and would encourage the reuse and scaling-up of successful approaches.

How Biodiversa+ can best support indicator development

Biodiversa+ is uniquely positioned to play a catalytic role in advancing the development, harmonisation, and effective implementation of biodiversity connectivity indicators across Europe by bridging research, policy, and practice. The workshop clearly highlighted that while many countries and institutions have developed or are using various indicators, there is a pressing need for stronger coordination and support at multiple levels. One of the most immediate contributions Biodiversa+ can make is to foster capacity building. This includes organizing training sessions, sharing best practices, and providing hands-on guidance on both the conceptual foundations and technical implementation of connectivity indicators. Many workshop participants emphasized the knowledge gap that exists, particularly in translating complex methodologies into usable outputs for policy and planning. Addressing this gap would significantly enhance the uptake and consistency of indicators across regions.

Equally important is the creation and nurturing of a transnational network for knowledge exchange. By facilitating regular interactions between developers of indicators, data providers, policymakers, and local practitioners, Biodiversa+ can ensure that different perspectives are considered in the development process and that indicators remain relevant to a variety of ecological and governance contexts. Hosting additional workshops and thematic sessions, like the one that informed this report, would allow for iterative refinement of indicators, better alignment with policy goals, and shared learning from both successes and challenges encountered in different regions.

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[17] Convention on Biological Diversity, K-M monitoring framework: Convention on Biological Diversity

Biodiversa+ can also play a pivotal role in promoting data accessibility and the use of open, standardized platforms for indicator computation. Many indicator frameworks are currently locked within project-based or institution-specific environments, limiting their replicability and broader application. By supporting the development of shared technical infrastructures and encouraging open-source tools, Biodiversa+ could help democratize access to powerful analytical methods and ensure consistency in how indicators are derived and applied.

Biodiversa+ can also play a role in guiding the transition between structural and network-based approaches. This means supporting both the operational use of mature indicators such as FAD for accounting, while supporting investment in research, capacity building, and infrastructure that make network-based metrics more accessible and computationally feasible. Through the BiodivConnect call, Biodiversa+ explicitly aims to fund new research on ecosystem connectivity, restoration, and scalable indicators[18]. Biodiversa+ can thus help bridge immediate policy needs with the innovation required for more ecologically realistic connectivity indicators.

Finally, as a science-policy interface platform, Biodiversa+ has the potential to bridge gaps between research and decision-making by ensuring that national experts and stakeholders are actively involved in indicator design and evaluation. This co-creation process is essential for building trust, improving the policy relevance of indicators, and ensuring they are embedded in national restoration strategies. In this way, Biodiversa+ can move beyond supporting individual tools or metrics and contribute to a more integrated, collaborative, and impactful European approach to biodiversity monitoring.

Conclusion

Connectivity indicators have become essential tools for supporting biodiversity policy and planning, especially in the context of the EU Biodiversity Strategy for 2030 and the NRR. They provide critical insights into the structural and functional linkages among habitats, helping policymakers assess ecosystem condition, identify restoration priorities, and track progress toward conservation targets. As outlined in this report, a variety of connectivity indicators are in use at global, European, and national levels, each tailored to specific ecological and governance contexts. However, the current landscape is marked by fragmentation in methods, uneven capacity, and significant challenges in data availability and accessibility.

The Biodiversa+ workshop revealed widespread recognition of the value of connectivity indicators but also underscored a number of critical bottlenecks. These include a lack of harmonized methodologies and harmonised input data of adequate and well-documented quality, limited capacity for implementation, and disconnects between science and policy. Participants highlighted that while technologies and methodologies are advancing rapidly, their full potential remains underutilized due to technical, institutional, and resource constraints. Furthermore, the need to integrate local ecological knowledge, involve national stakeholders, and ensure the relevance of indicators across diverse landscapes was identified as a key condition for their effective use.

Moving forward, a coordinated effort is required to harmonize indicators, build capacity across countries, and foster more robust science-policy interfaces. Biodiversa+ has an important role to play in this process, through facilitating knowledge exchange, supporting the co-development of methods, promoting open data and tools, and ensuring that indicators are both ecologically meaningful and practically useful. By

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[18] Biodiversa+ joint call BiodivConnect: https://www.biodiversa.eu/2025/09/09/2025-2026-joint-call/

strengthening collaboration across scales and sectors, Biodiversa+ can help ensure that connectivity indicators truly contribute to the ambitious biodiversity goals set by European and global frameworks. In doing so, it can help transform fragmented monitoring efforts into a cohesive system that supports long-term ecological resilience and nature restoration across Europe. Achieving this will require a pragmatic pathway: consolidating the use of structural indicators such as FAD for current reporting, while steadily advancing the uptake of network-based approaches that better capture functional connectivity at planning scales.

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