REVIEW SUMMARY

CONSERVATION

# A well-connected Earth: The science and conservation of organismal movement

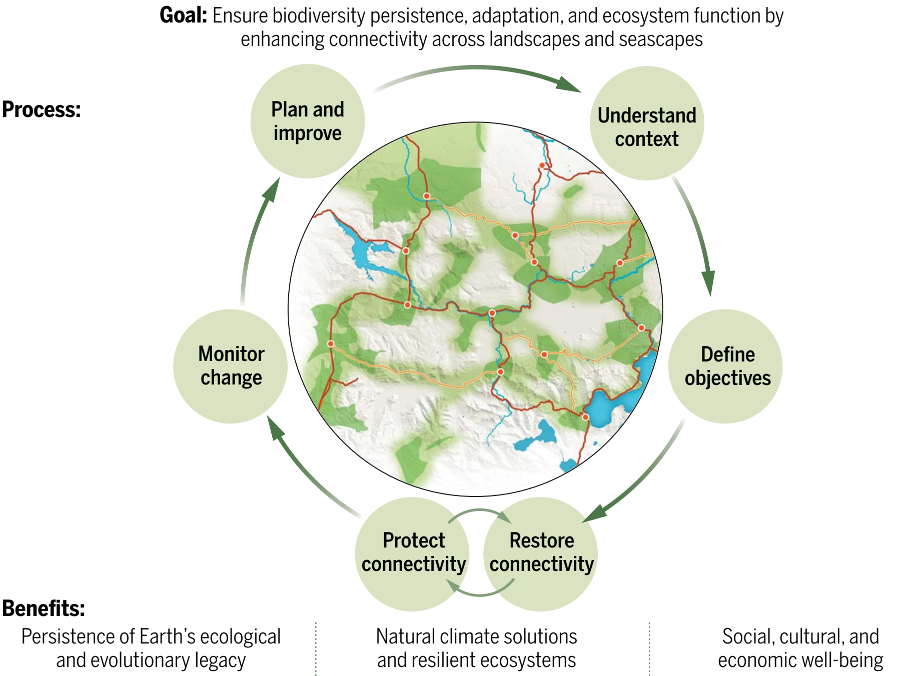
Jedediah F. Brodie*, Andrew Gonzalez, Jayasilan Mohd-Azlan, Cara R. Nelson, Gary Tabor, Divya Vasudev, Katherine A. Zeller, Robert J. Fletcher Jr.

**BACKGROUND:** New global biodiversity targets focus on the importance of protecting connectivity, the unimpeded flow of organisms and natural processes across landscapes and seascapes, as a foundational component of biodiversity conservation. The Kunming–Montreal Global Biodiversity Framework presents humanity's most ambitious conservation strategy to date: setting aside 30% of Earth as networks of "well-connected" protected areas by 2030. But the term "well connected" has not been defined and is difficult to quantify, making it problematic to ascertain whether actions will result in the protection and restoration of well-connected land- and seascapes. Because ecological connectivity varies across environmental contexts and scales, precise definitions and measurements have been elusive, rendering it difficult to quantify connectivity in robust and comparable ways that span multiple species and ecosystems. The clear challenge is to transform the concept of well connected from ambiguous to a scientifically grounded, robust, and quantifiable concept that is ecologically and socially meaningful across biomes, taxa, and scales.

**ADVANCES:** Recent advances allow the measurement and prediction of organismal movements and connectivity at multiple scales and highlight relationships between connectivity and ecological integrity. Connectivity influences population dynamics, with meta-analyses of natural and experimental corridors demonstrating their efficacy at enhancing organismal dispersal, which in turn affects fitness, abundance, and community diversity. By helping maintain populations and metapopulations, connectivity supports the ecological functions that species' movements provide, including provisioning of ecosystem services that benefit humanity. For example, models and empirical data show that loss of connectivity can affect pollination and the natural control of crop pests. Accumulating evidence also highlights ongoing and severe losses of connectivity globally, which now require action to bring connectivity back for nature and society.

We propose an operational definition of "well connected" that can be adapted to nearly any ecosystem or set of focal species (or focal ecological functions) for which data are available. Specifically, a landscape, seascape, or protected-area network is well connected if organismal movement is sufficient to maintain the long-term persistence of focal taxa, maintain ecological functions, and/or sustain the provisioning of ecosystem services relative to counterfactuals with the same amount of intact habitat and no barriers to movement. This definition allows flexibility in assessing counterfactuals based on real-world scenarios (for example, nearby undisturbed study areas) or computer simulations. A variety of existing metrics allow the measurement of particular aspects of connectivity across space and over time, but there is a pressing need for additional indicators that go beyond measuring structural connectivity to estimate the long-term persistence of species and the ecological functions they provide. Policy-driven action needs robust evidence provided by a detection and attribution framework demonstrating that connectivity change results in positive outcomes for biodiversity conservation.

**OUTLOOK:** Advances in connectivity science can guide biodiversity conservation, ecological restoration, and climate adaptation. But although connectivity has been incorporated into recent conservation plans, much of connectivity science and science-informed planning is not well implemented. Perhaps most critically, connectivity is not well integrated into the designation of protected-area networks, as evidenced by only ~10% of global protected areas being structurally connected. As we expand from ~15% global protected area coverage in 2020 toward 30% by 2030, incorporation of structural and functional connectivity will be critical to avoid extinctions in isolated parks and reserves. In addition, a coordinated international effort to produce and share data on the movement of animals, plants, and other taxa will help ensure that investments in climate resilience and large-scale conservation and restoration will result in anticipated biodiversity gains. Viewing connectivity as the conceptual link between biological, economic, and societal objectives provides a foundation for a strong connectivity science that informs conservation planning. ■




**Connectivity enables organisms to move and facilitates ecological processes across scales.**

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REVIEW

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# A well-connected Earth: The science and conservation of organismal movement

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**Global biodiversity targets focus on landscape and seascape connectivity as a foundational component of biodiversity conservation, including networks of connected protected areas. Recent advances allow the measurement and prediction of organismal movements at multiple scales. We provide a definition of connectivity that links movement to persistence and ecological function. Connectivity science can guide planning for biodiversity, ecosystem services, ecological restoration, and climate adaptation. Ongoing climate change and land and sea use are closing the window of opportunity for connectivity conservation. A coordinated global effort is required to implement scientific knowledge and to monitor, map, protect, and restore areas that promote movement and maintain well-connected ecosystems for biodiversity in the long term.**

Interest has surged in ecological connectivity—the unimpeded movement of organisms across landscapes and seascapes—as a foundational facet of biodiversity conservation and climate adaptation. The recent Kunming–Montreal Global Biodiversity Framework (GBF) includes as its first goal that "The integrity, connectivity, and resilience of all ecosystems are maintained, enhanced, or restored, substantially increasing the area of natural ecosystems by 2050" (*1*). The framework also sets out what may be humanity's most ambitious conservation strategy to date: setting aside 30% of Earth as networks of connected protected areas by 2030 (the "30 × 30" goal) (*1*).

Policies to enhance connectivity are being advanced within and among countries through multinational agreements. For example, more than US$1.2 billion was invested in 2023 alone to promote the Florida Wildlife Corridor (*2*), and a treaty among Brunei Darussalam, Indonesia, and Malaysia supports connectivity in the "Heart of Borneo"—one of the most biodiverse areas of the planet. At more local scales, efforts to restore connectivity include the demarcation of habitat corridors and the creation of wildlife crossing structures, thousands of which have been built across the world, many costing millions of dollars (*3*).

The need for this focus on connectivity is clear. Connectivity is critical for the persistence of many species and the maintenance of ecological functions but is being eroded across the globe through a variety of human impacts (*4*). More than 194 million birds and 29 million mammals are killed annually on European roads (*5*), and up to 1 billion birds die per year from building collisions in the United States (*6*). Urban sprawl, agricultural expansion, and deforestation fragment habitats and increase the resistance of the landscape to the movement of plants, animals, and other taxa (*7*).

In response to this urgency, connectivity science has advanced rapidly over the past decade. The number of papers with topic keywords "(connect* OR corridor) AND (ecolog* OR habitat OR landscape OR seascape)" increased threefold from 2014 to 2023 over the previous decade. But translating these advances in connectivity science to restoration and conservation practice remains a critical challenge that requires the implementation of a clear theory of change (*8*). What does the 30 × 30 goal mean that protected areas should be "well-connected," and how will we know when this has been achieved? Although there has been great emphasis on designating protected areas, the dialogue is much less advanced with respect to understanding what the vision of well-connected protected areas specifically entails and how we can achieve it. Without addressing how conditions and human activities in the areas between protected areas—known as the "landscape [or seascape] matrix" (*9*)—affect connectivity, the conservation benefits of protected areas will not be realized (*10*, *11*). The clear challenge facing the field is to transform the concept of "well connected" from nebulous to robust, quantifiable, and ecologically meaningful across a range of biomes, taxa, and scales.

Here, we review recent progress in connectivity science, identifying key advances and persistent uncertainties that help or hinder our ability to reach national and global goals for connectivity. We clarify what connectivity means at different spatial scales and provide an operational definition of "well connected." We highlight where connectivity science has and has not been effectively incorporated into conservation, restoration, and climate adaptation and call for an international effort to integrate connectivity into planning.

### Connectivity enhances species persistence, ecological function, and ecosystem services

Species movements are the core processes underlying connectivity and are key to understanding how connectivity affects populations and ecological functions (Fig. 1). Until the 21st century, it was notoriously difficult to measure movement across large distances, limiting the modeling and prediction of connectivity. But new technologies have enabled an unprecedented accrual of information on organismal movements from local to global scales (*12*). Computational advances and new sensing technologies (such as remote sensing capabilities, GPS collars, and genome sequencing) are catalyzing new insights into the movement of plants and animals while facilitating the measurement of connectivity at large spatial scales, the identification of habitat corridors, and the prediction of critical migration pathways. Advanced models with large datasets can predict and map potential movement pathways on the basis of an understanding that is better than ever before of organismal movement behavior (*13*–*15*).

Connectivity influences population persistence. Although early debates focused on the balance between positive and potentially negative impacts of corridors—the latter including movement of pathogens, invasives, and fire (*16*)—syntheses have shown a lack of consistent negative effects (*17*–*19*). Meta-analyses of natural and experimental corridors have demonstrated their efficacy at enhancing organismal dispersal (*20*), which in turn affects fitness, abundance, and community diversity (*21*). Conversely, loss of connectivity increases species extinction rates (Box 1) (*22*–*25*).

By maintaining populations or metapopulations across the landscape, connectivity can support the ecological functions and ecosystem services (ecological functions that benefit humans) that these species perform. For example, loss of connectivity can reduce the diversity and abundance of insects that provide benefits to agriculture (*26*, *27*). Habitat corridors

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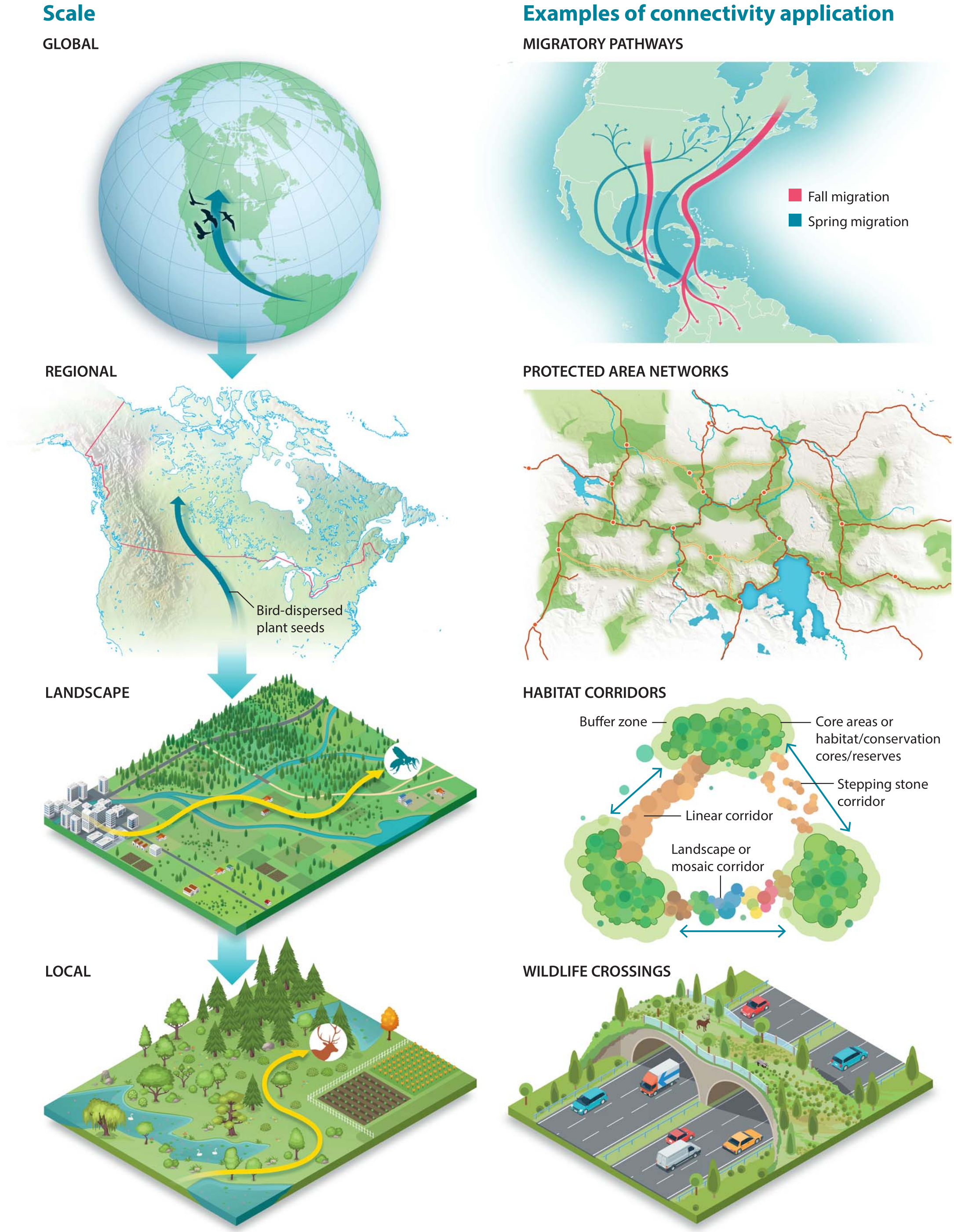


**Fig. 1. Connectivity enables organisms to move and facilitates ecological processes such as seed dispersal across scales.** [Figure was prepared by 5W Infographics.]

can facilitate the persistence of disturbance-intolerant species that benefit humans (*28*), such as forest trees that provide clean water and carbon storage (*29*). Moreover, areas that provide connectivity can enhance habitat quality for species that live in the landscape matrix, such as pollinators (*30*). As a result, connectivity is now explicitly incorporated into the assessment of ecosystem services.

### Connectivity is taxon-, context-, and scale-dependent

Assessing connectivity for different species or ecological processes must be matched to the appropriate scale (Fig. 1). This has complicated our understanding of what aspects of connectivity to protect, which actions will be the most beneficial to conservation, and over what scales to monitor connectivity change. In table S1, we clarify this lexicon to distinguish the different types of connectivity so as to facilitate communication and implementation.

Measures of connectivity differ in whether organismal movements are addressed explicitly or implicitly. The most common measure of connectivity used in models is structural connectivity: the physical contiguity of habitat features regardless of organism-specific responses

**Box 1. Case studies of connectivity on land and at sea.**

There may be no other region where the success of conservation efforts depends as heavily on maintaining a well-connected network of protected areas than the Central Indian Tiger Landscape. Despite the 16 reserves generally being relatively small (~1300 $km^2$) and the surrounding landscape being densely populated by humans (~250 people $km^{-2}$), the 400,000-$km^2$ network sustains a high-density tiger (*Panthera tigris*) population of ~1200 individuals—a quarter of the global population (*115*). These populations are still functionally connected but show spatial genetic structure, likely owing to increasing land cover changes that block connectivity (*10*). Connectivity is sustained by secondary forests, but many of these are at risk of being modified or cleared. Road and railway developments intersect habitat corridors and do not always have adequate mitigation. The high density of both humans and tigers leads to human-wildlife conflict. Yet efforts to protect corridors, mitigate linear infrastructure, and promote human-wildlife coexistence help support the region's connectivity for tigers and, secondarily, other sympatric species. Scientists have identified nearly 25,000 $km^2$ of important corridor locations along with threats to current and future connectivity (*75*, *94*). This also allows ecological restoration efforts in the area to optimally benefit biodiversity by targeting important corridor areas and creating buffer zones for small protected areas. Last, the identification of key connectivity areas allows the regulation of development so that tiger movements across the landscape can be maintained to substantially contribute to the viability of this globally important metapopulation (*10*).

Connectivity is also important at sea. The Philippines is one of the most biodiverse nations on Earth, with an incredible marine diversity. Its suite of marine protected areas was largely developed on the basis of local conservation and fisheries concerns rather than larger, seascape-scale considerations. A recent map of larval connectivity for branching corals, urchins, and grouper fish (*116*) suggests high dispersal among different reefs in the country but shows that many of the most important areas for connectivity are not covered by protected areas or "other effective area-based conservation measures" (*1*). This highlights the importance of incorporating connectivity into marine protected area planning. More broadly, it also draws attention to the need for marine connectivity indicators that can incorporate complexities such as the directional yet dynamic flow of ocean currents that are not issues in terrestrial systems.

to those features (*31*). In contrast to this species-agnostic approach, functional connectivity links habitat features to species responses. Notably, the meaning of functional connectivity varies across scales, from "home range connectivity," in which individuals meet their daily needs, to "dispersal connectivity," in which individuals move away from their natal ranges, to "migratory connectivity," in which individuals track seasonal or ephemeral resources over long distances (Fig. 1). Moreover, the various aspects of connectivity are all dynamic; costs and benefits of movement and the location of movement routes vary across seasons or years (*32*–*34*).

Because species differ so widely in dispersal traits, connectivity varies across taxa. A landscape that is well connected for species with high dispersal capabilities, or high tolerance for moving through degraded areas, might be impermeable to less-mobile species or specialists that require contiguous habitat. This variability is critical for assessing species' ecological functions and is an important hurdle for assessing and managing connectivity because it requires species- or guild-specific data that can be difficult to obtain. Allometric scaling of dispersal across species (*35*) offers the potential for predicting functional connectivity for rare or poorly understood species (*36*). However, this approach has yet to be widely adopted. Identifying connectivity "archetypes" of species that have similar movement capacities according to allometric relationships is an urgent need and may help scale modeling from dozens to thousands of species.

Critically, protecting habitat connectivity is not the end goal but rather a means of supporting or restoring the long-term persistence of biodiversity or ecological functions (Fig. 2). Therefore, a key outcome of connectivity is its influence on these attributes (*19*, *37*). Connectivity assessments can feed into our understanding of how organismal movements affect population persistence, through population or metapopulation models (*38*), or ecological functions, through ecological function analysis (*39*). Together, these methods allow for the prioritization of patches and corridors for maintaining not just organismal movements but ultimately biodiversity.

Despite these advances, additional work is needed to clarify the relationships between structural connectivity, functional connectivity, and species persistence (Fig. 3). Although evidence highlighted above demonstrates that connectivity can influence population dynamics, under what conditions persistence is dependent on movement remains unclear. Large-scale connectivity assessments generally address structural connectivity [for example, (*40*–*42*)] under the assumption that intact habitat structure will support organismal movements. But how much, under what conditions, and for which taxa structural connectivity actually predicts functional connectivity is not well understood, and discrepancies between the two could arise for a variety of reasons. For example, what humans consider to be a structurally intact habitat, such as forest cover, might not actually meet a given species' requirements and so would not facilitate functional connectivity (Fig. 3) (*43*). The spatial context of structurally intact habitat also matters; corridors that are too narrow or permeated by edge effects may not support the movement of many species (*44*). Moreover, overhunting, human-wildlife conflicts, or other nonhabitat human influences could render it impossible for particular taxa to move through a given landscape or seascape, even though the habitat is structurally intact (*45*)—a phenomenon called "anthropogenic resistance" (Fig. 3) (*46*). Structural and functional connectivity can also have variable influence on persistence. Without functional connectivity to support recolonization or rescue effects, species living in metapopulations will go extinct (*47*). Other taxa may be adapted to living in isolated populations and so can persist even without connectivity (*48*).

Last, in an applied context, connectivity assessments often focus on either the habitat patches (such as protected areas) being connected or the areas between them (the landscape matrix). Habitat patches are often envisioned as a network with connections between them, for which graph theory and related network analyses can quantify patches' contribution to connectivity [for example, (*49*)], resulting in maps of priority patches for protection or restoration. Conservation interventions that focus on the matrix often involve demarcating corridors, guided by spatially explicit functional connectivity maps, or encouraging land-use practices that foster movement (*50*, *51*). Tools should be selected to allow the assessment and mapping of movement costs and barriers (*52*), supporting strategies to prevent movement into risky areas (for example, through the use of fencing) (*53*) or reduce mortality risks (for example, reducing wildlife–building collisions) (*54*). Seamless and scalable approaches are needed that combine these perspectives to measure the contributions of both habitat and matrix to persistence (*55*, *56*).

## Quantifying connectivity

### *Defining "well connected"*

Only by being able to characterize connectivity in measurable terms will we be able to assess whether we have successfully met the 30 × 30 objective for well-connected protected areas. Existing indices allow the quantification of connectivity in a variety of ways but do not stem from clear criteria for how to determine whether a landscape or protected-area network could be considered well connected. Building on prior work that has linked connectivity to species persistence (*37*), ecological functions (including ecosystem services) (*26*, *57*, *58*), and the use of counterfactual cases (*59*, *60*) to

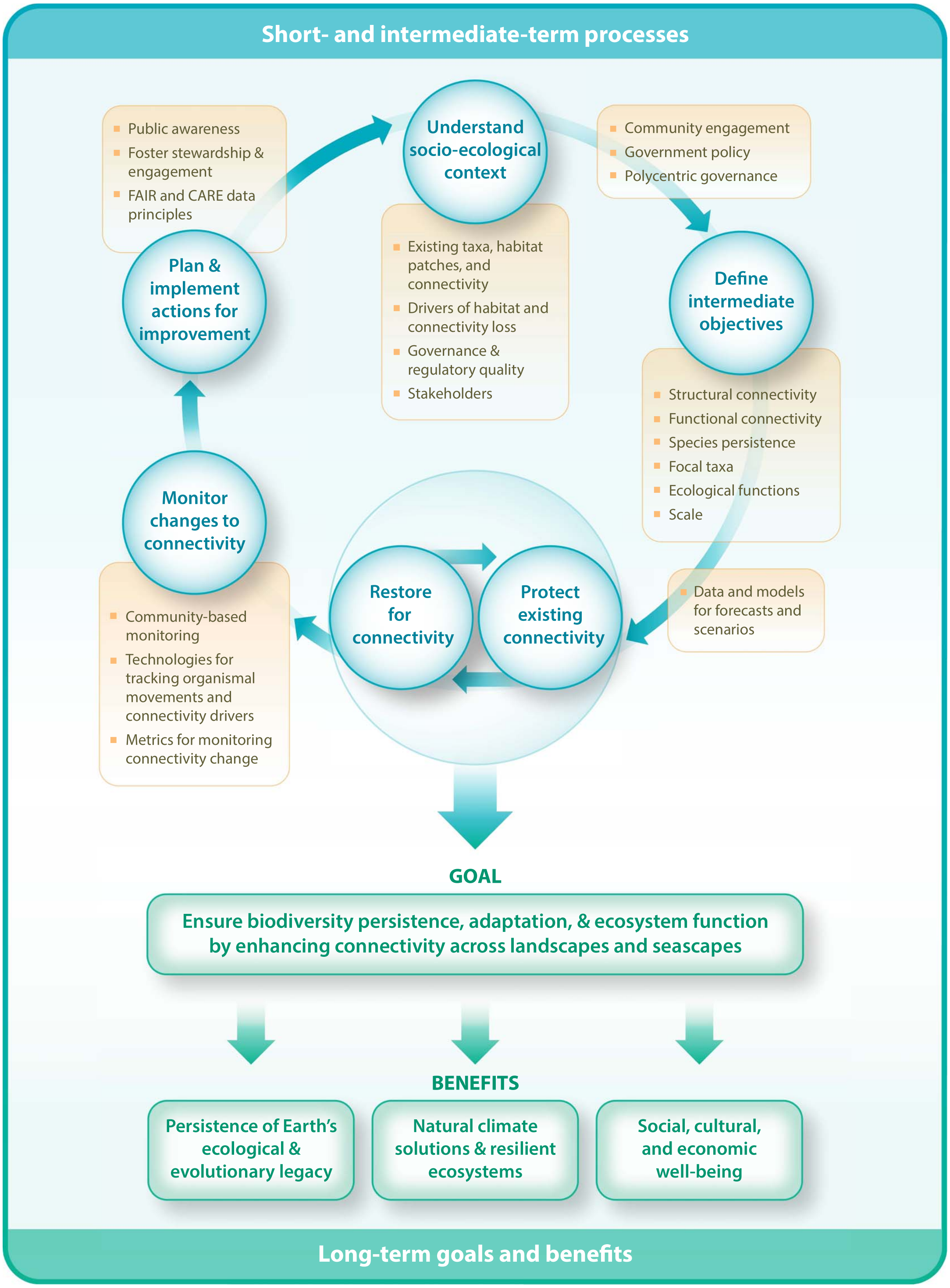


**Fig. 2. Connectivity theory of change.** [Figure was prepared by 5W Infographics.]

interpret the biological and social outcomes of planning and action for connectivity, we propose an operational definition that can be adapted to nearly any ecosystem or set of focal species (or focal ecological functions) for which data are available.

A landscape, seascape, or protected-area network is well connected if organismal movement is sufficient to maintain the long-term persistence of focal taxa, maintain ecological functions, and/or sustain the provisioning of ecosystem services relative to counterfactuals with the same amount of intact habitat and no barriers to movement.

This definition allows flexibility in assessing change in connectivity on the basis of counterfactuals in real-world scenarios (for example, nearby undisturbed study areas) or with computer simulations. It also allows for setting quantifiable connectivity goals and targets for focal systems. An illustration is provided in fig. S1, and example calculations are provided in fig. S2. The focus is on attributing change in the variable of interest (such as species persistence)

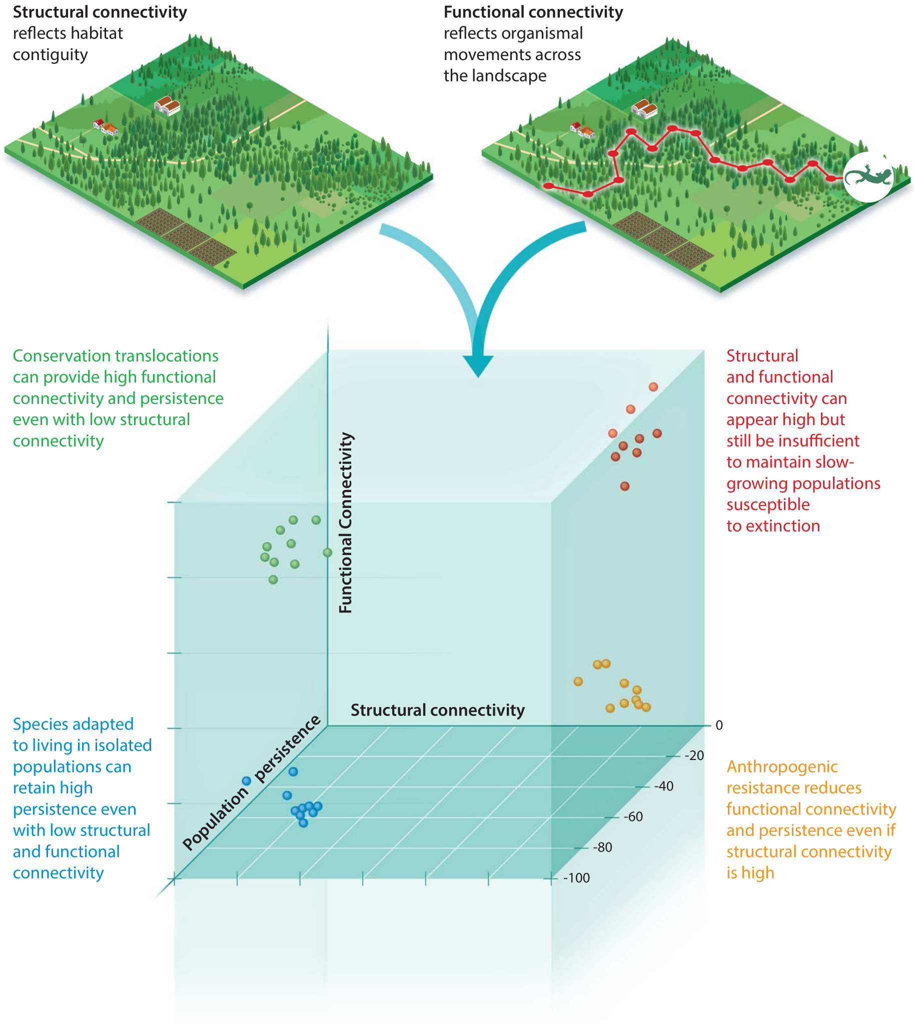


**Fig. 3. Structural connectivity, functional connectivity, and biodiversity persistence.** [Figure was prepared by 5W Infographics.]

to change in connectivity; causal inference comes from comparing the change in connectivity and persistence relative to the counterfactual. An area may lose or recover the status of well connected because of the way human pressures and drivers interact to modify movement and the expected long-term outcomes for ecological processes (fig. S1). Thus, taxa may vary in their sensitivity to human pressures because their movement may be more or less sensitive to human activities or because their persistence at patchy populations may be more or less sensitive to a loss in connectivity. The above also extends to ecological functions and their maintenance. Because taxa vary in life span, "long-term" persistence could be based on generation time or else set to policy-relevant time frames such as "by 2050" (*1*).

Our focus on persistence and ecological function allows for several criteria about the state of the system to be considered, including genetic, demographic, and ecosystem functions. Genetic connectivity supports sufficient movement to avoid substantial inbreeding in particular populations (*61*). Where species' persistence is the primary goal, we couch the definition of well connected in terms of demographic connectivity because this will generally require higher rates of movement than that for genetic connectivity. Demographic connectivity supports sufficient dispersal to facilitate demographic rescue (*62*), recolonization of empty habitats where species have been extirpated, or range expansion in the face of climate change (*63*, *64*). Alternatively, the primary goal of connectedness might be to support large-scale ecological functions such as species' effects on nutrient cycles or the provisioning of ecosystem services.

### *Connectivity indicators*

Robust indicators are necessary to measure and describe the gains and losses of connectivity across space and over time (*65*, *66*). There are many candidate connectivity indicators for the GBF, most of which address structural rather than functional connectivity, and none of which directly incorporate aspects of population persistence (table S3). Both structural indicators that are being considered (table S3) and more functional indicators (fig. S2) need to be validated to provide robust recommendations. Looking beyond the time frame of the GBF, connectivity indicators are needed that incorporate the ultimate goal of connectivity: to support the long-term persistence of species and the ecological functions they provide (Fig. 3) in the face of rapid climatic and environmental changes. An ideal connectivity indicator would integrate functional connectivity measures with a persistence metric such as metapopulation capacity (*60*, *67*), which quantifies the potential of a landscape to sustain populations, helping to advance understanding and to prioritize connectivity to support long-term biodiversity outcomes.

We propose a multistep framework toward achieving this goal. First, structural connectivity of natural areas is mapped, which can readily be quantified through remote-sensing approaches. Second, movement data are used to predict connectivity from movement routes and distances. Where such data are unavailable, species traits can provide proxies; for example, body size and related traits often scale with daily movement and dispersal distances (*4*, *36*). Third, the dynamics of connectivity across space are incorporated—for example, by assessing barriers and conditions of the landscape matrix—and over time, particularly as climatic and other changes alter organismal movement and landscape permeability. Again, where such data are not available, matrix characteristics and species traits could provide for generalizations and expectations of matrix permeability (*9*, *68*, *69*). Last, the process assesses how connectivity affects population persistence, which can be measured with a variety of tools for spatially explicit population [for example, (*70*)] or metapopulation models (*60*, *71*), or ecological function as measured by using ecological function analysis (*39*). Population models, ecological function analysis, and ecosystem service assessment run a wide gamut from coarse-grained to highly detailed (but data intensive), thus allowing flexibility in the estimation of connectivity impacts. We envision an adaptive process in which scalable models and metrics that directly capture connectivity processes are used for prediction and assessments of options for conservation action given resource constraints (Box 2).

## Applied connectivity to support biodiversity

Connectivity bridges the conservation, restoration, and climate adaptation agendas defined by international agreements such as the Convention for Migratory Species and the GBF.

The theory of change that we present (Fig. 2) articulates how international targets and goals can be realized through conservation action. Conserving well-connected protected areas and habitats at scale will require a whole-of-society approach to stakeholder engagement, with lasting partnerships often spanning nations. A primary goal is to map connectivity at different scales, prioritizing areas where conservation and restoration will improve organismal movements and in turn persistence. Monitoring that is geared toward detecting and attributing the causes for movement change and supported by next-generation technologies can then provide the evidence base for biodiversity and ecosystem outcomes.

### Connectivity for species conservation

Conservation planning that incorporates functional connectivity for species' persistence (Fig. 3) invariably focuses on the ecological needs of particular taxa. Landscapes or protected-area networks that are well connected from the point of view of one species may not be for another (*36*), raising the need to assess connectivity for the coexistence of multiple species. A critical question is thus which taxa we should focus on for assessing connectivity.

Identifying appropriate focal taxa for connectivity planning can be complex. Ideally, protecting connectivity for particular "surrogate species" will result in cobenefits to other taxa (*72*). Large herbivores or carnivores in Southeast Asia and southern Africa, for example, can be effective surrogates for other species in their respective guilds but not necessarily across guilds (*73*, *74*). As a general rule, connectivity surrogate species are likely to require intact habitat for survival and movement and to have dispersal capabilities neither too high (in which case any landscape would be well connected) nor too low (in which case no landscape would be well connected). This is likely to include a variety of vertebrates, vertebrate-dispersed plants, and wide-ranging insects such as butterflies (*75*). Ideally, a set of selected species would represent multiple guilds to cover a wide range of species requirements; the demographic consequences of connectivity (or its loss) for the focal taxa should also be representative of the expected impacts on other taxa (*72*).

**Box 2. Measuring and monitoring connectivity.**

A transformation is underway in our ability to observe and measure movements of many taxa in a variety of ecosystems. Observations from a range of technologies—including genetic markers, camera traps, and animal telemetry—are providing new insights into the spatial and temporal dynamics of animal movements and habitat use. These data provide insights into movement across a considerable range of scales (*12*, *117*, *118*) and allow us to track the impacts of the human footprint and climate change on movements (Fig. 4) (*4*).

This growing wealth of environmental, organismal movement, and occurrence data presents an opportunity to implement a systematic program dedicated to monitoring changing connectivity (*119*). This would greatly improve our ability to track progress toward the targets for connectivity conservation set by the GBF. Trends in the structural connectivity of habitats are commonly reported, by use of remote sensing products, but we do not systematically monitor how functional connectivity—in the form of realized movement within and among habitats—is changing in distance, direction, and rate. An example is the observation that climate change is altering migration distances and direction (*120*). Monitoring would also link observed changes to structural or functional connectivity to the long-term expectations for population persistence.

The movements of many species are monitored, particularly migratory taxa or those linked to natural resources or disease emergence, but monitoring of movement is not generally extended to a formal detection and attribution framework that provide estimates of movement change with clear causal links to human pressures (*107*). The latter requires that we jointly monitor both structural and functional facets of connectivity to gather the information needed to reliably assign statements of confidence to the potential ecological outcomes of connectivity change.

To monitor connectivity, we need to be able to detect how, where, and when it is changing. We have the technologies and models to do this, and we have the essential biodiversity variables needed to measure movement, including species traits that link movement to habitat needs. The six classes of essential biodiversity variables (EBVs) include the traits of organisms, and movement is identified as a key EBV (*96*). Traits that link features of organisms to phases of movement within a lifetime and across generations allow spatial genetic structure and range dynamics to be defined, measured, and modeled (*121*). Movement EBVs form the basis for interspecies assessment of connectivity change and the attribution of this change to human drivers. Similarly, EBVs for ecosystem structure and functioning can quantify connectivity change and measures of ecosystem connectivity, such as flows of biomass and nutrients. Essential ecosystem service variables have also been proposed to monitor changes in nature's contributions to people arising from loss or gain of connectivity (*122*).

Effective monitoring can guide investment in resources and conservation action. Monitoring connectivity will also allow us to assess whether conservation measures are resulting in desired outcomes, such as metapopulation and metacommunity persistence (*123*), protected migratory pathways (*124*, *125*), and facilitation of range shifts under climate change (*63*).

### Connectivity in restoration

Ecosystem restoration is at the heart of achieving the ambitious global goals for connectivity. Despite the important role that connectivity can play in prioritizing areas for effective restoration (*76*, *77*), it is rarely applied. For example, at the time of its adoption, the GBF's restoration target (Target 2) had an undefined placeholder for a connectivity indicator, whereas the conservation-focused target (Target 3) had specific connectivity indicators (Box 2 and table S3). This difference is due to the siloing of the conservation and restoration science communities. The principles and standards of practice for the United Nations Decade on Ecosystem Restoration (*77*) require explicit consideration of the landscape context to prioritize locations that reduce habitat fragmentation or that create corridors or habitat stepping stones to increase connectivity (*78*, *79*). Application of this principle and related standards requires connectivity science.

Connectivity scientists have much to contribute to restoration initiatives. For example, initiatives such as the Bonn Challenge aim to restore 350 million ha of land by 2030 (*80*); this presents an opportunity to make progress with the well-connected landscapes specified by the 30 × 30 goal. To guide restoration, connectivity indicators are needed to identify portions of the landscape where interventions would yield the greatest positive impact on species persistence. To maximize the benefits of restoration for biodiversity and human well-being, we need to integrate guidance across these communities. As a starting point, restoration scientists could apply existing indicators currently being considered in conservation. However, it will be helpful to advance restoration indicators that explicitly capture the potential for future connectivity enhancements through restoration interventions. Last, restoration for connectivity can entail cobenefits for ecosystem services, such as the creation of carbon sinks and other nature-based climate solutions (*81*).

### Connectivity and climate adaptation

Organisms have responded to climate change throughout Earth's history by shifting their geographical ranges to track suitable environmental conditions (*82*, *83*). But contemporary climate change is different; with habitat alteration and fragmentation nearly ubiquitous across the globe, many organisms face substantial barriers to movement, hindering their ability to track rapidly shifting climate conditions

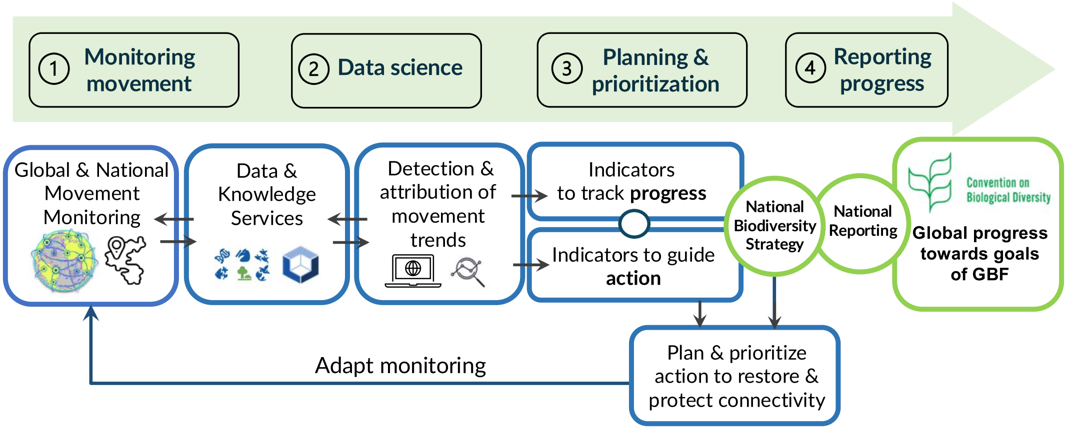


**Fig. 4. Illustration of the iterative process of measuring and monitoring connectivity.** This process is to support the reporting of progress to connectivity targets proposed by countries in their national strategies and action plans under the GBF (*1*).

(*84*). The link between connectivity and climate adaptation is so strong that species in the highly fragmented terrestrial realm appear to be tracking their climate niches substanitally more slowly than their marine counterparts (*64*). Recent work has demonstrated that the current global protected-area network will not provide the connectivity needed for most organisms to shift their ranges in response to climate change (*84*).

Connectivity for climate adaptation requires maintaining existing landscape connections and, where such connections have already been severed, focusing restoration on creating corridors for species to traverse for ongoing or future range shifts. Connectivity in the face of climate change also requires predicting changes to landscape permeability to reduce resistance to movement. In the myriad highly developed areas that lack connectivity and where near-term ecological restoration is unrealistic, conservation translocations (*85*) may effectively act to artificially increase functional connectivity (Fig. 3).

### *Incorporating connectivity into spatial planning*

Connectivity has been incorporated into conservation plans in both the terrestrial [for example, (*75*)] and marine [for example, (*86*)] realms, where it has improved area-based conservation (*75*). Advanced movement models can inform spatially explicit conservation decision-making (*45*, *87*). Planning for multiple objectives highlights the importance of not assessing connectivity for its own sake but rather for its contribution to ecological persistence; the planning strategy is streamlined if we have the single objective of maximizing population or metapopulation persistence through some combination of protecting areas of high integrity and corridors (*67*). Related approaches include modeling movement, gene flow, and demography across ecological networks to predict the population-level consequences of restoration and development (*10*). Advanced models can optimize multiple conservation objectives in the face of multiple constraints—for example, discriminating areas that both contribute to connectivity and have low human-wildlife conflict (areas of congruence) from areas that contribute to connectivity but have high human-wildlife conflict (areas where two conservation objectives clash) (*45*).

Incorporating connectivity in conservation and restoration planning must address potential trade-offs or synergies with other connectivity or ecological needs. Although planning can be optimized for multiple types and scales of connectivity for multiple species (*88*), there have been relatively few applications of this type of optimization. One example in Malaysia found that protecting connectivity among protected areas and also across elevations (to support climate-driven range shifts) was possible alongside protecting vertebrate, invertebrate, and plant species ranges and forest carbon (*75*).

### *Closing the science-implementation gap*

Although connectivity science has clearly demonstrated the importance of connectivity to species persistence and ecological function, scientific insights are often not incorporated into policy or management (*89*). Over the past three decades, connectivity conservation has increasingly moved from theory into planning (*90*) and land management (for example, the 2012 US Forest Service Planning Rule; NFMA; 77 FR 21162). However, although connectivity is more mainstreamed in conservation planning, explicit connectivity plans are seldom implemented (*90*). Perhaps most critically, connectivity is not well integrated into the designation of protected-area networks, as evidenced by only ~10% of global protected areas being structurally connected (*42*). As we expand from ~15% protected area coverage in 2020 toward 30% by 2030 (*1*), incorporation of connectivity will be critical to avoid extinctions in isolated parks (*91*, *92*). Even where plans and regulations to support connectivity are in place, additional effort is required to prevent infrastructure development that blocks organismal movements (*93*, *94*).

## Opportunities for advancing connectivity science and conservation

We present key opportunities to implement a theory of change (Fig. 2) involving the mainstreaming of connectivity science into management and policy for conservation, restoration, and climate adaptation.

### *Generalizing connectivity*

Methods for fine-scale observations of organismal movement are now contributing large amounts of data on animal movement (*12*); MoveBank (*95*), for example, has ~6 billion location records for nearly 1400 taxa. Translating raw observations of movement into essential biodiversity variables (*96*) will support rigorous and replicable analyses of movement and attribution of causes for change (Box 2). We still lack large datasets on functional connectivity for many areas, particularly in the Global South (*87*, *97*), as well as the population and functional data to attribute movement to anthropogenic predictors and link to the consequences for persistence and the provisioning of ecological functions. The ongoing accumulation of data from new regions and on understudied taxa will greatly enhance our understanding of connectivity; Brennan *et al.*, for example, demonstrate the utility of such large datasets, using data from 48 mammal species to identify connected protected areas across the globe (*98*). Future work could improve the resolution of such assessments and move beyond the focus on a relatively few vertebrate species.

In regions such as the tropics where tracking and movement data are sparse, widely available "static" data sources such as camera traps, acoustic monitors, or environmental DNA could be leveraged to infer movement and connectivity patterns. For example, big data approaches and statistical models could estimate movement probabilities on the basis of repeated detections of individuals across space, or predict connectivity by applying movement models to habitat selection maps generated from occurrence data (*60*, *73*). Such extrapolation can allow informed predictions about connectivity for understudied taxa and landscapes (*60*). Where such static data are unavailable, size-dispersal allometries (*99*) or movement proxies such as the hand-wing index in birds (*100*), combined with information on coarse habitat preferences, can be used to predict large-scale connectivity (*67*).

### New models and computational capacity

Connectivity models increasingly add ecological realism, and computational efficiencies are improving our ability to assess functional connectivity at scale (*101*). This has been accomplished through the use of high-performance computing, software that can better accommodate relevant computations, iterative approaches that circumvent costly calculations, and the partitioning of large regions through moving window- and tiling-based approaches (*102*–*104*). Although these approaches have been useful, more synergistic efforts between computer scientists, conservation biologists, and quantitative ecologists are needed to better scale connectivity models. Such advances could allow conservation to move toward global analyses for thousands of species, in which global data on conservation status [for example, International Union for Conservation of Nature (IUCN) status], threats, and habitats all combine to provide robust indicators of connectivity for conservation at global scales.

Many organizations in the Global South do not have easy access to sufficient computational power to allow large-scale analyses to make robust quantitative assessments of connectivity change. Modeling frameworks are needed to account for sparse data on organismal movements and the consequences of these movements for persistence and ecological function. Folding these processes into conservation prioritization models that account for uncertainty (*105*) could improve our ability to achieve well-connected wild spaces in an evidence-based and scientifically robust manner.

### Assessing dynamic connectivity

Existing models have not adequately addressed that connectivity changes (*104*); we lack an understanding of the relationship between the scale (spatial and temporal) and magnitude of connectivity change brought about by humans. Movements across hours and days allow access to critical resources, whereas dispersal across years or generations connects populations (*34*). Across tens of years, tracking connectivity responses to climate and other environmental changes is critical for understanding population persistence and range shifts.

Conservation action and policy also act at different timescales. Mitigation of connectivity loss driven by linear infrastructure (such as road overpasses or underpasses) may take months to implement, whereas ecosystem restoration for connectivity may span decades. Planning, too, can be for short- or long-term interventions. It is important that our conservation planning and actions align on a temporal scale with the appropriate timescales relevant to the persistence of focal ecological processes (for example, climate change mitigation planning must span multiple decades).

### Improving links with ecosystem services and socioecological drivers

We are improving our knowledge on what makes species vulnerable to the loss of connectivity. But we need a broader evidence base on how management for connectivity translates to outcomes that maintain biodiversity, species viability, and ecological functions; this information will be critical for assessing whether areas are well connected and the scale of investment needed to protect that status. For example, Tucker *et al.* (*4*) established the overwhelming impact that the human land-use footprint has on impeding mammal movements at the scale of days to weeks; emergence of such generalizations can lead to rules of thumb that make conservation or restoration policy and action more efficient and effective (*106*). Last, evidence that connectivity contributes to ecosystem services in working landscapes can guide management of better outcomes for people and nature (*26*, *27*).

### Improved monitoring

The application of better metrics for monitoring gains and losses of connectivity and their impacts on biodiversity persistence and ecological function is needed to support data-driven assessments of connectivity change and support the use of robust indicators that guide conservation interventions worldwide (Box 2). For example, the adaptation of organisms, or lack thereof, to changing environmental conditions can alter patterns of landscape connectivity in the long term. Tracking these changes requires reliable metrics tied to a rigorous framework for the detection and attribution of causes to observed changes in connectivity (*107*).

A coordinated international effort to produce and share movement and connectivity data would therefore benefit conservation, restoration, and climate adaptation worldwide. The establishment of a Global Biodiversity Observing System (GBiOS) (*107*) would encompass systematic observations of organismal movements (for example, with animal telemetry) and species' occurrences, which would contribute to global data repositories such as Movebank (*95*). National monitoring of connectivity can be achieved by establishing biodiversity observation networks (BONs) (*108*) that combine observations of movement made remotely with those made in situ—a "MoveBON" (*109*). The global implications of systematic connectivity monitoring are profound. Unless robust science and evidence are combined with strategic and operational approaches to planning and protecting connectivity, investments in climate resilience and large-scale conservation and restoration will not result in anticipated biodiversity gains.

### Enhanced communication

The movements of organisms often play out over large areas with a diversity of stakeholders. Better strategies and techniques for multidirectional communication about the state of connectivity and the array of options for conservation action among scientists, policymakers, Indigenous peoples, landowners, and local community members are critical (*110*). Partnerships among such groups are also key to the successful implementation of connectivity plans (*90*). Presenting information on connectivity in an accessible format to managers and the public can improve the social acceptability and uptake of connectivity science (table S2).

### Optimal implementation

Connectivity conservation tools include the acquisition of habitat corridors or stepping stones; management of field margins in agricultural landscapes; and faunal bridges, tunnels, and ladders to mitigate the impacts of barriers, such as roads and dams. We need a better understanding of the relative efficacy of these tools at enhancing connectivity in different settings. A landscape triage approach can be applied by using spatial and temporal patterns of connectivity change to prioritize restoration and conservation (*111*). The sociocultural context might determine whether land acquisition or rezoning, government regulations, community-led initiatives, economic incentives, other regulatory techniques, or a combination of the above are the most effective and just means to restoring connectivity.

New tools allow scenario comparison and prioritization mapping for terrestrial and marine connectivity. Determination of priority areas can, for example, be supported by decision-support software that identifies near-optimal trade-offs among multispecies conservation criteria and provides a ranking of all pixels in the landscape from lowest to highest conservation priority (*112*). Such analyses produce maps that allow a comparison of spatial conservation priorities based on a range of indicators and different climate scenarios (*88*, *113*). These tools can guide place-based action and collaboration for connectivity conservation sought by local communities, conservation nongovernmental organizations, and governments (*114*).

## Conclusion: A vision for a global effort to unify connectivity science and practice

Accounting for both protected areas and the movements of organisms among them is critical for large-scale conservation and for achieving global conservation targets (such as those of GBF). We have provided an operational definition of "well connected" and shown how the identification of well-connected landscapes and seascapes, along with connectivity monitoring and change attribution, can support these goals. To be most effective, standardized monitoring frameworks must be developed that incorporate structural and functional connectivity as well as how these aspects of connectivity affect species persistence and ecological functions.

Although there are gaps in our knowledge about connectivity, we know enough to act now. The goal should be to advance connectivity science while implementing connectivity conservation in the face of uncertainty. This requires more collaboration across different disciplines. Fostering synergies with restoration ecology and spatial prioritization tools can also ensure that we incorporate dynamics into connectivity planning in terrestrial, freshwater, and marine ecosystems. Monitoring these endeavors is key to assessing the changing status of connectivity and the success of conservation investments. Such monitoring requires well-defined, robust, and distinct sets of indicators for different connectivity goals that are applicable to different species and social-ecological contexts.

Last, because connectivity bridges multiple societal issues, we need to deepen our understanding of how it influences the achievement of conservation and societal goals across the spectrum of social-ecological contexts. Such complexity means that connectivity permeates multiple societal problems that affect many people around the world and therefore needs to be addressed through social as well as natural sciences. For example, because human disturbances such as agriculture and forest use impede the movement of many organisms (*98*), the areas important for connectivity will often overlap communities of rural, Indigenous, or marginalized peoples. Viewing connectivity as the conceptual link between biological, economic, and societal objectives provides a foundation for a strong connectivity science that informs conservation planning.

### REFERENCES AND NOTES


1. United Nations Convention on Biological Diversity (UN-CBD), Kunming-Montreal Global Biodiversity Framework, Fifteenth Meeting of the Conference of the Parties, Montreal, Canada (2022).
2. Florida Wildlife Corridor Foundation (FWCF), "2023 impact report" (2024); https://floridawildlifecorridor.org/2023-impact-report.
3. K. Soanes *et al*., Do wildlife crossing structures mitigate the barrier effect of roads on animal movement? A global assessment. *J. Appl. Ecol.* **61**, 417–430 (2024). doi: 10.1111/1365-2664.14582
4. M. A. Tucker *et al*., Moving in the Anthropocene: Global reductions in terrestrial mammalian movements. *Science* **359**, 466–469 (2018). doi: 10.1126/science.aam9712; pmid: 29371471
5. C. Grilo, E. Koroleva, R. Andrášik, M. Bíl, M. González-Suárez, Roadkill risk and population vulnerability in European birds and mammals. *Front. Ecol. Environ.* **18**, 323–328 (2020). doi: 10.1002/fee.2216
6. S. R. Loss, T. Will, S. S. Loss, P. P. Marra, Bird–building collisions in the United States: Estimates of annual mortality and species vulnerability. *Condor* **116**, 8–23 (2014). doi: 10.1650/CONDOR-13-090.1
7. K. A. Zeller, K. McGarigal, A. R. Whiteley, Estimating landscape resistance to movement: A review. *Landsc. Ecol.* **27**, 777–797 (2012). doi: 10.1007/s10980-012-9737-0
8. M. Beger *et al*., Demystifying ecological connectivity for actionable spatial conservation planning. *Trends Ecol. Evol.* **37**, 1079–1091 (2022). doi: 10.1016/j.tree.2022.09.002; pmid: 36182406
9. R. Fletcher *et al*., The prominent role of the matrix in ecology, evolution, and conservation. *Annu. Rev. Ecol. Evol. Syst.* **55**, 423–447 (2024). doi: 10.1146/annurev-ecolsys-102722-025653
10. P. Thatte, A. Joshi, S. Vaidyanathan, E. Landguth, U. Ramakrishnan, Maintaining tiger connectivity and minimizing extinction into the next century: Insights from landscape genetics and spatially-explicit simulations. *Biol. Conserv.* **218**, 181–191 (2018). doi: 10.1016/j.biocon.2017.12.022
11. J. Hilty *et al*., "Guidelines for conserving connectivity through ecological networks and corridors," Best Practice Protected Area Guidelines Series, no. 30 (IUCN, 2020).
12. R. Nathan *et al*., Big-data approaches lead to an increased understanding of the ecology of animal movement. *Science* **375**, eabg1780 (2022). doi: 10.1126/science.abg1780; pmid: 35175823
13. R. J. Fletcher Jr. *et al*., Towards a unified framework for connectivity that disentangles movement and mortality in space and time. *Ecol. Lett.* **22**, 1680–1689 (2019). doi: 10.1111/ele.13333; pmid: 31347244
14. B. Van Moorter, I. Kivimäki, M. Panzacchi, M. Saerens, Defining and quantifying effective connectivity of landscapes for species' movements. *Ecography* **44**, 870–884 (2021). doi: 10.1111/ecog.05351
15. R. J. Fletcher Jr. *et al*., A framework for linking dispersal biology to connectivity across landscapes. *Landsc. Ecol.* **38**, 2487–2500 (2023). doi: 10.1007/s10980-023-01741-8
16. D. Simberloff, J. Cox, Consequences and costs of conservation corridors. *Conserv. Biol.* **1**, 63–71 (1987). doi: 10.1111/j.1523-1739.1987.tb00010.x
17. N. M. Haddad *et al*., Potential negative ecological effects of corridors. *Conserv. Biol.* **28**, 1178–1187 (2014). doi: 10.1111/cobi.12323; pmid: 25115896
18. N. M. Haddad *et al*., Habitat fragmentation and its lasting impact on Earth's ecosystems. *Sci. Adv.* **1**, e1500052 (2015). doi: 10.1126/sciadv.1500052; pmid: 26601154
19. R. J. Fletcher Jr., N. S. Burrell, B. E. Reichert, D. Vasudev, J. D. Austin, Divergent perspectives on landscape connectivity reveal consistent effects from genes to communities. *Curr. Landsc. Ecol. Rep.* **1**, 67–79 (2016). doi: 10.1007/s40823-016-0009-6
20. L. Gilbert-Norton, R. Wilson, J. R. Stevens, K. H. Beard, A meta-analytic review of corridor effectiveness. *Conserv. Biol.* **24**, 660–668 (2010). doi: 10.1111/j.1523-1739.2010.01450.x; pmid: 20184653
21. J. Resasco, Meta-analysis on a decade of testing corridor efficacy: What new have we learned? *Curr. Landsc. Ecol. Rep.* **4**, 61–69 (2019). doi: 10.1007/s40823-019-00041-9
22. R. A. Magris *et al*., Biologically representative and well-connected marine reserves enhance biodiversity persistence in conservation planning. *Conserv. Lett.* **11**, e12439 (2018). doi: 10.1111/conl.12439
23. F. Valenzuela-Aguayo, G. R. McCracken, A. Manosalva, E. Habit, D. E. Ruzzante, Human-induced habitat fragmentation effects on connectivity, diversity, and population persistence of an endemic fish, *Percilia irwini*, in the Biobío River basin (Chile). *Evol. Appl.* **13**, 794–807 (2019). doi: 10.1111/eva.12901; pmid: 32211068
24. G. Cecino, E. A. Treml, Local connections and the larval competency strongly influence marine metapopulation persistence. *Ecol. Appl.* **31**, e02302 (2021). doi: 10.1002/eap.2302; pmid: 33565673
25. D. W. Johnson, M. R. Christie, T. J. Pusack, C. D. Stallings, M. A. Hixon, Integrating larval connectivity with local demography reveals regional dynamics of a marine metapopulation. *Ecology* **99**, 1419–1429 (2018). doi: 10.1002/ecy.2343; pmid: 29856493
26. M. G. Mitchell, E. M. Bennett, A. Gonzalez, Linking landscape connectivity and ecosystem service provision: Current knowledge and research gaps. *Ecosystems* **16**, 894–908 (2013). doi: 10.1007/s10021-013-9647-2
27. T. Lamy, K. Liss, A. Gonzalez, E. Bennett, Landscape structure affects the provision of multiple ecosystem services. *Environ. Res. Lett.* **11**, 124017 (2016). doi: 10.1088/1748-9326/11/12/124017
28. I. Grass *et al*., Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. *People Nat.* **1**, 262–272 (2019). doi: 10.1002/pan3.21
29. C. Ziter, E. M. Bennett, A. Gonzalez, Functional diversity and management mediate aboveground carbon stocks in small forest fragments. *Ecosphere* **4**, 1–21 (2013). doi: 10.1890/ES13-00135.1
30. D. Senapathi *et al*., Pollinator conservation—The difference between managing for pollination services and preserving pollinator diversity. *Curr. Opin. Insect Sci.* **12**, 93–101 (2015). doi: 10.1016/j.cois.2015.11.002
31. J. M. Calabrese, W. F. Fagan, A comparison-shopper's guide to connectivity metrics. *Front. Ecol. Environ.* **2**, 529–536 (2004). doi: 10.1890/1540-9295(2004)002[0529:ACGTCM]2.0.CO;2
32. F. Boschetti *et al*., Setting priorities for conservation at the interface between ocean circulation, connectivity, and population dynamics. *Ecol. Appl.* **30**, e02011 (2020). doi: 10.1002/eap.2011; pmid: 31556209
33. V. R. Goswami, D. Vasudev, B. Joshi, P. Hait, P. Sharma, Coupled effects of climatic forcing and the human footprint on wildlife movement and space use in a dynamic floodplain landscape. *Sci. Total Environ.* **758**, 144000 (2021). doi: 10.1016/j.scitotenv.2020.144000; pmid: 33338787
34. K. A. Zeller, R. Lewison, R. J. Fletcher, M. G. Tulbure, M. K. Jennings, Understanding the Importance of Dynamic Landscape Connectivity. *Land* **9**, 303 (2020). doi: 10.3390/land9090303
35. S. Straus *et al*., Macroecological constraints on species "movement profiles": Body mass does not explain it all. *Glob. Ecol. Biogeogr.* **33**, 227–243 (2024). doi: 10.1111/geb.13786
36. J. Hartfelder *et al*., The allometry of movement predicts the connectivity of communities. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 22274–22280 (2020). doi: 10.1073/pnas.2001614117; pmid: 32848069
37. J. F. Brodie *et al*., Connecting science, policy, and implementation for landscape-scale habitat connectivity. *Conserv. Biol.* **30**, 950–961 (2016). doi: 10.1111/cobi.12667; pmid: 26648510
38. E. S. Kim *et al*., Metapopulation models using landscape connectivity can better reflect landscape heterogeneity. *Ecol. Inform.* **80**, 102464 (2024). doi: 10.1016/j.ecoinf.2024.102464
39. J. F. Brodie, K. H. Redford, D. F. Doak, Ecological Function Analysis: Incorporating Species Roles into Conservation. *Trends Ecol. Evol.* **33**, 840–850 (2018). doi: 10.1016/j.tree.2018.08.013; pmid: 30292431
40. H. L. Beyer, O. Venter, H. S. Grantham, J. E. Watson, Substantial losses in ecoregion intactness highlight urgency of globally coordinated action. *Conserv. Lett.* **13**, e12692 (2020). doi: 10.1111/conl.12692
41. S. Ferrier, T. D. Harwood, C. Ware, A. J. Hoskins, A globally applicable indicator of the capacity of terrestrial ecosystems to retain biological diversity under climate change: The bioclimatic ecosystem resilience index. *Ecol. Indic.* **117**, 106554 (2020). doi: 10.1016/j.ecolind.2020.106554
42. M. Ward *et al*., Just ten percent of the global terrestrial protected area network is structurally connected via intact land. *Nat. Commun.* **11**, 4563 (2020). doi: 10.1038/s41467-020-18457-x; pmid: 32917882
43. M. G. Betts *et al*., A species-centered approach for uncovering generalities in organism responses to habitat loss and fragmentation. *Ecography* **37**, 517–527 (2014). doi: 10.1111/ecog.00740
44. M. Dennis, J. Huck, C. Holt, E. McHenry, A mechanistic approach to weighting edge-effects in landscape connectivity assessments. *Landsc. Ecol.* **39**, 68 (2024). doi: 10.1007/s10980-024-01865-5
45. D. Vasudev, R. J. Fletcher Jr., N. Srinivas, A. J. Marx, V. R. Goswami, Mapping the connectivity-conflict interface to inform conservation. *Proc. Natl. Acad. Sci. U.S.A.* **120**,

e2211482119 (2023). doi: 10.1073/pnas.2211482119; pmid: 36574696
46. A. Ghoddousi *et al*., Anthropogenic resistance: Accounting for human behavior in wildlife connectivity planning. *One Earth* **4**, 39–48 (2021). doi: 10.1016/j.oneear.2020.12.003
47. A. Gonzalez, J. H. Lawton, F. S. Gilbert, T. M. Blackburn, I. Evans-Freke, Metapopulation dynamics, abundance, and distribution in a microecosystem. *Science* **281**, 2045–2047 (1998). doi: 10.1126/science.281.5385.2045; pmid: 9748167
48. D. Tilman, *Plant Strategies and the Dynamics and Structure of Plant Communities* (Princeton Univ. Press, 1988).
49. E. S. Minor, D. L. Urban, A graph-theory framework for evaluating landscape connectivity and conservation planning. *Conserv. Biol.* **22**, 297–307 (2008). doi: 10.1111/j.1523-1739.2007.00871.x; pmid: 18241238
50. C. Kremen, A. M. Merenlender, Landscapes that work for biodiversity and people. *Science* **362**, eaau6020 (2018). doi: 10.1126/science.aau6020; pmid: 30337381
51. S. Blazquez-Cabrera, C. Ciudad, A. Gastón, M. A. Simón, S. Saura, Identification of strategic corridors for restoring landscape connectivity: Application to the Iberian lynx. *Anim. Conserv.* **22**, 210–219 (2019). doi: 10.1111/acv.12464
52. T. Dutta, S. Sharma, N. F. V. Meyer, J. Larroque, N. Balkenhol, An overview of computational tools for preparing, constructing and using resistance surfaces in connectivity research. *Landsc. Ecol.* **37**, 2195–2224 (2022). doi: 10.1007/s10980-022-01469-x
53. M. T. Matata, J. J. Kegamba, R. Mremi, A. Eustace, Electrified fencing as a mitigation strategy for human-elephant conflict in Western Serengeti: Community perspectives. *J. Nat. Conserv.* **70**, 126271 (2022). doi: 10.1016/j.jnc.2022.126271
54. B. B. Brown, E. Kusakabe, A. Antonopoulos, S. Siddoway, L. Thompson, Winter bird-window collisions: Mitigation success, risk factors, and implementation challenges. *PeerJ* **7**, e7620 (2019). doi: 10.7717/peerj.7620; pmid: 31534854
55. A. Ozgul, M. K. Oli, K. B. Armitage, D. T. Blumstein, D. H. Van Vuren, Influence of local demography on asymptotic and transient dynamics of a yellow-bellied marmot metapopulation. *Am. Nat.* **173**, 517–530 (2009). doi: 10.1086/597225; pmid: 19249978
56. Ż. Kaszta *et al*., Simulating the impact of Belt and Road initiative and other major developments in Myanmar on an ambassador felid, the clouded leopard, *Neofelis nebulosa*. *Landsc. Ecol.* **35**, 727–746 (2020). doi: 10.1007/s10980-020-00976-z
57. K. J. Bagstad, G. W. Johnson, B. Voigt, F. Villa, Spatial dynamics of ecosystem service flows: A comprehensive approach to quantifying actual services. *Ecosyst. Serv.* **4**, 117–125 (2013). doi: 10.1016/j.ecoser.2012.07.012
58. N. Shackelford, R. J. Standish, Z. Lindo, B. M. Starzomski, The role of landscape connectivity in resistance, resilience, and recovery of multi-trophic microarthropod communities. *Ecology* **99**, 1164–1172 (2018). doi: 10.1002/ecy.2196; pmid: 29603197
59. J. Huang, J. He, D. Liu, C. Li, J. Qian, An ex-post evaluation approach to assess the impacts of accomplished urban structure shift on landscape connectivity. *Sci. Total Environ.* **622-623**, 1143–1152 (2018). doi: 10.1016/j.scitotenv.2017.12.094; pmid: 29890583
60. J. F. Brodie, J. Mohd-Azlan, J. K. Schnell, How individual links affect network stability in a large-scale, heterogeneous metacommunity. *Ecology* **97**, 1658–1667 (2016). doi: 10.1890/15-1613.1; pmid: 27859156
61. T. Connor *et al*., Complex effects of habitat amount and fragmentation on functional connectivity and inbreeding in a giant panda population. *Conserv. Biol.* **36**, e13828 (2022). doi: 10.1111/cobi.13828
62. B. E. Reichert, R. J. Fletcher Jr., W. M. Kitchens, The demographic contributions of connectivity versus local dynamics to population growth of an endangered bird. *J. Anim. Ecol.* **90**, 574–584 (2021). doi: 10.1111/1365-2656.13387; pmid: 33179773
63. B. Freeman, J. Lee-Yaw, J. Sunday, A. Hargreaves, Expanding, shifting and shrinking: The impact of global warming on species' elevational distributions. *Glob. Ecol. Biogeogr.* **27**, 1268–1276 (2018). doi: 10.1111/geb.12774
64. J. Lenoir *et al*., Species better track climate warming in the oceans than on land. *Nat. Ecol. Evol.* **4**, 1044–1059 (2020). doi: 10.1038/s41559-020-1198-2; pmid: 32451428
65. S. Saura, J. Torné, Conefor Sensinode 2.2: A software package for quantifying the importance of habitat patches for landscape connectivity. *Environ. Model. Softw.* **24**, 135–139 (2009). doi: 10.1016/j.envsoft.2008.05.005
66. M. H. K. Hesselbarth, M. Sciaini, K. A. With, K. Wiegand, J. Nowosad, *landscapemetrics*: An open-source *R* tool to calculate landscape metrics. *Ecography* **42**, 1648–1657 (2019). doi: 10.1111/ecog.04617
67. M. Strimas-Mackey, J. F. Brodie, Reserve design to optimize the long-term persistence of multiple species. *Ecol. Appl.* **28**, 1354–1361 (2018). doi: 10.1002/eap.1739; pmid: 29723932
68. A. E. Eycott *et al*., A meta-analysis on the impact of different matrix structures on species movement rates. *Landsc. Ecol.* **27**, 1263–1278 (2012). doi: 10.1007/s10980-012-9781-9
69. J. F. Brodie, W. D. Newmark, Heterogeneous matrix habitat drives species occurrences in complex, fragmented landscapes. *Am. Nat.* **193**, 748–754 (2019). doi: 10.1086/702589; pmid: 31002574
70. W. F. Morris, D. F. Doak, *Quantitative Conservation Biology: Theory and Practice of Population Viability Analysis* (Oxford Univ. Press, 2002).
71. Y. Tao, A. Hastings, K. D. Lafferty, I. Hanski, O. Ovaskainen, Landscape fragmentation overturns classical metapopulation thinking. *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2303846121 (2024). doi: 10.1073/pnas.2303846121; pmid: 38709920
72. M. Meurant, A. Gonzalez, A. Doxa, C. H. Albert, Selecting surrogate species for connectivity conservation. *Biol. Conserv.* **227**, 326–334 (2018). doi: 10.1016/j.biocon.2018.09.028
73. J. F. Brodie *et al*., Evaluating multispecies landscape connectivity in a threatened tropical mammal community. *Conserv. Biol.* **29**, 122–132 (2015). doi: 10.1111/cobi.12337; pmid: 25065425
74. A. Brennan *et al*., Characterizing multispecies connectivity across a transfrontier conservation landscape. *J. Appl. Ecol.* **57**, 1700–1710 (2020). doi: 10.1111/1365-2664.13716
75. S. H. Williams *et al*., Incorporating connectivity into conservation planning for the optimal representation of multiple species and ecosystem services. *Conserv. Biol.* **34**, 934–942 (2020). doi: 10.1111/cobi.13450; pmid: 31840279
76. U. Ortega, I. Ametzaga-Arregi, U. Sertutxa, L. Peña, Identifying a green infrastructure to prioritise areas for restoration to enhance the landscape connectivity and the provision of ecosystem services. *Landsc. Ecol.* **38**, 3751–3765 (2023). doi: 10.1007/s10980-023-01789-6
77. C. Nelson *et al*., *Standards of practice to guide ecosystem restoration: A contribution to the United Nations Decade on Ecosystem Restoration 2021–2030* (Food & Agriculture Org, 2024).
78. A. T. H. Keeley *et al*., Making habitat connectivity a reality. *Conserv. Biol.* **32**, 1221–1232 (2018). doi: 10.1111/cobi.13158; pmid: 29920775
79. W. J. Liu *et al*., Using landscape connectivity tools to identify conservation priorities in forested areas and potential restoration priorities in rubber plantation in Xishuangbanna, Southwest China. *Landsc. Ecol.* **35**, 389–402 (2020). doi: 10.1007/s10980-019-00952-2
80. V. M. Temperton *et al*., Step back from the forest and step up to the Bonn Challenge: How a broad ecological perspective can promote successful landscape restoration. *Restor. Ecol.* **27**, 705–719 (2019). doi: 10.1111/rec.12989
81. P. Jantz, S. Goetz, N. Laporte, Carbon stock corridors to mitigate climate change and promote biodiversity in the tropics. *Nat. Clim. Chang.* **4**, 138–142 (2014). doi: 10.1038/nclimate2105
82. L. Carrera, M. Pavia, S. Varela, Birds adapted to cold conditions show greater changes in range size related to past climatic oscillations than temperate birds. *Sci. Rep.* **12**, 10813 (2022). doi: 10.1038/s41598-022-14972-7; pmid: 35752649
83. J. C. McElwain, Paleobotany and global change: Important lessons for species to biomes from vegetation responses to past global change. *Annu. Rev. Plant Biol.* **69**, 761–787 (2018). doi: 10.1146/annurev-arplant-042817-040405; pmid: 29719166
84. S. A. Parks, L. M. Holsinger, J. T. Abatzoglou, C. E. Littlefield, K. A. Zeller, Protected areas not likely to serve as steppingstones for species undergoing climate-induced range shifts. *Glob. Change Biol.* **29**, 2681–2696 (2023). doi: 10.1111/gcb.16629; pmid: 36880282
85. M. J. Gaywood, J. G. Ewen, P. M. Hollingsworth, A. Moehrenschlager, Eds. *Conservation translocations* (Cambridge University Press, 2022).doi: 10.1017/9781108638142
86. C. Podda, E. M. Porporato, Marine spatial planning for connectivity and conservation through ecological corridors between marine protected areas and other effective area-based conservation measures. *Front. Mar. Sci.* **10**, 1271397 (2023). doi: 10.3389/fmars.2023.1271397
87. G. Bastille-Rousseau, J. Wall, I. Douglas-Hamilton, G. Wittemyer, Optimizing the positioning of wildlife crossing structures using GPS telemetry. *J. Appl. Ecol.* **55**, 2055–2063 (2018). doi: 10.1111/1365-2664.13117
88. C. H. Albert, B. Rayfield, M. Dumitru, A. Gonzalez, Applying network theory to prioritize multispecies habitat networks that are robust to climate and land-use change. *Conserv. Biol.* **31**, 1383–1396 (2017). doi: 10.1111/cobi.12943; pmid: 28383758
89. D. Bormpoudakis, J. Tzanopoulos, The science-practice interface of connectivity in England. *Landsc. Ecol.* **34**, 2669–2685 (2019). doi: 10.1007/s10980-019-00913-9
90. A. T. Keeley *et al*., Thirty years of connectivity conservation planning: An assessment of factors influencing plan implementation. *Environ. Res. Lett.* **14**, 103001 (2019). doi: 10.1088/1748-9326/ab3234
91. W. D. Newmark, Insularization of Tanzanian parks and the local extinction of large mammals. *Conserv. Biol.* **10**, 1549–1556 (1996). doi: 10.1046/j.1523-1739.1996.10061549.x
92. M. Pacifici, M. Di Marco, J. E. Watson, Protected areas are now the last strongholds for many imperiled mammal species. *Conserv. Lett.* **13**, e12748 (2020). doi: 10.1111/conl.12748
93. A. Jain, K. Y. Chong, M. A. H. Chua, G. R. Clements, Moving away from paper corridors in southeast Asia. *Conserv. Biol.* **28**, 889–891 (2014). doi: 10.1111/cobi.12313; pmid: 24975570
94. J. M. Schoen *et al*., Synthesizing habitat connectivity analyses of a globally important human-dominated tiger-conservation landscape. *Conserv. Biol.* **36**, e13909 (2022). doi: 10.1111/cobi.13909; pmid: 35288989
95. R. Kays *et al*., The Movebank system for studying global animal movement and demography. *Methods Ecol. Evol.* **13**, 419–431 (2022). doi: 10.1111/2041-210X.13767
96. H. M. Pereira *et al*., Ecology. Essential biodiversity variables. *Science* **339**, 277–278 (2013). doi: 10.1126/science.1229931; pmid: 23329036
97. J. S. Lea, N. E. Humphries, R. G. von Brandis, C. R. Clarke, D. W. Sims, Acoustic telemetry and network analysis reveal the space use of multiple reef predators and enhance marine protected area design. *Proc. Biol. Sci.* **283**, 20160717 (2016). doi: 10.1098/rspb.2016.0717; pmid: 27412274
98. A. Brennan *et al*., Functional connectivity of the world's protected areas. *Science* **376**, 1101–1104 (2022). doi: 10.1126/science.abl8974; pmid: 35653461
99. L. Santini *et al*., Ecological correlates of dispersal distance in terrestrial mammals. *Hystrix* **24**, 181–186 (2013).
100. C. Sheard *et al*., Ecological drivers of global gradients in avian dispersal inferred from wing morphology. *Nat. Commun.* **11**, 2463 (2020). doi: 10.1038/s41467-020-16313-6; pmid: 32424113
101. S. Sloan, R. R. Talkhani, T. Huang, J. Engert, W. F. Laurance, Mapping remote roads using artificial intelligence and satellite imagery. *Remote Sens. (Basel)* **16**, 839 (2024). doi: 10.3390/rs16050839
102. K. R. Hall *et al*., Circuitscape in Julia: Empowering dynamic approaches to connectivity assessment. *Land (Basel)* **10**, 301 (2021). doi: 10.3390/land10030301
103. J. Hughes *et al*., Comparison and parallel implementation of alternative moving-window metrics of the connectivity of protected areas across large landscapes. *Landsc. Ecol.* **38**, 1411–1430 (2023). doi: 10.1007/s10980-023-01619-9
104. J. Oehri, S. L. Wood, E. Touratier, B. Leung, A. Gonzalez, Rapid evaluation of habitat connectivity change to safeguard multispecies persistence in human-transformed landscapes. *Biodivers. Conserv.* **33**, 4043–4071 (2024). doi: 10.1007/s10531-024-02938-2
105. M. W. Schwartz *et al*., Decision support frameworks and tools for conservation. *Conserv. Lett.* **11**, e12385 (2018). doi: 10.1111/conl.12385
106. K. Frank, C. Wissel, Spatial aspects of metapopulation survival–from model results to rules of thumb for landscape management. *Landsc. Ecol.* **13**, 363–379 (1998). doi: 10.1023/A:1008054906030
107. A. Gonzalez, J. M. Chase, M. I. O'Connor, A framework for the detection and attribution of biodiversity change. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **378**, 20220182 (2023). doi: 10.1098/rstb.2022.0182; pmid: 37246383
108. L. M. Navarro *et al*., Monitoring biodiversity change through effective global coordination. *Curr. Opin. Environ. Sustain.* **29**, 158–169 (2017). doi: 10.1016/j.cosust.2018.02.005
109. WildLabs, Introducing the Move BON Initiative. WildLabs.net; https://wildlabs.net/article/introducing-move-bon-initiative (accessed 10 October 2024), (2024).
110. V. Lucet, A. Gonzalez, Integrating land use and climate change models with stakeholder priorities to evaluate habitat

connectivity change: A case study in southern Québec. *Landsc. Ecol.* **37**, 2895–2913 (2022). doi: 10.1007/s10980-022-01516-7
111. D. I. Rappaport, L. R. Tambosi, J. P. Metzger, A landscape triage approach: Combining spatial and temporal dynamics to prioritize restoration and conservation. *J. Appl. Ecol.* **52**, 590–601 (2015). doi: 10.1111/1365-2664.12405
112. E. Bohnett *et al*., Consolidating diverse modeling methods and spatial prioritization for multispecies connectivity planning. *Front. Conserv. Sci.* **5**, 1406944 (2024). doi: 10.3389/fcosc.2024.1406944
113. B. Rayfield, D. Pelletier, M. Dumitru, J. A. Cardille, A. Gonzalez, Multipurpose habitat networks for short-range and long-range connectivity: A new method combining graph and circuit connectivity. *Methods Ecol. Evol.* **7**, 222–231 (2016). doi: 10.1111/2041-210X.12470
114. G. Cobb, J. Nalau, A. L. Chauvenet, Global trends in geospatial conservation planning: A review of priorities and missing dimensions. *Front. Ecol. Evol.* **11**, 1209620 (2024). doi: 10.3389/fevo.2023.1209620
115. Q. Qureshi, Y. Jhala, S. Yadav, A. Mallick, Eds., *Status of Tigers in India–2022: Photo-captured Tigers, Summary Report* (National Tiger Conservation Authority and Wildlife Institute of India, 2023).
116. P. R. Pata, A. T. Yñiguez, Spatial planning insights for Philippine coral reef conservation using larval connectivity networks. *Front. Mar. Sci.* **8**, 719691 (2021). doi: 10.3389/fmars.2021.719691
117. R. Kays, M. C. Crofoot, W. Jetz, M. Wikelski, ECOLOGY. Terrestrial animal tracking as an eye on life and planet. *Science* **348**, aaa2478 (2015). doi: 10.1126/science.aaa2478; pmid: 26068858
118. S. C. Davidson *et al*., Ecological insights from three decades of animal movement tracking across a changing Arctic. *Science* **370**, 712–715 (2020). doi: 10.1126/science.abb7080; pmid: 33154141
119. S. R. Supp, G. Bohrer, J. Fieberg, F. A. La Sorte, Estimating the movements of terrestrial animal populations using broad-scale occurrence data. *Mov. Ecol.* **9**, 60 (2021). doi: 10.1186/s40462-021-00294-2; pmid: 34895345
120. Y. Kanamori, T. Yano, H. Okamura, Y. Yagi, Spatio-temporal model and machine learning method reveal patterns and processes of migration under climate change. *J. Biogeogr.* **51**, 522–532 (2024). doi: 10.1111/jbi.14595
121. R. Nathan *et al*., A movement ecology paradigm for unifying organismal movement research. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 19052–19059 (2008). doi: 10.1073/pnas.0800375105; pmid: 19060196
122. P. Balvanera *et al*., Essential ecosystem service variables for monitoring progress towards sustainability. *Curr. Opin. Environ. Sustain.* **54**, 101152 (2022). doi: 10.1016/j.cosust.2022.101152
123. C. Song *et al*., Rapid monitoring of ecological persistence. *Proc. Natl. Acad. Sci. U.S.A.* **120**, e2211288120 (2023). doi: 10.1073/pnas.2211288120; pmid: 37155860
124. Y. Xu *et al*., Loss of functional connectivity in migration networks induces population decline in migratory birds. *Ecol. Appl.* **29**, e01960 (2019). doi: 10.1002/eap.1960; pmid: 31237968
125. D. Zhang *et al*., Genomic and phenotypic changes associated with alterations of migratory behaviour in a songbird. *Mol. Ecol.* **32**, 381–392 (2023). doi: 10.1111/mec.16763; pmid: 36326561
126. R. Fletcher, Well-connected calculation, Zenodo (2024); doi: 10.5281/zenodo.11477995

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## SUPPLEMENTARY MATERIALS

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Figs. S1 and S2
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MDAR Reproducibility Checklist

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