GLOBAL LAND OUTLOOK

Thematic Report on Ecological Connectivity and Land Restoration

United Nations
Convention to Combat Desertification

CMS

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Acknowledgements

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Foreword

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Life on our planet depends on ecological connectivity - not only for nature, but for people. The unimpeded movement of species and flow of natural processes that sustain life on Earth is vital for the health of our ecosystems, the productivity of our landscapes, the survival of plant and animal species and the well-being of communities around the world. When these connections are lost, it is people - particularly those who depend directly on the land for their food, water and livelihoods - who are most affected.

This Global Land Outlook Thematic Report on Ecological Connectivity and Land Restoration, jointly prepared by the United Nations Convention to Combat Desertification (UNCCD) and the Convention on the Conservation of Migratory Species of Wild Animals (CMS), shines a spotlight on the linkages between land degradation and connectivity loss and the critical importance of integrated solutions that prioritise sustainable land management and restoration while strengthening ecological connectivity. These efforts offer hope—hope for a future in which connected healthy ecosystems sustain life, support biodiversity, and ensure long-term access to food for people, clean water and climate resilience.

Agricultural intensification, infrastructure development, climate change, pollution and human conflicts fragment landscapes, degrade ecosystems and threaten biodiversity, undermining the resilience of both people and nature. Land restoration approaches that also promote ecological connectivity can restore vital ecosystem functions and deliver tangible benefits. These synergies not only help degraded ecosystems recover and thrive but also reinforce the services they provide - such as food production, water regulation, species movement and diversity and protection against extreme weather.

Restoring ecological connectivity is therefore critical, not just for conserving resilient landscapes, supporting biodiversity, enhancing climate adaptation and ensuring the provision of vital ecosystem services, but for supporting human health, food security and sustainable development. Reconnecting fragmented landscapes can deliver multiple benefits by enhancing carbon storage, improving water quality and securing access to critical resources for local populations. It is also key to achieving Target 2 of the Kunming-Montreal Global Biodiversity Framework, which calls for at least 30 per cent of degraded ecosystems to be under effective restoration by 2030 to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity.

This report provides a strong scientific foundation and evidence base for enhancing ecological connectivity, grounded in a comprehensive analysis of the natural and social processes that shape our landscapes, from hydrological cycles and energy fluxes to population dynamics and socio-ecological linkages. It highlights good practices from around the world and provides policy-relevant recommendations. Among these, the report emphasises that effective restoration requires inclusive governance frameworks that engage local communities, integrate traditional knowledge and ensure the equitable sharing of benefits.

As we enter the second half of the UN Decade on Ecosystem Restoration (2021–2030), the urgency to act has never been greater. This is our window of opportunity to reverse decades of land degradation, reconnect fragmented landscapes and and build a future where people and nature thrive together. We extend our heartfelt gratitude to the authors, contributors and reviewers of this report, as well as to the sponsors for their generous financial support. We hope this report will inspire and guide action - to restore to connect and connect to restore - delivering lasting benefits for people and the planet.

Executive **Summary**

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Connectivity is a critical yet frequently overlooked attribute of well-functioning ecological processes, which are essential for the survival of species, human well-being and the health of landscapes. All natural processes that support life on Earth take place within complex social-ecological systems in which humans and nature interact and influence each other. This multi-dimensional connectivity provides a framework for understanding the complex and dynamic interactions between society and the environment.

Ecological connectivity is far more than the movements of animals between different habitats. It is a broad concept that considers the biotic and abiotic structures and functions that support healthy populations and the delivery of ecosystem services that underpin our societies and economies. For instance, clean air and water, pollination and pest control, soil erosion and flood control and climate regulation are all dependent on ecological connectivity.

Connectivity allows for the flow of resources, information and species, enhancing the resilience of both social and ecological systems in the face of climate change, land degradation and biodiversity loss. This includes ecological processes that connect communities, ecosystems and landscapes, such as:

- water-mediated transfers of matter, energy and organisms within the hydrological cycle,
- regulation of energy fluxes, such as solar, wind and water;
- unimpeded movement of species on land, in water and in the air, including the exchange of genetic material and the dispersal of individuals among populations;
- spatial and temporal linkages associated with migratory patterns and climate change-induced range shifts;
- communication, collaboration and knowledge exchange, which for humans can lead to restorative measures that enhance connectivity.

Human activities have significantly altered most landscapes, resulting in the loss of biodiversity and ecosystem services and, in some cases, the creation of novel ecosystems. Consequently, landscapes are becoming increasingly fragmented, thereby eroding the natural structures and processes that support ecological connectivity. The most prominent drivers of fragmentation are changes in land use and the overexploitation of natural resources to meet the ever-increasing demand for food, water, energy and raw materials. These pressures are exacerbated by the expansion of infrastructure to deliver these goods and services, as well as climate change, invasive species and pollution which also contribute to the loss of ecological connectivity.

When ecosystems and landscapes are degraded and fragmented, they lose their ability to support wildlife, regulate nutrient and water cycles and withstand environmental stressors. This makes them more vulnerable to drought, desertification and further land degradation which has significant costs to society. However, sustainable land management and ecosystem restoration have the potential to restore biodiversity habitat and enhance ecological connectivity, thereby strengthening the resilience of people and nature. Greater investment and incentives for regenerative land management practices that re-establish connectivity are critical to mitigating and adapting to the impacts of multiple, interconnected crises.

'Connect to restore, restore to connect' serves as a guiding principle for the design, implementation and monitoring of large-scale landscape conservation, recognising that connectivity and restoration are mutually reinforcing. It emphasises that maintaining or enhancing connectivity is crucial for effective restoration, and conversely, that restoring the health and productivity of the land can improve ecological connectivity. This could involve removing barriers that impede the movement of species or water flows, conserving wildlife corridors, restoring habitats and managing soils to support nutrient cycling and vegetation recovery.

Addressing the current extent of land degradation and fragmentation requires the strategic, systematic and holistic combination of nature-based solutions adapted to local social-ecological contexts. This involves radical changes to the way we use and manage land resources, such as soil, water and biodiversity, to create more connected and resilient ecosystems and landscapes. A first step is to integrate sustainable land and water management and ecological connectivity considerations into key policy areas and economic sectors, such as agriculture, forestry, water management, extractive industries, ecotourism, nature conservation and urban planning. Implementation and monitoring must also consider any new challenges that may arise from restored connectivity, such as the spread of fire, invasive species and diseases.

Ecosystems and landscapes that are well-connected, such as networks of protected areas, are considerably more resilient to disasters, stresses and shocks. For instance, unimpeded water and nutrient cycling can enhance drought resilience, while connected vegetation cover can regulate the local climate by maintaining moisture levels and reducing heat stress. Reconnecting natural and agricultural landscapes, such as through agroforestry and regenerative agriculture, can improve soil health, farm productivity and food security. Restoring wetland and riparian ecosystems – reconnecting 'blue lifelines' – improves hydrologic and aquatic connectivity, enabling fish and amphibians to migrate between their breeding and feeding grounds.

Technical measures to restore degraded land and enhance ecological connectivity cannot be implemented in isolation. Without due consideration of local conditions and knowledge, as well as incentives, supportive policies and inclusive decision-making, ecological connectivity and land restoration initiatives are likely to encounter significant challenges. Increased attention to data collection, participatory governance, gender equality, land rights and the participation of Indigenous Peoples and local communities can help to ensure that these initiatives contribute to broader goals, such as reducing poverty and promoting more equitable and sustainable development.

Photo: ©Will Parson / Alliance for the Chesapeake Bay

1

Introduction

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This report focuses on land as an interconnected socio-ecological system, which encompasses freshwater cycles, as well as terrestrial and freshwater biodiversity. It also considers the connections between these systems through the natural and social processes that support ecological connectivity. It explores the potential of enhanced ecological connectivity to promote sustainable land management and restoration, addressing global environmental crises such as desertification, land degradation and drought (DLDD), biodiversity loss and climate change.

The Link Between Healthy Land and Ecological Connectivity

DLDD are among the most pressing contemporary environmental challenges, threatening food security, biodiversity and water availability, as well as the livelihoods of billions of people.[1] [2] [3] Climate change is exacerbating these issues by increasing the frequency and intensity of droughts,[4] while unsustainable land use continues to fragment natural habitats and reduces ecosystem resilience.[5] Against this backdrop of interconnected challenges, ecological connectivity is receiving increasing attention as it plays a pivotal role in determining the resilience of ecosystems and human communities.[6]

Ecological connectivity is defined as *"the unimpeded movement of species, connection of habitats without hindrance and flow of natural processes that sustain life on Earth"*.[7] These processes include the flow of organisms, propagules and genes, as well as the flow of energy, nutrients, water, sediments, information, knowledge, culture and cooperation.[8] These are all vital for functioning ecosystems that support people and their economies. Without urgent action, the breakdown of ecological connectivity will accelerate the loss of fertile land, intensify desertification and reduce the resilience of people, ecosystems and economies to droughts.

Over the past few decades, the concept of ecological connectivity has become increasingly relevant in environmental science and policy, playing a key role in responses to species loss, habitat fragmentation, changes in land use and climate change. The loss of connectivity worldwide is attributed to increasing socio-economic pressures on land use, as well as other direct and indirect human-caused impacts. This can impede or even prevent ecological processes at various scales, affecting the overall functionality and health of ecosystems.[9] Consequences include declines in soil health and productivity,[10] water quality,[11] the ability of ecosystems to adapt and recover from disturbances,[12] interrupted gene flows,[13] species extinction and the loss of vital ecological interactions needed for community stability.[14] Fragmentation also affects trophic interactions, shifting species assemblages, resource use patterns, and consequently nutrient cycles and energy flows. [15]

The loss of connectivity has detrimental impacts on landscape productivity and resilience, making it more vulnerable to DLDD. Maintaining ecological connectivity, by contrast, is synonymous with maintaining processes such as nutrient and mineral flow, pollination, seed dispersal, the free flow of rivers, the transmission of genetic material, animal movement, and species adaptation to environmental change.[16] [17] When ecosystems and landscapes remain connected, they are more resilient to environmental stressors, recover faster and can provide key regulatory services more effectively.[18]

Ecological connectivity encourages policymakers to reconsider nature conservation as more than merely increasing the number and size of protected areas. By understanding how the natural world and ecological processes are interconnected and not confined within the boundaries of human geographies, we can move towards more sustainable landscape management and development. A holistic and integrated approach prioritises sustainable land and water management and restoration, while also strengthening ecological connectivity. In the global policy context, connectivity and restoration initiatives align closely with goals and targets, such as the Kunming-Montreal Global Biodiversity Framework (GBF), Land Degradation Neutrality (LDN) and climate adaptation strategies, which have been agreed to ensure that land use decisions support both people and nature.


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The Policy Context for Ecological Connectivity

The United Nations General Assembly (UNGA) proclaimed the period between 2021 and 2030 the Decade of Ecosystem Restoration to recognise the urgent need to prevent, halt and reverse degradation. Prioritising ecological connectivity as part of the land restoration agenda will play an important role in ensuring that ecosystems and landscapes regain their functionality and capacity to meet societal needs, and achieve the Sustainable Development Goals (SDGs).[19] Several multilateral environmental agreements and international organisations have incorporated ecological connectivity into their policy frameworks (Table 1).

Structure and Objectives of the Report

This *Global Land Outlook Thematic Report on Ecological Connectivity and Land Restoration* explores the intricate relationships between DLDD and ecological connectivity. It provides insights into how sustainably managing healthy landscapes and restoring degraded land and water resources can reconnect fragmented ecosystems ('restore to connect'),[20] while enhancing connectivity can increase landscape resilience to impacts of degradation and climate change ('connect to restore').[21]

Chapter 2 examines the functional dimensions of ecological connectivity, the key natural processes contributing to ecological connectivity and the drivers of fragmentation.

Chapter 3 outlines the current state of DLDD, explores their interlinkages with ecological connectivity and how tackling these issues simultaneously can create a reinforcing cycle that strengthens the resilience of ecosystems and communities.

Chapter 4 presents land-based approaches and technical measures. It showcases successful case studies that integrate land restoration with ecological connectivity to deliver multiple benefits.

Chapter 5 discusses the enabling environment required to implement these approaches and measures.

Chapter 6 offers some concluding remarks with an indication of the potential roles and responsibilities of various stakeholder groups engaged in connectivity and restoration efforts around the world.

TABLE 1

Ecological Connectivity in International Policy Frameworks

UN General Assembly	In 2021, Resolution 75/271, 'Nature knows no borders: transboundary cooperation a key factor for biodiversity conservation, restoration and sustainable use', for the first time recognised the importance of ecological connectivity in maintaining healthy ecosystems and habitats. The resolution affirms that connectivity is necessary for conserving, restoring and sustainably using biodiversity, and for ensuring that nature can continue to provide people with ecosystem services. While encouraging Member States to implement the UN Decade on Ecosystem Restoration (2021–2030), the General Assembly also urges them to maintain and enhance connectivity within and beyond protected areas and to employ other area-based conservation measures that contribute to their healthy functioning.
International Union for the Conservation of Nature (IUCN)	In 2021, the IUCN adopted various resolutions (e.g. 073[22] and 081[23]). Policy Resolution 073, 'Ecological connectivity conservation in the post-2020 global biodiversity framework: from local to international levels', emphasises the importance of ecological networks and corridors in sustaining biodiversity and the contributions of nature to people. It recommends that all IUCN members conserve connectivity by documenting it across ecosystems, informing policies, laws and plans, identifying key drivers of fragmentation and building synergies across institutions and borders to implement solutions.[24] Resolution 071, 'Wildlife-friendly linear infrastructure', recognises the importance of avoiding and mitigating the fragmentation caused by linear infrastructure, such as roads, railways and canals, in order to conserve ecological connectivity.[25]
Convention on Migratory Species (CMS)	In the context of the Convention on Migratory Species (CMS), connectivity is an expression of entire migration systems, as it enables the functioning of the migration process and the conditions that maintain the cyclical and predictable movements of animals. Article III4(b) of the convention text emphasises the importance of Parties endeavouring "*to prevent, remove, compensate for or minimise, as appropriate, the adverse effects of activities or obstacles that seriously impede or prevent the migration of the species*" listed in Appendix 1. Species migration can only be achieved if animals can access the sites, habitats, food resources and breeding conditions they need at different stages of their life cycles and journeys.[26] The CMS and its family of agreements provide a specialised framework for cooperative efforts on ecological connectivity in relation to the conservation needs of migratory species. The convention's new strategic plan for 2024–2032 includes the following goal: "*The habitats and ranges of migratory species are maintained and restored, supporting their connectivity*".[27]
United Nations Convention to Combat Desertification (UNCCD)	In technical documents, the UNCCD references ecological connectivity as a means of achieving SDG target 15.3: Land Degradation Neutrality (LDN).[28] Maintaining or enhancing the quantity and quality of land resources necessary to support ecosystem functions and services, and enhancing food security, are ways in which ecological connectivity can contribute to LDN. At the 15th Conference of the Parties to the UNCCD in 2022, the Land, Life and Legacy Declaration was adopted. This encourages the signatory countries to consider the 'connectivity of ecosystems' in order to speed up their commitment to achieving land degradation neutrality by 2030.[29]
Convention on Biological Diversity (CBD)	In 2022, the CBD adopted the Kunming-Montreal Global Biodiversity Framework (GBF), with ecological connectivity being central to Goal A and Targets 2, 3 and 12. Target 2 calls for the restoration of 30% of degraded land, freshwater and ocean areas to benefit biodiversity, ecosystem functions and services, and ecological integrity and connectivity. Target 3 aims to effectively conserve and manage 30% of land, freshwater and of ocean areas by 2030, through ecologically connected and representative systems. Target 12 emphasises the importance of maintaining and enhancing connectivity in urban and non-urban environments to ensure the persistence of biodiversity and ecosystem services. Target 4 includes maintaining and restoring genetic diversity to maintain their adaptive potential.[30]
United Nations Framework Convention on Climate Change (UNFCCC)	In the context of the UNFCCC, the 2021 Glasgow Leaders' Declaration on Forests and Land Use commits to halting deforestation and restoring degraded landscapes, thereby reinforcing the importance of large-scale connectivity efforts.[31] The Sharm el-Sheikh Adaptation Agenda (2022), meanwhile, calls for 2.5 billion hectares of land to be restored and for landscape connectivity to be improved in order to build resilience against extreme climate events.[32]
Ramsar - The Convention on Wetlands and United Nations Educational, Scientific and Cultural Organization (UNESCO)	Annex 3 of Ramsar Resolution XI.12 recognises the fundamental connection between the health of humans, domestic livestock and wildlife, and calls for ecosystem-based approaches to be implemented.[33] Resolution VI.23 focuses on maintaining hydrological functions and linkages across catchments and floodplains.[34] Meanwhile, Resolution XIV.6 encourages the Ramsar Secretariat to "*contribute to ongoing efforts to improve ecological connectivity of the world's flyways for migratory birds and potentially of other taxa*".[35] Alongside UNESCO's Man and the Biosphere Programme and World Heritage designations, these resolutions provide scalable governance models that support cross-border corridors, large-scale restoration projects and strategies that balance biodiversity, water and cultural values. The Ramsar Convention, UNESCO's Man and the Biosphere Programme and the World Heritage Programme also offer valuable case studies in the form of implemented resolutions and site-level management plans that support integrated, land-based ecological connectivity. Reviewing and scaling up these experiences could strengthen global restoration strategies.

2

The Multiple Dimensions of Ecological Connectivity

Photo: ©Dewald Kisrten

This chapter explores the many dimensions of ecological connectivity that are essential for maintaining and restoring ecosystem functions and the benefits they provide. It explains why it has been defined as **"the unimpeded movement of species, connection of habitats without hindrance and flow of natural processes that sustain life on Earth"**.[36] It describes several of these natural and socio-ecological processes and discusses the difference between structural and functional connectivity. It also sets out the main drivers of connectivity loss and its impacts on ecosystems.

2.1

The Flow of Natural Processes and Movement of Species

Over the past few decades, human activities have transformed around 32% of the Earth's land surface,[37] profoundly fragmenting landscapes and seascapes and undermining the productivity, functioning and resilience of ecosystems. Ecological connectivity has gradually become a key topic in environmental science and policy discussions, as it is essential for responding to species loss, habitat fragmentation, land use changes, climate change and maintaining vital ecosystem services for human well-being.[38] [39]

Ecological connectivity not only enables the movement of animals and the connection of habitats without hindrance, but also allows for the unimpeded flow of the natural processes that sustain life on Earth. These processes include various fluxes, such as the movement of organisms, propagules, genes, energy and materials like nutrients, water and sediments. These processes depend on both structural and functional connectivity.

Understanding the dynamics and interactions of these processes and how they connect and interrelate within social-ecological systems helps us to understand how degradation and fragmentation affect not only adjacent ecological systems, but also systems functioning at much wider scales, including transcontinental and transoceanic systems.[40] Thus, ecological connectivity is a broad concept that can be applied to different contexts and circumstances, depending on the scale and social-ecological processes under consideration.[41] Figure 1 shows a simplified connected and fragmented landscape with various land uses. It highlights structural elements and different approaches (green) and functional elements (yellow) that contribute to and are associated with ecological connectivity. These include hydrological connectivity, energy fluxes, population connectivity, communicative transmissions of non-human organisms, species movement, migratory connectivity, climate connectivity and socio-ecological connectivity. These are outlined further below. The orange labels in the fragmented landscape highlight some of the barriers and disturbances, as well as their consequences on ecological connectivity.

FIGURE 1

This figure presents a simplified example of a connected landscape, illustrating key structural elements and different approaches and functional elements that support ecological connectivity and ecosystem processes.

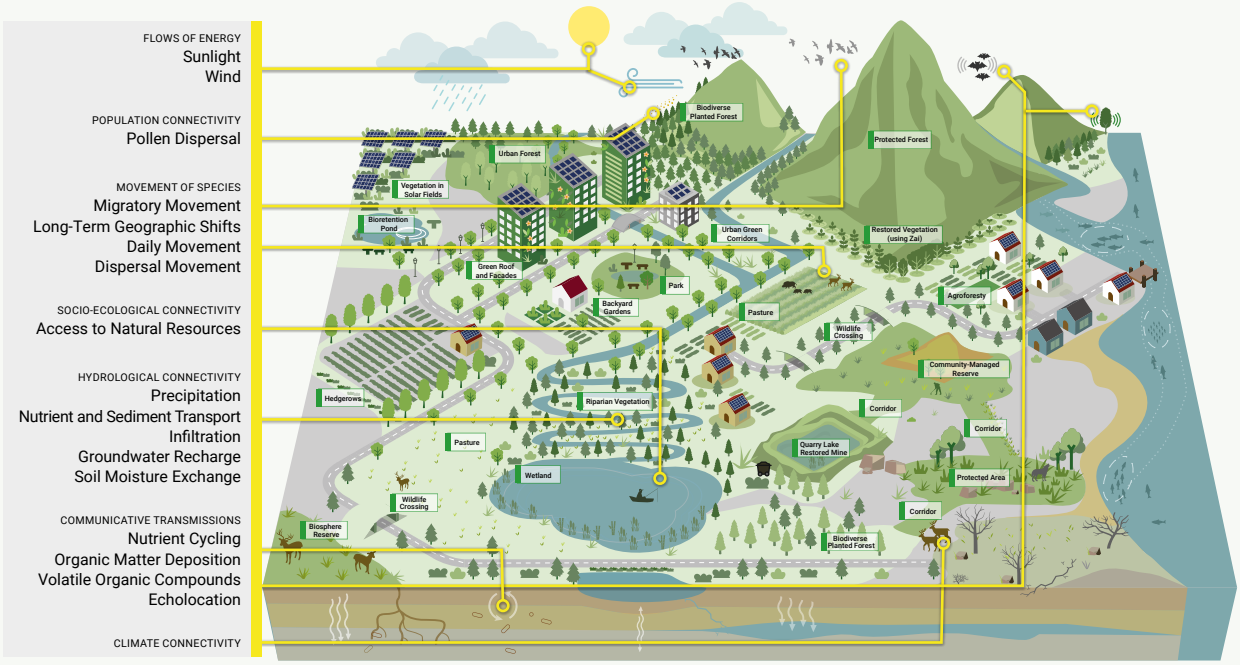
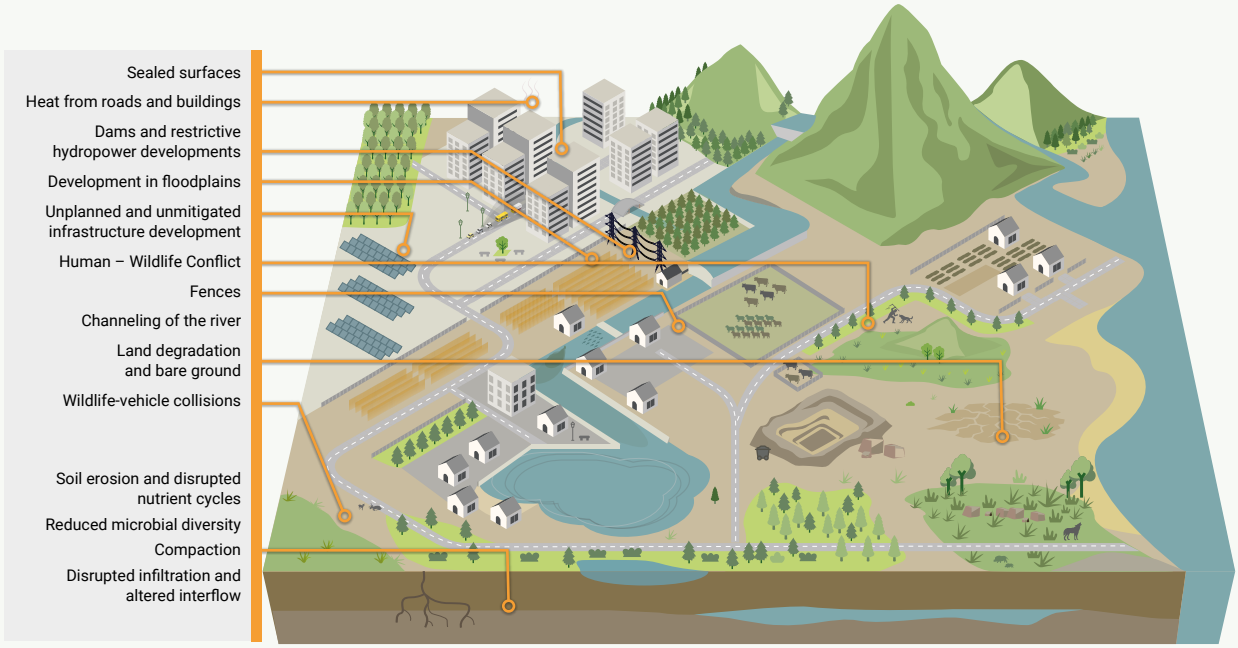


FIGURE 2

This figure presents a simplified example of a fragmented landscape, highlighting barriers to connectivity and disturbances, along with their potential ecological and socio-environmental consequences.



Structural connectivity refers to the extent to which elements of a landscape or system are physically linked, based on their physical features, configuration, interrelations, extent and spatial distribution.[42] Structural connectivity is relatively straightforward to understand, measure and communicate. For example, the state of a landscape or habitat can often be observed via aerial photographs or satellite images of the Earth's surface or through other mapping methods.[43] [44] However, these methods do not take into consideration how organisms effectively move across the landscape.

Functional connectivity, on the other hand, is the degree to which landscapes facilitate the movement of organisms or the flow of natural processes. It also takes into account the behaviour patterns of the organisms themselves.[45] It includes the combined effects of landscape or ecosystem structure, and how organisms and ecological processes respond to this structure. This means that the same landscape will have different levels of functional connectivity for different ecological flows, species and organisms, as their ability to move through or between the landscape matrix (permeability) can change based on several factors. For wildlife, these factors can include an individual's condition and motivation to move, the social organisation of the population, the level of risks encountered and differential vulnerability to risks, including natural predation and anthropogenic disturbance.[46] [47]

Socio-Ecological Connectivity

Ecosystems and landscapes comprise social and ecological components, all of which are influenced by external forces and adapt as they interact with each other in a dynamic network of interdependencies and feedback loops.[48] [49] Managing ecological connectivity requires an understanding of, and governance over, cross-boundary ecological processes, as well as the coordination of management actions across different levels of society, policy sectors and scales.

To fully understand dynamic landscape processes, it is necessary to analyse the patterns of both ecological and social systems and their complex interactions. In an urban setting with a growing population, for example, both physical structures and demographic patterns change over time and space. A comprehensive assessment of the flow of ecosystem services in a dynamic urban landscape requires an evaluation of how ecological processes, green and blue spaces and biodiversity, which are all supported by ecological connectivity in the city, are related to people, their well-being and their activities.[50]

Social connectivity refers to the connections between people, such as communication, the exchange of goods and ideas and cultural exchange,[51] as well as cooperation, including the exchange of information between institutions and the exchange of knowledge between different fields of interest and sectors of expertise.[52] Socio-ecological connectivity expresses the ecological linkages between different users and communities who share natural resources. For instance, a community of small-scale fishermen could influence a neighbouring fishing community located a considerable distance away if they impact shared fish stocks.[53] Similarly, pastoralists moving across country boundaries along traditional migration routes influence vegetation and soil health in these areas.[54] The protection of forests by users in one area can influence species movement between countries and across continents, enhance water regulation and contribute to ecological stability far beyond the forest ecosystem.[55]

These socio-ecological dynamics can be influenced by traditional and other cultural values. Migratory animal species connect places with each other and, consequently, people. Many migratory species are culturally and economically important to Indigenous Peoples and local communities, who often suffer the most if these species decline. This is referred to as 'cultural connectivity', acknowledging the contributions that migratory species make to spiritual and religious life, cognitive development, aesthetic and recreational experiences as well as the cultural significance and symbolic importance that traditional communities associate with them.[56] [57] Cultural values must be considered in connectivity management strategies, recognising the fundamental role of exchange and collaboration.[58]

Discovering mutual ecological connections between local communities, even where social ties are relatively weak, highlights the importance of adopting a landscape perspective and collaborative approaches.[59] This also involves considering the potential negative effects of greater ecological connectivity. Although ecological connectivity can also mitigate human disease risk, connected social-ecological systems can facilitate the transmission of diseases and pathogens among and between animals and humans.[60] The spread of Swine Fever among free-ranging wild boar (*Sus scrofa*) in Belgium, Germany, Italy and Switzerland was facilitated by habitat connectivity.[61] In the United States, forest connectivity has contributed to the spread of Lyme disease, which is transmitted by *Ixodes* ticks.[62]

Hydrological Connectivity

Hydrological connectivity refers to the transfer of matter, energy and organisms within or between elements of the hydrological cycle.[63] This type of connectivity spans all scales, from local to global, and can exhibit significant temporal complexity.[64] [65] Wetlands, rivers, streams and ponds, for example, exhibit considerable inter-annual variability and may be more connected in wetter years than in drier years.[66] Hydrological connectivity can be divided into three components: longitudinal connectivity (upstream–downstream), lateral connectivity (land–water) and vertical connectivity (atmosphere–surface–groundwater).


Photo: © Will Parson @ Alliance for the Chesapeake Bay

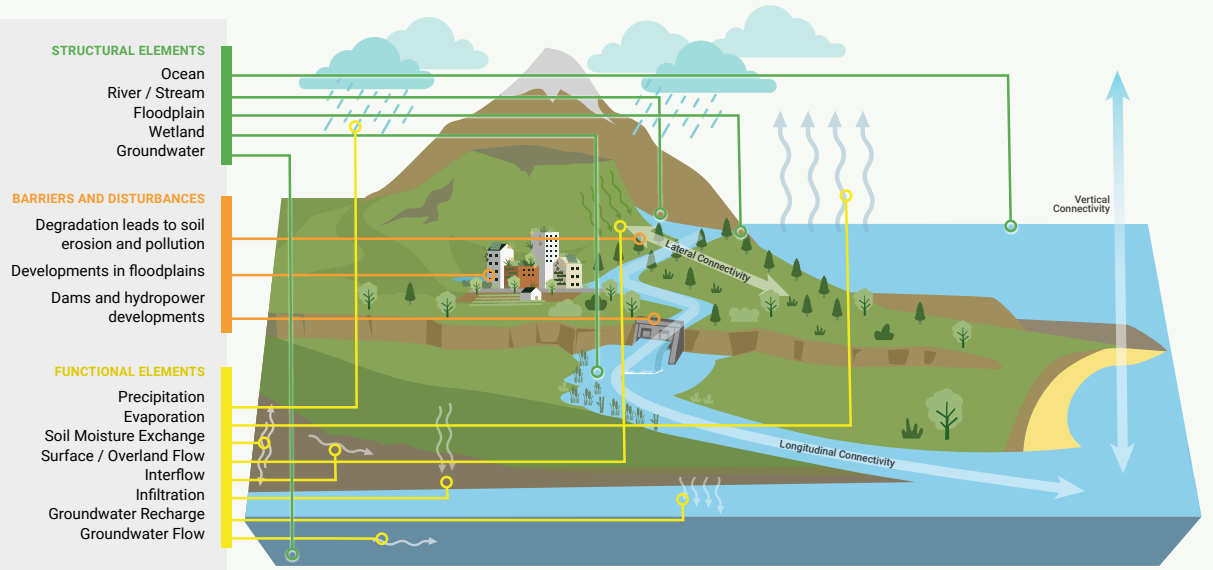
- Longitudinal connectivity involves the flow of water from upstream to downstream in river systems, facilitating processes such as the migration of organisms, the transport of sediments and nutrient cycling. Upstream areas, such as headwaters or wetlands, help to regulate water quality downstream.[67]

- Lateral connectivity refers to the interactions between aquatic and terrestrial ecosystems, including deltas and floodplains. This encompasses the movement of materials, organisms and energy between landscapes and waterscapes, for instance via runoff, subsurface flows or anthropogenic drainage. It also includes fluxes such as the deposition of water, sediments and organisms in floodplains during overbank flooding.[68] [69]

- Vertical connectivity is vital for regulating climate and water cycles, describing interactions between groundwater systems, surface water, deep water and the atmosphere. This includes processes such as evapotranspiration, infiltration and precipitation,[70] as well as the interplay between groundwater and surface water, which affects water availability and soil moisture.[71]

FIGURE 3

This is a basic representation of the hydrological cycle and the various components of hydrological connectivity.



Human activities have significantly altered hydrological connectivity at local, regional and global scales.[72] Even minor alterations can have significant consequences for the health of ecosystems and landscapes.[73] Humans influence hydrological connectivity through activities such as extracting groundwater, building dams and channels, regulating water flow and developing floodplains and riparian areas.[74] [75]

Due to the complex nature of hydrological connectivity, changes to it can have both beneficial or detrimental impacts on the wider ecosystem depending on the landscape and flows under consideration. On the one hand, hydrologically connected habitats facilitate species dispersal and gene exchange, enhancing genetic diversity and species resilience to environmental stressors.[76] [77] In this instance, reduced connectivity can isolate populations and create genetic bottlenecks[78] with profound implications for human populations that depend on the natural functioning of such systems for food security (e.g. fisheries and nutrient deposition in floodplains), water quantity and quality (e.g. access to drinking water and irrigation), sanitation and other ecosystem services.[79] [80]

While hydrological connectivity offers important benefits for ecosystem health and resilience, it is also important to consider and manage potential downsides. Increased hydrological connectivity, for instance, can also facilitate the transport of pollutants, sediment and excess nutrients. For instance, degraded soils as well as urban infrastructure and sealed surfaces increase stormwater runoff, which can elevate nutrient levels in freshwater bodies,[81] [82] [83] contributing to eutrophication.[84] These changes in runoff patterns and volumes can have significant effects on soil integrity, vegetation production, seedling dispersal and establishment,[85] [86] which directly impact the ecological balance.[87] [88] [89]

Fluxes of Energy

Fluxes of energy, such as sunlight, wind and water, are another important aspect of ecological connectivity. Human activities that alter or obstruct these flows, increasing or decreasing them beyond their natural levels, can diminish the functional aspects of connectivity. The dispersal of seeds, pollen, spores and other propagules depends heavily on wind energy,[90] which plays an important role in determining the distribution and reproduction of species.[91] For instance, in a chronically deforested landscape in the United Kingdom, the seeds and pollen of the common ash (*Fraxinus excelsior*) are typically dispersed by wind over tens of kilometres, thereby contributing to genetic connectivity in a highly fragmented landscape.[92]

Other manifestations of energy fluxes in the environment may include the scouring of river sediments by hydraulic energy and changes in ocean currents that determine colonisation zones and migration pathways of organisms, from the largest to the smallest.[93] [94] Sunlight is fundamental to sustaining life on Earth. Obstructions that prevent light from reaching plant communities reducing photosynthesis can impact ecological connectivity. Vertical obstructions, such as trees and buildings, can lead to understorey vegetation receiving insufficient light, which suppresses plant growth and influences soil structure and microhabitats.[95] This can have consequences further along the food chain, impacting herbivores relying on understory plants and changing the behaviour and movement patterns of pollinators.[96] [97] Significant decreases in vegetative cover due to changes in land use can also influence heat fluxes, increasing land surface temperatures, creating thermal stress which affects the photosynthetic efficiency of plants.[98] Changes in vegetation also influence the radiative properties of surfaces, thereby affecting the energy balance and local climatic conditions.[99]

Population Connectivity

The exchange of genes, propagules and larvae, as well as the dispersal of individuals among populations, is referred to as population connectivity. This is relevant when assessing the health and productivity, as well as the genetic and evolutionary processes, of populations.[100] [101] One of the key aspects of population connectivity is its relationship to genetic diversity within populations,[102] which is crucial in the face of mounting environmental pressures.[103] Small, isolated populations can lead to the accumulation of harmful mutations and genetic erosion. Less genetically diverse species also tend to have considerably shorter lifespans than more diverse populations, often due to the negative effects of inbreeding.[104]

Range expansions can greatly improve the fitness of populations.[105] The structure of the landscape strongly affects the distances travelled by plant seeds, regardless of whether they are dispersed by abiotic factors, such as wind, or by animals. Any type of disturbance, such as habitat fragmentation or modification by invasive plant species, is likely to alter the patterns of seed movement and potentially affect the genetic structure of plant populations. Evidence shows that the loss of even a single animal species that assists in the long-

distance dispersal of seeds can significantly reduce plant population connectivity across large areas.[106] [107]

Communicative Transmissions

Collective systems, ranging from multicellular organisms to social insect colonies, have evolved numerous mechanisms for sharing information. Examples include the waggle dance of honey bees, which is used to communicate the location of food sources, and the use of hormones by plant cells to communicate environmental stressors, such as drought.[108]

In underground networks, plant roots, bacteria and fungal mycelium interact with each other, delivering chemical signals and information[109] that support a mutually sustaining relationship between plants and fungi.[110] With an estimated five billion tonnes of carbon passing from plants to fungi annually below ground, it is clear that these networks are vital for life on the surface.[111] This type of connectivity within the soil is essential for healthy plant communities, yet it is vulnerable to threats from human-induced soil disturbances, such as tillage, drainage, compaction, deforestation and the use of inputs that alter soil chemistry.[112] Interrupting these forms of connectivity could have unforeseen consequences for the ecological fitness and evolutionary trajectory of many communities of organisms.

Volatile organic compounds (VOCs) play a crucial role in plant communication and interactions with their environment, including protection against abiotic and biotic stressors (e.g. herbivores, pathogens and competitors) and the capacity to attract pollinators, seed dispersers, beneficial microbes and predators/parasitoids.[113] [114] Pheromones are another chemical signal that influences the behaviour and population dynamics of plants and animals.[115] This type of connectivity can be affected by physical obstructions and discontinuities as well as noise and light pollution.

Science continues to make new discoveries about the variety of communication methods exhibited by non-human life forms. Unimpeded sound transmission through air, water or ground is important for animal communication, informing social behaviours, territorial integrity and echolocation of food.[116] Recent studies have investigated the potential of broadcasting soundscapes to support the restoration of disturbed areas by encouraging recolonisation by animals, microbes and propagules.[117]

Movement of Species

Unimpeded movement refers to the ability of species to move freely from place to place on land, in water and in the air. This allows them to access resources such as food, water, shelter and mates for reproduction. This type of connectivity plays a key role in the resilience and adaptation of species to climate change, as it enables plant and animal species to follow shifts in the range of climatically favourable environments.[118] Depending on the species, animal movements can influence the landscape they cross and facilitate many functions, such as pollination, seed dispersal, pest control and maintaining the openness of forest canopies, among others.[119]

Ecological connectivity facilitates and maintains these movements, which take place across spatial and temporal scales (daily, seasonal, annual, multi-generational or evolutionary), including:

- **Daily movements** during the day or night, which allow for roaming and travel among relatively close sites for the purpose of locating resources and carrying out daily activities. For instance, eastern grey squirrels (*Sciurus carolinensis*) forage among nearby trees and ground surfaces to collect nuts and seeds. These movement patterns are often influenced by environmental factors, such as the availability of food and the structure of the habitat.[120]

- **Dispersal movements**, unlike migration, usually involve a one-way relocation to an area with more suitable conditions.[121] Dandelion (*Taraxacum officinale*), for example, use the wind to disperse their seeds and spread to new areas.[122] Dispersal movements are crucial for maintaining genetic diversity within populations, reducing the risk of extinction due to genetic isolation or inbreeding, overcoming competition and shortages of breeding individuals and enabling species to colonise new habitats.[123]

- **Migratory movements** include cyclical and seasonal migrations. For example, the annual migration of blue wildebeest (*Connochaetes taurinus*) in East Africa is in response to seasonal rainfall patterns and the availability of resources as they search for fresh grazing grounds. Migratory animals move across space and time, connecting continents, oceans, countries, habitats and sites as they do so.

Their migrations are often regular and predictable within the annual cycle. The survival of migratory species is closely linked to their ability to migrate, which depends on their access to suitable sites and habitats along their migratory route.

Many of these migrations are disappearing at an alarming rate, primarily due to infrastructure development and the construction of fences and other barriers in areas experiencing high levels of human-wildlife conflict.[124] [125] While fences threaten all ecosystems, dryland systems are particularly vulnerable to their negative impacts because they cause significant reductions in wildlife movement, affecting the ecosystem's capacity to respond to unpredictable rainfall patterns.[126] For birds that fly long distances twice a year between breeding and non-breeding sites, the removal of any key staging sites can lead to population collapse.

Migratory Movement of Monarch Butterflies

Monarch butterflies play a vital role in North American grassland ecosystems. As they migrate across vast distances, they pollinate wildflowers and provide food for birds, insects and small animals.[127] Every year, they migrate to California, Mexico and Florida to overwinter before returning north in spring and summer to breed. However, their habitats are under increasing threat. Deforestation is shrinking their overwintering habitats, while the loss of native grasslands and the intensification of agriculture, coupled with pesticide use, are reducing the number of nectar-producing plants and milkweed, which are essential for feeding and breeding.[128] In order to avoid extinction, habitats are being restored along Monarch migration corridors. This involves maintaining sufficient milkweed in breeding areas and preserving forested overwintering sites. It also involves creating stepping stones of feeding habitat to ensure continuous access to nectar-producing plants during their long migrations.[129] Focusing on habitat connectivity means that even small patches of habitat restoration, placed strategically, can significantly reduce the risk of Monarch extinction.

- **Long-term geographic shifts in population range** over multiple generations are often caused by external factors, such as changing environmental conditions and human pressures.[130] [131] One example is the American pika (*Ochotona princeps*), which is losing its alpine habitat due to global warming and is increasingly moving to higher elevations as temperatures rise. Over generations, these slow shifts in range can significantly alter the distribution of species and the composition of ecosystems.[132]

Migratory Connectivity

Migratory connectivity is a special type of ecological connectivity. It can be broadly understood as the spatial and temporal linkages of individuals and populations between seasons or different stages of their migration cycles.[133]

While ecological connectivity generally refers to the ease of movement across geographical areas, with easier movement indicating stronger connectivity, migratory connectivity refers to the retention of population structure in areas where individuals spend different parts of their annual life cycle and the effect of conditions and events in one area on populations in another.[134] [135] It therefore focuses on how processes and events occurring in one geographical area are transmitted to a physically distant location through the migration of individuals and their associations. Migratory connectivity is 'strong' when individuals stay together in an area and collectively migrate to a wintering area, and 'weak' when they are spread among many different areas.[136]

Understanding migratory connectivity patterns is essential for assessing individual behaviours, population dynamics and the evolution of migratory populations.[137] Consideration of migratory connectivity is essential for conservation and management plans, including species recovery programmes, integrated land use planning and the development of networks of protected areas and other effective area-based conservation measures.[138]

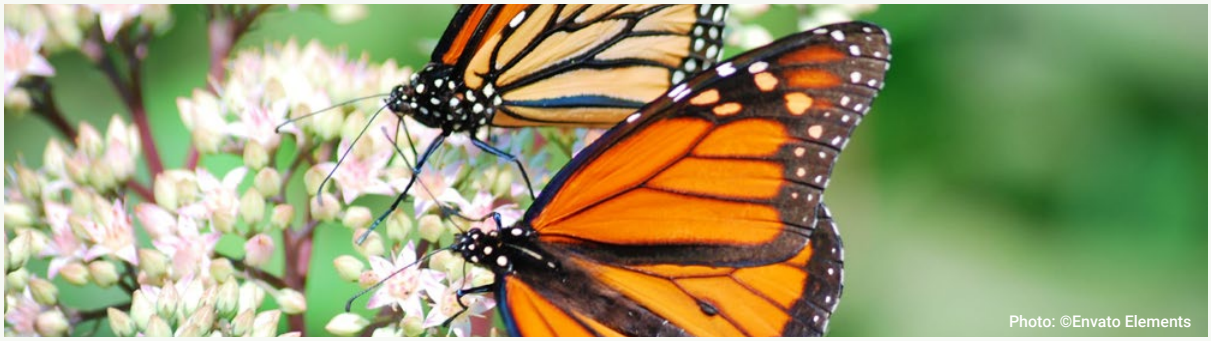


Photo: ©Envato Elements

Climate Connectivity

From a species perspective, ecological connectivity enables them to shift their ranges in search of more favourable climates.[139] [140] For example, wetter and warmer winters have made some historically important breeding and wintering areas unsuitable for migratory birds, which have instead chosen to 'short stop', ending their migration closer to their breeding grounds rather than continuing to their former wintering areas. Affected populations are forced to change their migration times and/or destinations to maintain their migratory cycle.[141] The ability of a landscape to promote or hinder species movement and ecological flows in response to a changing climate is referred to as climate connectivity.[142]

Strengthening ecological connectivity facilitates the dispersal and colonisation of species when their distribution changes, thereby increasing their resilience to climate change.[143] As part of a larger effort to make protected areas climate resilient, Mexico has identified key biodiversity areas and proposed climate corridors as key connectivity routes that allow species to move between habitat fragments while avoiding major human disturbances, thereby helping flora and fauna track suitable climatic conditions under global change. They have developed a framework for a participatory approach to the development of climate corridors.[144] [145]

2.2

Causes and Consequences of Connectivity Loss

Human activities have altered landscapes to an unprecedented degree, often resulting in the creation of new ecosystems.[146] [147] These landscapes and ecosystems are becoming increasingly fragmented, which erodes natural processes and contributes to the loss of ecological connectivity.[148] [149]

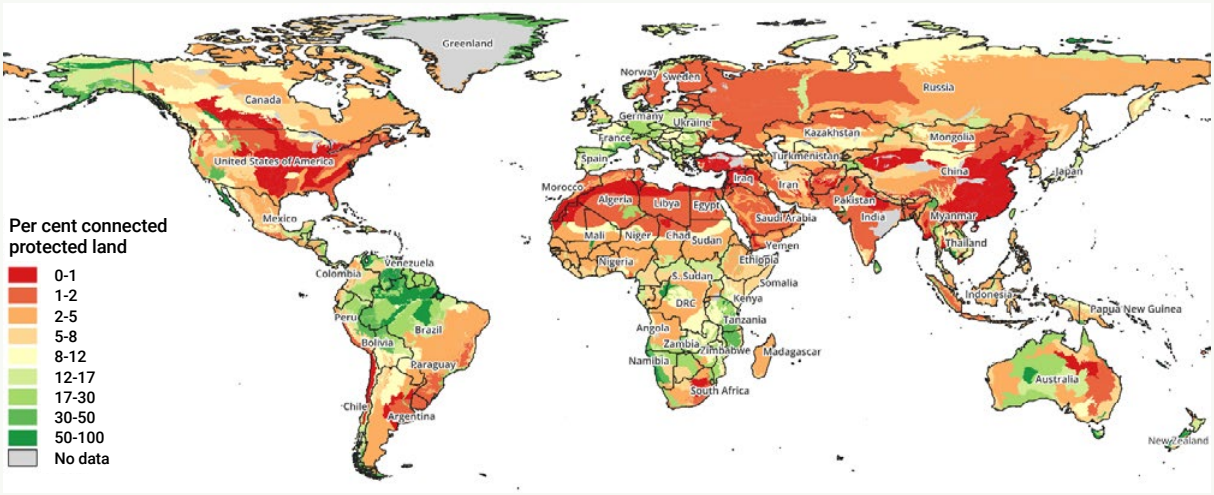
Changes in land, freshwater and sea use, as well as the exploitation of natural resources, have been the dominant drivers of ecological fragmentation in recent decades, often exacerbated by climate change. Other important drivers include pollution, alien and invasive species,[150] [151] [152] urbanisation and the expansion of human development,[153] including energy, water and transportation infrastructure. These factors have had a significant impact on ecosystems and the services they provide.[154] However, not all ecosystems are affected equally by these drivers. Tropical forests, for instance, are being converted into agricultural land much faster than other ecosystems.[155]

Agriculture and Forestry

The demand for agricultural and forestry commodities is increasing due to population growth and economic development.[156] Current short-term management practices can enhance provisioning services, such as food and timber production, while reducing regulating and supporting services that undermine connectivity and biodiversity.[157] [158]

FIGURE 3

One way of measuring the connectivity of protected area systems is by using the Protected Connected (ProtConn) Index, (Saura et al. 2017), which is available on the European Commission's (EC) Joint Research Centre's (JRC) Digital Observatory for Protected Areas (DOPA). It assesses the percentage of an area covered by connected protected lands, and it is computed and available at the level of countries and terrestrial ecoregions.[703]



Poor land management, deforestation, cultivating marginal land and using agricultural chemicals can affect ecosystems and landscape level processes in various ways:

1. Production landscapes tend to have lower overall plant biomass.
2. Important resources required by some species, such as fruit, seeds, insects, pollinators, detritus, nectar and fungi, are no longer available.
3. Habitats become fragmented, which has a disproportionate effect on small organisms with lower dispersal abilities.
4. Land use change alters the local climate.
5. Land conversion for agriculture leads to the expansion of linear transport and energy infrastructure, which drives further fragmentation and opens new areas up to exploitative land uses, such as unsustainable timber harvesting or hunting.
6. Lower plant biomass, exposed soils and agricultural chemicals can lead to soil erosion and acidification, which compromises hydrological and biological functioning.[159]
7. Irrigation can lead to the salinisation of soils, leaving them degraded and unproductive.[160]
8. Grazing beyond the carrying capacity of rangelands can lead to a decline in land health and productivity in the medium to long term.[161]
9. Drylands are particularly vulnerable to overcultivation and overstocking which, when coupled with drought, can lead to more exposed soils. This creates a negative spiral where rainfall is reduced as a result of increased bare ground and vegetation declines.[162] [163]

These human factors can have a significant impact on ecological connectivity. Healthy soil processes play a vital role in carbon storage, net primary productivity and plant growth. Degraded soils often have reduced organic matter content and infiltration capacity,[164] as well as lower diversity and abundance of soil biota.[165] Low organic matter and nutrient content weakens soil structure, which affects water retention and infiltration.[166] Reduced soil microbial activity affects nutrient cycling and other biophysical processes, resulting in isolated patches of vegetation. This further fragments landscapes and limits the ability of organisms to move, thrive and reproduce within connected ecological networks.[167] [168]

Reduced vegetation cover also impacts the ability of ecosystems to retain and distribute water effectively, disrupting hydrological connectivity.[169] The loss of soil due to wind and water erosion, as well as diminished infiltration capacity, can further alter hydrological connectivity by increasing water runoff and decreasing groundwater recharge. Crusted or compacted soils further exacerbate runoff, which can increase peak flows and contribute to flooding.[170] [171]

The intensification and expansion of agriculture disproportionately impacts specific functional groups, with the highest losses typically occurring at the highest trophic levels. This can lead to the restructuring of ecological communities, which has considerable effects on the functioning and structure of ecosystems. For instance, large carnivores play a vital role in regulating populations of species at lower trophic levels, while large herbivores mitigate the risk of human diseases carried by rodents.[172] The loss of certain functional groups can result in shifts in species composition, with non-native or colonising species replacing endemic ones.[173] In highly degraded and fragmented agricultural landscapes, reduced seed dispersal impacts plant populations and community persistence.[174] These drastic changes often have legacy or biotic lag effects on biodiversity, including ecological memory effects, colonisation credit and extinction debt, whereby changes in ecosystems and ecological connectivity are not immediately evident. [175]

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Urbanisation

Urbanisation can introduce drastic changes to both structural and functional connectivity. Unregulated and unplanned urban and peri-urban expansion is driving land use change in many countries around the world. The size of urban areas has increased from 33 million hectares in 1992 to 71 million hectares in 2015.[176] Around one third of the global urban population live in informal settlements.[177] These areas often lack secure tenure and access to basic services, making them highly vulnerable to environmental risks, including droughts, floods, landslides, water scarcity, pollution and ecosystem degradation.[178] [179] [180]

Due to their high demand for food, water and other natural resources, urban areas are highly dependent on goods and services from rural areas. The pollution generated by cities, largely due to poor waste management, can have a considerable impact beyond their borders.[181] These urban-rural linkages can lead to land degradation in rural areas, the creation of exurban residential areas and new transport and communication structures to facilitate these connections.[182] Barriers such as buildings, roads and walls and fences pose a particular challenge to ecological connectivity, especially for mammals, in both urban and rural areas.[183] The predominance of impervious surfaces in urban environments, such as asphalt and concrete, causes ambient and surface temperatures in cities to be higher than in surrounding rural areas. This phenomenon is known as the 'heat island effect'.[184]

Urban areas can have positive or negative impacts on species movement. Some highly adaptable species can thrive in urban environments, showing increased mobility and gene flows.[185] In contrast, species with more specific habitat requirements experience significant movement barriers[186] [187] and genetic isolation, resulting in reduced genetic diversity and increased inbreeding.[188] Furthermore, some studies have indicated that human disturbance at the urban-rural interface, for instance in the form of hunting or recreation, can have a greater adverse impact on animal movement than habitat modification.[189]

Impermeable surfaces[190] and the construction of channels and other structures alongside urban rivers and other bodies of water can affect hydrological connectivity, limiting the movement of water and aquatic species and disrupting their reproductive and feeding behaviours.[191] Urbanisation can also alter energy flow dynamics and disrupt natural energy transfer processes.[192] Higher temperatures in cities compared to the surrounding areas influence evaporation and rainfall patterns (hydrological connectivity),[193] act as a barrier to species movement, impede genetic exchanges (population connectivity) and disrupt traditional migratory routes and timings.[194] Finally, artificial lighting, higher ambient temperatures and reflective surfaces – such as windows –[195] found in urban areas can mislead wildlife, disrupting their natural behaviours and turning these areas into ecological traps. Many species use natural light cues for navigation and foraging. Urban lights can attract some species to these areas, where they face a higher risk of predation and mortality.[196] Reflective surfaces can mimic bodies of water, leading them into inhospitable environments with a lack of resources.[197] Increased pollution, road traffic and noise disturbance in urban areas also contribute to habitat degradation.[198]

Photo: ©Nelemson Guevara

Infrastructure Development

The **transport sector** plays a vital role in the global economy and is essential for economic development.[199] Linear infrastructure, such as railways, roads, canals, pipelines, walls and fences, is being constructed at a record rate in previously undeveloped areas, particularly in tropical regions. It is expected that around 25 million kilometres of new roads will be constructed across the world by 2050, 90% of which will be in developing countries.[200] This will lead to land degradation, deforestation and fragmentation through direct land clearing for infrastructure as well as indirectly by attracting settlements, agriculture and secondary road development (creating what is known as the 'fishbone effect'[201]). This increased accessibility to natural or protected areas can lead to increased poaching[202] and can impact the livelihoods of those who directly depend on forest resources.[203] [204] The stabilisation of rivers through levees and pinch points to allow for transportation and utility crossings leads to 'structural starvation', eroding the health and complexity of river ecosystems.[205]

Photo: ©Antony Trivet

Perceived Environmental Impact of the Kenya Standard Gauge Railway (SGR) [206]

The Kenya Standard Gauge Railway (SGR) is an ambitious transport infrastructure project that forms part of Kenya's Vision 2030. It is also part of a broader plan to revitalise and connect the Eastern African SGR network, which extends from Tanzania and Kenya to Uganda, Burundi, Rwanda, Ethiopia and South Sudan. Construction of the first two phases in Kenya began in 2014 with the building of a railway line through eight counties from Mombasa to Narok. Several safety protection measures were installed along the SGR, including speed limits, safety buffers, earth embankments, fencing, underpasses, bridges, flyovers and culverts, particularly in areas with high human and wildlife population densities. Additionally, a noise barrier was installed within Nairobi National Park.

Following the completion of these phases, a study assessed the perceptions of local communities, the government and civil society actors. Despite the protection measures, these stakeholders reported negative ecological effects, highlighting the importance of considering socio-ecological connectivity. They were particularly concerned about ecosystem degradation caused by soil, water and air contamination. In Tsavo National Park, some of the underpasses were used by local communities to graze livestock, leading to considerable soil degradation in some areas. Community Forest Associations observed that sediment eroded from the rail embankments blocked streams and reduced their size in Kilindini, affecting the development and germination of mangrove seeds along the coast. In Narok County, the underpasses caused gulley erosion and sediment transport blocked rivers, leading to the siltation of Lake Magadi. Some also reported the spread of invasive alien plants along the SGR corridor, as well as the reappearance of invasive plants due to soil disturbance during construction. They were also concerned about the fragmentation of ecosystems. Underpasses created to support wildlife movement were blocked by illegal settlers and converted for agricultural use. They believed that the traffic noise made the wildlife more aggressive and that human-wildlife conflict intensified as the animals moved away from the railway line and roads towards human settlements. Quarrying and construction also removed considerable vegetation and forest cover.

Transport infrastructure development can have various impacts on ecological connectivity, that can be avoided or at least mitigated when well-planned. For example, roads and bridges alter natural water flows, disrupting the hydrological connectivity of rivers and streams and affecting the distribution of water with

significant socio-economic impacts on human and animal communities that depend on these resources.[207] Railways and roads can act as barriers to species movement, influencing genetic flow and population stability or causing wildlife-vehicle collisions.[208] [209] Although transport infrastructure is a major cause of landscape fragmentation, the surrounding areas can still support connectivity by promoting new movement and dispersal patterns for various species, including plants, pollinators and small mammals, which can improve habitat connectivity at local scales.[210] [211] Transport networks can also enhance socio-ecological connectivity, facilitating positive human interactions with the environment and supporting the effective sharing of ecological resources and knowledge. At the same time, this enhanced connectivity created by transport infrastructure can contribute to the spread of invasive species[212] and parasites or pathogens, which affects both ecosystem and human health.[213]

Water infrastructure, such as dams, reservoirs and other diversions, impacts flow regimes, leading to the degradation of freshwater ecosystems and the associated decline of habitats and species. These structural transformations disrupt both longitudinal and lateral connectivity.[214] Almost 60% of the world's rivers are already divided into sections by dam projects, which have a negative impact on 93% of natural river flows in terms of volume. This considerably affects the ecological functioning of river basins, with devastating consequences for communities that depend on these natural resources for their livelihoods. For instance, in the Amazon basin, freshwater connectivity contributes around US$200 million to the fishing sector annually and provides employment for 200,000 fisher folk.[215]

Furthermore, extracting groundwater and redirecting surface water for human use can reduce overall water storage in aquifers and stream baseflows. This alters groundwater regimes and the vertical connectivity between groundwater and surface water availability. This can reduce river flows, increase the duration and frequency of low baseflows and promote land subsidence.[216] It can also contribute to the pollution of watercourses. Any infrastructure that alters natural flow regimes can result in river basins drying up and the loss of wetlands, leaving local communities vulnerable to droughts and floods. [217] [218]

The Impact of Damming on the Mekong River

The Mekong River is home to the world's largest inland fishery[219], which is valued at an estimated US$17 billion each year.[220] It provides income to nearly two-thirds of households in the Lower Mekong Basin[221] and accounts for more than half of the animal protein consumed in the region.[222] The health of the Mekong fishery sector depends on connectivity. Of the 899 recorded fish species in the basin, over one-third are migratory.[223] One migration route, between the Tonle Sap Lake nursery and the main stem of the river, is home to one of the largest annual animal migrations on Earth.[224]

As well as supporting fisheries, the river carries vast quantities of nutrients and sediment downstream each year. This provides the foundation for productive agriculture in one of the world's most fertile deltas.[225] However, the construction of dams and other river barriers for hydropower and irrigation in recent decades has increasingly disrupted the river's natural functions.[226] These structures impede the flow of sediment and nutrients, resulting in the loss of farmland in the Mekong Delta. They also fragment the river system, disrupting migratory pathways and altering the natural flood cycle, which is essential for fish reproduction and maintaining habitat.[227]

These changes have contributed to a significant decrease in fish populations. For example, fish stocks in Tonle Sap Lake dropped by 88 per cent between 2003 and 2019.[228] One study suggested that a reduction in wild-capture fisheries by 50 per cent would necessitate replacing them with more resource-intensive sources of protein, such as farmed fish, beef and pork. This would lead to dramatically higher greenhouse gas emissions, water pollution and land use changes.[229] In Lao PDR, declining fish catches have already forced many fishermen to adopt unsustainable agricultural practices, accelerating land conversion and environmental degradation.[230]


Photo: ©Galyna Andrushko

Energy infrastructure is expanding exponentially as societies transition away from fossil fuels to cleaner, renewable energy systems. In order to achieve emission reduction targets, the development of renewable energy sources, especially solar and wind, and their required infrastructure is accelerating worldwide. However, negative impacts include habitat loss due to land clearance; electrocution and turbine blade collision mortality; and vibration, noise, light and dust pollution.[231]

Large-scale wind, hydropower and solar plants can fragment the landscape, disrupting ecological continuity and having a cumulative impact on species populations.[232] Hydropower can alter the natural flow of rivers, reducing the size and fertility of floodplains and affecting downstream habitats.[233] Dams can also influence stream temperatures, thereby affecting habitat availability.[234] The water required for many renewable technology systems can contribute to the overexploitation of water resources, impacting freshwater availability and hydrology in arid areas.[235] [236]

The electromagnetic radiation emitted by electricity transmission infrastructure can interfere with animal reproduction, migration and plant growth.[237] Additionally, many renewable energy technologies, such as large-scale concentrated solar power plants and bioenergy crops, require significant land areas that cannot usually be used for other purposes.[238] This can disrupt landscape patterns on a large scale, fragmenting habitats, disrupting ecological corridors and impeding the movement of species and the flow of genetic material.[239] Ground-mounted photovoltaic solar sites, for example, have been found to alter the flight paths of bats and fragment their habitat.[240] Energy infrastructure can also disrupt migratory behaviour by prolonging migration distances or distracting species from their natural routes.[241]

Renewable energy infrastructure can have both positive and negative impacts on socio-ecological connectivity. For example, it can reduce carbon emissions, improve economic opportunities and diversify livelihoods. However, it can also lead to conflicts over resource allocation and land use, particularly in areas where communities depend heavily on natural resources for their livelihoods.[242] [243] [244]

Grasslands under Threat: Energy Development in the Great Plains of the United States [245] [246]

The grassland states of the United States are an important source of energy, providing coal, natural gas, oil and wind power. Seven of the 12 US states that produced more energy than they consumed are located within the Great Plains. Although coal production has declined, the development of natural gas and renewable energy increased, particularly wind power generated by over 42,300 turbines. This has had a significant impact on the grassland ecosystem. Energy production, together with the required infrastructure — such as roads, pipelines, electricity transmission and distribution lines— has led to direct habitat loss. While surface coal mines cause significant disturbance over several hundred hectares, the main reason for large-scale grassland conversion was biofuel production. Federal subsidies encouraged the conversion of 526,000 hectares in Iowa, Minnesota, Nebraska and South Dakota, which considerably reduced the nesting habitat of grassland birds and honeybees. The conversion of smaller areas, when considered cumulatively, had significant regional impacts. For instance, converting 3 million hectares of land for oil and gas development between 2000 and 2012 reduced dry biomass by 10 billion kilograms across central North America. The resulting fragmentation of the landscape negatively affects seed dispersal and animal movement, threatening genetic diversity, population connectivity and viability. Furthermore, studies on the prairie chicken (*Tympanuchus pallidicinctus*) have observed behavioural changes within 8 km of wind turbines.

Energy production in the Great Plains grasslands can also impact aquatic ecosystems. Waste products from energy production, such as the toxic chemicals used for hydraulic fracturing, as well as ice melters, dust suppressants and soil stabilisers applied to roads, can have a significant effect on soil and water resources. Soil disturbance can also lead to sediment pollution in streams and wetlands. Grassland ecosystems rely on vegetation to prevent soil erosion. The construction of roads to expand energy infrastructure can lead to significant soil erosion, altering nutrient cycling and creating opportunities for early successional plant species that thrive in disturbed soil. Many of these species in the Great Plains are non-native and the loss of native vegetation can have a snowball effect on soil biological communities, insects and wildlife. The recovery of many grasslands in the Great Plains is expected to take many decades.

Climate Change

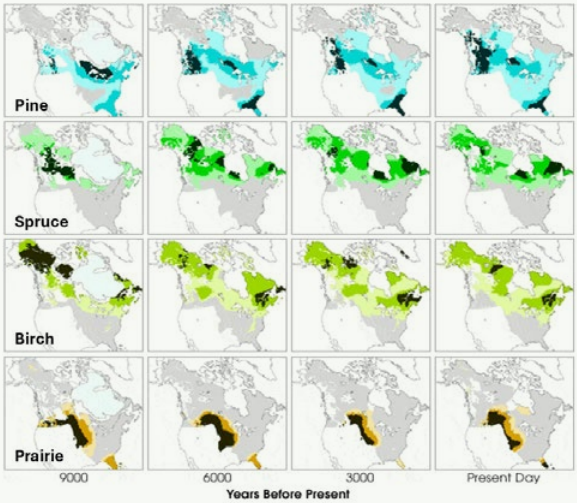
Climate change is the most intensifying threat to global biodiversity.[247] Rising temperatures, droughts, changes in rainfall patterns and natural fire regimes, phenological shifts and other impacts caused or exacerbated by climate change require a range of adaptation strategies from humans and other species, [248] which can be supported by ecological connectivity.

Many terrestrial, freshwater, coastal and marine species have already begun to alter their geographic ranges, seasonal rhythms and migration patterns in response to ongoing environmental change.[249] Similar considerations apply to plant species. Although plants are sedentary, vegetation ranges tend to shift due to changes in climate, with some species capable of colonising areas considerably distant from their original habitats (Figure 4).[250] However, plant migration can be significantly constrained by the loss of suitable habitats for colonisation and by dispersal barriers. If this kind of reduced connectivity impedes species' ability to migrate and escape the consequences of climate change, they may ultimately become extinct.[251]

Fire is an important component of many ecosystems. However, changes in fire seasonality, intensity or frequency, can alter vegetation structures and the provision of ecosystem services. The frequency of wildfires is expected to increase with climate change.

FIGURE 4

The geographic range and abundance of boreal tree and plant species in North America has changed from 9,000 years ago until now. Increasing colour intensity indicates an increase in pollen concentration, suggesting that southern pine species have migrated towards the southeast, while spruce and birch have migrated north. © Earth Observatory, NASA[704]



More frequent fires can considerably alter landscapes and encourage the growth of non-native, fire-tolerant species, creating faster fire cycles and causing native species to decline.[252] [253] Modified vegetation cover also affects water cycles and hydrological connectivity. Intense fires can degrade soils and increase runoff, disrupting infiltration and reducing the land's ability to absorb water.[254] While many species have adapted to natural fire regimes, abrupt changes can lead to habitat loss and fragmentation, which negatively impacts species movement and population connectivity by isolating populations and reducing gene flow.[255] [256]

The relationship between ecological connectivity, fire risk and other disturbances is complex and depends on the characteristics of the ecosystem. In fire-dependent ecosystems, ecological connectivity ensures that natural fire regimes support natural regeneration. However, in areas with high fuel loads, for example due to fire suppression, high connectivity can also lead to devastating and difficult-to-control wildfires that can threaten livelihoods and biodiversity.[257] [258] In highly fragmented landscapes, fire progression can be obstructed, further altering the landscape due to fire suppression.[259] Ecological connectivity is an important consideration when re-establishing vegetation and wildlife in post-fire environments.

Changes in precipitation and storm events will also impact hydrological connectivity.[260] In arid systems, changes in precipitation, including extreme weather events such as droughts, can alter river flow and morphology, weakening the connectivity between lakes and rivers. This can lead to the degradation of hydrological functions, water quality and essential ecosystem services.[261]

Invasive Species

Biological invasion is defined as *"the process of transporting (moving) and introducing a species outside of its natural range by human activities, either intentionally or unintentionally, to new regions where it may become established and spread"*.[262] This can involve non-native species introduced by humans to areas outside their natural range, as well as native species shifting their range without human involvement. For example, in southern Africa, mismanaged land, disrupted fire regimes, declining wild grazer and browser populations, livestock overgrazing and climate change have all led to native woody plants encroaching on the landscape.[263] [264] [265]

This has had considerable negative effects on the hydrology, soils,[266] biodiversity and livelihoods that are dependent on livestock farming and tourism.[267] [268]

Invasive species can quickly reduce ecological connectivity for native species. They may have different root structures and higher evapotranspiration rates than native species, resulting in different water uptake. This can influence soil moisture[269] and thus hydrological connectivity. Invasives can also restrict the growth of native plant species, thus reducing habitat availability for wildlife that relies on native plants and altering the structure of food webs.[270] Many invasive species are better at adapting to climate change than native plants.[271] [272] The presence of invasive species can drive extinction through predation, for example, of ground-nesting birds on islands, and negatively impact the recovery or re-establishment of native species following disturbance. Invasive species can also attract disturbance. For instance, introducing non-native grass species, such as cheatgrass (*Bromus tectorum*), can significantly increase fuel loads, thereby increasing the risk and intensity of fires when compared to native species. Cheatgrass's ability to thrive following fires ensures it outcompetes native flora that are not adapted to frequent fire disturbance.[273] [274] Invasive species present a particular management challenge for initiatives to enhance ecological connectivity, since more connected landscapes can also support the spread of invasive species.

The impact of invasive species on socio-ecological connectivity is more nuanced. On the one hand, they can provide ecosystem services, such as fodder, fuelwood or timber, as well as cultural services. However, they can also harm livelihoods and decrease the availability of important natural resources used by farms and households, thereby reducing their income and making them more vulnerable to environmental change. They can also impact human health and safety.[275]

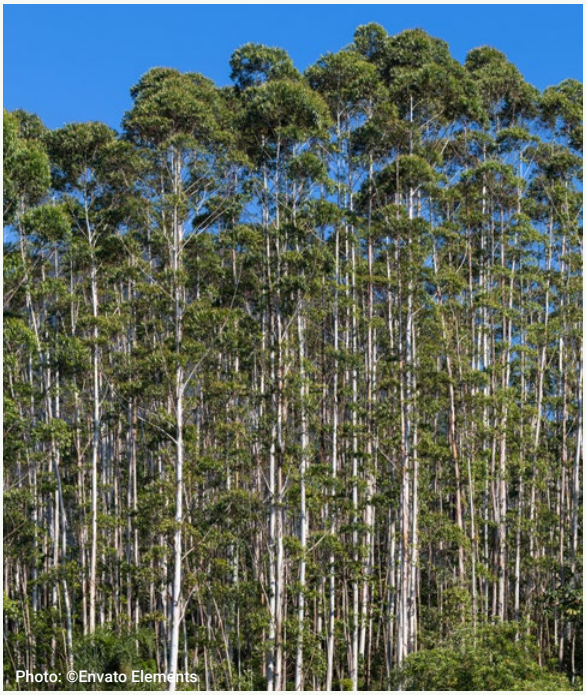


Photo: ©Envato Elements

The Cross-Ecosystem Impacts of Invasive Species [705]

A recent study assessed the impact of invasive species on ecosystems. Assuming that all ecosystems are connected and exchange living and non-living organisms (e.g. nutrients, chemicals and organic matter), the researchers identified three main pathways through which invasive species can have a cascading effect beyond the ecosystem they invade. These pathways are: (1) altering the magnitude of spatial flows, (2) altering the quality of spatial flows and (3) introducing new flows.

The authors used the example of the lake trout (*Salvelinus namaycush*) invading North American lakes to illustrate these cascading cross-ecosystem impacts altering the magnitude of spatial flows. The lake trout preys on the native Yellowstone cutthroat trout (*O. clarkii bouvieri*), which migrates around 50 km from lakes to rivers. This has considerably reduced the abundance of the native species and impacted nutrient cycles to the extent that it has drastically reduced river otter populations, which are important ecosystem engineers. The absence or reduced abundance of the native trout has also impacted food webs, with bears shifting their diet from 10% to 50% juvenile elk (*Cervus canadensis*).

To demonstrate the effect on spatial flow quality, the impact of Japanese knotweed (*Reynoutria japonica*) was compared with that of the invasive river red gum (*Eucalyptus camaldulensis*). Japanese knotweed has a low carbon-to-nitrogen ratio and structural content, resulting in higher leaf litter breakdown in freshwater ecosystems. This has a positive impact on food webs and community structures, species richness and the fitness and production of freshwater organisms. In contrast, the invasive river red gum tree has a much higher C:N and structural content, which reduces leaf breakdown and the richness and efficiency of streams, as well as the fitness and production of organisms.

One example of an invasive species creating novel flows is the *Melaleuca quinquenervia* plant, also known as the broad-leaved paperbark, which has displaced native plants in Florida, reducing the home range of Florida panthers (*Puma concolor coryi*) by 16%. Consequently, the panthers had to travel further in search of habitat and resources, establishing new connections between ecosystems.

Pollution and Contamination

Pollution is often a consequence of some of the other human activities mentioned above. For instance, urbanisation and the industrial and domestic activities that result from it are a significant source of pollution. Around 80% of wastewater is discharged into waterways without adequate prior treatment. Agriculture can also contribute to pollution in multiple ways, affecting the quality and connectivity of ecosystems. Increased nitrogen deposition can lead to the eutrophication of soils and water, impacting vegetation composition and faunal diversity. Furthermore, the widespread use of antibiotics and pesticides can influence various soil processes such as rainwater infiltration, the decomposition of organic matter and the activity of soil organisms. This reduces functional connectivity and impacts plant biodiversity.[276] [277] Spillages of oil and other contaminants, including mercury, plastics, metals and paper, resulting from industrial activities, mining, energy production and waste management can impact vegetation, terrestrial and aquatic biodiversity, as well as the quality of water, soil and air.[278]

Storks Transporting Pollutants between Morocco and Spain [706]

Enhanced connectivity can also contribute to pollution. White storks (*Ciconia ciconia*) are known opportunists, often foraging in landfills, where food is constantly accessible and requires little energy to obtain. A study analysing the movements of storks wintering in Morocco and Spain's Iberian Peninsula found that landfills were important nodes in the ecological connectivity of white storks. The storks then used wetlands or rice fields to rest, drink and forage further. This can lead to contaminants being transported by bio vectors into conservation areas. Landfills can be a source of antibiotic-resistant bacteria and genes, which can be distributed by storks. White storks can also ingest plastic, seeds and aquatic invertebrates, some of which can be invasive, and transport them to other terrestrial or aquatic habitats. The authors found a particularly high level of connectivity between landfills and saltpans, irrigated areas and rice fields in Southern Spain, which could also impact human health. The storks then moved from the rice fields to areas containing fish farms, marshes, ponds, dams and rivers, potentially spreading contaminants and pollutants further afield.

Contamination in freshwater systems reduces habitat quality and causes fragmentation, disrupting the movement and foraging efficiency of organisms.[279] [280] Polluted soils with heavy metals can limit their primary functions and cause bioaccumulation along the food chain, posing risks to humans and animals.[281] Light pollution can affect the behaviour of nocturnal migratory species that depend on dark environments for foraging, breeding and migration. This can lead to habitat fragmentation and reduced connectivity among and between populations.[282] For instance, bats, which play an important role in seed dispersal, have exhibited a notable decrease in activity in illuminated areas, resulting in adverse effects on forest regeneration and habitat connectivity.[283] The cumulative impacts of light pollution can affect the wider landscape by altering the behaviour of keystone species and ecological engineers, thereby altering habitat structure and ecosystem functions.[284] Similarly, noise pollution can impact ecological connectivity by influencing foraging behaviour,[285] pollination, seed dispersal,[286] animal communication[287] and causing animals to avoid certain habitats. [288]

As with the spread of invasive species, enhanced ecological connectivity can facilitate the spread of pollutants. For instance, increased surface runoff resulting from soil degradation and urbanisation can cause more sediments and nutrients to enter bodies of water and groundwater, thereby triggering eutrophication.[289]

Photo: ©Envato Elements

Human Conflict

The number of armed, state-based conflicts doubled between 2010 and 2020, with 82.4 million people being forcibly displaced in that time.[290] Human conflict has direct and indirect impacts on ecosystem functioning, land and biodiversity,[291] ranging from highly negative to highly positive. Positive effects mainly arise from the temporary suspension or disruption of intensive land uses, which can temporarily protect and regenerate land productivity. [292]

However, the negative environmental impact of war and conflict can be substantial. In 2022, the military accounted for 5.5% of global carbon emissions.[293] Conflict can also result in investments being redirected away from environmental causes,[294] thereby weakening conservation and other environmental programmes.[295] Furthermore, it can exacerbate the loss of biodiversity and connectivity by the sheer destruction of the landscape and the contaminated residue of war.[296]

The direct effects of conflict include the degradation of fertile land, the contamination of water sources and the destruction of forests. Removal of vegetation can encourage the growth of invasive species, which can have an impact on ecological connectivity. Munitions can pollute soil and water with hazardous chemicals and heavy metals, thereby affecting the environment and human health.[297] This can lead to large-scale land degradation and habitat destruction, disrupting broader ecological networks and influencing vegetation through changes in herbivory and predator–prey relationships. Conflict also has indirect effects on other ecosystems due to the displacement of people, leading to changes in land use in other areas and shifts in resource demand and exploitation, as well as increases in illegal resource extraction and poaching.[298]

Impacts of Colombia's Armed Conflict on Forests Conservation

In Colombia, unequal access to land and the government's failure to protect the rights of peasants lay at the heart of the 52-year-long armed conflict.[299] During this period, the FARC (Fuerzas Armadas Revolucionarias de Colombia) maintained control over large swathes of primary forest. These dense forests provided the guerrilla group with strategic protection and their presence prevented agribusiness and mining companies from entering the area. As violence escalated, many smallholder farmers also migrated away from FARC-controlled regions, abandoning large tracts of land. While some of these depopulated areas saw forests regrow, this was offset by conflict-related deforestation, particularly the clearing of land for timber, fuel and illicit crop cultivation.[300]

The 2016 peace agreement ended the conflict and resulted in the FARC's withdrawal from the forest. Although the agreement dedicates its first chapter to comprehensive rural land reform, it lacks provisions for forest conservation or governance. This meant that the conversion of forests into pasture land became profitable and was largely unchecked in regions with weak local governance.[301] The influx of large-scale ranchers further consolidated land ownership in the hands of the wealthy elite,[302] causing a sharp increase in deforestation and a decline in forest ecosystem connectivity between 2016 and 2021.[303]

Photo: ©Adobe Stock

3

Connect to Restore and Restore to Connect


Photo: ©Envato Elements

The 2019 global assessment report on biodiversity and ecosystem services, produced by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), showed that maintaining and restoring connectivity is essential for many ecological systems to function and provide ecosystem services.[304] Sustainable management and restoration of degraded land can reconnect fragmented ecosystems, improve key functions, reinforce natural processes and enable species movement.[305]

This chapter explores how sustainable land management and ecological connectivity can support each other to create healthier, more resilient ecosystems. First, it discusses the important role of land in addressing environmental and socio-economic challenges, before outlining how the sustainable management of land resources can support ecological connectivity and how considering ecological connectivity in sustainable land management can enhance restoration success.

3.1

Land at the Heart of Environmental and Socio-Economic Challenges

Land is a fundamental asset and a source of income, food security, livelihoods, shelter and cultural identity.[306] Healthy, functioning ecosystems are essential for life on Earth, yet they are increasingly being degraded due to profit-driven, short-sighted exploitation by humans.[307]

Parties reporting under the UNCCD estimate that one out of every five hectares of land globally is degraded, affecting approximately 3.2 billion people worldwide, with a disproportionate impact on vulnerable groups. Land Degradation Neutrality (LDN), enshrined in SDG target 15.3, is a concept designed to enhance and maintain the land resource base, striving for no netloss of healthy and productive land.[308] [309]

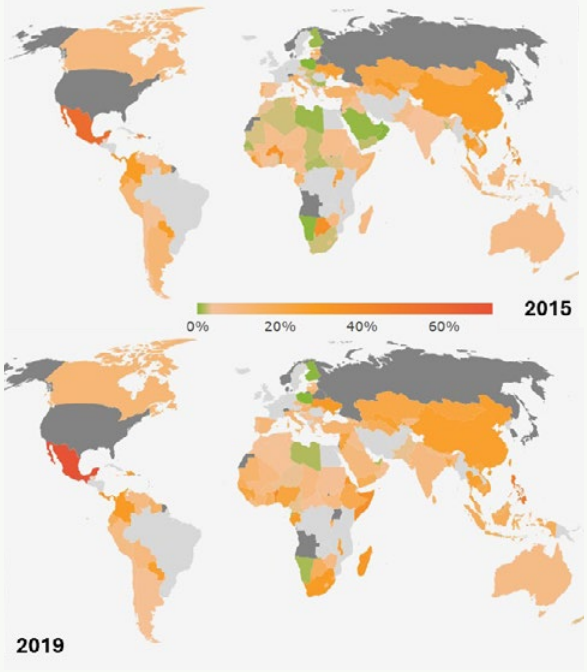

Photo: ©Envato Elements

Land degradation is defined as *"the reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from a combination of pressures, including land use and management practices."*[707]

Land Degradation Neutrality (LDN) is defined as *"a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and to enhance food security, remain stable or increase within specified temporal and spatial scales and ecosystems."*[310] LDN starts from the premise that land is limited and thus interventions in each land type should ensure, at a minimum, no net loss into the future.[311] [312] According to the LDN response hierarchy — an overarching framework designed to guide decision-makers in planning measures to achieve LDN — interventions should be targeted at avoiding, reducing and reversing land degradation in order to improve land-based natural capital.[313]

FIGURE 5

The proportion of degraded land over the total land area was reported by the Parties to the UNCCD. Data was generated by 120 countries. For the remaining 47 countries, the UNCCD generated estimates based on default data, with the respective countries' permission to publish the data. Permission to generate data based on default data was not granted for countries in dark grey.[314]



The ability to tackle multiple, overlapping global crises, including soil erosion, climate change, food insecurity, water scarcity and biodiversity loss, will largely depend on the trajectory of decisions made regarding land use and management practices.[315] [316]

3.2

Sustainable Land Management and Restoration for Enhanced Connectivity

Sustainable management and restoration of degraded land can enhance its functioning, improve connectivity and contribute to the recovery of its ecological integrity.

According to the World Overview of Conservation Approaches and Technologies (WOCAT) **sustainable land management** is defined as *"the use of land resources including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and ensuring their environmental functions."* Sustainable land management approaches can avoid degradation in natural ecosystems, reduce degradation on managed land and contribute to reversing past degradation.[317]

In line with the UNCCD's Global Land Outlook and the UN Decade on Ecosystem Restoration, this report defines **land restoration** broadly as a *"continuum of activities that avoid, reduce and reverse land degradation with the explicit objective of meeting human needs and improving biosphere stewardship. The priority is to avoid degradation by eliminating the drivers and expanding conservation and protected areas; reduce degradation through the adoption of sustainable land and water management practices in production landscapes; and reverse degradation through the passive or active restoration of biodiversity and ecosystem functions. Restoration activities, tailored to local conditions and societal choices, aim to regenerate natural capital for the benefit of human health and livelihoods, environmental and planetary resilience as well as to promote greater equity, social justice and shared prosperity."*[318]

Sustainable land management contributes to enhanced ecological connectivity by:

1. **Restoring soil and hydrological connectivity.** Healthy soil provides the basis for many ecosystem services. For example, soil microbes play a key role in biochemical cycling and influence many processes that regulate plant diversity and productivity,[319] and thus the functioning and response of terrestrial ecosystems to global change.[320] Sustainable land management and restoration can also contribute to hydrological connectivity by enhancing water retention and soil stability and by reconnecting natural water cycles.[321] [322]

2. **Large-scale land restoration can strengthen climate resilience.** Restoring and sustainably managing land can help species migrate and persist in a changing environment, as well as strengthen the resilience of humans and their livelihoods.[323] It also enhances carbon storage.

3. **Using existing land more efficiently and reducing the need for land conversion.** Taking a sustainable and restorative approach to land management can enhance land productivity and prevent the clearing and degradation of new areas and intact ecosystems,[324] which can further disrupt ecological connectivity.

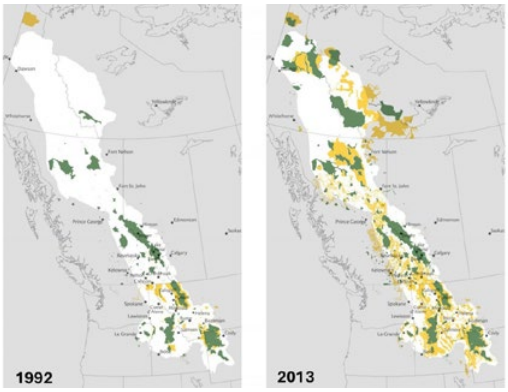
4. **Reconnecting fragmented habitats and ecological corridors.** Sustainable land management and restoration can contribute to the rebuilding of ecological corridors and stepping stone habitats, preventing further degradation and fragmentation. In the case of birds, these attributes can provide staging sites for migratory movements.[325] [326]


Photo: ©Galyna Andrushko

Restore to Connect - The Yellowstone to Yukon Initiative

The Yellowstone to Yukon Initiative (Y2Y) is one of the world's longest-running and largest landscape restoration projects. For over 30 years, Y2Y has worked alongside local communities to restore and conserve ecosystem functions across a 3,400 km stretch of the Rocky Mountains. Unlike earlier fortress conservation models, Y2Y focuses on establishing inclusive governance processes and long-term partnerships with local stakeholders, particularly First Nations communities.[327]

As its name suggests, ecological connectivity lies at the heart of the initiative's mission. To advance this goal, Y2Y has acquired land for conservation purposes and collaborated with landowners to restore habitats on private land. Consequently, the area of formally protected land within the region has increased by 80 per cent, alongside significant gains in other types of conserved land. With funding from various foundations, corporations and government agencies, the initiative has treated hundreds of acres for invasive plant species, replanted sections of disused roads, restored riparian vegetation and constructed 177 wildlife over- and under-passes to facilitate species movement.[328] These interventions have reduced wildlife-vehicle collisions by over 90 per cent[329] and contributed to the increased population and range of grizzly bears and gray wolves, both of which are endangered keystone species.[330] At the same time, its inclusive governance approach has fostered greater social connectivity and knowledge sharing among stakeholders.[331]



Increases in protected areas (green) and other conservation areas (yellow) in North America as a result of the Yellowstone to Yukon Initiative.[332]

3.3

Ecological Connectivity Delivers Multiple Benefits

Ecological connectivity can contribute to avoiding, reducing and reversing land degradation. Understanding and managing the integrity of land-based connectivity is central to land use planning and management decisions, recognising the suite of benefits that accrue from a fully functioning ecosystem.[333] [334] Ecological connectivity can contribute to sustainable land management and restoration in the following ways:

1. **Supporting ecosystem stability and recovery.** Connected ecosystems are considerably more resilient to shocks and environmental stressors.[335] The complete recovery of social-ecological systems requires species and abiotic processes to persist in order to support natural regeneration, which is considerably enhanced by ecological connectivity.[336] [337]

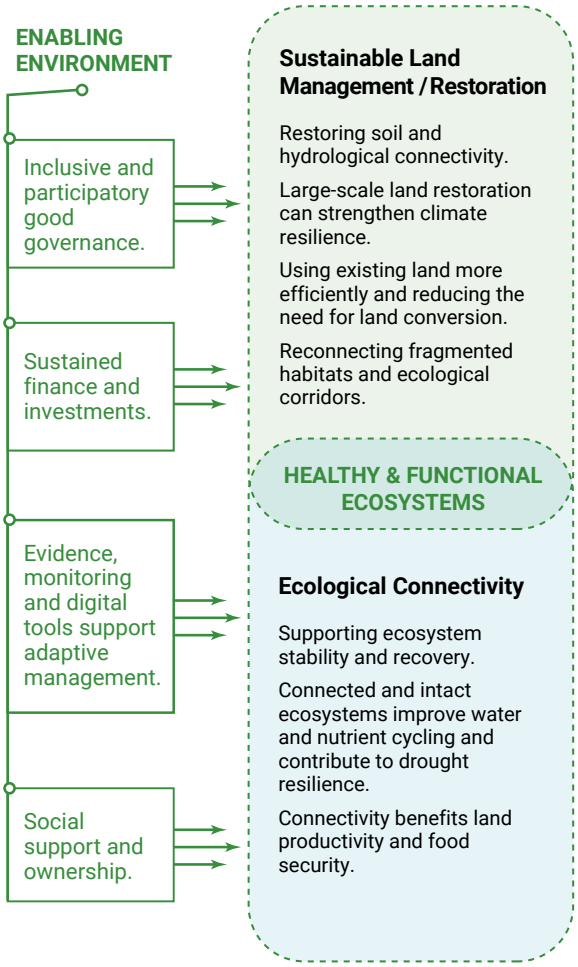
2. **Connected and intact ecosystems improve water and nutrient cycling and contribute to drought resilience.** Connected native vegetation helps to regulate the local climate by maintaining moisture levels and reducing heat stress. While some vegetation can reduce net groundwater recharge by increasing withdrawals, healthy natural vegetation can support connected landscapes and enhance water availability. This can buffer against droughts and reduce the risk of desertification.[338]

3. **Connectivity benefits land productivity and food security.** Reconnecting natural and agricultural landscapes, for instance through agroforestry and regenerative agriculture, can support pollination and pest control, and improve soil health and crop resilience. This can enhance food security and support the resilience of communities dependent on natural resources for their livelihoods and culture.[339]

While some restoration efforts focus on structural components and returning an ecosystem to a state similar to its pre-degradation condition in terms of physical arrangement and species composition, they often fail to ensure the ecosystem's ability to sustain and maintain ecological processes.[340] [341] The success of these efforts depends on maintaining or re-establishing the natural flow of water, energy, species and nutrients across landscapes, as well as enhancing the functioning of social-ecological systems.[342] Similarly, connectivity-based conservation strategies must be combined with sustainable land management to ensure long-term resilience. Efforts to both improve land condition and ecological connectivity can generate multiple benefits, creating more resilient landscapes and enhancing ecosystem services for biodiversity and human well-being.

FIGURE 6

Reinforcing connections between sustainable land management, restoration and ecological connectivity and the enabling conditions required.



4

Land-Based Approaches and Measures for Restoration and Connectivity

Photo: ©2024_AfDB_MADAGASCAR_PEJAA_BLP_Félix_Vigné

Supporting ecological connectivity requires multiple land-based solutions at different levels and scales. These must be adapted to local social and ecological circumstances, integrating supply- and demand-side dynamics in a strategic and holistic manner that considers entire landscapes.[343] [344] This chapter explores practical solutions that can be implemented to restore land and enhance connectivity. For each approach, the chapter outlines the potential benefits in terms of enhanced ecological connectivity.

The approaches and measures presented in this chapter are indicative only and may not be suitable for all ecosystems or local contexts. Integrated and participatory land use planning, alongside a robust evidence base, can best inform decision-making processes. Chapter 5 outlines further enabling conditions that can contribute to the success and sustainability of these approaches.

	Positive impacts on ecological processes that influence air quality.
	Positive impacts on flows of water and their quality.
	Positive impacts on ecological processes related to land and soils.
	Positive impacts on biodiversity and habitat that support species movements, migration and population connectivity.
	Positive impacts on nature's contribution to people and socio-ecological connectivity.

Photo: ©Seifutdinova Olga

4.1

Sustainable Agriculture: Cultivating Resilience and Connectivity

The world's population is expected to reach 9.7 billion by 2050. This will put considerable pressure on food production systems, protected and conservation areas and land and water resources.[345] In spite of agriculture's significant impact on land and natural resources, it also has the potential to contribute to healthier and more connected landscapes.

Agriculture is the backbone of many of the world's poorest and most vulnerable communities.

A multidimensional approach focusing on risk mitigation — such as reducing crop failures, promoting equitable food distribution and access, supporting pollination and enhancing agrobiodiversity is required to ensure subsistence and support community farmlands.

Sustainable agricultural practices can improve soil health and water retention, helping to maintain the functional ecological networks that contribute to more connected and resilient ecosystems. These practices can also contribute to the integration of biodiversity into farmland, conserving linear and stepping stone corridors for species and enhancing natural flows.[346] The table below outlines some of the approaches that have been adopted to increase sustainable agricultural production and support multiple environmental objectives.

TABLE 2

A description of some agricultural approaches and their potential benefits for enhanced ecological connectivity.

Approach	Description	Potential Benefits
Conservation Agriculture Improved Ground Cover [347] Minimum Tillage [348] Crop Rotation [349]	A set of technologies based on the above approaches, including minimum soil disturbance, permanent soil cover, diversified crop rotation and integrated weed management. The aim is to reduce and/or reverse the negative effects of conventional farming practices, such as soil erosion, declines in soil organic matter, water loss, physical degradation of the soil and increased fuel use.[350] Any measure aimed at **improving ground cover**, such as adding dead material or mulch or planting vegetation.[351] **Minimum tillage** involves planting crops after a light, shallow and non-inversion tillage of the soil.[352] **Crop rotation** involves using different types of crops in the same field over successive seasons.[353]	Improved carbon sequestration reduces concentrations of greenhouse gases (GHGs), which affects energy flows. Reduced emissions Reduced runoff Reduced evaporation losses Improved hydrological connectivity can reduce erosion and turbidity in streams Reduced wind erosion Higher soil moisture[354] Improved soil structure, soil temperature and nutrient retention Improved soil health and fertility by enhancing water retention organic matter content Habitat improvement and creation of microhabitats Reduced disturbance of soil biota Maintenance of habitat Higher species diversity Enhanced disaster resilience and lower crop insurance losses[355] Reduced vulnerability to floods and droughts Reduced need for fertilisers, labour and fuel costs Higher crop yields and diversified livelihoods
Agroecology [356]	There is no single, dominant definition of agroecology as countries and institutions have adapted the term to local contexts and priorities. For this report, we consider agroecology as an interdisciplinary science drawing on biological, agricultural sciences and social sciences, integrating these with traditional and farmer knowledge in some of its applications.[357] An agroecosystem should mimic the functioning of local ecosystems, exhibiting tight nutrient cycling, a complex structure and enhanced biodiversity. Practices involved may include crop rotation, polycultures, agroforestry systems, cover crops and mulching, green manures and crop-livestock mixtures.[358] A guide to agroecology developed by the international High-Level Panel of Experts on Food Security and Nutrition (HLPE) in 2019 outlines 13 agroecological principles.[359]	Improved carbon sequestration reduces concentrations of GHGs, which affects energy flows. Enhanced soil moisture Increased water use efficiency[360] Improved structure and nutrient cycling More diverse habitat for above and below ground biodiversity Dependency on agrochemical inputs and energy is reduced, which cuts costs and disruption to landscapes.

Regenerative Agriculture [361] [362]	Regenerative agriculture is a holistic land management practice that aims to improve soil health and nutrient availability, as well as the resilience of crops. It supports climate change mitigation and adaptation by improving soil carbon sequestration and water retention and restoring degraded soil biodiversity.[363] Examples of such practices include reduced tillage, reduced use of fertiliser and chemicals, cover crops and integrated crop-livestock systems.	Improved carbon sequestration reduces concentrations of GHGs, which affects energy flows. Reduced runoff and thus erosion and pollution Improved water retention and infiltration Reduced erosion Increased biomass production enhancing soil fertility Supported habitat and species diversity Enhanced resilience of communities to climate change and improved social and economic wellbeing Higher crop yields and optimised land use efficiency Livelihood diversification
Regenerative Grazing Management [364] [365]	Regenerative grazing management is an agricultural practice that uses principles of soil health and adaptive livestock management to improve farm profitability, human health, ecosystem health and food system resilience. A component of regenerative agriculture, it is characterised by short periods of dense grazing followed by long periods of forage rest, the reduction or elimination of synthetic inputs and tillage, increased diversity of plant, animal and microbial life and the generation of sufficient revenue to build viable farm businesses and fairly compensate farm labour.	Improved carbon sequestration reduces concentrations of GHGs, which affects energy flows Enhanced water retention Enhanced soil structure and biology Enhanced nutrient availability Increased diversity of plant, animal and microbial life Enhanced diversity and abundance of perennial, productive forage grasses enhancing resource availability and habitat quality Local resilience to extreme weather events Reduced input costs
Irrigation Management [366]	Irrigation management involves regulating the use of irrigation water in order to maximise efficiency without wasting water, nutrients, soil or energy, sacrificing crop yields or increasing salinity.[367]	If renewable energy powered, reduced emissions[368] [369] Reduced extraction of groundwater and surface water Reduced irrigation-caused salinity disrupting soil functions[370] Enhanced productivity levels and resilience to drought
Water Harvesting and Soil Moisture Management [371] [372] Microcatchments Contour bunds Planting pits or Zaï	Water harvesting involves collecting runoff from roofs and ground surfaces for productive use. Here, the focus is on water harvesting for plant production.	Improved carbon sequestration reduces concentrations of GHGs, which affects energy flows Reduced evaporation Enhanced infiltration and soil moisture Reduced erosion Enhanced fertility and productivity Enhanced vegetation improving resource availability and habitat quality Increased yields[373]
Windbreaks [374]	Windbreaks are a line of trees or shrubs planted around the edges of fields on farms to provide shelter from the wind and protect the soil from erosion.[375]	Filtered wind-blown soil particles Controlled ambient temperatures Reduced crop water use Reduced runoff Reduced soil erosion Enhanced pollination Woody cover and food for wildlife contribute to stepping stones in a landscape Increased crop yields Energy conservation Aesthetic value
Integrated Soil Fertility Management (ISFM) [376] [377]	ISFM improves soil quality by combining soil fertility amendments with soil and water conservation measures. Its approach focuses on maximising the use of organic fertiliser, such as manure and compost application, nitrogen-fixing green manure and cover crops; minimising nutrient loss; and judicious use of inorganic fertiliser.[378]	Reduced emissions from fertiliser use Improved soil water retention Improved soil structure Increased nutrient replenishment Increased soil microbiota[379] Supported vegetation Agronomic efficiency and enhanced productivity, nutritious food and fuelwood, income for smallholders.
Vertical Agriculture, Hydroponics & Aquaponics	In vertical agriculture, crops are grown in vertically stacked layers or integrated into structures such as buildings. This method allows for intensive agricultural production with minimal land requirements.[380] **Hydroponics** involves growing plants in nutrient-rich water solutions rather than soil. This can lead to higher yield rates and fewer pests and diseases.[381] **Aquaponics** combines aquaculture (the raising of fish) with hydroponics, creating a symbiotic environment in which fish waste provides nutrients for plant growth, while the plants help to filter and purify the water for the fish.[382]	Reduced emissions from fertilisers and pesticides[383] Reduced water demand and extraction due to recycling of water[384] [385] More efficient use of land resources reducing conversion / degradation[386] Reduced soil pollution and erosion[387] Enhanced pollination in urban environments Reduced habitat degradation from conversion Local food production and economies[388]

It is important to consider the suitability of management approaches for specific ecosystems. For example, when it comes to the restoration and sustainable management of arid ecosystems, the consideration of ecohydrology is often particularly important. Traditional agricultural practices commonly use terracing, contour lines and micro-catchments to manage hydrological connectivity in drylands. These methods can enhance infiltration, improve the microclimate and biological activity, protect soil carbon and nitrogen and support the growth of perennial herbaceous plants.[389] [390]

The presence of natural vegetation or areas with low levels of exploitation can support ecological connectivity. Maintaining diverse vegetation in agricultural areas can help reduce the risk of land degradation and fragmentation.[391] These multi-functional, multi-storey landscapes can provide significant ecosystem, social and economic benefits,[392] and act as stepping stones to connect natural processes within a wider landscape.

Photo: ©Adobe Stock

Mechanised Micro-Water Harvesting in Jordan

[393] [394]

A large part of eastern and southern Jordan is covered by the 'Badia', a dry rangeland and desert landscape where less than 200 mm of rain falls per year. This area is vital for agropastoralists. Overgrazing and highly mechanised monoculture agriculture have considerably degraded the soils and native vegetation, decreasing biodiversity. This was further exacerbated by political conflict and the subsequent migration of livestock herders to the area. The amount of palatable dry biomass in the Badia halved between the 1990s and 2010. Reduced vegetation cover decreased the retention and infiltration of rainwater, increasing hydrological connectivity and driving surface runoff and erosion. Rill and gulley erosion contributed to rainwater draining quickly from watersheds. This further exacerbated Jordan's existing water scarcity, as it is already one of the most water-scarce countries in the world, with demand from various sectors growing quickly. The lack of vegetation and degraded soils led to considerable evaporation losses, affecting vertical hydrological connectivity and the water balance across large areas. This issue is expected to be exacerbated by climate change, which is predicted to reduce rainfall and increase temperatures.

In this particularly dry environment, mechanised micro-water harvesting (MWH) was used to rehabilitate vegetation by planting native shrub seedlings. Soil moisture levels were much higher in the water harvesting pits than in the interspaces. Where surface runoff exceeded the soil's water holding capacity, the pits supported deep percolation into the fractured bedrock, contributing to groundwater recharge. By accumulating runoff and making it available to the seedlings over a longer period, the pits supported plant growth and heat stress regulation. The microbiota of the soil in the pits was enhanced, with a higher abundance of fungi and bacteria and improved prokaryotic diversity, which can positively affect communicative transmissions. The pits and the resulting infiltration and leaching also resulted in lower salinity. Soils with enhanced microbial communities were expected to improve the long-term stability and functionality of the ecosystem.

Rangelands play an important role in enhancing ecological connectivity by influencing various socio-ecological processes, such as wildlife migration[395] and the livelihoods of pastoralists.[396] When managed sustainably, these extensive, often biodiversity-rich areas can contribute to conserving plant species and enhancing the resilience of ecosystems and their ability to recover from disturbances.[397]

Sustainable grazing management involves adapting stocking density and the duration and timing of grazing, thereby contributing to a shifting mosaic of land uses that reduces negative environmental impacts. This can be complemented by other management tools, such as fire management in fire-dependent ecosystems. This can enhance structural heterogeneity and contribute to profitable livestock production and rangeland health.[398]

Photo: ©Envato Elements

Agroecological Practices Enhancing Coffee Production in the Atlantic Forest of Brazil [399]

In the Zona da Mata region of Minas Gerais, Brazil, coffee (*Coffea arabica L.*) is a key cash crop for farmers. The area's main land uses are pasture for livestock production, coffee fields and secondary forest patches. Since the 1980s, the area has undergone a transformation, driven by farmers' organisations, a local NGO (the Center for Alternative Technologies of Zona da Mata, or CTA-ZM) and a university (the Federal University of Viçosa), who have introduced agroecological practices. These included minimising the use of agrochemicals, as well as using manure and intercropping trees, rather than weeding.

In 2021, a study assessed the benefits to the ecosystem of these practices in three municipalities of Zona da Mata (Araponga, Divino and Espera Feliz) that connect two nature reserves. These municipalities are located within the Atlantic Forest biome, which is ranked fifth on the list of the world's biodiversity hotspots. Despite having a much higher weeding intensity and using considerable external inputs, conventional farms did not achieve higher productivity or better soil chemical quality. Fields that used agroecological principles and relied on biodiversity achieved similar yields and soil nutrients and higher levels of soil biological quality. The higher species richness in the agroecological fields was associated with enhanced soil cover, litter thickness and structural diversity. This created a more favourable environment for the microbiota responsible for cycling carbon and nutrients. The presence of diverse plant communities and reduced weeding supports pollinators, providing a natural means of pest control. Higher biodiversity also attracted more associated biodiversity, enhancing multi-trophic diversity. The agroecological fields also had higher functional richness. Where the yields of agroecological farms could not match those of conventional farms, reduced costs of external inputs compensated for the difference in profitability. Combining agroecology with agroforestry and more diverse coffee systems can also generate additional income streams.

4.2

Restoring Connectivity in Forest Landscapes

Deforestation and forest degradation account for almost 12% of global greenhouse gas emissions and significantly contribute to land degradation, disrupted water and carbon cycles, fragmented ecosystems and biodiversity loss.[400] Sustainable forestry can support connected wildlife habitats, the free movement of species and well-connected ecological processes.

Photo: ©Albert Mwangi / ILRI

TABLE 3

A description of some sustainable forest management approaches and their potential benefits for enhanced ecological connectivity.

Approach	Description	Potential Benefits
Forest Conservation [401] [402]	The careful management and sustainable use of existing forest areas. The aim is to protect, maintain and restore the health of forests, ensuring their long-term viability. Activities include preventing deforestation, tackling degradation and promoting the overall health of forest ecosystems.[403]	Carbon sequestration and climate regulation Enhanced air quality, particularly with regard to the concentration of pollutants in the atmosphere.
		Decreased runoff (capturing nutrients and sediments), enhanced infiltration and groundwater recharge.[404]
		Enhanced nutrient cycling, shaping the chemical properties of the soil and the biological interactions within it.[405] Enhanced microbial activity and communicative transmissions.[406]
		Maintained habitat quality, species movement and population connectivity.[407]
		Enhanced health and resilience to climate hazards Safeguarded livelihoods Social and cultural benefits
Reforestation [408] [409]	Reforestation involves the deliberate and strategic replanting of trees in areas that have undergone deforestation or experienced a significant reduction in tree cover. This proactive approach aims to restore areas that were once forested but have subsequently been cleared, either due to human activities or natural events.[410]	Carbon sequestration and climate regulation Enhanced air quality (especially in terms of the concentration of pollutants in the atmosphere)
		Decreased runoff (capturing nutrients and sediments), enhanced infiltration and groundwater recharge[411]
		Enhanced nutrient cycling, shaping the chemical properties of the soil and the biological interactions within it. [412] Enhanced microbial activity[413] and communicative transmissions
		Enhanced habitat for wildlife Reestablished connectivity between habitats (movement and gene flow) [414]
		Enhanced resilience to climate hazards Safeguarded livelihoods Social and cultural benefits
Agroforestry[415][416] **and Silviculture**	Dynamic, ecologically based natural resource management systems that integrate trees and wooded areas into farms and productive landscapes in order to diversify agricultural production.	Carbon sequestration
		Improved infiltration
		Reversed habitat degradation Improved land productivity, organic carbon content, soil structure, microbial activity and enhanced microclimate
		Trees can provide habitats, food resources, breeding sites and landscape linkages.[417]
		Diversified food and income sources
Assisted Natural Regeneration [418] **and Applied Nucleation** [419]	**Assisted natural regeneration** is a technique that combines active planting with passive restoration, allowing native trees and vegetation to recover naturally by removing barriers, such as alien invasive species.[420] **Applied nucleation** is a technique that integrates tree planting and natural succession to restore and regrow forests. Trees are planted in clusters, or 'tree islands', to reduce costs and labour.	Enhanced carbon sequestration and sinks Ambient temperature regulation
		Decreased runoff (capturing nutrients and sediments), enhanced infiltration and groundwater recharge[421]
		Enhanced soil cover and fertility[422]
		Scattered tree canopies act as nurseries, attract birds and other key seed dispersing animals Habitat provision
		Cost-efficient way of regenerating forest Job opportunities for communities

When done correctly, reforestation can achieve several objectives in addition to restoring connectivity, such as conserving biodiversity, sequestering carbon, retaining water, producing timber and supplying fuel wood.[423] In naturally forested landscapes, reforestation is important for restoring connectivity for forest-dependent species. While continuously linked areas of forest habitat are ideal for the movement of many species, even small patches of suitable habitat between remnant forests can provide functional connectivity.[424] However, inappropriate afforestation that simplifies, fragments or destroys important natural habitats, such as peatlands, can reduce ecological connectivity and biodiversity richness and limit carbon sequestration.

The location and design of reforestation projects and programmes is important. In large, degraded landscapes, proximity to other restoration sites improves landscape permeability, enabling species movement.[425] Planting trees on steep slopes limits erosion and improves water infiltration, contributing to restored hydrological connectivity often at the scale of the watershed. Meanwhile, planting a variety of tree species promotes the connectivity of diverse biota associated with the trees.[426] Ecosystems with complex food webs containing multiple pollinators and seed dispersers for each plant species, multiple food sources for each animal species and multiple predators to regulate prey populations tend to be more resilient to disturbance.[427] [428] Selecting tree species that are likely to be resilient in the face of future climate change, or that are adapted to the projected conditions, will ensure the long-term success of the restoration project or programme.

Indigenous Agroforestry in Bolivia [429]

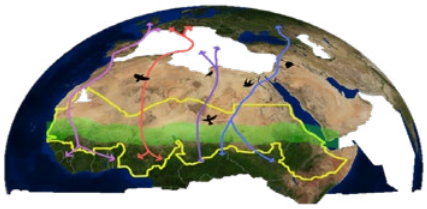
The land inhabited by the Tsimane', Mosetene, Leco and Tacana indigenous communities in Bolivia covers around one million hectares, intersecting two protected areas: Madidi and Pilón Lajas. This area boasts considerable biodiversity, which is under threat from illegal deforestation for agriculture and settlements as well as from gold mining. These activities have a significant negative impact on the livelihoods of these indigenous groups, locking them into a cycle of poverty. A project implemented by the Wildlife Conservation Society and supported by the Association of Organic Cacao Producers of Mapiri (APCAO MAPIRI), the Association of Ecological Coffee Producers of Larecaja (APCERL), the Association of Producers of Indigenous Leco Cacao (CHOCOLECOS) and the Fundación Teko Kavi, supported 271 indigenous cocoa and coffee producers in implementing sustainable agroforestry practices. These focused on creating a diverse forest canopy alongside cocoa and coffee crops. Key practices included planting diverse native canopy shade trees, managing the soil and pruning. The project also implemented digital solutions to strengthen Indigenous land tenure and collaboration between Indigenous communities and national park authorities, preventing illegal encroachment onto their land. The higher diversity of native species in the agroforestry plots resulted in greater carbon capture and improved habitat quality, increasing avian diversity by 22% (69% higher than in monoculture fields). At the same time, cacao production increased by 85% and coffee production by 203%, considerably enhancing the socioeconomic connectivity and income of Indigenous farmers (by an average of 102% for cacao producers).

Photo: ©YOSS SABALET

The Great Green Wall of Africa and migratory birds: Restoring land to allow birds to fly - a matter of connectivity [430] [431]

The Great Green Wall of Africa is a flagship initiative aimed at combatting soil erosion in sub-Saharan Africa. It seeks to improve soil quality and agricultural productivity, the basis of local communities' livelihoods and to create a mosaic of restored, productive green landscapes across the sub-Saharan region. The initiative involves more than simply planting a wall of trees; it incorporates a variety of Sustainable Land Management (SLM) practices. As part of the Great Green Wall Initiative, countries have implemented various SLM methods, including forestry and agricultural activities such as reforestation, restoration, agroforestry, Zaï and assisted natural regeneration; water management activities such as irrigation, water provision and watershed management; and soil enhancement techniques such as dune fixing, wind or fire breaks and terraces.

Comprising a variety of restored and productive landscapes, the Great Green Wall has the potential to support the restoration and improvement of ecological connectivity on many different scales. Envisioned as a vast corridor of revitalised lands, the Wall counteracts the lack of ecological connectivity between West and East Africa. It fosters renewed natural processes and ecosystem functions in the landscape, ranging from nutrient cycling to climate resilience, at surface and sub-surface levels. Furthermore, these restoration projects could restore the ecological connectivity necessary to support processes that occur on an even larger scale, such as the remarkable bird migrations that take place along the African-Eurasian flyway.



Within the Palaearctic-African avian migratory system, the Sahara Desert and the Mediterranean Sea are the main ecological barriers that migrants encounter, in addition to other threats that birds face, such as illegal killing and capture. The progressive expansion of these barriers can lead to significant demographic declines among migrants, whose maximum potential flight range may quickly become insufficient for crossing them effectively. In this context, initiatives that address soil erosion and degradation, known as 'regreening', can provide habitats for migrants during their northbound migration, allowing them to rest and feed. By doing so, these interventions can help maintain the functional connectivity necessary for birds to complete their migratory cycles.

These benefits can be maximised by choosing the right types of vegetation. It is important to select plants that are endemic to the area, providing value and utility for local people, as well as adequate energy sources for birds. Examples include trees with edible berries or fruits or those that are rich in nectar. In turn, the choice of bird-friendly plants benefits sustainable agriculture because the presence of birds favours pollination, seed dispersal and the consumption of agricultural pests. Trends in the populations of birds using the habitats of the Great Green Wall could act as an indicator of land use sustainability, in the same way that the EU uses the Wild Bird Indicator.

Afforestation initiatives must be carefully planned and implemented. Afforestation, particularly the planting of non-native species or in areas that are naturally devoid of trees, can undermine attempts to restore the land and enhance ecological connectivity. Plantation monocultures fail to replicate the structure and diversity of native ecosystems.[432] They provide a suitable habitat for only a narrow range of other species and consume significant amounts of water, depleting soil nutrients and putting greater pressure on surrounding agricultural landscapes.[433] This homogenisation can have far-reaching impacts along the trophic hierarchy, reducing overall biodiversity and habitat availability (for example, for migratory birds in grasslands and wetlands) and influencing species migration.[434] [435] It can also lead to changes in soil microbial communities, influencing soil health and nutrient flows,[436] as well as hydrological connectivity — especially if water-intensive trees are introduced to treeless ecosystems.[437]

In addition, care should be taken to avoid favouring the introduction or increased spread of invasive non-native species or the spread of plant pathogens when establishing nurseries for restoration initiatives.[438] Due to climate change, causing many species to shift their ranges in pursuit of suitable climatic conditions, novel species may arrive at restoration sites. It is important to differentiate between non-native invasive species and more friendly climate migrants and to adjust management accordingly, either encouraging or discouraging the new species.[439]

Photo: ©Envato Elements

4.3

Water Management: Reconnecting Blue Lifelines

Water availability and flow are key factors in maintaining healthy, connected landscapes. Effective water management is crucial for preventing land degradation and the collapse of ecosystems, given the interconnected nature of terrestrial and aquatic ecosystems.[440] Improved hydrological connectivity and integrated water resource management can help landscapes to regain moisture, thereby enhancing soil health and resilience against droughts. Riparian and wetland ecosystems provide vital regulating services and often serve as critical refuges for flora and fauna.


Photo: ©Jim Henderson

TABLE 4

A description of some integrated water management approaches and their potential benefits for enhanced ecological connectivity.

Approach	Description	Potential Benefits
River and Stream Naturation [441] Bank and bed renaturation Stream daylighting Bioengineering techniques Natural regeneration	Stream and river renaturation aims to restore the river's natural dynamics. **Daylighting:** This technique involves removing layers of concrete to recreate the natural shape and dynamics of streams. **Bioengineering:** This recreates the natural course of a river and connects it to its landscape, facilitating floodplain and riparian corridor revegetation, riverbank stabilisation and riverbed restoration. **Natural processes** such as vegetation, wood or beaver structures can be used to ensure 'active' channels and floodplains.[442]	Reduced ambient temperatures and pollution Eliminated barriers to water flows[443] Enhanced water retention, infiltration and groundwater recharge[444] Stabilised water temperature Enhanced lateral connectivity for managing floodwaters and storing water and nutrients[445] Reduced pollution and soil erosion Stabilised soils Increased nutrients and organic matter due to connectivity with floodplains [446] Enhanced habitat, movement and propagation of biota Food, shelter, nesting and breeding areas for wildlife Stimulated local economies and job creation Recreation and social interaction
Bioretention Areas [447] Bioswales and rain gardens Detention ponds Retention ponds Permeable pavements	**Bioretention areas** are typically designed as shallow, vegetated depressions that intercept, infiltrate and divert rainwater, treat stormwater and alter water volume and velocity. **Bioswales and rain gardens:** These are shallow, densely vegetated ground depressions containing a variety of trees, shrubs and grasses. **Detention ponds:** Deeper bioretention areas with less biological diversity. **Retention ponds:** A permanent body of water with vegetated edges. **Permeable pavements:** An alternative to traditional paving materials such as asphalt, pervious concrete, interlocking pavers and plastic grid pavers.	Reduced surface and air temperatures Carbon sequestration and storage Removed pollutants from stormwater and soils from surrounding vegetation Balanced water table, enhanced infiltration and groundwater recharge Enhanced soil structure and microbial activity through organic matter accumulation[448] Habitats and improved ecological connectivity Food and pollination Social interaction, local economy and job creation
Natural Inland Wetlands[449] Drainage reduction Improving lateral connectivity Maintenance and cleaning	Removal of drainage systems, artificial berms and canals that drained or disconnected wetlands and floodplains, in order to restore lateral connections between bodies of water and wetlands and to restore natural hydrological conditions. Controlling undesired invasive plants may be necessary.	Carbon sequestration Reduced ambient temperatures Attenuated stormwater Removed pollutants Enhanced groundwater recharge Enhanced water retention and soil moisture Reduced soil erosion from water Enhanced soil stability from vegetation Key habitats for local and migratory species Building materials and food for communities Supported local economies (e.g. tourism) Enhanced resilience against floods and droughts

Constructed / Artificial Wetlands [450] Surface constructed wetlands Subsurface gravel wetlands Floating wetlands Treatment wetlands [451]	**Constructed/artificial wetlands** are engineered systems designed to use natural processes (e.g. wetland vegetation, soils and their microbial assemblages) to treat wastewater and perform other functions. **Surface constructed wetlands** clean water through a series of planted marshes and engineered soils. **Horizontal subsurface flow constructed wetlands:** Water is slowly pumped through subsurface gravel beds and filtered through the root zone and soil. **Constructed floating wetlands:** Plants are installed on floating structures in existing bodies of water to filter out contaminants. **Treatment wetlands** utilise native plants, soil, porous media and bacteria to remove pollutants from wastewater.	Carbon sequestration Reduced organic, inorganic and excess nutrient contaminants Enhanced groundwater recharge Reduced soil erosion from water Enhanced soil stability from vegetation Habitat for species Healthy multifunctional landscapes, connected to the larger landscape mosaic Scenic, recreational, educational, psychological and economic value to communities Resilience to water shortages
River Floodplains [452] Levee setback Oxbows Incised floodplains Horticultural restoration	River floodplains provide additional space for rivers to safely accommodate higher water levels. **Levee setback:** Relocating a levee further back in the floodplain to provide extra space for flooding. **Oxbow:** Re-connection of a historical river meander that has been cut off from the main channel, either naturally or through human intervention. **Incised floodplains:** A new, meandering stream channel is excavated on the original floodplain by raising the elevation of the stream bed. **Horticultural restoration in floodplains:** Planting nursery-grown trees and shrubs.[453]	Reduced ambient temperatures Carbon sequestration and storage Reduced pollution Controlled water temperatures Room for seasonal water fluctuations Mitigated soil erosion Facilitated sediment and nutrient transport and storage Habitat for wildlife, birds and other animals Important conduits for wildlife movement Scenic and cultural value Opportunities for tourism, fishing and sustainable agriculture practices
Overcoming Barriers Fish passes [454]	**Fish passes** are structures designed to help aquatic organisms migrate upstream or downstream over obstructions such as dams and weirs. Examples include 'fish ladders', 'fishways', 'fish passes' and 'fish stairs'.	Enhanced nutrient cycling[455] Maintained natural hydrological processes[456] Supported migration[457] Maintained genetic diversity[458] Enhanced aquatic foodwebs[459] Supported fisheries[460] and cultural values

Most efforts to restore riparian ecosystems focused on recreating simplified streams have met with limited success. Streams have been altered for so long that there is often little knowledge of their historic condition. Restoration practitioners and river scientists are beginning to recognise the full potential of these ecosystems, moving away from the perception that an ideal stream is a meandering, single-thread channel towards more complex wetland-stream complexes. There is a growing focus on using natural processes, such as vegetation, wood and beaver structures, to ensure 'active' channels and floodplains that support higher ecological connectivity and value at a significantly lower cost with fewer technological inputs. This kind of restoration can enhance carbon sequestration and stabilise stream flow and temperature in the face of global warming and drought, as well as capture nutrients. Restored wetlands, floodplains and streams can serve as natural infrastructure, reducing flood damage.[461]

Photo: ©Envato Elements

Beavers Supporting Restoration and Enhancing Connectivity [462] [463]

Beavers are well-known ecosystem engineers that build dams out of wood, mud and stone, creating wetlands and ponds. They also dig canals from these wetlands and ponds into the surrounding landscape, thereby increasing their area of influence. These structures slow the flow of water and store it, which can support riparian vegetation in dry conditions and make river landscapes more resilient to drought. Studies from the United States further demonstrate the important role of beaver structures in protecting riparian vegetation during wildfires, creating 'emerald refuges', particularly for species unable to escape fire. The dams, ponds and canals keep vegetation hydrated, creating a fire-resistant barrier. Therefore, the wetlands created by beavers can enhance the resilience of ecosystems to droughts, floods and fires, which are expected to increase with climate change. The Bridge Creek Wilderness Area in Oregon, United States, is an example of where conservation authorities have successfully partnered with beavers to restore riverscapes. The installation of stick and post dams by beavers has led to a dramatic improvement in the quality and quantity of the aquatic habitat, restoring the hydrological functionality.

Ponds created by beavers in a burnt landscape in Idaho (Photo: Creative Commons Attribution Only – Joe Wheaton 2018) [464]

Photo: ©Envato Elements

Both communities and practitioners are becoming more aware of the limitations of traditional water infrastructure. Recent approaches focus on removing these constraints by setting back levees, removing pinch points and structures from floodplains, redesigning crossings and bridges to allow for more dynamic channels and restoring native riparian vegetation. When a dam is no longer needed for its original purpose or when the benefits of a dam and reservoir can be achieved through alternative means, the removal of the dam may be a desirable option, offering significant environmental benefits including the restoration of longitudinal connectivity.[465] These approaches can often provide a greater return on investment, support climate change adaptation and resilience to floods and have considerable long-term ecological recovery benefits.[466] The resulting periodic inundation of the floodplain ensures that plants can access groundwater and that sediment dynamics and related nutrient exchanges are re-established. It also gives fish greater mobility through the matrix of habitats, among other effects. Provided there is a sufficiently variable flow regime that incorporates the necessary volumes of water and periodic flood events, and the project is conducted on a sufficiently large geographic scale, restoring hydrological connectivity can be the most important action to enable the ecosystem to recover naturally over time.[467] [468]

Removing Dams in Europe: The Case of the Danube River in Ukraine

Enhanced river connectivity is a key component of the recently finalised EU Nature Restoration Law, which aims to remove barriers and restore at least 25,000 km of rivers by 2030.[469] Dam Removal Europe is a collaborative initiative involving organisations such as WWF, The Rivers Trust, The Nature Conservancy, the European Rivers Network, Rewilding Europe, Wetlands International and the World Fish Migration Foundation. It also includes volunteers, river practitioners, biologists and others interested in restoring freshwater ecosystems. The network has over 5,000 members, who aim to restore free-flowing rivers by identifying changemakers who can drive dam removal initiatives, sharing solutions, raising awareness as well as recording existing and removed barriers across Europe. They also produce annual reports, connect practitioners and support organisations in finding funding for dam removal.[470]

The Dam Removal Website showcases the removal of ten dams in the Ukrainian part of the Danube River Delta as one example. Spanning 4,000 km², the Danube River Delta is the largest natural river delta in Europe and one of the largest remaining wetlands. Spanning Moldova, Romania and Ukraine, it offers diverse habitats to over 300 species of birds and 100 species of fish. As part of a broader initiative by Bulgaria, Romania, Ukraine and Moldova to restore the Danube River Delta and establish a Lower Danube Green Corridor, Ukraine removed ten dams from the Kogilnik, Sarata and Kagach rivers in 2019. This will restore natural hydrological processes and create free-flowing rivers, generating around 20 km of new habitats such as flooded meadows. This would have a positive impact on water quality and several species of wildlife, including frogs, carp, otters and many breeding and migratory birds. It would also reduce damage caused by flooding to agricultural land and roads, prevent soil erosion and store considerable amounts of carbon. The carbon sequestration potential alone was estimated at EUR 29 million annually for the entire Danube basin. Local fishermen are also expected to benefit from increased fish populations.[471] [472]

Riparian areas deserve special attention in restoration projects because they are a highly effective and often inexpensive means of promoting ecological connectivity. Rivers, streams and ephemeral drainage systems in arid regions are important for the movement of animals, sediments, water and nutrients. Riparian areas also provide suitable soils for moisture-dependent plants and accessible water for many animals, which can be crucial in arid regions and during droughts.[473] [474] As riparian areas tend to span temperature and moisture gradients, a riparian corridor can act as a climate corridor, connecting low (often warm) and high (often cool) elevations.[475] Restoring riparian areas can increase the connectivity of ecological networks and sustainably managed landscapes to urban areas. Riparian areas are particularly well-suited to restoring connectivity because of their linear dimensions.[476] Almost every nation has policies for protecting rivers and limiting flood risks and the vegetation along degraded riparian corridors can be rapidly restored due to the rich, moist soil that supports new growth.[477]

In urban environments, restoring streams that were forced underground as storm water conveyance structures or building swales to manage flooding can recreate aquatic and riparian habitats that offer significant protection from storms. They can also provide passages and corridors for terrestrial and aquatic species, increase water infiltration and groundwater recharge and enhance vertical connectivity.[478]

Photo: ©Envato Elements

Stream Daylighting in Seoul, Republic of Korea

About 600 years ago, the Cheong Gye Cheon stream in Seoul was known as the 'valley of clean water'. However, during the industrialisation period, the stream became increasingly polluted and the surrounding area was dominated by informal settlements, which were characterised by considerable degradation. Starting in 1967, six kilometres of the stream were covered by concrete to make way for a 10-lane road and the area became an industrial hub. Years later, when industry moved to the outskirts of Seoul, the area had deteriorated considerably, raising hygiene concerns around the polluted stream beneath the road and posing safety hazards due to ageing infrastructure. This, together with growing demands from citizens, scholars and environmental activists for an improved living environment, led to the development of the Cheong Gye Cheon Restoration Project in 2002. The project aimed to transform the area into a vibrant space. This began with the demolition of the existing road and stream-covering structures. Sufficient water to ensure good quality was taken from the Han River, 15 km upstream and from the groundwater in the subway tunnels. In close collaboration with the public, it was decided that the northern side of the stream would become a promenade for citizens, while the southern side would focus on ecology, including creating habitats for birds, fish and plants.[479]

The restored stream offers flood protection against a 200-year flood event, with flow rates of 118 mm per hour. Biodiversity has increased by 639% compared to before the restoration project and temperatures alongside the stream are 3.3°C to 5.9°C cooler than those on surrounding streets, which helps to mitigate the heat island effect. Air pollution from small particles has also decreased by 35%, considerably reducing the risk of respiratory diseases. Removing the road also had a positive impact on public transport usage and the area's tourism and recreational potential contributes up to 2.1 billion won (£1.9 million) per day to Seoul's economy.[480]

The Cheong Gye Cheon channel in Seoul before and after daylighting. [481]

As rivers are important for water storage, supply and purification as well as for transport and commerce, finding a balance between the continued demand on water courses and the restoration of river connectivity is challenging yet vital. This requires collaboration and coordination between many stakeholders.[482]

Photo: ©Sophie N.

4.4 Conservation Strategies for Enhancing Ecological Connectivity

The IPBES global assessment report found that, while the overall coverage of protected and conserved areas has increased over the past decade, the connectivity of these areas remains inadequate. Weak connectivity within and between these areas leaves the land vulnerable to further degradation and hinders species' ability to move and adapt to environmental changes, including climate change. The assessment concludes that future protected area targets and management strategies will be more effective if they prioritise connectivity. [483]

Much of the science of ecological connectivity focuses on establishing connections and facilitating the movement, migration and genetic flow of species between areas of high biodiversity value, such as protected areas and key biodiversity areas.

TABLE 5

A description of conservation strategies and their potential benefits for enhanced ecological connectivity.

Approach	Description	Potential Benefits
Protected Area [484]	A clearly defined geographical space that is recognised, dedicated and managed through legal or other means to achieve the long-term conservation of nature, along with the associated ecosystem services and cultural values.[485]	Carbon sequestration and storage Reduced air pollution
		Purification and detoxification of water Water / waterflow regulation
		Soil formation, nutrient cycling, primary production Erosion and soil fertility regulation
		Nursery habitats, seed dispersal, species interactions Genetic, species and habitat diversity Pollination Enhanced resilience against natural hazards
		Provisioning of raw material and medicinal resources Opportunities for recreation and tourism Aesthetic values
Rewilding [486]	Restores self-sustaining, complex ecosystems with interlinked ecological processes, while minimising or gradually reducing human intervention. It emphasises the emotional experience of wild nature and wild ecosystems without human intervention.[487] [488] It often involves reintroducing wildlife or species that act as food-web proxies where the original native species are extinct.[489] [490]	Increased carbon sequestration
		See stream naturation in 4.3
		Soil stabilisation and reduced erosion[491] Increased soil aeration and enhanced nutrient cycling from wildlife grazing[492] Diverse vegetation increases litter inputs[493]
		Enhanced species and habitat diversity Potential to connect areas with high biodiversity
		Improved human health and wellbeing
Ecological Corridors [494]	An ecological corridor is a clearly defined geographical area that is managed in the long term to maintain or restore effective ecological connectivity.[495]	Improved air quality Carbon sequestration
		Regulated water flow Improved water quality and filtered pollutants
		Reduced soil erosion Pathway to restore degraded land and promote the growth of native vegetation
		Facilitated movement of various species Maintained genetic diversity Supported pollinators
		Access to green spaces and recreational opportunities
Removal of Fences [496] [497]	Fences are removed or modified in favour of 'wildlife-sensitive land use planning', with the aim of conserving landscapes that cater for the needs of both people and wildlife.	Enhanced vegetation
		Enhanced connectivity and wildlife movement Supported climate adaptation by wildlife
		Potential for community involvement
Management of Invasive Species [498]	Strategies to address biological invasions include preventing the arrival of new alien species at high risk of becoming invasive, detecting and responding rapidly to new invasions, containing invasions where eradication is not feasible, reducing the extent and impact of widespread invasive species and restoring areas degraded by invasive species.[499] *Note that benefits can vary considerably based on context, management and the species involved (native and alien).*	Enhanced freshwater quality and surface water availability[500]
		Restoration of natural soil dynamics[501]
		Enhanced pollination Safeguarded native biodiversity Enhanced resource availability for species through reestablishment of native vegetation
		Reduced losses in agriculture and forestry
Fire Management [502]	Activities associated with fire-prone land, including the use of fire to achieve land management goals and objectives as well as activities related to fire suppression and/or prescribed burning.[503]	In some cases, potential for reduced emissions from avoided high intensity wildfires
		Increased water use efficiency by plants
		Increased soil sorption capability Enhanced proliferation of microbial communities
		Improved habitat quality through regeneration of some vegetation species Increased forage and grazing for wildlife Prevention of bush encroachment and control of alien invasives (*species dependent)*
		Reduced vegetative fuel load can reduce risk of uncontrollable fires and the associated socio-economic damages

Conservation efforts play a critical role in maintaining and restoring connectivity. These efforts not only protect existing natural areas but also help to restore degraded areas by conserving corridors that reconnect fragmented habitats. Conservation approaches, from protected areas and ecological corridors to controlling invasive species and removing barriers such as fences, can contribute to resilient ecosystems and enhanced connectivity. Protected areas provide important refuges for wildlife and vegetation, supporting the restoration of surrounding areas, playing a key role in maintaining ecological integrity as well as sustaining biodiversity and ecosystem services in the long term.[504]

An ecological network is a widely recognised approach to restoring ecological connectivity. It may include a system of protected and conserved areas as well as the ecological corridors that connect them. Alternatively, it may comprise an international system of sites that are critical to the movements of migratory species, such as flyways and swimways. Defining a network requires a holistic view of the interconnectedness of areas, sites and corridors within the wider landscape matrix, taking into account the ecological processes that bind them together.[505] Studying the interactions between species and habitat patches improves our understanding of the dynamics of recovering ecosystems and helps us to identify priority areas for restoration.[506] The first critical phase is identifying core areas, which are areas of high natural value based on their biodiversity (e.g. internationally important proportions of biogeographical populations) or their ecological functioning. Network analysis of connectivity data[507] can be used to determine sites with high ecological connectivity, including protected areas, hotspots and bottlenecks, ecologically intact and key biodiversity areas, as well as other effective area-based conservation measures (OECMs), private areas and wilderness.[508] Buffer zones are also important for providing 'reserve capacity' in times of ecological distress and disruption, as well as for distributing risks over a number of sites. Based on these sites and the identified ecological processes, linkages can be conserved and actions to avoid, reduce and reverse land degradation can be implemented to enhance wider landscape connectivity and increase socio-ecological benefits.

Many human-made barriers restrict the movement of species or ecological processes or cause direct mortality. These barriers are often linear, such as roads, railways, canals, power lines, pipelines, fences and dams.[509] The direct and indirect impacts of linear infrastructure on ecological connectivity are well documented. These include habitat fragmentation and the segregation of animal populations, as well as habitat degradation and the introduction of pollutants.[510] [511] The mitigation hierarchy (avoid, reduce and reverse) provides a framework for addressing the impact of such infrastructure on ecological connectivity. Where possible, new or expanded infrastructure should be avoided. When this is not possible, tools are available to minimise its impact and mitigate residual impacts. Existing infrastructure can be removed and the land restored. Lastly, investments can be made in the surrounding landscape to compensate for the unavoidable impacts of infrastructure. Environmental impact assessments and spatial planning tools can be used to identify risks and prevent environmentally harmful development.[512]

Fences often form large networks of barriers across landscapes, obstructing the movement of large mammals.[513] [514] Modifying fences to ease crossing or removing them completely is an example of mitigation which can improve access to seasonally used areas for wide-ranging species.[515] [516] Restoring large areas of land to a fenceless state will benefit ecosystems and improve the services they provide.


Photo: ©Rudmer Zwerver

FIGURE 7

Once an ecological network has been defined, actions to avoid, reduce and reverse land degradation can expand to the wider landscape to further increase socio-ecological benefits.

1. Core areas are isolated in an otherwise degraded, fragmented landscape.

2. Core areas are connected by ecological corridors.

3. Sustainable land management incorporated across the landscape supports a more permeable ecological network.

Fence Modification and Migratory Mammals in Central Asia [517]

Published in 2019, the CMS Central Asian Mammals Migration and Linear Infrastructure Atlas maps and analyses the impact of linear infrastructure on large migratory mammals in Central Asia. Created by a group of experts, the document identified that, of all types of linear infrastructure (including roads, railways, pipelines and fences), fences are the most harmful barrier for large mammals. They cause direct injury and death, cut animals off from vital resources and lead to die-offs and the genetic isolation of populations. In 2014, the CMS published the 'Guidelines for Addressing the Impact of Linear Infrastructure on Large Migratory Mammals in Central Asia' as part of the Central Asian Mammals Initiative (CAMI). This document provides background information on the migratory patterns of Central Asian mammals such as khulans (*Equus hemionus*), saiga antelopes (*Saiga tatarica*), goitered gazelles (*Gazella subgutturosa*) and Mongolian gazelles (*Procapra gutturosa*), wild camels (*Camelus ferus*) and so on. It outlines the related legislation and requirements for considering migratory species in linear infrastructure planning in eight countries. It further recommends ways to avoid and mitigate the impacts of linear infrastructure.

Despite the dramatic impact of fences on migratory wildlife, the guidelines found that none of the analysed countries required an impact assessment of fences. Through advising its parties and organising technical expertise, the CMS Secretariat has facilitated the removal of fences along the Trans-Mongolian Railway and the modification of the border fence between Kazakhstan and Uzbekistan. This has created passages for wildlife in a defined area. More recently, the 14th CMS Conference of the Parties (COP14) reaffirmed its long-standing commitment to connectivity, focusing on addressing knowledge gaps relating to habitats, areas, corridors and networked sites of the greatest global importance for the conservation of migratory species. The conference also strengthened its focus on addressing threats to connectivity, including those posed by existing and planned infrastructure, by integrating the needs of species into national spatial planning processes. The conference also identified opportunities for mitigating barriers to migration and pinpointing mortality hotspots and bottlenecks and prioritised the restoration of connectivity and the planning of new infrastructure using a green infrastructure approach.

Wildlife crossing structures, such as overpasses and underpasses, with guiding fencing, are the most effective means of facilitating the safe passage of animals across roads and railways.[518] While these structures are most cost-effective when included in original construction plans, they can also be retrofitted.[519] [520]

Flyovers to Improve Connectivity near Kaziranga National Park, India [521]

The construction of new highways and the expansion of existing infrastructure pose a significant threat to ecological connectivity, particularly when these projects interfere with the migration routes of wide-ranging, endangered mammals. However, adequate resources and a commitment to conservation can minimise these impacts. India's Kaziranga National Park is home to populations of Bengal tigers (*Panthera tigris tigris*), Asian elephants (*Elephas maximus*), one-horned rhinoceroses (*Rhinoceros unicornis*) and countless other species of wildlife. National Highway 37 (NH-37) runs along the southern border of the park, connecting the state of Assam to the rest of India. NH-37 is in need of widening and the planning process has involved numerous NGOs, research institutions and government agencies. Given the extreme ecological and biocultural importance of Kaziranga and its wildlife, the widened highway must be built in such a way as to avoid wildlife-vehicle collisions.

Traditionally, impact mitigation has been achieved by constructing small wildlife overpasses or underpasses at 'hotspots', where collisions occur most frequently. In the case of NH-37, however, the government has pledged to take a bolder approach. As of 2024, the National Highways Authority of India was reported to be preparing a project that would include a 35 km flyover. This structure, divided into three sections, will leave the underlying forest intact while vehicles travel on the elevated surface. The flyover will be the largest in India and a prime example of large-scale investment in nature conservation. The concept of the mitigation hierarchy, where full avoidance is the first choice, should be employed when considering whether to build new infrastructure. In the case of NH-37, where the highway is at capacity and must be expanded, planners have determined that the cost of degrading natural habitats and connectivity would be higher than the cost of the flyover. This kind of cost-benefit analysis is at the heart of decisions to preserve connectivity rather than relying on restoration after damage has occurred.

Integrated land use planning and modelling, especially based on remote sensing, can help identify barriers that need to be removed or modified in order to achieve the best restoration outcomes.[522] In some cases, removing a barrier that has a significant impact on an ecological process may be the most appropriate measure to ensure the effectiveness of an ecological corridor. Therefore, a strategic spatial analysis of options is needed to optimise restoration design and implementation.

4.5 Greening Cities and Buildings

The connectivity of green (and blue) spaces in cities varies greatly. The need for urban greening has been recognised globally due to motivations to improve habitat conditions and ecosystem processes within cities, growing concern about the potential impact of frequent droughts and climate change on urban populations and increasing evidence that cities have outgrown the natural ecosystems that previously supported them.[523]

The adoption of the concept of 'working with nature' rather than against it is spreading quickly. Urban design strategies can be employed to increase ecological permeability throughout a city and tie urban nature to the surrounding landscape. Nature-based solutions (NbS) can offer multiple co-benefits that enhance ecosystems and their services and contribute to the wellbeing and health of urban residents. They are often most effective when planned and implemented in an integrated way. In complex urban environments, there is no single solution. Therefore, it is vital to understand the local ecology and biodiversity, as well as the challenges to ecological connectivity and resilience, in order to identify practical ways to use NbS and embed them in policies, planning, projects and programmes.[524]


Photo: ©Unsplash

TABLE 6

A description of nature-based solutions for green cities and buildings and their potential benefits for enhanced ecological connectivity.

Approach	Description	Potential Benefits
Urban Forests [525] Phytoremediation forest Ecological forest corridors	**Urban forests** are often established along drainage lines. A **phytoremediation forest** consists of trees and shrubs with specific metabolic qualities that enable them to clean polluted soils, including those in landfills and abandoned urban areas. **Ecological forest corridors** can also be established in upland areas to link important habitats. These forests should be structurally complex and species-rich to facilitate movement for various species.	Reduced urban heat island effect and air pollution Carbon sequestration Protected rivers due to intercepted runoff, enhanced infiltration and reduced flooding Regulated water cycles (retention, infiltration, evapotranspiration) Cleaned soils Enhanced soil structure and fertility due to organic matter deposition[526] Connectivity and safe movement of species in the landscape Habitat provision Reduced light and noise pollution facilitating communicative transmissions Enhanced property values, recreational opportunities, health and community stewardship over the environment[527]
Urban Green Corridors[528] Street tree canopies Green avenues Urban green corridors	The most efficient way to create green corridors in urban areas is to plant green avenues and boulevards. This involves planting trees in open spaces alongside streets, open train tracks and other transport and infrastructure corridors.These street trees provide corridors for the daily movement of insects, birds and small mammals between forest remnants, riparian vegetation and other green spaces.[529]	Temperature regulation, shade and supported local microclimate Improved air quality from absorbed pollution Reduced stormwater runoff and pollution Improved water quality Stepping stones for biodiversity / enhanced connectivity Promoted social interaction Reduced noise
Open Green Spaces [530] Pocket parks Natural playgrounds Residential gardens	**Pocket parks** are small open spaces located throughout urban areas. **Playgrounds** containing trees, flowers, rocks and water features can help children to develop sensory and tactile perception, creativity and an appreciation of nature. If they are integrated into larger green infrastructure networks, **residential gardens** can have a significant impact on reducing stormwater.	Enhanced heat regulation Enhanced air quality[531] Urban flood risk management through enhanced infiltration, water retention and reduced runoff Habitat and critical refugia for biodiversity Stepping stones for biodiversity Increased property values Mental wellbeing and physical health Social interaction / urban gardening
Green Infrastructure [532] Extensive and intensive green roofs Ground-based green facades Facade-bounded greening Plant towers	**Extensive green roofs** consist of several horizontal layers; a bioengineered growth medium; membranes to support and control plant roots; and buffers to collect, filter, store, reuse or discharge water. There are also structural and insulation layers. **Intensive green roofs** have a thicker substrate layer that supports a greater variety of vegetation. **Ground-based green facades** are a type of green wall consisting of climbing plants that are rooted in ground planters. **Facade-bound greening** uses technology for irrigation and special substrates to reduce the weight of green facades.	Heat regulation Reduced air pollution Captured and stored rainwater Reduced drought impacts by promoting the reuse of water stored in roofs Habitats for species, birds, bees and other pollinators Opportunities for gardening and recreation Reduced building energy bills

Considering biodiversity values and ecological connectivity in urban planning is becoming increasingly important. Although urban areas are generally considered to be an unfavourable habitat for wildlife, some green (and blue) spaces in cities provide vital refuges and feeding grounds that can contribute to ecological connectivity. While these green spaces are generally too small to sustain viable populations of species, they can serve as vital stopovers.[533] [534] Areas with intermediate or high vegetation coverage tend to have higher species diversity. Strategically planned green (and blue) infrastructure can enhance landscape connectivity, while also contributing to cleaner air and water and regulated temperatures. [535] [536]

Connectivity mapping tools can be used to model the strength of connectivity among open spaces. The resulting maps can inform strategic decisions on the creation of new parks and the planting of street trees, enhancing ecological connectivity and enabling municipalities to compare their performance in providing green spaces for natural processes, wildlife and human wellbeing.[537] [538]

Urban areas are complex social-ecological systems and managing ecosystem services in urban landscapes is challenging due to high social diversity and spatial heterogeneity in land use. The integration of human behaviour into ecological processes, with a focus on both ecological and social connectivity in urban environments, has attracted significant interest from urban planners, scientists and conservationists. In order to make cities more resilient and sustainable, we need a better understanding of how to enhance ecological connectivity and the flow of ecosystem services across social-ecological systems.[539]

The Green Roofs of Basel, Switzerland [540] [541] [542] [543]

Switzerland is one of the leading countries in the systematic implementation of green roofs, with an average of 5.71 m² per person in Basel in 2019. A systematic assessment in 2006 found that the city had 1,711 extensive and 218 intensive green roofs, covering 23% of its flat roofs. Since then, around 100 green roofs, equating to 80,000 m², have been added annually. Unlike many other cities implementing green roofs, Basel insists on using native plants, soils and seeds. Consequently, the green roofs in Basel resemble nature-rich grasslands. Green roof development in Basel began in the 1990s. It was one of the solutions financed by a fund for energy-saving measures, which residents voted to allocate part of their bills to. Compared to other countries, Basel has scaled up its efforts by making green roofs a legal requirement for all new and renovated buildings with slopes of less than 10 degrees and by subsidising their implementation. During the design and implementation process, the city or developers must collaborate closely with scientists. Green roofs can provide insulation, remove pollutants, enhance water retention and provide a habitat for biodiversity, thereby enhancing the quality of life for residents. Carefully choosing substrate depth and drainage regimes can create different microhabitats above and below the soil surface, enhancing the diversity of plant and wildlife species that colonise green roofs. Initially, green roofs made use of unused space, but this has changed with the boom in renewable energy, creating competition for roof space. To resolve this conflict, many cities are starting to combine green roofs with elevated solar panels, which protect the plants from the sun and wind while the plants help cool the solar panels.

Photo: ©Envato Elements

A Whole-of-Society Approach to Urban Greening: The Case of Singapore

Singapore is a city-state and the most urbanised area in Southeast Asia. It is also one of the world's leading commercial hubs, boasting one of the five busiest ports and the fourth-largest financial centre. In a mere five decades, the country has transitioned from being a developing to a developed nation by prioritising both economic development and environmental sustainability. The first Singapore Green Plan was published in 1992, followed by a new 10-year plan in 2002 which introduced a national approach to integrated planning. This was followed by the Sustainable Singapore Blueprint in 2009, which set out key strategies for sustainable development and five-year plans to make Singapore a more liveable city. Additionally, the country has a variety of policies, regulations, standards, pricing systems, demonstration projects, information management systems and initiatives to raise awareness of environmental issues.[544]

The Singapore Green Plan 2030 takes a whole-of-nation approach to promoting sustainable development and achieving the SDGs and other key international commitments. It is based on five main pillars: City in Nature, Energy Reset, Sustainable Living, Green Economy and Resilient Future.[545] As part of the 'City in Nature' pillar, the city-state intends to expand the network of protected areas, enhance the natural features of gardens and parks, restore more natural habitats within the urban landscape, strengthen connectivity between green spaces and improve animal management and veterinary care, all in close collaboration with the local community. Four nature reserves protect Singapore's native ecosystems and vital ecosystem services. They are surrounded by nature parks, which act as a buffer against urbanisation, and ecological corridors to connect reserves, parks and gardens. By 2030, the government aims to ensure that every household is within a 10-minute walk of a park.[546] [547]

By 2023, Singapore had opened new parks, developed species recovery plans for 120 plant and animal species and achieved its target of restoring 30 hectares of habitats. The target was then increased to 80 hectares by 2030. An Ecological Profiling Exercise (EPE) had also been completed. The EPE aimed to improve understanding of the ecological profile of green spaces and their contribution to ecological connectivity. The authority responsible for national parks is also working to naturalise bodies of water, and daylight concrete canals to transform them into natural reservoirs and floodplains to provide flood protection and promote biodiversity. Over 500,000 trees have been planted as part of the OneMillionTrees initiative since its inception in 2020, with 90,000 trees planted in industrial estates. Furthermore, Singapore has become the world leader in vertical greening, boasting approximately 155 hectares of skyrise greenery.[548]

Community Gardens Enhancing Socio-Ecological Connectivity in the United States [549]

A study conducted in New York, Chicago and Baltimore examined the contribution of community gardens to networks of biophysical and social connectivity in urban landscapes. In all three cities, community gardens were found to play an important role in enhancing food security, fostering a sense of community, building social cohesion and supporting low-income and minority communities. These gardens support social connectivity and ecological interactions between biotic and abiotic features in the environment. In addition to fostering social connections, the gardens established various ecological networks that support the flow of ecosystem services. The tighter the clusters, as in New York, the higher the connectivity. However, in dense cities such as New York, these flows struggled to extend beyond the clusters of gardens. In less dense cities, such as Baltimore, community gardens created linkages in broader ecological networks, including parks, residential gardens and other green spaces beyond the clusters. The hot and cold spot analysis used in the study can inform urban planning to enhance ecological connectivity. Taking social and biophysical features into account can help to create socio-ecological networks that increase resilience to environmental and demographic changes.

Photo: ©Envato Elements

4.6

Responsible Industry

The industrial sector, which includes the energy, mining, transport, waste management and manufacturing industries, plays a significant role in the stewardship of land and ecosystems worldwide. Transformative action requires a paradigm shift towards more responsible industrial practices. Adopting sustainable land use practices, circular economy principles and nature-based solutions enables industries to minimise their ecological footprint while actively contributing to land restoration and ecological connectivity.

Pollution from brownfield sites or mining areas can travel great distances, affecting soils, water and air far from the source. Restoring these areas offers opportunities for improved land management and enhanced ecological connectivity. Firstly, brownfield sites can be used for urbanisation and other developments, thus avoiding the further conversion of natural areas and fragmentation of landscapes. For instance, the European Commission has adopted an initiative to support 'no net land take by 2050', based on the reuse of brownfield sites.[550] Secondly, brownfield sites and mining areas can be restored to enhance biodiversity and ecosystem services, as well as to support climate change mitigation and adaptation. Studies from Australia suggest that landfill sites can contribute to environmental rehabilitation by creating habitats and improving ecological connectivity, particularly in densely populated areas. Geographic information system (GIS) tools can be used to identify areas with considerable restoration potential.[551] This can reduce the risk of further pollution from mining sites due to climate-related hazards, such as droughts, floods and wildfires, which can mobilise contaminated materials, thereby increasing exposure to animals and humans. Thirdly, some brownfield sites may serve as biodiversity refuges that have been established through natural succession, warranting their conservation.[552] [553]

TABLE 7

A description of approaches that support more responsible industry and their potential benefits for enhanced ecological connectivity.

Approach	Description	Potential Benefits
Restoration of garbage areas and "brown fields" [554] Post mining restoration Restoration of polluted or abandoned industrial sites	Converting abandoned industrial areas, such as mines and landfills, into green spaces is one option. This can involve reforestation, rewilding, creating wetlands and replacing lost habitats.[555]	Reduced emissions and air pollution Enhanced carbon sequestration[556] Reduced heat island effect
		Enhanced water quality and aquatic ecosystems[557] Reduced runoff and enhanced infiltration through the creation of permeable surfaces[558]
		Reduced pollution and soil remediation[559] Stabilised soil, enhanced organic matter and microbial diversity
		Habitat provision Reduced land conversion for urbanisation[560] Stepping stones enhancing ecological connectivity
		Increased property values[561], improved public health[562] and recreational value
Quarry Lakes [563]	Suitable abandoned mining pits can be converted into reservoirs to provide critical groundwater aquifer recharge or water storage for local areas.	Temperature regulation
		Water storage for water scarce periods Reduced flood risk Enhanced groundwater recharge[564]
		Habitat creation and resource availability that can support species movement[565]
		Recreational value[566]
Road Decommissioning and Restoration of Abandoned Infrastructure [567]	Formal closure of any road that is not regularly inspected and maintained. Decommissioning stream crossings by removing culverts to prevent erosion and pollution of the downstream environment, as well as seeding and mulching exposed areas and planting native and/or naturalised species.	Enhanced carbon sequestration Reduced emissions Improved air quality
		Slowed overland flow reduces flood risk and pollution Improved infiltration to shallow and deep groundwater
		Reduced soil erosion
		Enhanced habitat availability from native and naturalised species Removal of barriers to species movement
Phytocapping [568]	Phytocapping involves planting native species as a vegetated cover over rock piles, tailings or bare earth surfaces in order to reduce acid mine drainage. This vegetation absorbs infiltrating water, thereby reducing the leaching of contaminants into the local water supply.	Reduced windblown erosion and air pollution
		Improved water quality by reducing leaching into the local water supply Enhanced infiltration
		Reduced erosion and pollution
		Improved biodiversity by increasing native and naturalised species
		Health benefits
Nature-Positive Energy [569] Wildlife-friendly wind turbines and energy transmission lines Fish-friendly hydropower Pollinator-friendly solar Agrivoltaics Solar gardens	Nature-positive energy is defined as an energy system that minimises environmental harm and actively contributes to the restoration and enhancement of natural ecosystems. This approach incorporates conservation goals into energy planning, guaranteeing that the development of renewable energy supports biodiversity and the health of ecosystems.[570]	Carbon sequestration Reduced air pollution
		Enhanced soil moisture from shading
		Conservation of habitat and creation of new microhabitats Reduced conversion Protected vegetation
		Enhanced community acceptance

Transforming Landfills to Functional Ecosystems

Sydney Olympic Park in Australia was a nearly 800-hectare landfill site between 1950 and 2001, containing 100 million tonnes of waste of various levels of toxicity. Today, Sydney Olympic Park is an urban biodiversity hotspot, home to a wetland system that provides a variety of ecosystem services. For example, it filters pollutants, regulates water flows and sequesters carbon, while also maintaining pollination services for plant and animal populations.[571] [572]

The transformation of the landfill site began when Sydney was awarded the 2000 Olympic Games. It was Australia's largest urban land remediation project to date, involving the reconstruction of an entire landscape once the waste had been removed. The aim was to create functional ecosystems that resemble nature within an urban parkland setting. This involved remediating 160 hectares of contaminated land, removing 9 million cubic metres of waste and 400 tonnes of contaminated soil and restoring some of the remaining estuarine wetlands and eucalyptus forests. It also involved daylighting a 2 km stormwater canal and creating an estuarine creek with salt marshes. The tidal flushing of the wetlands was restored to enhance the habitat of protected migratory shorebirds. New habitats were constructed, including wetland, grassland, forest, saltmarsh and intertidal areas, as well as over 90 freshwater ponds and wetlands for the endangered Green and Golden Bell Frog (*Litoria aurea*).[573] Today, the park is home to over 400 native plant species, more than 250 native vertebrates, including over 200 native bird species, as well as bats, reptiles, invertebrates, fish and frogs, some of which are endangered or threatened. Around 300 hectares of the park specifically provide and protect habitat for species of conservation concern and have become an important stepping stone for migratory and nomadic species. [574]

Photo: © Envato Elements

Mine Restoration in Germany [575] [576]

Germany's industrial strength was largely built on the extraction of mineral resources. Since the 19th century and particularly after unification in 1871, mining, especially coal mining, had increased considerably, transforming the landscape. Coal production peaked in the 1960s at over 140 million tonnes per year, after which it decreased as imports of coal and petroleum increased. Most of the domestic coal production came from the Ruhr area, which became one of the largest industrial regions in Europe. However, due to the considerable air and water pollution, the region soon became known as the 'coal scuttle' (Kohlenpott). Sinkholes as deep as 20 metres were created, causing water runoff issues that threatened neighbourhoods and damaged homes. Starting in the 1960s, concerns about the environmental impact of mining grew, leading to the closure of many mines. These were then transformed into agricultural fields, lakes or forests. The International Architecture Exhibition Emscher Park (IBA Emscher Park, 1989–1999) was a major programme of structural changes to the Ruhr region. This involved reconstructing the landscape to create the Emscher Landscape Park as well as the ecological restoration of the Emscher river system. The aim was to improve the area's social value for housing, employment, recreation and showcasing industrial cultural heritage. In total, 800 km² were rehabilitated, transforming the region of 2.3 million inhabitants from the 'coal scuttle' into an area with a new ecological and social identity and considerably enhancing socio-ecological connectivity. Based on the IBA Emscher Park experience, guidelines for the rehabilitation of former industrial sites were developed and implemented in other parts of Germany and Europe.

Taking ecosystem functioning and ecological connectivity into account when planning and constructing roads can considerably reduce fragmentation and make the transport sector more sustainable. For instance, incorporating erosion control, slope stabilisation and the creation of green corridors into the transport planning process can mitigate some of the connectivity-related challenges associated with road infrastructure. Good drainage planning and placement, taking into account water flows and fisheries, can help retain water in dry areas, enhance groundwater recharge and remove unwanted standing water. Quarries and borrow areas can be rehabilitated and various options are available for managing waste, dust and noise pollution. Furthermore, innovative technologies are available to reduce emissions, waste, energy consumption and disruption. Roads that are no longer required should be decommissioned, with the area being restored to a more

Enhancing Nature around Roads: The Case of Keyn Glas, UK [577] [578]

National Highways and Arup, a global consulting firm, have adopted a unique regenerative approach to the management and restoration of landscapes and habitats along the A30 in Cornwall, United Kingdom. Keyn Glas, which is Cornish for 'green ridge', is a road mitigation scheme that takes a landscape-based approach, implementing a series of individual projects on surrounding farmland and estates up to three kilometres from the road. These projects include natural flood management solutions, pond restoration, the creation of flower-rich grasslands and hedgerows, woodland and wetland restoration, green bridges and wildlife crossings and the restoration of historic ecological corridors. Together, these interventions enhance biodiversity and contribute to climate change adaptation and mitigation.

Arup used Condatis, a GIS-based tool developed by the University of Liverpool, to assess the landscape and identify the areas with the greatest potential for enhancing ecological connectivity and generating net gain in biodiversity. Arup collaborated with the Cornwall Wildlife Trust to adapt individual projects to the local context, existing agricultural practices and farm assets. National Highways funded restoration initiatives on individual farms, with farmers agreeing to sustainably manage their land for 10 years.

The first phase of the scheme connected 32 habitat patches across nine farms. According to the UK Government's Biodiversity Net Gain Calculator, this was estimated to result in a 250% net gain in biodiversity. Biodiversity management in eight woodlands was improved and eight kilometres of field boundaries comprising traditional hedges, hedgerows and fences were created. Together, these initiatives are expected to absorb around 10 tonnes of CO_2 every year. The catchment approach to water management reduced runoff and flooding, while enhancing water quality.

Photo: ©Sergey Dzyuba

natural state through measures such as revegetation and the removal of road infrastructure (e.g. bridges, drainage systems, embankments and cuttings), as well as the restoration of natural slopes.[579]

In order to meet climate change mitigation targets, a transition to renewable energy systems is unavoidable. Renewable energy is crucial for improving access to energy for the 750 million people without electricity, enhancing their well-being and prosperity.[580] There is growing awareness that the development of renewable energy sources should also have a positive impact on biodiversity, contributing to healthier ecosystems. In order to reduce land conversion and fragmentation, energy developers and practitioners are increasingly trying to integrate renewable energy production with other land uses. Pilot projects are exploring the use of offshore wind farms as coral habitats, solar panels to enhance food production, vegetation and surrounding habitats[581] and integrated green roofs or shade for water bodies to reduce evaporation.

Minimising the Impact of Energy Infrastructure Development on Birds

Each year, over 1.5 million birds migrate across the Red Sea and the Rift Valley. The increasing density of electricity and renewable energy infrastructure is killing birds in flight, with potentially thousands dying each year across the region.[582] The impact varies by species, with fast-flying, heavy-bodied birds being particularly affected by power lines crossing their flight paths. Soaring birds, particularly birds of prey, are also highly susceptible to collisions with wind turbines. Many of these species are already endangered and have low reproductive rates. [583]

Deaths from energy infrastructure could be considerably reduced at relatively low cost by taking bird migration routes into account when planning sites. For example, power lines could be routed away from wetlands and other areas with high concentrations of birds, cross flight paths at non-right-angles and coloured to enhance visibility.[584] Similarly, wind turbines could be placed away from major bird migration routes. As part of broader efforts to protect globally significant bird migration corridors, BirdLife International has developed an online tool that identifies locations where different types of energy infrastructure would have a relatively low impact on migratory birds.[585] Consequently, future energy infrastructure can be planned to cause less harm without significantly impacting the supply of renewable energy.

5

Creating an Enabling Environment for Land Restoration and Ecological Connectivity

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Technical solutions for implementing sustainable land management, restoring degraded land and enhancing ecological connectivity cannot be implemented in isolation. Without due consideration of local conditions, traditional knowledge and inclusive decision-making, supportive policies for sustainable land management and connectivity initiatives will struggle to succeed.

While some of the approaches and measures outlined above are 'do no harm' approaches that can be implemented immediately, the restoration of entire landscapes requires long-term, large-scale implementation to realise their full benefits. This necessitates sustained financing, monitoring and research to communicate impact and transboundary collaboration.

Paying attention to inclusive governance, gender equality, land rights and the involvement of Indigenous Peoples and local communities can ensure that land and connectivity restoration initiatives contribute to broader goals, such as reducing poverty and achieving sustainable development.

5.1

Inclusive and Participatory Governance Frameworks

As land degradation is rarely the result of a single cause, restoration efforts must address multiple pressures, drivers and complexities. This requires long-term planning as well as the immediate implementation of well-known and proven techniques and principles (such as crop rotation, organic fertilisation, agroforestry, protection against soil erosion) to address land degradation and fragmentation. These efforts must also consider policy instruments, development sectors, institutional responses and the engagement of government and society in a coordinated manner.[586] [587] The success of restoration initiatives depends on their long-term durability, since natural processes require sustained effort to recover. Good governance and land management policies are also essential.[588] [589] Focusing on connectivity can improve the strategic choices of those involved across multiple levels of governance, enhancing cooperation and providing a

stronger foundation for long-term sustainability.[590] Creating a supportive policy environment for land restoration and enhanced ecological connectivity requires action at various governance levels and spatial scales.

Governance at the Global Level: Working Together and Enhancing Synergies

To avoid negative trade-off effects that could unintentionally disrupt ecological connectivity, synergies are required between international, regional and national level commitments to address land degradation, climate change and biodiversity loss. Such trade-offs may arise from competing demands for land use or from prioritising certain ecosystem services over others. This can exacerbate habitat degradation and fragmentation and disrupt natural processes. For instance, the extensive cultivation of bioenergy crops or tree plantations for carbon sequestration can transform complex ecosystems into monocultures, thereby disrupting ecological networks.[591] [592] What is needed are integrative management approaches that recognise the interconnectedness of ecosystem functions and integrate biodiversity conservation, climate change and land management goals within a cohesive implementation framework.[593]

Ecological processes do not stop at geopolitical boundaries. Connectivity and restoration require transboundary and international cooperation.[594] In the Mekong River Basin, which supports over 60 million people across six countries, deforestation and upstream dam construction have reduced, and are expected to continue reducing, water availability and quality downstream, threatening livelihoods, such as agriculture and fishing, as well as biodiversity.[595] Sand and dust storms typically originate in deserts or degraded areas, but their impacts are often felt thousands of kilometres away, with fine dust particles degrading air quality and affecting human health, disrupting social and economic activities in areas far from their sources.[596]

In regions such as the Sahel and the Horn of Africa, pastoralist communities migrate across borders in response to droughts, changing grazing conditions and scarce resources,[597] which can lead to conflicts, displacement and tensions between neighbouring countries. Wildlife also moves or migrates across borders. The Serengeti-Mara ecosystem, which is shared by Tanzania and Kenya, is home to the world's largest terrestrial migration: over 1.3 million wildebeest, zebras and gazelles move seasonally in search of fresh grazing land.[598]

Supporting Local Livelihoods to Support Conservation[708] [709] [710] [711] [712] [713]

The Kavango-Zambezi Transfrontier Conservation Area (KAZA TFCA) is one of the world's largest transboundary conservation areas, covering nearly 520,000 km² across the Okavango and Zambezi river basins in Angola, Botswana, Namibia, Zambia and Zimbabwe. The area is home to over 3,000 plant species, 100 of which are endemic to the sub-region. It also has substantial populations of wild dogs and elephants, with an estimated 250,000 elephants – around 50% of the world's savannah elephant population. Although several protected areas are linked by corridors, the KAZA TFCA is also home to around 2.5 million people who rely heavily on rain-fed subsistence agriculture and livestock production. Poaching and illegal logging are increasing, while poor harvests and poverty are forcing smallholder farmers to convert valuable habitats into agricultural fields, thereby exacerbating human-wildlife conflict. Local communities and their livelihoods are also under considerable pressure due to the impacts of climate change, weather extremes, droughts and water scarcity.

The KAZA ARISE Project is funded by the German Federal Ministry for Economic Cooperation and Development (BMZ) through the Engagement Global Programme and is implemented by the World Wildlife Fund (WWF) Germany in collaboration with local partners in Namibia, Zambia and Zimbabwe. The project aims to enhance both food security and habitat protection, acknowledging that 'only those who have enough food are interested in conservation'. Building on the idea that improved livelihoods for local communities can lead to better conservation, the project has supported 2,300 smallholder farming families and 225 livestock herders operating outside ecological corridors.

The project provided farmers with knowledge of sustainable agricultural practices and the resources needed for new farming methods, securing their long-term livelihoods. In Zimbabwe, farmers were provided with equipment to reduce tillage and improved seeds, which considerably reduced erosion and enhanced soil structure. Separate, distant boreholes were used to reduce human-wildlife conflict. In Namibia, farmers implemented agroecology in their fields and backyard gardens to enhance soil fertility by using composting, mulching and biochar. They also improved their rangeland management and livestock practices by using mobile livestock enclosures (kraals), for example, to protect animals at night while their manure and urine revitalised the soil. In Zambia, the project supported livestock health workers and trained farmers in conservation agriculture. The project also established joint working groups across the three countries, organised exchange visits to share knowledge and experiences and integrated agriculture into Transboundary Natural Resource Management (TRNRM) forums.

The proposed airport at Portugal's Tagus Estuary highlighted the complex interdependence of migratory bird conservation across international borders.

The Black-tailed Godwit (*Limosa limosa*) is a species that breeds in the Netherlands and relies on the estuary as a crucial non-breeding site. Damage to any intermediate habitats along a migratory species' route, including breeding, wintering or staging areas, can undermine conservation investments made elsewhere. Concerned about the impact on godwit populations, Dutch local authorities — who invest heavily in agri-environment schemes to support breeding success — petitioned the Portuguese government to reconsider its airport plans, leading to the project's cancellation following a national court case.[599] [600] [601] Shared resources require shared solutions, necessitating strong transboundary cooperation, data sharing, joint policy frameworks (including procedures for preventing, managing and resolving conflicts) and resource mobilisation.


Photo: ©Envato Elements

Integrated Planning to Create a Vision at the National Level

Governments are responsible for developing a national vision and governance framework that aligns with international commitments and addresses local challenges. This framework should set out how these challenges will be addressed and commitments achieved . This requires leadership and a clear mandate and is ideally facilitated by high-level government institutions, that can bring together sector ministries to guarantee integrated and inter-sectoral planning.

Getting the Planning Right: Integration is Key

Integrated land use planning intentionally *"assesses and assigns the use of resources, taking into account different uses, and demands from different users, including all agricultural sectors - pastoral, crop and forests - as well as industry and other interested parties"*.[602] It takes into account the biophysical and socio-economic factors, including demographic trends, infrastructure requirements, valuable natural resources, critical ecosystem services, geophysical constraints and administrative boundaries.[603] Modern land use plans indicate which types of land use changes and development are permitted in specific areas, the standards development must meet and where particular environmental safeguards apply. Land use planning is a useful tool for mainstreaming environmental targets, such as sustainable land management, ecosystem restoration and ecological connectivity, into decision-making processes that impact the landscape.[604] Ideally, land use plans should be guided by a long-term vision that aligns different sectors and governance levels in order to achieve maximum impact. Several aspects must be considered in integrated land use planning to address land degradation and enhance ecological connectivity.

Considering Ecological Connectivity in Integrated Land Use Planning: The Ridge to Reef Concept [605] [606]

Some Small Island Developing States (SIDS) have adopted context-specific integrated approaches to planning that focus on ecological connectivity. These islands are characterised by considerable variations in topography, climate and soil types, typically with high biodiversity and limited space for human settlements and economic activities. This makes them dependent on a healthy natural environment for socio-economic development, requiring consultation and planning in order to maintain and enhance connectivity processes and ecosystem services. The Reef to Ridge approach is a 'whole-of-ecosystem' planning and management strategy for SIDS that recognises and leverages the close connections between terrestrial, freshwater and marine ecosystems, ensuring effective cross-sectoral coordination.

Integrated land use planning should consider and address the drivers of environmental change, providing integrated, multi-sectoral solutions. Many land degradation and connectivity issues arise from fragmented governance and sector-specific decision-making. Integrated land use planning can ensure

that decisions account for environmental, social and economic factors, thereby promoting long-term resilience.[607] Implementing isolated restoration actions will not deliver the ecological connectivity needed to increase landscape integrity and resilience.[608] Integrated approaches that harmonise sectoral development policies can support the restoration of ecosystem functionality, particularly in human-modified and production landscapes, while minimising 'environment-development' trade-offs.[609] The importance of land use planning across sectors is particularly evident in the development of linear infrastructure (e.g. roads and railways) and the expansion of urban areas, both of which are major causes of connectivity loss.[610]

Integrated land use planning must consider multiple drivers of fragmentation and degradation while ensuring socio-economic, ecological and cultural benefits and realising the plurality of values associated with nature's contribution to people.[611] In order to enhance ecological connectivity on a landscape scale, the planning process involves multiple land units, which often have different land uses, jurisdictions and land tenure rights.[612] Integrated land use planning should be a participatory process involving broad stakeholder input in order to maximise win-win solutions for human well-being and sustainability. When assessing the social and economic context, important considerations include land tenure, poverty, the pressure to convert land for productive use, the capacity of local governments, social acceptance and political support.[613] The success of sustainable land management and restoration for enhanced connectivity relies on community support and delivering socio-economic benefits.[614]

Photo: ©Envato Elements

Ecological Connectivity is Front and Centre in South African Land Use Planning [615] [616]

The Republic of South Africa has become a world leader in integrated land use planning. The nation, which covers an area of over 1.2 million km², adopted the National Environmental Management Act and the Biodiversity Act in 2004. This landmark legislation required planners in every province to draft a bioregional conservation plan. These plans are fundamental to land use decision-making at local, municipal and provincial levels, influencing everything from habitat restoration to public works projects. Furthermore, the Spatial Planning and Land Use Management Act of 2013 categorises land use zoning and regulations.

This land use scheme covers rural and industrial development, conservation areas and more. A recent global assessment of connectivity conservation plans found that South African jurisdictions had produced dozens of plans calling for the legal protection or restoration of ecological corridors, largely as a result of this national legislation. In the northernmost province of Limpopo, for instance, planners identified four large-scale ecological corridors connecting significant protected areas and other critical biodiversity sites. Numerous smaller corridors were modelled using least-cost pathway analysis and manual refinement. From a large-scale planning perspective, these riparian and terrestrial corridors offer significant natural resilience in the face of climate change. Furthermore, they help government agencies in Limpopo prioritise areas for biodiversity conservation.

Integrated land use planning should be based on the best available data in order to support decision-making and prioritise solutions. An important step in landscape planning is to prioritise areas for restoration based on connectivity needs and opportunities, as this is critical for achieving the best possible outcome at regional, national and subnational levels.[617] It is fundamental to understand which areas are the most critical for supporting ecological flows and migratory animal movements that depend on networks of areas (often distributed across multiple countries). Mapping connectivity and the state of degradation, using methods such as least-cost path analysis helps identify where proposed developments are likely to impede connectivity and establish spatial priorities for restoring or preserving connectivity within landscapes. This can inform the allocation of resources to areas where they will have the greatest impact, as well as guide the design of connected landscapes by natural resource agencies, city and county planners, NGOs, and other entities.

It is considerably more efficient to act before land is degraded than to initiate complex and costly restoration initiatives afterwards.[618] Focusing on restoring functional connectivity, as well as structural connectivity, helps to identify areas with important ecological functions. This is particularly valuable for addressing the more extensive systems of functional sites, ecological networks and 'green infrastructure'.[619] [620]

Planning for Connectivity for Jaguars in South America [621]

Jaguars (*Panthera onca*) are wide-ranging carnivores at the top of the food web, found from Argentina to Mexico. Over 20 years ago, the Wildlife Conservation Society and the Universidad Nacional Autonóma de México brought together a group of jaguar experts to develop a comprehensive conservation plan for the species. After identifying over 50 jaguar population centres, the group undertook a genetic assessment that provided evidence of genetic exchange across the species' range. These findings led to the Jaguar Corridor Initiative, which aims to maintain and restore connectivity and gene flow across the jaguar's entire range. The initiative modelled connectivity among the population centres and identified 182 corridors covering 4.5 million km². Sixty-seven per cent of population centres and 46 per cent of the associated corridors were under some level of protection. The researchers then used a set of criteria to prioritise the conservation of jaguar populations and corridors, providing guidance for practical conservation efforts led largely by the non-profit organisation Panthera. The Jaguar Corridor Initiative can serve as a blueprint for conservation work, enabling species such as the jaguar to move across their entire range.

In a parallel effort, researchers in South America developed a connectivity model for the Maya Forest in Belize, identifying key sites for jaguar conservation. The model considers known jaguar locations, habitat suitability, the availability of prey, patch size and configuration and impact variables, such as road density and human population density. As drought, exacerbated by climate change, threatens the region's resilience, an additional analysis identified areas most susceptible to drought. The model predicts areas suitable for movement and identifies pinch points and barriers. It also helps prioritise areas where improving forest cover, promoting sustainable, drought-resistant agroforestry activities and reducing the effects of barriers would be most effective in increasing connectivity between jaguar populations. Spatial models are key tools for conservation and restoration planning, as they help prioritise areas for protection. The two connectivity modelling approaches for jaguar population centres described above can be applied or adapted to range-wide conservation and restoration planning for other 'umbrella' species.

Putting Plans into Practice: Adapting Policy and Legal Frameworks

In order to scale up sustainable land management and restoration for ecological connectivity, these concepts must be integrated into environmental, social and economic policies.[622] Any policy or legal framework must be based on sound science and the application of the precautionary principle and adhere to principles of good governance - including the meaningful participation of Indigenous Peoples and local communities, adhering to social safeguards and ensuring Free Prior and Informed Consent, equity, fairness, transparency and benefit sharing.

EU Green Infrastructure Strategy: One Solution for Multiple Objectives

The EU Green Infrastructure Strategy recognises that green infrastructure and nature-based solutions can contribute significantly to achieving multiple policy objectives and that investments in green infrastructure and restoration typically offer low cost-benefit ratios. Adopted in 2013, the Strategy is the EU's primary policy instrument on green infrastructure and aims to promote its deployment in urban and rural areas to halt biodiversity loss and ensure the delivery of ecosystem services. It also contributes to Target 2 of the EU Biodiversity Strategy. Guiding the implementation of green infrastructure at regional, national and local levels, the Strategy aims to restore ecosystem health, ensure the connectivity of natural areas and support natural habitats and healthy species populations to ensure the delivery of a range of ecosystem services. A key feature of the Strategy is its aim to integrate green infrastructure into other relevant policy areas, including the Common Agricultural Policy, the Water Framework Directive, the Floods Directive, the Adaptation Strategy, the Marine Strategy Framework Directive, the Mapping and Assessment of Ecosystem Services (MAES) initiative and urban planning policies.

Photo: ©CuatroK77

5.2

Engaging Local Communities and Integrating Traditional Knowledge

Although transboundary and national governance frameworks establish the broader policy context, local communities and organisations are at the forefront of implementation.[623] Due to the complexity of managing ecological connectivity at a national level with social and geographical complexities, governments in many regions lack the resources and capacity to effectively manage vast landscapes. It is often community-led governance structures, cooperatives and local NGOs that implement programmes, monitor land health and ecological connectivity and mediate conflicts over resources.[624]

Photo: ©Envato Elements

Biological Corridors in Costa Rica: Participatory Connectivity Restoration[714] [715] [716]

In Costa Rica, biological corridors are used to restore ecological connectivity and re-establish ecological processes in areas with different land ownership and usage. This involves a participatory process with all local stakeholders. Costa Rica has promoted biological corridors since 1990, beginning with the establishment of the Talamanca-Caribe Corridor. In 2006, the process of institutionalising biological corridors as a strategy for conserving and restoring biodiversity began with the establishment of the National Bio-Corridor Programme (PNCB) (Executive Order 33106 of the Ministry of Environment, Energy and Telecommunications). In 2018, the Second Strategic Plan of the National Programme of Biological Corridors for the period 2018–2025 was approved. The programme's mission is: *"Promoting ecological connectivity and social integration for the conservation, restoration and sustainable use of natural resources for human well-being"*.

According to the Second Strategic Plan, biological corridors are defined as "*continental, marine-coastal and island delimited territory whose primary purpose is to provide connectivity between protected wild areas, as well as between landscapes, ecosystems and habitats, natural or modified, being rural or urban to ensure the maintenance of biodiversity and ecological and evolutionary processes; providing spaces of social agreement to promote investment in the conservation and sustainable use of biodiversity in those spaces*" (Art 4. Executive Order N°40043 of Ministry of Environment and Energy). The Plan introduces two new types of biological corridor: inter-urban biological corridors (IBCs) and coastal-marine biological corridors (CBMCs) (Article 5, Executive Decree 40043, Ministry of Environment and Energy). The goals of the Strategic Plan include increasing the extent of natural cover and green spaces (known as 'Trama Verde') in IBCs through restoration, recovery and/or reforestation. Carbon emission reduction strategies are applied in biological corridors to benefit soil restoration and conservation. In this regard, biological corridors provide opportunities to establish mitigation projects that promote carbon sinks through soil management.

Biological corridors contribute to the conservation and restoration of biodiversity, as well as to sustainable development and socio-ecological benefits, by improving the quality of life for communities dependent on local biodiversity. Recognising this, they were established in close collaboration with local stakeholders. As most of the land is privately owned and cultivated, securing the support of farmers and landowners is essential. Landowners are encouraged to participate in the corridors by allocating land for conservation, agroforestry and reforestation. This is supported by Payment for Ecosystem Services (PES) which prioritise and target specific areas to increase forest cover and connectivity within the corridor.

The involvement of local communities, stakeholders and landowners in the management of the biological corridor is essential. Participatory platforms known as Local Committees of Biological Corridors establish goals for the sustainable use of natural resources. These committees facilitate governance, negotiation and dialogue. They support partners and civil society at local levels in drawing up corridor management regimes. The success of a biological corridor depends greatly on the composition and functioning of the local committee. Widespread participation and the representation of diverse interests and sectors can facilitate the integration of their perspectives on the use and conservation of natural resources within the corridor. Over 40 individuals from the local committees, environmental and scientific NGOs, regional agencies, the national government and universities were involved in drafting the management plan for the Amistosa Biological Corridor. Costa Rica currently has 44 biological corridors representing 33% of its land area, 26 of which already have a management plan in place.

Sustainable land management is most effective when top-down policies align with bottom-up actions and when socio-ecological connectivity is considered and enhanced. Nature creates many different values, often associated with Indigenous Peoples' and local communities' world views, that are not considered in policymaking. They often overlook the non-market values of nature's contribution to people and their livelihoods.[625] To ensure that national and regional policies are responsive to local realities, governance frameworks must recognise and incorporate local knowledge and needs into decision-making processes. They must also strengthen local governance structures, such as community forestry groups and water user associations and improve capacity building efforts to enhance communities' ability to manage land sustainably and engage in policy dialogues. Equitable benefit sharing and a just transition to more sustainable management practices and restoration, that considers potential alternative income streams for impacted communities, must also be ensured. In many regions, the success of connectivity and restoration projects and programmes depends on effective and equitable collaboration with Indigenous Peoples and local communities.[626]

Secure land tenure and resource rights are crucial for incentivising sustainable management practices.[627] Tenure security — the assurance that individuals, communities, organisations or the private sector have long-term rights to use, manage and benefit from land — is one of the most important factors in encouraging sustainable land use and restoration.[628] When tenure is unclear or insecure, communities are often discouraged from investing in management practices that could support ecological connectivity, as they fear eviction or loss of income. Conversely, secure tenure has been linked to the increased adoption of practices such as agroforestry, soil conservation and reforestation.[629]

It is crucial to recognise the importance of Indigenous lands and leadership in achieving landscape connectivity and restoration.[630] Indigenous Peoples and local communities often possess in-depth knowledge of ecological interactions. Strengthening their role in land stewardship can include recognising the territorial rights of Indigenous Peoples and local communities,[631] involving them in leading or co-leading partnerships[632] and acknowledging their knowledge, innovations, practices, institutions and values.[633] It is also crucial to include Indigenous Peoples and local communities in scientific studies, impact assessments and monitoring activities.[634]

The Value of Traditional Management Practices: Sacred Groves in Ghana[635]

Sacred groves are small areas of pristine forest or habitat that are protected by local religious or cultural organisations. These small pockets of biodiversity are maintained by traditional institutions, often without government involvement, and can help to preserve natural forests and rare species for religious, cultural and medicinal purposes. They are protected on religious or cultural grounds – for example to maintain water courses, plants or animals for traditional deities or royal burial grounds – and enforced by strict customary laws or beliefs.

It is estimated that Ghana has around 2,000 to 3,000 sacred groves, mostly in the south of the country. These areas can range in size from a single tree or rock to several hectares. Together, the sacred groves in Ghana form the most extensive connected forest cover outside of protected areas. Local communities have established rules and taboos regarding the use of natural resources within the groves, which can differ from one grove to another. For instance, hunting, farming and collecting snails is forbidden in the Numafoa and Kobri sacred groves in the village of Nanhini in south-west Ghana, while gathering medicines and tapping palms for wine is permitted. Although these rules have no legal basis, they are strong enough to ensure adherence. This often leads to reservoirs of biodiversity being maintained across generations, in contrast to the degradation in the surrounding areas. In the case of the Tamale sacred grove in northern Ghana, for example, the community's protective measures transformed the open canopy forest into a canopy forest, further increasing the area's already rich biodiversity and providing a refuge for native species that can no longer be found anywhere else in the region. Studies of the Jaagbo sacred grove revealed 220 plant species, compared to just 60 species found in neighbouring areas. It is also estimated that the last specimens of southern marginal forest types, as well as inner-zone subtypes of dry semi-deciduous forest, are found in Ghana's sacred groves.

These traditionally maintained remnants of natural ecosystems play an important role in conserving and restoring flora and fauna. However, sacred groves and other traditional management methods are under considerable pressure due to rapid population growth, associated migration and resettlement and urbanisation. This leads to increased resource exploitation and agricultural encroachment, as well as the erosion of traditional beliefs and practices.

Women play a vital part in managing land and water resources and must be involved in decisions about ecological connectivity.[636] [637] Many societies have gender-specific roles built into their environmental resource management. Understanding the cultural context in which efforts to restore ecological connectivity are implemented[638] and analysing gender dynamics and inequalities can help identify appropriate entry points and strategies to ensure women's involvement and empowerment.[639] Conditions that enable equitable participation and benefits for women and men should be created, acknowledging the important role women play in the management of natural resources.

5.3

Financing Large-Scale Initiatives to Restore Land and Ecological Connectivity

In the long term, supporting the restoration of ecological connectivity requires considerable and sustained investment, integrating innovative financial instruments and leveraging public-private partnerships and blended finance. It is also essential to ensure that funding reaches local actors, who are best positioned to implement solutions on the ground. Currently, there is no systematic approach to financing the scale of restoration required to recover ecological connectivity. Various options are being explored in different countries.

Public Funding: Governments play a critical role in providing the initial funding required for land restoration, conservation and improving ecosystem connectivity. Some governments have allocated direct funding for large-scale restoration projects. For instance, China's Grain-for-Green programme has restored over 30 million hectares of degraded land by providing subsidies to farmers for planting trees.[640] Other countries have developed Payment for Ecosystem Services (PES) schemes. Programmes such as Costa Rica's PES scheme compensate farmers and landowners for maintaining forests and safeguarding ecosystem services.[641] International funds and multilateral financing mechanisms can provide essential resources, particularly for developing countries, where budget constraints can limit the scope of large-scale restoration projects. The Global Environment Facility (GEF) and the Green Climate Fund (GCF), for example, have supported projects such as the African Great Green Wall Initiative, which aims to restore 100 million hectares of degraded land across the Sahel which could benefit the connectivity of migratory species.

Incentivising Watershed Management: An Example from Jesus de Otoro, Honduras [642]

The Programme for Sustainable Agriculture in the Hillsides of Central America (PASOLAC), based in Jesús de Otoro, established a Payment for Environmental Services (PES) scheme to incentivise sustainable watershed management. In the 1990s, the town experienced significant problems with water quality and access, fuelling conflict between upstream coffee producers and downstream residents concerned about drinking water pollution. The scheme compensated landowners for adopting sustainable land management practices and conserving forest cover. These practices included avoiding slash-and-burn techniques, practising agroforestry, building irrigation ditches and terraces, constructing vegetation fences, using organic fertiliser, managing waste and recycling, practising organic agriculture and conserving existing forests. The scheme was administered by a local NGO, whose members were elected in general assemblies in the ten different areas of the town. The NGO signed agreements with funders, setting out the commitments of upstream land users and the payment amounts, which were determined based on the practices adopted. Each household was then charged 3.6% of the estimated willingness to pay per month. The municipality was also expected to contribute 1% of its annual income.

Photo: ©Envato Elements

Examples of Large-Scale Donor Funding to Enhance Ecological Connectivity [643]

The Amazon Sustainable Landscapes Programme and the Global Wildlife Programme, both of which are funded by the Global Environment Facility (GEF) and led by the World Bank, focus on supporting national efforts to enhance landscape connectivity. The specific methods employed to achieve this vary from country to country. For instance, a national-level project in the Colombian Amazon under the Amazon Sustainable Landscapes Programme aims to enhance forest connectivity and the resilience of people and wildlife by investing in low-carbon development. Another project in Ecuador involves establishing corridors and management mechanisms to conserve the surrounding ecosystems in the long term.

Private Finance: The private sector is becoming more aware of the risks posed by land degradation and fragmentation to supply chains, water supply and long-term economic stability. Evidence that sustainable land management and restoration can contribute to yields and makes business-sense can incentivise the private sector to scale up success stories, especially in agricultural production. Sustainable finance mechanisms and impact investment funds are channelling investments towards regenerative agriculture, sustainable forestry and biodiversity conservation. Some companies have introduced sustainable supply chain programmes to encourage smallholder farmers to adopt sustainable practices, thereby ensuring long-term productivity and ecosystem health.[644] Financial institutions are issuing green bonds to support land restoration, reforestation and watershed protection projects. The World Bank's Green Bond Initiative has financed climate-smart agriculture and land restoration projects worldwide.[645] By combining public and private investment, blended finance mechanisms help to reduce the risk associated with sustainable land management projects. The Land Degradation Neutrality (LDN) Fund, which is managed by Mirova in collaboration with the UN Convention to Combat Desertification (UNCCD), mobilises private investment in sustainable land management and restoration projects.[646] [647]

Incentivising the Recovery of Degraded Land for Soy Production in the Cerrado, Brazil [648]

Brazil is one of the world's leading soy producers, accounting for 30% of global production in 2020/21. Half of Brazil's soy production takes place in the Cerrado region, which has considerable natural value due to its biodiversity and water reserves. It is estimated that the amount of land used for soy production in Brazil will increase by 10.3 million hectares between 2021 and 2030. To avoid clearing native vegetation, this growth could be achieved by increasing productivity in existing cleared areas, such as degraded pasture land. In the Cerrado region, around 18.5 million hectares of cleared land are available to support soy crop production, of which 7 million hectares are considered degraded. The Reverte Programme, implemented by the Nature Conservancy, supports rural producers in the Cerrado region in rehabilitating degraded areas using regenerative agricultural practices, integrated crop-livestock systems, integrated pest management, intercropped harvests and input protocols.

Financial tools and incentives play an important role in the project. TNC collaborated with Itaú BBA to improve access to finance and establish socio-environmental and agronomic criteria for obtaining credit. The two main criteria for accessing financing under the programme are the non-conversion of native vegetation and ensuring that grain production does not exceed 25% of the total property area. Qualified technical experts evaluate the state of degradation and support the implementation of environmental and agricultural practices in line with the programme, ensuring that any implemented practices enhance native vegetation, avoid soil degradation and increase productivity in former degraded areas. In return for implementing these sustainable practices, participants can access loans with favourable payment terms and interest rates, with a disbursement period of seven to ten years. Of the 144,600 hectares that will be restored in the first phase of the project, over 31,000 hectares will be restored using funds from the US$32.7 million credit line.

Photo: ©Envato Elements

Financing Catchment Management of the Wyre Catchment, UK [649] [650]

The Wyre is a 45 km-long river which originates in the Forest of Bowland in north Lancashire and flows towards the Irish Sea near Blackpool. As part of a collaborative initiative, the Rivers Trust, the Wyre Rivers Trust, Triodos Bank UK, the Environment Agency, United Utilities, Flood Re, Co-op Insurance and the Esmée Fairbairn Foundation are set to implement over 1,000 targeted measures, including woodland creation, bunded hedgerows, ponds and leaky dams, across 70 hectares and 10 landholdings. These measures are designed to manage peak flows and mitigate flood risk within the Wyre catchment. This initiative was launched following the flooding of 5,200 homes and the disruption of power to 43,000 households caused by Storm Desmond in 2015. The Wyre Catchment Natural Flood Management Project will implement nature-based solutions using a blend of public and private finance. Nine investors were involved in providing an £850k loan from Triodos Bank UK. The Woodland Trust provided grant funding of £627,500. The annual management costs and the loan were financed through payments for improving water quality, among other sources.

A group of potential buyers, consisting of the Environment Agency, Flood Re, United Utilities and Co-op Insurance, initiated the project. These buyers were interested in natural flood management to support existing grey infrastructure and reduce damage to their physical assets during floods, amongst other objectives. Two additional buyers, Wyre Council and the North West Regional Flood and Coastal Committee (RFCC), later joined the group. The buyers pay land managers steadily increasing rates to implement and maintain nature-based solutions through an initial nine-year contract. The initial capital costs were paid by external investors, which reduced the capital delivery risk for the buyers. After the sixth year, the buyers make outcome-based payments based on monitoring data and the Wyre Rivers Trust's assessment of the performance in delivering ecosystem services. If the project is successful, the contracts can be extended for periods of up to 50 years. As well as enhancing natural flood management, the project is also expected to improve carbon sequestration, water quality and biodiversity.

Community-Based Finance: For financing to be effective, local stakeholders, including Indigenous Peoples and local communities, smallholder farmers, pastoralists and grassroots conservation groups, must have access to flexible, long-term funding designed to support their needs. Local communities in rural areas often face considerable barriers when trying to access funding to implement measures that support sustainable land management and enhanced connectivity due to their limited organisational capacity.[651] Consequently, they frequently depend on donor funding to implement restoration projects and programmes, reverting to unsustainable practices once project support concludes.[652] This issue is exacerbated by the absence of local markets for certified products and ecosystem services.[653] Local communities must benefit from restoration efforts to incentivise the maintenance of good practices in the long term and enhance ecological connectivity. These benefits can include monetary incentives, in-kind benefits, income from diversified livelihoods,[654] [655] access to markets and key services, such as electricity.[656] Decentralised and community-based funding mechanisms can address some of these barriers, enhancing local ownership and autonomy in prioritising management and restoration actions based on specific needs and local contexts,[657] thereby improving their standard of living.[658]

Community Finance in Germany's Organic Sector [659]

Considerable investments are required to transform agri-food systems and shift towards regenerative agricultural practices. Private finance has emerged as an important source of funding, particularly for small and medium-sized enterprises (SMEs), to complement public funding. However, increasing awareness of sustainable production and consumption has also led to the emergence of community-based finance as another potential source of funding. These models involve citizens or consumers in financing more sustainable agricultural practices. These models can increase SMEs' financial independence from credit institutions and ensure funding for initiatives that may struggle to access credit, since community investors are often more willing to accept low financial returns and a lack of collateral. Although it is still a niche market, community financing is being used more and more in the German organic food sector to complement or substitute traditional credit financing. Various models are employed, including pure financing instruments such as direct loans, crowdfunding or profit participation; financing models based on legal forms such as cooperatives; financing through intermediary organisations to pool citizen capital such as land purchase cooperatives or citizen shareholder corporations; and other mechanisms including leasing, sponsorship and community-supported agriculture (CSA).

Enhancing Access to Finance Through Microloans

Kiva and Root Capital are two organisations that aim to improve smallholders' access to finance using community-based financing. **Kiva** operates using a crowdfunding model and works with lending partners to reduce the administrative burden of screening borrowers, disbursing funds and carrying out other administrative duties. Kiva has partnered with over 77 lending organisations, primarily microfinance institutions, non-profits and social enterprises, and has disbursed around US$2 billion to 5 million borrowers. These partners are committed to enhancing financial inclusion for the 1.4 billion people worldwide without access to banking services. They support borrowers in creating savings accounts and offer financial literacy programmes, business management training, healthcare screening and peer support. Once a smallholder has applied for a loan, their request is posted on the Kiva website, where citizens from around the world can contribute to the cause. Kiva then transfers the funds to the lending partners, who disburse them to the borrower. Once the smallholder has achieved their goal and is able to earn a profit, they repay the loan through the lending partner. Over 96% of loans are repaid.[660] [661]

Root Capital focuses on supporting agricultural enterprises in countries experiencing economic and political instability, climate shocks and extreme market fluctuations , which requires an increased risk appetite. Their work is based on four pillars designed to enhance rural resilience: access to finance, next-generation jobs, climate action and women's empowerment. Root Capital is an impact-first investor that uses donations to support small, growing agricultural businesses. Over the last 20 years, Root Capital has supported 1,000 businesses, positively impacting 2.3 million farming families.[662] [663]

To create accessible, long-term, results-oriented funding streams that prioritise ecosystem health, community resilience and sustainable livelihoods, governments, businesses and financial institutions must work together. This requires an enhanced understanding of, and guidelines for, considering ecological connectivity in restoration, biodiversity and climate change adaptation projects and programmes.

5.4

Research and Monitoring for Informed Decision Making

To ensure effective plans, legislation and regulations, as well as projects and programmes, planners, decision-makers and project/programme developers must be supported by the best available knowledge.

Evidence-Based Decision-Making

There is a significant research gap manifest in the limited integration and optimisation of ecological networks and the application of ecological connectivity for different ecological flows. Although considerable research has been conducted on ecological connectivity in terms of wildlife movement and hydrological functions, the contribution of other natural flows to ecosystem functioning and the drivers disrupting these processes, has received considerably less attention, despite these flows playing a vital role in maintaining healthy ecosystems. Consequently, there is a lack of policy-relevant information on connectivity in more complex and human-modified social-ecological systems, such as urban areas and agricultural landscapes.

Another knowledge gap concerns the applicability, costs and benefits of nature-based solutions, such as those described in Chapter 4. While certain approaches, such as regenerative agriculture and grazing management, have received increasing attention from farmers and researchers, large-scale and long-term studies demonstrating their contribution to ecosystems and people are still limited. As these practices are adopted more widely, diligent monitoring of their positive and negative impacts in different contexts can contribute to a better understanding of the challenges and opportunities.

While the ultimate objective of efforts to enhance ecological connectivity should be to preserve and restore functional connectivity, monitoring these attributes is often more time-consuming, labour-intensive and costly than modelling structural connectivity.[664] [665] Consequently, country-level monitoring (e.g. for reporting progress towards international agreements) and past research have focused on structural connectivity data and indicators derived from remote sensing. This monitoring primarily involves measuring changes in landscape composition and configuration over time,[666] which only provides limited information on the state of ecological flows and the extent to which structural elements support these processes.

An overview of trends in land degradation and fragmentation over time would be an asset for policymakers. Data on the state of ecosystems is often patchy, with considerable bias towards areas where substantial research has been conducted. Remotely sensed data can be a useful and relatively cost-effective way of identifying changes in land cover, as in the case of land degradation indicators. If these data sets could be analysed more frequently and used in combination with other data, it would allow for the more accurate detection of changes in connectivity and degradation processes. Considering both processes in tandem could help to identify areas at risk whose further decline could be prevented through sustainable land management, as well as areas that require intervention to avoid catastrophic disruption to ecological processes. This dual monitoring approach could also help to identify hotspots and cold spots, enabling initiatives to prioritise connectivity measures.[667]

Enhanced Monitoring for Adaptive Management

The optimal approach to restoring connectivity is often unclear. Implementing a variety of strategies, alongside systematic monitoring and evaluation, enhances our understanding and increases the likelihood of achieving successful outcomes.

Monitoring is essential for adaptive management - a structured, science-based approach to improving our understanding, reducing uncertainties and adjusting restoration strategies.[668] The benefits of adaptive management are numerous: it can engage and empower communities and organisations to take action; guide monitoring efforts; make a case for methodical data management and reporting; and improve understanding of the effects of actions. Ultimately, adaptive management provides decision-makers and stakeholders with greater certainty and leads to course corrections and better decision-making. Sharing lessons learnt with other communities working towards similar goals will promote the restoration of connectivity at a landscape level.[669]

The complexity of landscape interactions, coupled with the limited availability of data, makes it difficult to monitor ecological connectivity. While there are a few established monitoring frameworks for species movement, ecological corridors and protected areas, there are still no systematic assessment protocols that incorporate the majority of the key elements of structural and functional connectivity. Annex 1 illustrates some of the essential variables and indicators of change that could be used to evaluate connectivity within complex social-ecological landscapes. Taking into account the relevant spatial scales and their relationships enables more effective design and implementation, as well as supports decision-making at different levels.

Effective management and use of monitoring data depends on information being findable, accessible, interoperable and reusable (FAIR).[670] Data on DLDD, land restoration and ecological connectivity is often fragmented and there is limited collaboration, coordination and knowledge sharing between institutions working on these issues. Restoring land to enhance ecological connectivity requires information on various ecological parameters, including soil quality, hydrology and biodiversity as well as socio-economic metrics.[671] Standardising, harmonising and sharing data is vital to ensure interoperability and the exchange of reliable information on connectivity and restoration progress.[672] This can also facilitate collaboration among government, non-governmental and community-based organisations, driving a unified approach towards achieving land restoration and ecological connectivity goals.

Scientific research can provide data-driven solutions, while traditional knowledge offers time-tested, place-based land management practices. Combining these knowledge systems enhances resilience and the effectiveness of connectivity initiatives.[673] [674] This ensures that implemented solutions are locally appropriate, strengthen community trust and are self-sustaining. Involving communities — men, women and young people — in monitoring connectivity can increase their support for restoration projects and programmes, enhancing community awareness and engagement with environmental issues.[675] Collecting data on plant and animal species at fine resolutions can inform connectivity assessments at a local level. If this is done across broad spatial scales by involving many communities over many years, it is possible to make inferences about landscape-level connectivity and species responses to environmental changes.[676]

Digital Solutions and Technologies

Digital tools and platforms can support regular monitoring and assessment of the risk of land degradation and fragmentation, enabling proactive measures to mitigate social and economic impacts.[677] One fundamental technological advancement used in land restoration and ecological connectivity is remote sensing. It has considerably enhanced ecosystem management, enabling land managers to assess ecosystem dynamics at relevant scales

over time and adopt integrated land use planning and adaptive management practices.[678] [679] Participatory geographic information systems are a mapping and scenario planning approach that incorporates the ecological knowledge and values of local communities and experts in specific fields. Engaging with local stakeholders can improve understanding of complex ecological and social dynamics and identify ecological opportunities adapted to complex, multi-scale human interactions. [680] [681]

Supporting Digitalisation and Data Driven Decision-Making: The SMART Way [682] [683]

SMART is a suite of software and analytical tools designed for a variety of conservation applications. The platform standardises and streamlines the collection, visualisation, analysis, storage and reporting of various types of data, including those relating to biodiversity conservation, tourism management, law enforcement and intelligence, as well as natural resource use, performance and threat level assessments. It facilitates the dissemination of critical field-level information to key decision-makers and can be customised for various contexts and requirements. SMART also has a specific mobile app called SMART Collect to support citizen science and community reporting.

The Albany Biosphere Initiative (ABI) in the Eastern Cape of South Africa, implemented by the Conservation Landscapes Institute and the Wilderness Foundation Africa, used SMART to support their goals of restoring, protecting and connecting functional ecosystems covering state, private and community land, including the Addo Elephant National Park and the Great Fish River Reserve. The initiative aims to establish robust monitoring protocols and comprehensive baseline data to support planning, identify the implementation needs, facilitate periodic impact assessments and enable adaptive management on a day-to-day basis. SMART was used to standardise data collection across wildlife areas and capture the state of health of the intervening land. Ecologists and managers of the game reserves were brought together to discuss key data collection needs, existing requirements and individual research and monitoring objectives, ranging from water and waste management to game counts and vegetation surveys. Based on these workshops, standardised models and a data collection framework tailored to their needs were developed, saving valuable time and human resources in a large, under-resourced landscape. Adjustments to the framework and models can be made after the first round of reporting. The Initiative has started planting native vegetation and is using SMART to record the growth and survival rates of new plants.

Innovations in digital technology can facilitate the integration of different data sources and automate data collection and analysis. Recent studies have assessed the potential of combining blockchain technology with geospatial data and cloud-based solutions to enhance the efficiency of land administration processes.[684] This can be used to support land use planning, improve coordination between institutions and sectors and prevent conflicts over land use that could undermine restoration and connectivity-related goals. Artificial intelligence, supported by a robust ethical framework,[685] can streamline environmental data management processes,[686] optimise resource use and help to identify the most suitable management interventions.[687] It can also support land restoration by optimising the use of drones for automated assisted natural regeneration.[688]

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6

Conclusion

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Ecological connectivity, in all of its diversity, supports the productivity and resilience of the natural systems that underpin the health and wealth of our societies. There is increasing awareness of the importance of integrating measures to restore and enhance ecological connectivity into landscape management, taking into account its structural and functional dimensions at all levels of land use planning. While targeted interventions can help to preserve certain species or habitats, we urgently need to conserve, restore and sustainably manage land and water resources beyond protected areas. This includes the interconnected processes and ecological flows that contribute to human wellbeing and a healthy environment.

Desertification, land degradation and drought fragment landscapes and impede connectivity processes. This exacerbates the loss of vital support services such as healthy soils, forests and watersheds which provide clean water, air and food and act as buffers against disasters. Restoring ecological connectivity enables flora and fauna to migrate and maintain healthy populations, facilitating the exchange of genes and thereby increasing their resilience and adaptability. These species interact across landscapes, maintaining key ecological processes that replenish natural capital and provide benefits that enrich lives and livelihoods.

Restoring degraded land can help to reconnect isolated patches within a landscape, re-establishing connectivity to safeguard important ecosystem services.

- Buffer zones, wildlife corridors and riparian strips that link natural areas facilitate species movement and enhance resilience by enabling range shifts in response to climate change or natural disturbances.
- Restoring wetland and riparian ecosystems – reconnecting 'blue lifelines' – improves hydrological and aquatic connectivity, enabling fish and amphibians to migrate between their breeding and feeding grounds.
- Reconnecting natural and agricultural landscapes, such as through agroforestry and regenerative agriculture, can improve soil health, farm productivity and food security.
- Nature-based solutions to enhance connectivity in urban and peri-urban areas can include parks, forests and green belts, terraces and constructed wetlands, the renaturation of streams, additional green and blue spaces and strategic wildlife corridors.
- Economic incentives, regulation, impact assessments and corporate responsibility in the energy, mining, transport and manufacturing sectors can help to minimise their ecological footprint while actively contributing to land restoration and greater ecological connectivity.

Sustainable land management and restoration are active processes that foster resilience and connectivity within landscapes. These practices ensure that ecosystems and species, including humans, have the capacity to adapt, survive and thrive. 'Connect to restore and restore to connect' represents a paradigm shift in how we use and manage land, water and biodiversity resources. It requires a combination of quick action using proven technical approaches and an integrated, participatory planning process with committed leadership by a strong government entity to restore entire landscapes. Raising awareness of and building capacities to implement specific roles and responsibilities is a first step towards transformational changes that will reinstate ecological connectivity and engage diverse stakeholders in land and ecosystem restoration.

- **Governments** at all levels can demonstrate leadership by establishing normative frameworks, enforcing regulations, promoting responsible governance, providing stability and security for all citizens, financing ecosystem restoration and sustainable land use and creating the necessary infrastructure to monitor results. This involves integrating ecological connectivity into land administration and institutions responsible for land, water, climate and biodiversity planning, as well as creating incentives for sustainable management practices and monitoring progress towards connectivity and restoration commitments.

- **Private sector** actors should minimise their land footprint by investing in sustainable and transparent supply chains and supporting large-scale restoration efforts that enhance connectivity. This entails a shift from short-term extractive models to long-term investments in regenerative land management, avoiding, reducing and reversing land degradation and fragmentation. This may require incentives and regulations that transform business models and supply chains, such as participation in certification schemes for sustainable products. Technology providers and start-ups could offer imagery and analytics for precision agriculture, as well as tools for monitoring changes in land use and fragmentation, such as dashboards and apps for citizen science with real-time data, or the use of artificial intelligence, drones and sensors for the precise monitoring of connectivity indicators.

- **Local communities, Indigenous Peoples and smallholder farmers** are the frontline stewards of land, water and biodiversity. Their traditional knowledge, human rights and development priorities must be recognised and supported by providing them with secure land tenure, building their capacities and giving them direct financial access. Their observations and understanding of the land, biodiversity and seasonal patterns can contribute significantly to the design, implementation and monitoring of connectivity and restoration initiatives. They can also play a pivotal role in collecting relevant land use data, including information on nature-positive agricultural practices, soil health and water availability, crop and livestock rotations and overall land productivity.

- **International organisations and donors** can support the integration of ecological connectivity into the landscape restoration and conservation initiatives that they fund and implement while ensuring that financial mechanisms are accessible to local stakeholders and aligned with national development priorities. They can also contribute to more effective monitoring, beyond their own projects and programmes, by providing guidance on the use of indicators through open-access platforms, such as SEPAL, Trends.Earth and Global Forest Watch, which facilitate data exchange and technical assistance.

- **Civil society organisations and academia** also play a critical role in collecting data and developing standardised monitoring frameworks that facilitate knowledge exchange, stimulate innovation and create practical tools that ensure transparency and accountability in restoration and conservation initiatives. They can provide third-party assessments and audits and train local stakeholders in project design, implementation and monitoring techniques and data analysis. In addition to making their findings accessible to governments and the private sector, they can raise public awareness and educate young people about the importance of ecological connectivity and restoration.

Ecological connectivity is not an abstract concept, rather it is comparable to the cardiovascular system of a living planet. Connectivity enables water and nutrients to flow, vegetation to grow, seeds to disperse, animals to migrate and cultures to flourish. However, as these networks are increasingly being severed, we find ourselves at a crossroads. Focusing solely on maintaining pockets of connected ecosystems through ecological corridors and protected areas will not be sufficient to achieve land degradation, biodiversity and climate change targets if surrounding areas continue to be severely degraded and fragmented. A holistic approach, adapted to local realities and challenges, should be adopted integrating connectivity considerations into broader development priorities that rely on land use planning, landscape management, biodiversity conservation and ecosystem restoration initiatives.

Annex 1

Monitoring Ecological Connectivity

Monitoring is essential for measuring progress towards goals and targets relating to ecological connectivity and land restoration. It facilitates iterative learning and the adoption of adaptive management practices, thereby enhancing the effectiveness of conservation and restoration projects and programmes. However, effective monitoring of ecological connectivity is hindered by the complexity of the interactions between biophysical and socioeconomic variables that shape a landscape and its management, coupled with a lack of available data.

While there are a few established monitoring frameworks for species movement, ecological corridors and protected areas, there are no systematic assessment protocols that incorporate the majority of the key elements of structural and functional connectivity. Figure 8 illustrates some of the essential variables and indicators of change that could be employed to evaluate ecological connectivity within complex social-ecological landscapes. These indicators can be adapted to different contexts and spatial scales and further refined using guidance from existing monitoring frameworks relating to agricultural biodiversity, rangeland health, ecological corridors and protected areas, nature-based solutions and integrated land use planning. They can also be used for national reporting under the Rio conventions.

The choice of variables and indicators to monitor ecological connectivity depends on the nature and objectives of the interventions implemented and resource availability. Some illustrative monitoring scenarios have been developed as part of Annex 1 to showcase how different variables and indicators can be combined to meet specific monitoring objectives. It is also necessary to consider the relevant spatial scales and their relationships to enable more effective design and implementation. At the **management unit level**, land users (whether acting individually or collectively) typically require contextual data to evaluate the effectiveness of their efforts on a project scale. This may include:

- basic or core indicators of profitability and productivity;
- process indicators to provide insights into efficiency and quality of the implementation; and
- impact indicators to assess the overall performance of management interventions.

At the **landscape level**, data is needed to inform integrated land use planning. This ensures that different sectors and stakeholders work towards a common goal and that limited resources are allocated cost-effectively and efficiently. The data should also guide management units in permitted or encouraged land uses and management practices, promoting functional and connected landscapes. At the **national and regional levels**, information on the health of ecosystems (e.g. fragmentation, degradation and the impact of climate change) is required to support the management of shared natural resources, whether within or across national borders. For example, enhanced cooperation on transboundary watershed management and shared protected areas, aligned with landscape-level planning, can significantly boost efforts to restore ecological connectivity.

FIGURE 8

Some variables and key indicators that can support the development of context and scale-specific monitoring frameworks for ecological connectivity.

Nature-Positive, Integrated and Sustainable Agriculture

Integrated management practices, such as those that combine agroforestry with agroecological crop-livestock systems, can be employed in croplands and rangelands to reduce fragmentation and re-establish structural and functional ecological connectivity. Key considerations at the management unit level include the extent to which the existing vegetation contributes to (i) reconnecting fragmented land parcels, (ii) conserving wildlife corridors or facilitating wildlife movement, (iii) providing riparian buffer zones, and (iv) enhancing soil and water conservation. Monitoring objectives typically include:

- Assessing the extent by which diversified land use and management practices support agricultural **productivity and resilience**.
- Monitoring the contribution of sustainable food production to **biodiversity conservation** and the provision of key **ecosystem services.**

Potential Indicators

Category	Indicator	Method
Productivity and Resilience	Crop and Livestock Species Production Volumes Incomes Carrying Capacity & Stocking Rates Land Degradation & Productivity Connectivity & Permeability Structural Features (Hedgerows, Shelterbelts, Riparian Buffers, Wetlands etc.)	Remote Sensing & GIS (NDVI, LiDAR), reported & economic data, farmer surveys
Biodiversity	Structural Vegetation Diversity Pollination Abundance & Diversity Soil Health, Diversity & Microbial Activity Abundance & Movement of Indicator Species Abundance of Pests & Invasive Species	Biodiversity assessments (transects, scorecards, camera traps, passive acoustic monitoring, traps, netting, tagging), remote sensing and GIS (vegetation classifications, spectral diversity), soil sampling
Ecosystem Services	Above and Below Ground Carbon Microclimate Regulation Soil Nutrients Soil Erosion Bare Ground & Litter Depth Soil Moisture Infiltration & Runoff Capture	Soil, water & vegetation assays, remote sensing and GIS (LiDAR, USLE)

Photo: ©Envato Elements

Additional Resources

Herzog, F. & Franklin, J. (2016). State-of-the-art practices in farmland biodiversity monitoring for North America and Europe. *Ambio,* 45(8):857–871. https://pmc.ncbi.nlm.nih.gov/articles/PMC5102971/

Pellant, M. *et al*. (2020). Interpreting Indicators of Rangeland Health, Version 5. Tech Ref 1734-6. U.S. Department of the Interior. https://www.nrcs.usda.gov/sites/default/files/2022-09/Interpreting%20Indicators%20of%20Rangeland%20Health_0.pdf

Valeri, S., Zavattero, L. & Capotorti, G. (2021). Ecological connectivity in agricultural green infrastructure: Suggested criteria for fine scale assessment and planning. *Land*, 10(8), 807. https://www.mdpi.com/2073-445X/10/8/807

Harrison S. *et al*. (2021). The Farmland Biodiversity Score for consistent monitoring of biodiversity based on the measurement of trees on farms. ICRAF Working Paper No. 321. World Agroforestry, Nairobi, Kenya. https://dx.doi.org/10.5716/WP21038.PDF

Hawes, C. (2022). Farmland Biodiversity, Soil Health & Sustainability Assessment: A handbook of simple, on-farm indicators. https://csc.hutton.ac.uk/resource/Handbook_of_indicators_v1.pdf

Ecker, K.T., Meier, E.S. & Tillé, Y. (2023). Integrating spatial and ecological information into comprehensive biodiversity monitoring on agricultural land. *Environmental Monitoring and Assessment,* 195(10), 1161. https://link.springer.com/article/10.1007/s10661-023-11618-7

OECD (2023). Guidelines for the Development of an OECD Farmland Habitat Biodiversity Indicator. OECD, Paris. https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/07/guidelines-for-the-development-of-an-oecd-farmland-habitat-biodiversity-indicator_e4e022e4/09d45d55-en.pdf

BfN (2024). Monitoring of high nature value farmland. German Federal Agency for Nature Conservation. https://www.bfn.de/en/monitoring-high-nature-value-farmland

Ruck, A. *et al*. (2024). Farmland biodiversity monitoring through citizen science: A review of existing approaches and future opportunities. *Ambio*, 53(2), 257-275. https://link.springer.com/article/10.1007/s13280-023-01929-x

Roilo, S. *et al*. (2024). The untapped potential of camera traps for farmland biodiversity monitoring: current practice and outstanding agroecological questions. Remote sensing in ecology and conservation, Volume 11, Issue 3.. https://zslpublications.onlinelibrary.wiley.com/doi/full/10.1002/rse2.426

IEEP (2024). Advancing biodiversity monitoring in agricultural landscapes. Institute for European Environmental Policy, Brussels. https://ieep.eu/wp-content/uploads/2024/06/Advancing-biodiversity-monitoring-in-agricultural-landscapes-IEEP-2024.pdf

Ecological Corridors and Protected Areas

Protected areas alone cannot sustain biodiversity if they are isolated. Wildlife needs connected habitats in order to move around, find food, breed and adapt to environmental changes. This often necessitates the establishment, restoration and management of ecological corridors to link existing protected areas, buffer zones and community-managed lands. The main aim is to reconnect fragmented habitats within and between protected areas, enabling gene flow and seasonal migration for key species and facilitating range shifts to build climate resilience. This also encourages multi-stakeholder engagement in conservation and management initiatives. Monitoring objectives typically include:

- Assessing improvements in **physical linkages** within and between protected areas.
- Monitoring **wildlife responses** to enhanced ecological connectivity (e.g. movement and genetic exchange).
- Assessing the **quality and resilience** of biodiversity habitats to support the conservation and restoration of ecological corridors.
- Tracking **community perceptions and involvement** in the management of ecological corridors.

Potential Indicators

Category	Indicator	Method
Physical Linkages	Percentage of Area Protected Land Cover Change & Fragmentation Permeability (Corridor Configuration & Condition) Linear Infrastructure (Fences, Roads, Rail) Reductions in Disturbance (Roadkill, Poaching, HWC)	Remote sensing & GIS (land cover change detection), spatial corridor modelling (e.g. linkage mapper), barrier analysis, transect counts, point surveys, bioacoustics monitoring
Wildlife Responses	Species Distribution & Abundance Species Movement Gene Flow Recolonisation Population Health	Transects, biodiversity scorecards, camera traps, passive acoustic monitoring, traps, netting, GPS tagging/collars, attractants, environmental DNA sampling, canopy surveys), genetic sampling
Habitat Quality and Resilience	Landscape Composition & Condition (Vegetation Complexity, Canopy Structure, Hydrological Connectivity & Invasive Species) Above and Below Ground Carbon Frequency & Severity of Fire & Water Stress	Periodic field surveys, remote sensing and GIS (LiDAR, vegetation classifications, spectral diversity, burn scar detection), streamflow analysis
Community Perceptions and Involvement	Land Use Type IPLC Engagement & Partnerships Benefits from Conservation & SLM	Stakeholder mapping and surveys, participatory workshops, policy review

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Additional Resources

Hilty, J. *et al.* (2020). Guidelines for conserving connectivity through ecological networks and corridors. IUCN, Gland. https://iucn.org/resources/publication/guidelines-conserving-connectivity-through-ecological-networks-and-corridors

Wang, Y., Lu, Z., Sheng, Y., & Zhou, Y. (2020). Remote sensing applications in monitoring of protected areas. *Remote Sensing*, 12(9), 1370. https://www.mdpi.com/2072-4292/12/9/1370

Gregory, A. *et al.* (2021). Toward best management practices for ecological corridors. *Land*, 10(2), 140. https://www.mdpi.com/2073-445X/10/2/140

Keeley, A., Beier, P. & Jenness, J.S. (2021). Connectivity metrics for conservation planning and monitoring. *Biological Conservation*, 255, 109008. https://www.sciencedirect.com/science/article/pii/S0006320721000604

Theobald, D.M., Keeley, A.T., Laur, A. & Tabor, G. (2022). A simple and practical measure of the connectivity of protected area networks: the ProNet metric. *Conservation Science and Practice*, 4(11), e12823. https://conbio.onlinelibrary.wiley.com/doi/10.1111/csp2.12823

Dalton, D. *et al.* (2024). A framework for monitoring biodiversity in protected areas and other effective area-based conservation measures. IUCN, Gland. https://iucn.org/resources/publication/framework-monitoring-biodiversity-protected-areas-and-other-effective-area

Yang, W., Kedron, P. & Frazier, A.E. (2024). Percentage of area protected can substitute for more complicated structural metrics when monitoring protected area connectivity. *Ecological Indicators*, 158, 111387. https://www.sciencedirect.com/science/article/pii/S1470160X23015297?via%3Dihub

Keeley, A. *et al.* (2025). Monitoring Ecological Corridors for Nature and People. Ecoevorixiv. https://doi.org/10.32942/X25K82

Gatti, R.C. (2025). Ecological Peace Corridors: A new conservation strategy to protect human and biological diversity. *Biological Conservation*, 302, 110947. https://www.sciencedirect.com/science/article/pii/S0006320724005123

Ecological Corridors And Connectivity Resources Library hosted by the Global Wildlife Program and the Amazon Sustainable Landscapes, funded by the Global Environment Facility and led by the World Bank. https://spatialagent.org/ECCRL/

Integrated Land Use Planning

Landscapes are often characterised by a variety of land uses, including croplands, plantations, forests, urban areas, industrial sites, protected areas and bodies of water. Without proper planning and coordination, managing these diverse land uses can lead to landscape fragmentation and disrupt natural ecological processes. Integrated Land Use Planning (ILUP) aims to harmonise these uses, creating a cohesive mosaic that supports human needs and ecological connectivity. A wide range of data is required to inform negotiations, balance trade-offs and make well-informed decisions that enhance connectivity.

Key considerations for monitoring ILUP processes include comprehensive land use zoning, strategic decisions about the placement of stepping stones, corridors and other approaches and stakeholder engagement in designing and adopting management practices that support livelihoods and ecological connectivity. The main aim is to ensure structural and functional connectivity across the landscape. This enables species movement and genetic flow, as well as the delivery of other ecosystem services, such as water cycling and pollination. These services support resilient natural systems alongside productive land use. Monitoring objectives typically include:

- Mapping and assessing changes in the **landscape configuration and condition**.
- Ensuring that existing land uses do not compromise the **natural resource base** needed for human wellbeing in the medium- to long-term.
- Monitoring the flow of key **ecosystem processes** and services between land use types.
- Assessing **ecosystem integrity** following interventions to enhance ecological connectivity.
- Monitoring social involvement, **human wellbeing** and nature's contribution to people.

Potential Indicators

Category	Indicator	Method
Landscape Configuration and Condition	Ecosystem Type Land Use/Cover Change Land Fragmentation Land Degradation Connectivity between Patches (Stepping Stone Density)	Remote sensing and GIS (NDVI, bare ground, erosion gully detection), landscape connectivity modeling (landscape graphs, circuit modelling, least cost analysis), expert assessments, citizen science
Sustainable Resource Base	Vegetation Stocks (Harvestable Woody Biomass, Herbaceous Biomass, Above Ground Carbon), Regrowth & Harvested Biomass Water Supply & Extraction (Groundwater & Surface Water)	Crop yield monitoring, carbon inventory sampling, water sampling and sensors
Flow of Ecosystem Processes	Movement of Indicator Species Gene Flows Pollinator Abundance, Diversity & Distribution Population Synchrony	Pollinator transects, biodiversity scorecards, camera traps, passive acoustic monitoring, traps, netting, GPS tagging/collars, attractants, environmental DNA sampling, canopy surveys, genetic sampling
Ecosystem Integrity	Land Productivity Soil Organic Carbon Soil Moisture/Infiltration Vegetation Water Content Invasive Species Abundance	Field surveys, soil testing, hydrological sensors, NDVI (via remote sensing)
Human Wellbeing and Involvement	Participation in Planning Workshops Capacity Building Land Tenure Security Dependence on Natural Resources Income & Livelihoods	Stakeholder surveys, workshops, census information

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Additional Resources

Rudnick, D. *et al*. (2012). The role of landscape connectivity in planning and implementing conservation and restoration priorities. Issues in Ecology. https://scholars.unh.edu/geog_facpub/19/

Scolozzi, R. & Geneletti, D. (2012). Assessing habitat connectivity for land-use planning: a method integrating landscape graphs and Delphi survey. *Journal of Environmental Planning and Management*, 55(6), 813-830. https://www.tandfonline.com/doi/abs/10.1080/09640568.2011.628823

Parrott, L. *et al*. (2019). Planning for ecological connectivity across scales of governance in a multifunctional regional landscape. *Ecosystems and People*, 15(1), 204-213. https://www.tandfonline.com/doi/full/10.1080/26395916.2019.1649726

Jalkanen, J., Toivonen, T. & Moilanen, A. (2020). Identification of ecological networks for land-use planning with spatial conservation prioritization. *Landscape Ecology*, 35, 353-371. https://link.springer.com/article/10.1007/s10980-019-00950-4

FAO (2020). Framework for integrated land use planning - An innovative approach. FAO, Rome. https://openknowledge.fao.org/items/6adb6c14-e656-4e7a-96d9-44a7f88d446b

Jennings, M.K. *et al*. (2020). Planning for dynamic connectivity: operationalizing robust decision-making and prioritization across landscapes experiencing climate and land-use change. *Land*, 9(10), 341. https://www.mdpi.com/2073-445X/9/10/341

Sedy, K. *et al*. (2022). A Methodology for Standardised Monitoring of Ecological Connectivity – Guidelines for the Analysis of Structural and Functional Connectivity, Danube Transnational Programme DTP3-314-2.3 SaveGREEN project, Environment Agency Austria, Vienna, Austria. https://dtp.interreg-danube.eu/uploads/media/approved_project_output/0001/56/dc86e1c6e3dac3299b3b411262b93dcd0210f85f.pdf

Hordley, L.A. *et al*. (2022). Developing a national indicator of functional connectivity. *Ecological Indicators*, 136, 108610. https://www.sciencedirect.com/science/article/pii/S1470160X22000814?via%3Dihub

Perrin, M., Bertrand, N. & Vanpeene, S. (2022). Ecological connectivity in spatial planning: From the EU framework to its territorial implementation in the French context. *Environmental Science & Policy*, 129, 118-125. https://www.sciencedirect.com/science/article/abs/pii/S146290112100366X

Godínez-Gómez, O., Correa Ayram, C. A., Goicolea, T. & Saura, S. (2025). Makurhini: An R package for comprehensive analysis of landscape fragmentation and connectivity (3.0.0). Zenodo. https://doi.org/10.5281/zenodo.14940436

Nature-based Solutions in Urban Landscapes

The highly fragmented nature of urban landscapes poses significant challenges to biodiversity conservation, the functioning of ecological processes and climate resilience. Reconnecting these spaces and processes requires a coordinated approach involving pocket parks, green roofs, greenways, riparian buffer zones and networks of ecological corridors. Green and blue infrastructure are nature-based solutions that can link existing parks, natural areas and waterways, thereby enhancing structural and functional connectivity within cities and their surrounding areas. The main aim is to enhance and restore ecological connectivity within the urban matrix, thereby improving ecosystem services, supporting species movement and creating more liveable, resilient urban environments. Monitoring objectives typically include:

- Assessing **green (blue) spaces** in the urban landscape and identifying opportunities to enhance ecological connectivity.
- Monitoring the extent to which connectivity and restoration initiatives contribute to **biodiversity conservation**.
- Monitoring provisioned **ecosystem services**, such as air and water quality, temperature regulation and stormwater retention.
- Monitoring **public access to and usage** of green and blue spaces and evaluating stakeholder perceptions to assess co-benefits for human wellbeing.

Potential Indicators

Category	Indicator	Method
Green (Blue) Spaces	Green Area (Size, Vegetation Complexity & Proximity to Surrounding Green Area) Land Fragmentation & Permeability Number, Length & Quality of Corridors (e.g. Green Streets, Vegetated Pathways, Waterways & Riparian Buffers) Barriers (Roads, Railways, Buildings, etc.) Imperviousness	Remote sensing and GIS (land cover change), landscape connectivity modeling (landscape graphs, circuit modelling, least cost analysis), landscape metrics software
Biodiversity Conservation	Species Movement & Habitat (Distribution, Abundance, Composition & Reproduction) Genetic Flows of Selected Species Pollinator Abundance & Diversity Invasive Species Abundance Vegetation Structure & Diversity	Camera traps, bird point counts, pollinator surveys, acoustic sensors, eDNA, biodiversity plot sampling, flora/fauna inventories, remote sensing
Ecosystem Services	Water Infiltration, Flood & Stormwater Regulation, Water Quality NO_2 & PM Concentrations Temperature (Air & Surface) Above & Below Ground Carbon	Microclimate sensors (universal thermal climate index), soil, water & vegetation assessments
Public Inclusion and Access	Public Access & Usage Rates of Green (Blue) Spaces Community Perception of Life Quality Improvement & Connection to Nature Involvement in Planning and Monitoring (Capacity Building, Workshops etc.)	Public/stakeholder surveys, attendance records, proximity analysis, user surveys

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Additional Resources

Andersson, E. *et al.* (2014). Reconnecting cities to the biosphere: stewardship of green infrastructure and urban ecosystem services. *Ambio*, 43, 445-453. https://link.springer.com/article/10.1007/s13280-014-0506-y

Childers, D.L. *et al.* (2019). Urban Ecological Infrastructure: An inclusive concept for the non-built urban environment. *Elem Sci Anth*, 7, 46. https://online.ucpress.edu/elementa/article/doi/10.1525/elementa.385/112509/Urban-Ecological-Infrastructure-An-inclusive

Greenaway, G., Lee, T. & Kahal, N. (2019). Planning to Connect: A Guide to Incorporating Ecological Connectivity into Municipal Planning. Miistakis Institute, Calgary. https://www.rockies.ca/files/reports/planning_for_ecological_connectivity.pdf

Furberg, D., Ban, Y. & Mörtberg, U. (2020). Monitoring urban green infrastructure changes and impact on habitat connectivity using high-resolution satellite data. *Remote Sensing*, 12(18), 3072. https://www.mdpi.com/2072-4292/12/18/3072

Andrade, A. *et al.* (2020). IUCN global standard for nature-based solutions. IUCN-2020-020. https://iucn.org/our-work/topic/iucn-global-standard-nature-based-solutions

Firkowski, C.R. *et al.* (2021). Monitoring social–ecological networks for biodiversity and ecosystem services in human-dominated landscapes. *Facets*, 6(1), 1670-1692. https://www.facetsjournal.com/doi/10.1139/facets-2020-0114

Hardy, C. *et al.* (2022). Ecosystem connectivity for liveable cities: a connectivity benefits Framework for Urban Planning.Ecology and Society, Volume 27, Issue 2.. https://ecologyandsociety.org/vol27/iss2/art36/

Kirk, H. *et al.* (2023). Ecological connectivity as a planning tool for the conservation of wildlife in cities. MethodsX, 10, 101989. https://www.sciencedirect.com/science/article/pii/S2215016122003636

Langemeyer, J. *et al.* (2024). Planning, Designing and Monitoring of Nature-based Solutions: Guidelines to urban transformations Bogotá, D.C.: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Interlace. https://interlace-hub.com/sites/default/files/uploads/planning-designing-and-monitoring-nature-based-solutions-guidelines-urban-transformations.pdf

Wang, D., Xu, P.Y., An, B.W. & Guo, Q.P. (2024). Urban green infrastructure: Bridging biodiversity conservation and sustainable urban development through adaptive management approach. *Frontiers in Ecology and Evolution*, 12, 1440477. https://www.frontiersin.org/journals/ecology-and-evolution/articles/10.3389/fevo.2024.1440477/full

Aleixo, C. *et al.* (2024). Urban Green Connectivity Assessment: A Comparative Study of Datasets in European Cities. *Remote Sensing*, 16(5), 771. https://www.mdpi.com/2072-4292/16/5/771

Marion, S. & Hoskins, H. (2024). Review of opportunities for urban biodiversity monitoring (Guidance report). JNCC Report 754, JNCC, Peterborough. https://hub.jncc.gov.uk/assets/476b6b62-cea8-48e6-931e-b597d8b3d8b9

Pierce, J.R. *et al.* (2024). Urban Nature Indexes tool offers comprehensive and flexible approach to monitoring urban ecological performance. *Urban Sustainability*, 4(1), 22. https://www.nature.com/articles/s42949-024-00143-2

Sharma, M., Pasha, M.K.S. & Chassot, O. (2025). Building urban ecological networks for conservation in the ASEAN region: A discussion paper on increasing connectivity amongst urban protected areas, OECMs, and green and blue spaces. IUCN, Gland. https://iucn.org/sites/default/files/2025-04/building-urban-ecological-networks-for-conservation-in-the-asean-region-compressed.pdf

Torne, D.J. (2025). Analyzing Urban Ecological Connectivity–A Comparative Study. https://www.uni-bremen.de/fileadmin/user_upload/sites/artec/Publikationen/artec_Paper/236_artec_paper.pdf

Annex 2

Glossary

Agroecology - Science that draws on biological and agricultural sciences, and in some of its applications social science, and integrates these with traditional knowledge and farmers' knowledge. Agroecosystems should mimic the functioning of local ecosystems, thus exhibiting tight nutrient cycling, complex structure and enhanced biodiversity. It can involve practices such as crop rotation, polycultures, agroforestry systems, cover crops and mulching, green manures, crop-livestock mixtures.[689]

Biological diversity - The variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.[690]

Ecological connectivity - The unimpeded movement of species, connection of habitats without hindrance and the flow of natural processes that sustain life on Earth.[691]

Ecological corridor - Clearly defined geographical space that is governed and managed over the long term to maintain or restore effective ecological connectivity.[692]

Ecological integrity - The ability of an ecological system to support and maintain a community of organisms that has species composition, diversity and functional organisation comparable to those of natural habitats within a region.[693]

Ecological networks - A system of core habitats (protected areas, OECMs and other intact natural areas), connected by ecological corridors, which is established, restored as needed and maintained to conserve biological diversity in systems that have been fragmented.[694]

Land degradation - The reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from a combination of pressures, including land use and management practices.[695]

Land Degradation Neutrality (LDN) - A state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems. The aim of land degradation neutrality (LDN) is to maintain or enhance land-based natural capital and its associated ecosystem services. Neutrality implies no net loss of the land-based natural capital relative to a reference state, or baseline.[696]

Land restoration - Continuum of activities that avoid, reduce and reverse land degradation with the explicit objective of meeting human needs and improving biosphere stewardship. The priority is to avoid degradation by eliminating the drivers and expanding conservation and protected areas; reduce degradation through the adoption of sustainable land and water management practices in production landscapes; and reverse degradation through the passive or active restoration of biodiversity and ecosystem functions. Restoration activities, tailored to local conditions and societal choices, aim to regenerate natural capital for the benefit of human health and livelihoods, environmental and planetary resilience as well as to promote greater equity, social justice and shared prosperity.[697]

Land-use planning - The systematic assessment of land and water potential, alternatives for land use and economic and social conditions in order to select and adopt the best land-use options. **Integrated land-use planning (ILUP)** - Assesses and assigns the use of resources, taking into account different uses and demands from different users, including all agricultural sectors - pastoral, crop and forests - as well as industry and other interested parties.[698]

Nature-based Solutions (NbS) - Actions aimed at protecting, conserving, restoring and sustainably managing natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits.[699]

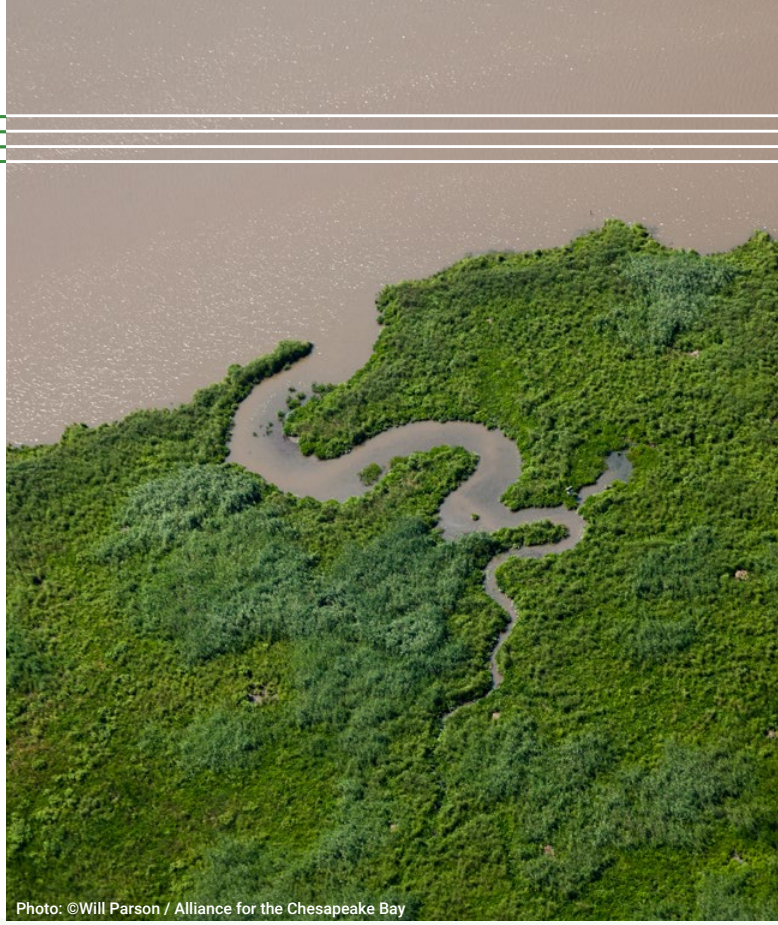
Other Effective Area-based Conservation Measures (OECM) - A geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the *in situ* conservation of biodiversity, with associated ecosystem functions and services and where applicable, cultural, spiritual, socioeconomic and other locally relevant values.[700]

Protected areas (PA) - A clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.[701]

Rewilding - The process of rebuilding, following major human disturbance, a natural ecosystem by restoring natural processes and the complete or near complete food web at all trophic levels as a self-sustaining and resilient ecosystem with biota that would have been present had the disturbance not occurred.[702]

Sustainable Land Management (SLM) - The use of land resources including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and ensuring their environmental functions. Sustainable land management approaches can avoid degradation in healthy ecosystems, reduce degradation on managed land and contribute to reversing past degradation.

Endnotes



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1 IPBES (2018). The IPBES assessment report on land degradation and restoration. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 744 pages. https://www.ipbes.net/assessment-reports/ldr

2 UNCCD (2022). Drought in Numbers 2022. https://www.unccd.int/resources/publications/drought-numbers

3 FAO (2021). State of the World's Land and Water Resources for Food and Agriculture (SOLAW 2021). https://openknowledge.fao.org/server/api/core/bitstreams/ecb51a59-ac4d-407a-80de-c7d6c3e15fcc/content

4 IPCC (2021). Climate Change 2021: The Physical Science Basis. https://www.ipcc.ch/report/ar6/wg1/

5 Newbold, T., Hudson, L.N., Arnell, A.P. *et al.* (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary?. *Science*, 353(6296). https://www.science.org/doi/10.1126/science.aaf2201

6 Hilty, J., Worboys, G.L., Keeley, A. et al. (2020). Guidelines for conserving connectivity through ecological networks and corridors. Best Practice Protected Area Guidelines Series No. 30. Gland, Switzerland: IUCN. https://iucn.org/resources/publication/guidelines-conserving-connectivity-through-ecological-networks-and-corridors

7 Convention on Migratory Species (CMS) (2024). Resolution 14.16: Ecological connectivity. Conference of the Parties, 14th meeting UNEP/CMS, Samarkand, Uzbekistan. https://www.cms.int/sites/default/files/document/cms_cop14_res.14.16_ecological-connectivity_e.pdf

8 Keeley, A.T.H., Fremier, A.K., Goertler, P.A.L. *et al.* (2022). Governing Ecological Connectivity in Cross-Scale Dependent Systems. *BioScience*, Volume 72, Issue 4, April, Pages 372–386. https://doi.org/10.1093/biosci/biab140

9 Crooks, K.R. & Sanjayan, M.A. (2006). Connectivity Conservation: Maintaining Connections for Nature. In: Crooks, K.R. & Sanjayan, M. (2006). Connectivity Conservation. Cambridge University Press, Cambridge, 1-20. http://dx.doi.org/10.1017/cbo9780511754821.001

10 Han, X., Lv, P., Zhao, S. *et al.* (2018). The effect of the gully land consolidation project on soil erosion and crop production on a typical watershed in the loess plateau. *Land*, 7(4), 113. https://doi.org/10.3390/land7040113

11 Wang, J., Yan, S., Guo, Y. et al. (2015). The effects of land consolidation on the ecological connectivity based on ecosystem service value: a case study of da'an land consolidation project in jilin province. *Journal of Geographical Sciences*, 25(5), 603-616. https://doi.org/10.1007/s11442-015-1190-y

12 Timpane-Padgham, B.L., Beechie, T. & Klinger, T. (2017). A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. *Plos One*, 12(3), e0173812. https://doi.org/10.1371/journal.pone.0173812

13 Tang, Y., Shen, S., Wen, Z. *et al.* (2022). Ecological importance evaluation of the changzhutan ecological green heart. *Wireless Communications and Mobile Computing*, 1-18. https://doi.org/10.1155/2022/2711719

14 Valiente-Banuet, A., Aizen, M.A., Alcántara, J.M. *et al.* (2014). Beyond species loss: the extinction of ecological interactions in a changing world. *Functional Ecology*, 29(3), 299-307. https://doi.org/10.1111/1365-2435.12356

15 Thébault, É. & Loreau, M. (2003). Food-web constraints on biodiversity–ecosystem functioning relationships. *Proceedings of the National Academy of Sciences*, 100(25), 14949-14954. https://doi.org/10.1073/pnas.2434847100

16 Cloern, J.E. (2007). Habitat Connectivity and Ecosystem Productivity: Implications from a Simple Model. *The American Naturalist*, 169(1), E21–E33. https://doi.org/10.1086/510258

17 Ward, M., Saura, S., Williams, B. *et al.* (2020). Just ten percent of the global terrestrial protected area network is structurally connected via intact land. *Nat Commun* 11, 4563. https://doi.org/10.1038/s41467-020-18457-x

18 Costanza, J.K. & Terando, A.J. (2019). Landscape Connectivity Planning for Adaptation to Future Climate and Land-Use Change. *Curr Landscape Ecol Rep* 4, 1–13. https://doi.org/10.1007/s40823-019-0035-2

19 UN DESA, The 17 Goals. https://sdgs.un.org/goals

20 Haddad, N.M., Brudvig, L.A., Clobert, J. *et al.* (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science*, 347(6228). https://www.science.org/doi/pdf/10.1126/sciadv.1500052

21 Tucker, M.A., Böhning-Gaese, K., Fagan, W.F. *et al.* (2018). Moving in the Anthropocene: Global reductions in terrestrial mammalian movements. *Science*, 359(6374). https://www.science.org/doi/10.1126/science.aam9712

22 IUCN (2021). WCC-2020-Res-073-EN Ecological connectivity conservation in the post-2020 global biodiversity framework: from local to international levels. https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2020_RES_073_EN.pdf

23 IUCN (2021). WCC-2020-Res-081-EN Strengthening national spatial planning to ensure the global persistence of biodiversity. https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2020_RES_081_EN.pdf

24 IUCN (2020). WCC 2020 Res 073. https://portals.iucn.org/library/node/49212

25 IUCN (2020). WCC-2020-Res-071-EN Wildlife-friendly linear infrastructure. https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2020_RES_071_EN.pdf

26 CMS (2017). UNEP/CMS/COP12/Inf.20, Migratory Animals Connect The Planet: The Importance of Connectivity as a Key Component of Migration Systems and a Biological Basis for Coordinated International Conservation Policies. https://www.cms.int/sites/default/files/document/cms_cop12_inf.20_migratory-animals-connect-the-planet_e.pdf

27 Convention on Migratory Species (2024). UNEP/CMS/COP14/Doc.14.2 – New Strategic Plan for Migratory Species. https://www.cms.int/sites/default/files/document/cms_cop14_doc.14.2_new-strategic-plan-for-migratory-species_e_0.pdf

28 UNCCD (2022). The LDN Target setting programme. https://www2.unccd.int/actions/ldn-target-setting-programme

29 UNCCD (2022). Land, Life and Legacy Declaration. https://www.unccd.int/sites/default/files/2022-10/29_cop15.pdf

30 CBD (2022). CBD/COP/DEC/15/4 - Kunming-Montreal Global Biodiversity Framework. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

31 The National Archives (2021). Glasgow Leaders' Declaration on Forests and Land Use. https://webarchive.nationalarchives.gov.uk/ukgwa/20230418175226/https:/ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/

32 UNFCCC (2022). Sharm el-Sheikh Implementation Plan. https://unfccc.int/sites/default/files/resource/cop27_auv_2_cover%20decision.pdf

33 Ramsar (2012). Resolution XI.12 Wetlands and health: taking an ecosystem approach. https://www.ramsar.org/sites/default/files/documents/pdf/cop11/res/cop11-res12-e.pdf

34 Ramsar (1996). Resolution VI.23: Ramsar and Water. https://www.ramsar.org/sites/default/files/documents/pdf/res/key_res_vi.23e.pdf

35 Ramsar (2022). Resolution XIV.6 Enhancing the Convention's visibility and synergies with other multilateral environmental agreements and other international institutions. https://www.ramsar.org/sites/default/files/documents/library/xiv.6_synergies_e.pdf

36 Convention on Migratory Species (CMS) (2024). Resolution 14.16: Ecological connectivity.

37 Winkler, K., Fuchs, R., Rounsevell, M. *et al.* (2021). Global land use changes are four times greater than previously estimated. *Nat Commun* 12, 2501. https://doi.org/10.1038/s41467-021-22702-2

38 Tabor, G., Bankova-Todorova, M., Correa Ayram, C. *et al.* (2019). Ecological Connectivity: a bridge to preserving biodiversity. In *Frontiers* 2018/19. UNEP. https://www.researchgate.net/publication/337919910_Ecological_Connectivity_a_bridge_to_preserving_biodiversity

39 Stanworth, A., Peh, K.H. & Morris, R.J. (2024). Linking network ecology and ecosystem services to benefit people. *People and Nature*, 6, 1048–1059. https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.10632

40 Hillman, J.R., Lundquist, C.J. & Thrush, S.F. (2018). The Challenges Associated With Connectivity in Ecosystem Processes, *Frontiers*. Mar. Sci. Vol 5. https://doi.org/10.3389/fmars.2018.00364

41 Gonzalez, A., Thompson, P.L. & Loreau, M. (2017). Spatial ecological networks: planning for sustainability in the long-term. *Current Opinion in Environmental Sustainability*, 29, 187-197. https://doi.org/10.1016/j.cosust.2018.03.012

42 Tischendorf, L. & Fahrig, L. (2000). On the usage and measurement of landscape connectivity. *Oikos*, 90(1), 7-19. https://doi.org/10.1034/j.1600-0706.2000.900102.x

43 Kimberley, A., Hooftman, D., Bullock, J.M. et al. (2021) Functional rather than structural connectivity explains grassland plant diversity patterns following landscape scale habitat loss. *Landscape Ecol* 36, 265–280 https://doi.org/10.1007/s10980-020-01138-x

44 Harrison, L.J., White, P.C.L. & Odell, S. (2016). Connectivity and ecological networks: Technical Information Note 01/2016. Research Report. Technical Information Note. The Landscape Institute. https://eprints.whiterose.ac.uk/106609/1/Landscape_Institute_2016_Connectivity_and_Ecological_Networks.pdf

45 Hilty, J.A., Keeley, A.T., Merenlender, A.M. *et al.* (2019). Corridor ecology: linking landscapes for biodiversity conservation and climate adaptation. *Island Press*. https://doi.org/10.1002/jwmg.21836

46 Bélisle, M. (2005). Measuring landscape connectivity: the challenge of behavioral landscape ecology. *Ecology*, 86(8), 1988-1995. https://doi.org/10.1890/04-0923

47 Elliot, N.B., Cushman, S.A., Loveridge, A.J. *et al.* (2014). Movements vary according to dispersal stage, group size, and rainfall: the case of the African lion. *Ecology*, 95(10), 2860-2869. https://doi.org/10.1890/13-1793.1

48 Zuercher, R. (2018). Social and Ecological Connectivity in Kelp Forest Ecosystems. *University of California, Santa Cruz*. https://escholarship.org/uc/item/7hn563w5

49 Virapongse, A., Brooks, S., Covelli Metcalf, E. *et al.* (2016). A social-ecological systems approach for environmental management. *Journal of environmental management*. Vol.178 :83-91 10.1016/j.jenvman.2016.02.028

50 Egerer, M. & Anderson, E. (2020). Social-Ecological Connectivity to Understand Ecosystem Service Provision across Networks in Urban Landscapes. *Land* 9(12):530. https://doi.org/10.3390/land9120530

51 Kondolf, G.M. & Pinto, P.J. (2017). The social connectivity of urban rivers. *Geomorphology* 277: 182–196. https://doi.org/10.1016/j.geomorph.2016.09.028

52 Keeley, A.T.H., Fremier, A.K., Goertler, P.A.L *et al.* (2022). Governing Ecological Connectivity in Cross-Scale Dependent Systems.

53 Munguia-Vega, A., Zepeda-Dominguez, J.A., Perez-Alarcon, M.F. *et al.* (2022). Social-ecological networks and connectivity within and between two communities of small-scale fishers in Mexico. *Ecology and Society*. Vol 27. https://doi.org/10.5751/ES-13055-270124

54 Domínguez, P., Bourbouze, A., Demay, S. *et al.* (2012). Diverse ecological, economic and socio-cultural values of a traditional common natural resource management system in the moroccan high atlas: the aït ikiss. *Environmental Values*, 21(3), 277-296. https://doi.org/10.3197/096327112x13400390125939

55 Lindenmayer, D.B., Franklin, J.F., Lõhmus, A. *et al.* (2012). A major shift to the retention approach for forestry can help resolve some global forest sustainability issues. *Conservation Letters*, 5(6), 421-431. https://doi.org/10.1111/j.1755-263x.2012.00257.x

56 Popova, E., Vousden, D., Sauer, W.H.H. *et al.* (2019). Ecological connectivity between the areas beyond national jurisdiction and coastal waters: Safeguarding interests of coastal communities in developing countries. *Marine Policy*. Vol.104: 90-102. https://doi.org/10.1016/j.marpol.2019.02.050.

57 López-Hoffman, L., Chester, C.C., Semmens, D.J. *et al.* (2017). Ecosystem Services from Transborder Migratory Species: Implications for Conservation Governance. *Annual Review of Environment and Resources*. Vol42:1, 509-539. https://doi.org/10.1146/annurev-environ-110615-090119

58 Nevins, H.M., Adams, J., Moller, H. *et al.* (2009). International and cross-cultural management in conservation of migratory species. *Journal of the Royal Society of New Zealand*, 39:4, 183-185. https://doi.org/10.1080/03014220909510576

59 Munguia-Vega, A., Zepeda-Dominguez, J.A., Perez-Alarcon, M.F. *et al.* (2022). Social-ecological networks and connectivity within and between two communities of small-scale fishers in Mexico.

60 Herrera, J.P., Moody, J. & Nunn, C.L. (2021). Predictions of primate–parasite coextinction. Philosophical Transactions of the Royal Society. *Biological Sciences*, 376(1837), 20200355. https://doi.org/10.1098/rstb.2020.0355

61 Amado, M.E.V., Vidondo, B., Fischer, C. *et al.* (2023). Potential effect of managing connectivity to contain disease spread among free-ranging wild boar (sus scrofa) in disparate landscapes. *Ecological Solutions and Evidence*, 4(4). https://doi.org/10.1002/2688-8319.12270

62 Wang, Y., Matson, K.D., Xu, Y. et al. (2019). Forest connectivity, host assemblage characteristics of local and neighboring counties, and temperature jointly shape the spatial expansion of lyme disease in united states. *Remote Sensing*, 11(20), 2354. https://doi.org/10.3390/rs11202354

63 Pringle, C.M. (2001). Hydrologic connectivity and the management of biological reserves: a global perspective . Ecological Applications 11, no. 4 (2001): 981-998. https://www.jstor.org/stable/3061006

64 Covino, T. (2017). Hydrologic connectivity as a framework for understanding biogeochemical flux through watersheds and along fluvial networks. *Geomorphology*, Vol. 277, Pages 133-144. https://doi.org/10.1016/j.geomorph.2016.09.030.

65 Grill, G., Lehner, B., Thieme, M. *et al.* (2019). Mapping the world's free-flowing rivers. *Nature*. 569. https://www.nature.com/articles/s41586-019-1111-9

66 Perry, G. & Lee, F. (2019). How does temporal variation in habitat connectivity influence metapopulation dynamics?. *Oikos*, 128(9), 1277-1286. https://doi.org/10.1111/oik.06052

67 Leibowitz, S., Wigington, P., Schofield, K. *et al.* (2018). Connectivity of streams and wetlands to downstream waters: an integrated systems framework. *Jawra Journal of the American Water Resources Association*, 54(2), 298-322. https://doi.org/10.1111/1752-1688.12631

68 Puttock, A., Macleod, C., Bol, R. *et al.* (2013). Changes in ecosystem structure, function and hydrological connectivity control water, soil and carbon losses in semi-arid grass to woody vegetation transitions. *Earth Surface Processes and Landforms*, 38(13), 1602-1611. https://doi.org/10.1002/esp.3455

69 Mason, R.J., Johnson, M.F., Wohl, E. *et al.* (2025). Rebalancing River Lateral Connectivity: An Interdisciplinary Focus for Research and Management. *WIREs Water*, 12: e1766. https://doi.org/10.1002/wat2.1766

70 Liu, D., Wang, X., Zhang, Y. *et al.* (2019). A landscape connectivity approach for determining minimum ecological lake level: implications for lake restoration. *Water*, 11(11), 2237. https://doi.org/10.3390/w11112237

71 Wei, C., Wang, X., Cai, J. *et al.* (2022). A new framework combining hydrological connectivity metrics and morphological spatial pattern analysis for the hydrological connectivity evaluation of wetlands. *Integrated Environmental Assessment and Management*, 19(4), 1064-1078. https://doi.org/10.1002/ieam.4708

72 Zhang, Y., Huang, C., Zhang, W. *et al.* (2021). The concept, approach, and future research of hydrological connectivity and its assessment at multiscales. *Environ Sci Pollut Res* 28, 52724–52743. https://doi.org/10.1007/s11356-021-16148-8

73 Shao, X., Fang, Y. & Cui, B. (2020). A model to evaluate spatiotemporal variations of hydrological connectivity on a basin-scale complex river network with intensive human activity. *Science of The Total Environment*, Volume 723, 138051. https://doi.org/10.1016/j.scitotenv.2020.138051.

74 Zhang, Y., Huang, C., Zhang, W. *et al.* (2021). The concept, approach, and future research of hydrological connectivity and its assessment at multiscales.

75 Pringle, C.M. (2001). Hydrologic connectivity and the management of biological reserves: a global perspective.

76 Nakajima, S., Suzuki, H., Nakatsugawa, M. *et al.* (2022). Inferring future changes in gene flow under climate change in riverscapes. *Landscape Ecology*. http://dx.doi.org/10.1007/s10980-023-01633-x

77 Liu, C., Chen, Y., Huang, W. *et al.* (2024). Climate warming positively affects hydrological connectivity of typical inland river in arid Central Asia. *Clim Atmos Sci* 7, 250. https://doi.org/10.1038/s41612-024-00800-4

78 Venarsky, M., Anderson, F. & Wilhelm, F. (2008). Population genetic study of the U.S. federally listed Illinois cave amphipod, gammarus acherondytes. *Conservation Genetics*, 10(4), 915-921. https://doi.org/10.1007/s10592-008-9579-0

79 Zhang, Y., Huang, C., Zhang, W. *et al.* (2021). The concept, approach, and future research of hydrological connectivity and its assessment at multiscales.

80 Pringle C.M. (2001) Hydrologic connectivity and the management of biological reserves: a global perspective.

81 Janke, B., Finlay, J. & Hobbie, S. (2017). Trees and streets as drivers of urban stormwater nutrient pollution. *Environmental Science & Technology*, 51(17), 9569-9579. https://doi.org/10.1021/acs.est.7b02225

82 Xie, H., Ma, Y., Jin, X. *et al.* (2024). Land use and river-lake connectivity: Biodiversity determinants of lake ecosystems. *Environmental Science and Ecotechnology*, Volume 21, 100434. https://doi.org/10.1016/j.ese.2024.100434.

83 Liu, C., Chen, Y., Huang, W. *et al.* (2024). Climate warming positively affects hydrological connectivity of typical inland river in arid Central Asia.

84 Uno, H., Utsumi, S., Morita, K. *et al.* (2025). Hydrological Connectivity and Local Environment Alternately Drive Spatial Structure of Floodplain Aquatic Community Across Seasons. *Ecol Evol*, 15. https://doi.org/10.1002/ece3.70880

85 Meng, X., Zhu, Y., Yin, M. *et al.* (2021). The impact of land use and rainfall patterns on the soil loss of the hillslope. *Scientific Reports*, 11(1). https://doi.org/10.1038/s41598-021-95819-5

86 Bautista, S., Mayor, Á.G., Bourakhouadar, J. *et al.* (2007). Plant spatial pattern predicts hillslope runoff and erosion in a semiarid mediterranean landscape. *Ecosystems*, 10(6), 987-998. https://doi.org/10.1007/s10021-007-9074-3

87 Li, J., Zhang, F., Si, M. *et al.* (2022). Response of soil water storage to meteorological factors in alpine shrub meadow on northeastern qinghai–tibetan plateau. *Diversity*, 14(3), 185. https://doi.org/10.3390/d14030185

88 Feddema, J. & Freire, S. (2001). Soil degradation, global warming and climate impacts. *Climate Research*, 17, 209-216. https://doi.org/10.3354/cr017209

89 Herrick, J., Shaver, P., Pyke, D. *et al.* (2019). A strategy for defining the reference for land health and degradation assessments. *Ecological Indicators*. 97. 225-230. https://doi.org/10.1016/j.ecolind.2018.06.065

90 Hillman J.R., Lundquist C.J. & Thrush S.F. (2018). The Challenges Associated With Connectivity in Ecosystem Processes.

91 Nathan, R., Katul, G.G., Horn, H.S. *et al.* (2002). Mechanisms of long-distance dispersal of seeds by wind. *Nature*, 418(6896), 409-413. https://doi.org/10.1038/nature00844

92 Bacles, C.F.E., Lowe, A.J., & Ennos, R.A. (2006). Effective seed dispersal across a fragmented landscape. *Science*, 311(5761), 628-628. https://doi.org/10.1126/science.1121543

93 Caballero-Coranguez, C.A., Mendoza, A., Berezowsky, M.*et al.* (2023). Numerical–experimental study of scour in the discharge of a channel: case of the carrizal river hydraulic control structure, tabasco, mexico. *Water*, 15(15), 2788. https://doi.org/10.3390/w15152788

94 Sokolov, S. & Rintoul, S.R. (2007). On the relationship between fronts of the antarctic circumpolar current and surface chlorophyll concentrations in the southern ocean. *Journal of Geophysical Research: Oceans*, 112(C7). https://doi.org/10.1029/2006jc004072

95 Nettesheim, F.C., Conto, T.D., Pereira, M.G. *et al.* (2015). Contribution of topography and incident solar radiation to variation of soil and plant litter at an area with heterogeneous terrain. *Revista Brasileira De Ciência Do Solo*, 39(3), 750-762. https://doi.org/10.1590/01000683rbcs20140459

96 Kara, F., Turfan, N. & Alay, M. (2023). Understory junipers, and light environment effects on biomass, chemical composition, and nutrient contents of black pine seedlings. *BioResources*, 18(3), 6025-6043. https://doi.org/10.15376/biores.18.3.6025-6043

97 Villegas, J.C., Breshears, D.D., Zou, C.B. *et al.* (2010). Seasonally pulsed heterogeneity in microclimate: phenology and cover effects along deciduous grassland–forest continuum. *Vadose Zone Journal*, 9(3), 537-547. https://doi.org/10.2136/vzj2009.0032

98 Gogoi, P.P., Vinoj, V., Swain, D. *et al.* (2019). Land use and land cover change effect on surface temperature over eastern india. *Scientific Reports*, 9(1). https://doi.org/10.1038/s41598-019-45213-z

99 Duveiller, G., Hooker, J. & Cescatti, A. (2018). The mark of vegetation change on earth's surface energy balance. *Nature Communications*, 9(1). https://doi.org/10.1038/s41467-017-02810-8

100 Lowe, W.H. & Allendorf, F.W. (2010). What can genetics tell us about population connectivity? *Molecular ecology*. Vol 19 Issue 15. https://doi.org/10.1111/j.1365-294X.2010.04688.x

101 Cramer, A.N., Hoey, J.A., Dolan, T.E. et al. (2023). A unifying framework for understanding ecological and evolutionary population connectivity. *Front. Ecol. Evol*. 11:1072825. https://doi.org/10.3389/fevo.2023.1072825

102 DiLeo, M., Rico, Y., Boehmer, H. *et al.* (2017). An ecological connectivity network maintains genetic diversity of a flagship wildflower, pulsatilla vulgaris. *Biological Conservation*, 212, 12-21. https://doi.org/10.1016/j.biocon.2017.05.026

103 Jangjoo, M., Matter, S.F., Roland, J. *et al*. (2016). Connectivity rescues genetic diversity after a demographic bottleneck in a butterfly population network. *Proceedings of the National Academy of Sciences*, 113(39), 10914-10919. https://doi.org/10.1073/pnas.1600865113

104 Lohr, J. & Haag, C.R. (2015). Genetic load, inbreeding depression, and hybrid vigor covary with population size: an empirical evaluation of theoretical predictions. *Evolution*, 69(12), 3109-3122. https://doi.org/10.1111/evo.12802

105 Peischl, S., Dupanloup, I., Kirkpatrick, M. *et al.* (2013). On the accumulation of deleterious mutations during range expansions. *Molecular Ecology,* 22(24), 5972-5982. https://doi.org/10.1111/mec.12524

106 Perez-Mendez, N., Jordano, P. & Valido, A. (2017). Persisting in defaunated landscapes: Reduced plant population connectivity after seed dispersal collapse. *Journal of Ecology*. Vol 106. Issue 3, Pages 936-947. https://doi.org/10.1111/1365-2745.12848

107 Auffret, A.G., Rico, Y., Bullock, J.M. *et al*. (2017). Plant functional connectivity – integrating landscape structure and effective dispersal. *J Ecol*, 105: 1648-1656. https://doi.org/10.1111/1365-2745.12742

108 Staps, M., Tarnita C.E. & Kawakatsu M. (2024). Ecological principles for the evolution of communication in collective systems *Proc. R. Soc. B.*291**.** http://doi.org/10.1098/rspb.2024.1562

109 Sheldrake, M. (2020). Entangled life: how fungi make our worlds, change our minds & shape our futures. Random House. https://archive.org/details/entangled-life_202203

110 Heil, M. & Bueno, J.C.S. (2007). Within-plant signaling by volatiles leads to induction and priming of an indirect plant defense in nature. *Proceedings of the National Academy of Sciences*, 104(13), 5467-5472. https://pubmed.ncbi.nlm.nih.gov/17360371/

111 Sengupta, S. & Munita, T. (2022). Unearthing the Secret: superpowers of fungus. In the fight against warming, a formidable ally ides just beneath out feet. The New York Times (22 July). https://www.nytimes.com/interactive/2022/07/27/climate/climate-change-fungi.html

112 Chen, A. (2020). The Wood Wide Web: Underground Fungi-Plant Communication Network. The Aggie Transcript. https://aggietranscript.ucdavis.edu/the-wood-wide-web-underground-fungi-plant-communication-network/

113 Ponzio, C., Gols, R., Pieterse, C. *et al.* (2013). Ecological and phytohormonal aspects of plant volatile emission in response to single and dual infestations with herbivores and phytopathogens. *Functional Ecology*, 27(3), 587-598. https://doi.org/10.1111/1365-2435.12035

114 Baldwin, I.T. (2010). Plant volatiles. *Current Biology*, Volume 20, Issue 9, R392 - R397. https://doi.org/10.1016/j.cub.2010.02.052

115 Johansson, B.G. & Jones, T.M. (2007). The role of chemical communication in mate choice. *Biological Reviews*, 82(2), 265-289. https://doi.org/10.1111/j.1469-185x.2007.00009.x

116 Farina, A. (2014). Soundscape ecology: principles, patterns, methods and applications. Springer Science & Business Media. https://link.springer.com/book/10.1007/978-94-007-7374-5

117 Znidersic, E. & Watson, D.M. (2022) Acoustic restoration: Using soundscapes to benchmark and fast-track recovery of ecological communities. *Ecology Letters*, 25, 1597–1603. https://doi.org/10.1111/ele.14015

118 Imbach, P.A., Locatelli, B., Molina, L.G. *et al*. (2013). Climate change and plant dispersal along corridors in fragmented landscapes of Mesoamerica. *Ecology and Evolution, 3*(9), 2917–2932. https://doi.org/10.1002/ece3.672

119 Ripple, W.J., Newsome, T.M., Wolf, C. *et al.* (2015). Collapse of the World's Largest Herbivores. *Science Advances* 1, no. 4 (May). https://doi.org/10.1126/sciadv.1400103

120 Lai, Y., Lin, Y.J. & Ko, C. (2024). How would estimation of geographic range shifts of marine fishes be different when using occurrence and abundance data?. *Diversity and Distributions*, 30(10). https://doi.org/10.1111/ddi.13919

121 Breed D.M. & Moor J. (2012). Movement: search, navigation, migration and dispersal. In: Breed D.M. & Moor J. (2012). Animal Behavior. Academic Press. Pages 219-252. https://doi.org/10.1016/B978-0-12-372581-3.00008-8

122 Wu, D., Zhao, X., Liang, S. *et al*. (2015). Time-lag effects of global vegetation responses to climate change. *Global Change Biology*, 21(9), 3520-3531. https://doi.org/10.1111/gcb.12945

123 Hilty, J.A., Keeley, A.T., Merenlender, A.M. *et al*. (2019). Corridor ecology: linking landscapes for biodiversity conservation and climate adaptation.

124 Harris, G., Thirgood, S.I., Hopcraft, J.G.C. *et al.* (2009). Global decline in aggregated migrations of large terrestrial mammals. *Endangered Species Research*. 7. 55-76. https://doi.org/10.3354/esr00173

125 Tucker M.A., Böhning-Gaese, K., Fagan, W.F. *et al.* (2018). Moving in the Anthropocene: Global reductions in terrestrial mammalian movements.

126 Beudels-Jamar de Bolsee, R.C. (2017). Terrestrial mammals and in particular ariland mammals. In: In CMS UNEP/CMS/COP12/inf.20 Migratory animals connect the planet: the importance of connectivity as a key component of migration systems and a biological basis for coordinated international conservation policies. https://www.cms.int/sites/default/files/document/cms_cop12_inf.20_migratory-animals-connect-the-planet_e.pdf

127 Ghazanfar, M., Malik, M.F., Hussain, M. *et al.* (2016). Butterflies and their contribution in ecosystem: A review. *Journal of Entomology and Zoology Studies*, *4*(2), 115-118. https://www.entomoljournal.com/archives/2016/vol4issue2/PartB/4-2-36.1.pdf

128 Belsky, J. & Joshi, N.K. (2018). Assessing role of major drivers in recent decline of monarch butterfly population in North America. *Frontiers in Environmental Science*, *6*, 86. https://doi.org/10.3389/fenvs.2018.00086

129 Fisher, K.E. & Bradbury, S.P. (2023). Monarch butterfly-breeding habitat restoration: how movement ecology research can inform best practices for site selection. *Current Opinion in Insect Science*, *59*, 101108. https://doi.org/10.1016/j.cois.2023.101108

130 Supp, S.R., Bohrer, G., Fieberg, J. *et al.* (2021). Estimating the movements of terrestrial animal populations using broad-scale occurrence data. *Mov Ecol* 9, 60. https://doi.org/10.1186/s40462-021-00294-2

131 Harrison, L.J., White, P.C.L., Odell, S. *et al.* (2016). Connectivity and ecological networks: Technical Information Note 01/2016.

132 Lai, Y., Lin, Y.J. & Ko, C. (2024). How would estimation of geographic range shifts of marine fishes be different when using occurrence and abundance data?.

133 Gao, B., Hedlund, J., Reynolds, D.R. *et al*. (2020). The 'migratory connectivity' concept, and its applicability to insect migrants. *Movement Ecology*, 8(1), pp.1-13. https://movementecologyjournal.biomedcentral.com/articles/10.1186/s40462-020-00235-5

134 Marra, P.P., Norris, D.R., Haig, S.M. *et al.* (2006). Migratory connectivity. In: Crooks K, Sanjayan M (eds) Connectivity Conservation. Cambridge University Press, New York, pp 1062–1065.

135 Ambrosini, R. & Spina, F. (2017). The Past, Present and Future of Migratory Connectivity. In: CMS UNEP/CMS/COP12/inf.20 Migratory animals connect the planet: the importance of connectivity as a key component of migration systems and a biological basis for coordinated international conservation policies. https://www.cms.int/sites/default/files/document/cms_cop12_inf.20_migratory-animals-connect-the-planet_e.pdf

136 Webster, M.S., Marra, P.P., Haig, S.M. *et al.* (2002). Links between worlds: unraveling migratory connectivity. *Trends in Ecology and Evolution* 17:76-83. https://doi.org/10.1016/S0169-5347(01)02380-1

137 Galbraith, C.A., Jones, T., Kirby, J. *et al.* (2014). A Review of Migratory Bird Flyways and Priorities for Management. UNEP / CMS Secretariat, Bonn, Germany. 164 pages. CMS Technical Series No. 27. https://www.cms.int/en/publication/review-migratory-bird-flyways-and-priorities-management-0

138 Webster, M.S. & Marra, P.P. (2005). The importance of understating migratory connectivity and seasonal interaction. In: Greenberg, R.S. & Marra, P.P. (2014). Birds of Two Worlds: The Ecology and Evolution of Temperate-Tropical Migration,199–209. Johns Hopkins University Press.

139 Heller, N.E. & E.S. Zavaleta (2009). Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, 142:14–32. https://doi.org/10.1016/j.biocon.2008.10.006

140 Krosby, M., Tewksbury, J., Haddad, N.M. *et al*. (2010). Ecological Connectivity for a Changing Environment. *Conservation Biology* 24(6):1686-9. https://doi.org/10.1016/j.cois.2023.101108

141 Møller, A.P., Rubolini, D. & Leihikoinen, E. (2008). Populations of migratory bird species that did not show a phenological response to climate change are declining. *Proc Natl Acad Sci*;105(42):16195-200. https://doi.org/10.1073/pnas.0803825105

142 Parks, S.A., Carroll, C., Dobrowski, S.Z. *et al*. (2020). Human land uses reduce climate connectivity across North America. *Global Change Biology*. 26: 2944-2955. https://doi.org/10.1111/gcb.15009

143 Albright, W., Ament, R., Callahan, R. et al. (2021). Connectivity and climate change toolkit. National Climate Adaptation Science Center. USGS Publications Warehouse. https://pubs.er.usgs.gov/publication/70218826

144 CONABIO, CONANP & UNDP (2020). Conservación, restauración y conectividad: la biodiversidad de México ante el cambio global. Síntesis y mensajes clave. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad - Comisión Nacional de Áreas Naturales Protegidas, Semarnat - Programa de las Naciones Unidas para el Desarrollo, México. https://bioteca.biodiversidad.gob.mx/janium/Documentos/15226.pdf

145 Godínez-Gómez, O., Cuervo-Robayo, A.P., Ramírez-Mejía, D. et al. (2019) Planning Landscape Connectivity in Mexico under Global Change. Biodiversity Information Science and Standards 3: e38199. https://doi.org/10.3897/biss.3.38199

146 Balzotti, C.S., Asner, G.P., Adkins, E.D. *et al.* (2020). Spatial drivers of composition and connectivity across endangered tropical dry forests. *J Appl Ecol*. 2020; 57: 1593–1604. https://doi.org/10.1111/1365-2664.13632

147 Venter, O., Sanderson, E.W., Magrach, A. *et al.* (2016). Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nature Communications* 7, 12558. https://doi.org/10.1038/ncomms12558

148 Brennan, A., Naidoo, R., Greenstreet, L. *et al*. (2021). Functional Connectivity of the World's Protected Areas. *Science, Vol 376, Issue 6597*. https://doi.org/10.1126/science.abl8974

149 Tabor, G., Bankova-Todorova, M., Correa Ayram, C. *et al*. (2019). Ecological Connectivity: a bridge to preserving biodiversity.

150 Jaureguiberry, P., Titeux, N., Wiemers, M. *et al*. (2022). The direct drivers of recent global anthropogenic biodiversity loss. *Sci Adv*. 8(45). https://doi.org/10.1126/sciadv.abm9982

151 Maxwell, S., Fuller, R., Brooks, T. *et al* (2016). Biodiversity: The ravages of guns, nets and bulldozers. *Nature* 536, 143–145. https://doi.org/10.1038/536143a

152 Banks-Leite, C., Ewers, R., Folkard-Tapp, H. *et al*. (2020). Countering the effects of habitat loss, fragmentation, and degradation through habitat restoration. *One Earth*. https://doi.org/10.1016/j.oneear.2020.11.016

153 IPBES (2018). The IPBES assessment report on land degradation and restoration.

154 Mitchell, M.G.E., Qiu, J., Cardinale, B.J. *et al.* (2024). Key questions for understanding drivers of biodiversity-ecosystem service relationships across spatial scales. *Landsc Ecol* 39, 36. https://doi.org/10.1007/s10980-024-01842-y

155 Banks-Leite, C., Ewers, R., Folkard-Tapp, H. *et al*. (2020). Countering the effects of habitat loss, fragmentation, and degradation through habitat restoration.

156 López, J., Qian, Y., Murillo-Sandoval, P.J. *et al*. (2024). Landscape connectivity loss after the de-escalation of armed conflict in the Colombian Amazon (2011–2021). *Global Ecology and Conservation*, Volume 54, e03094. https://doi.org/10.1016/j.gecco.2024.e03094.

157 IPBES (2018). The IPBES assessment report on land degradation and restoration.

158 Van der Esch, S., ten Brink, B., Stehfest, E. et al. (2017). Exploring future changes in land use and land condition and the impacts on food, water, climate change and biodiversity: Scenarios for the UNCCD Global Land Outlook. The Hague: PBL Netherlands Environmental Assessment Agency. https://www.unccd.int/resources/publications/exploring-impact-changes-land-use-and-land-condition-food-water-climate

159 Ritchie, H. & Roser, M. (2021). Renewable Energy, Our World in Data. https://ourworldindata.org/renewable-energy

160 IPBES (2018). The IPBES assessment report on land degradation and restoration.

161 Anthony, P., O'Grady, D.S., Mendham, K.M. *et al*. (2024). Grazing systems and natural capital: Influence of grazing management on natural capital in extensive livestock production systems. *Nature-Based Solutions*, Volume 6. https://doi.org/10.1016/j.nbsj.2024.100181.

162 IPBES (2018). The IPBES assessment report on land degradation and restoration.

163 Liu, C., Chen, Y., Huang, W. *et al.* (2024). Climate warming positively affects hydrological connectivity of typical inland river in arid Central Asia.

164 Herrick, J., Shaver, P.,Pyke, D. *et al*. (2019). A strategy for defining the reference for land health and degradation assessments.

165 Critchley, W., Harari, N. & Mekdaschi-Studer, R. (2021). Restoring Life to the Land: The Role of Sustainable Land Management in Ecosystem Restoration. UNCCD and WOCAT. https://www.unccd.int/resources/publications/restoring-life-land-role-sustainable-land-management-ecosystem-restoration

166 Li, W., Cai, J.F., Chen, G. *et al*. (2025). Microbial community succession mediated by planting patterns in the loess plateau, China: implications for ecological restoration. *PLOS One*, 20(5), e0324786. https://doi.org/10.1371/journal.pone.0324786

167 Shu, X., Hu, Y., Liu, W. *et al*. (2023). Linking between soil properties, bacterial communities, enzyme activities, and soil organic carbon mineralization under ecological restoration in an alpine degraded grassland. *Frontiers in Microbiology*, 14. https://doi.org/10.3389/fmicb.2023.1131836

168 Silva, D.E.O., Costa, R.M., Campos, J.R. *et al*. (2024). Short-term restoration practices change the bacterial community in degraded soil from the brazilian semiarid. *Scientific Reports*, 14(1). https://doi.org/10.1038/s41598-024-57690-y

169 Li, W., Cai, J.F., Chen, G. *et al*. (2025). Microbial community succession mediated by planting patterns in the loess plateau, China: implications for ecological restoration.

170 Chen, Y., Li, X., Zhang, H. *et al.* (2023). Overgrazing impacts plant species diversity in alpine wetlands indirectly by altering its environmental dependency. *Ecological Indicators*, 150, 110123. https://doi.org/10.1016/j.ecolind.2023.110123

171 Zhang, Y., Huang, C., Zhang, W. *et al.* (2021). The concept, approach, and future research of hydrological connectivity and its assessment at multiscales.

172 Newbold, T., Bentley, L.F., Hill, S.L.L. *et al.* (2020). Global effects of land use on biodiversity differ among functional groups. *Funct Ecol*. 34: 684–693. https://doi.org/10.1111/1365-2435.13500

173 Jung, M., Rowhani, P. & Scharlemann, J.P.W. (2019). Impacts of past abrupt land change on local biodiversity globally. *Nat Commun* 10, 5474. https://doi.org/10.1038/s41467-019-13452-3

174 Tiang, D.C.F., Morris, A., Bell, M. *et al.* (2021). Ecological connectivity in fragmented agricultural landscapes and the importance of scattered trees and small patches. *Ecol Process* 10, 20. https://doi.org/10.1186/s13717-021-00284-7

175 Jung, M., Rowhani, P. & Scharlemann, J.P.W. (2019). Impacts of past abrupt land change on local biodiversity globally.

176 Ke, X., van Vliet, J., Zhou, T. *et al*. (2018). Direct and indirect loss of natural habitat due to built-up area expansion: A model-based analysis for the city of Wuhan, China. *Land Use Policy*, Volume 74, Pages 231-239. https://doi.org/10.1016/j.landusepol.2017.12.048.

177 Samper, J., Shelby, J.A. & Behary, D. (2020). The Paradox of Informal Settlements Revealed in an ATLAS of Informality: Findings from Mapping Growth in the Most Common Yet Unmapped Forms of Urbanization. *Sustainability* 12:22: 9510. https://doi.org/10.3390/su12229510

178 Kamjou, E., Scott, M. & Lennon, M. (2024). A bottom-up perspective on green infrastructure in informal settlements: Understanding nature's benefits through lived experiences. *Urban Forestry & Urban Greening*, Volume 94. https://doi.org/10.1016/j.ufug.2024.128231.

179 Hailu, T., Assefa, E. & Zeleke, T. (2024). Land use transformation by urban informal settlements and ecosystem impact. *Environ Syst Res* 13, 32. https://doi.org/10.1186/s40068-024-00359-2

180 Oyinloye, M.A., Ogunlade, S.O. & Owoeye, J.O. (2018). Geo-spatial analysis of informal settlements on landuse/cover change areas of Osogbo, Nigeria. *Am J Environ Sustain Dev* 3(3):55–70. https://doi.org/10.13140/RG.2.2. 23637.27367

181 IPBES (2018). The IPBES assessment report on land degradation and restoration.

182 Arnaiz-Schmitz, C., Díaz, P., Ruiz-Labourdette, D. *et al.* (2018). Modelling of socio-ecological connectivity. The rural-urban network in the surroundings of Madrid (Central Spain). *Urban Ecosyst* 21, 1199–1212. https://doi.org/10.1007/s11252-018-0797-z

183 Hernández Romero, P.C., Von Thaden Ugalde, J.J., Muench, C.E. *et al.* (2024). Species richness and ecological connectivity of the mammal communities in urban and peri-urban areas at Mexico City. *Urban Ecosyst* 27, 1781–1794. https://doi.org/10.1007/s11252-024-01553-x

184 Salvadore, E., Bronders, J. & Batelaan, O. (2015). Hydrological modelling of urbanized catchments: a review and future directions. *Journal of Hydrology*, 529, 62-81. https://doi.org/10.1016/j.jhydrol.2015.06.028

185 Miles, L.S., Dyer, R.J. & Verrelli, B.C. (2018). Urban hubs of connectivity: contrasting patterns of gene flow within and among cities in the western black widow spider. *Proceedings of the Royal Society B: Biological Sciences*, 285(1884), 20181224. https://doi.org/10.1098/rspb.2018.1224

186 Fusco, N., Pehek, E. & Munshi-South, J. (2020). Urbanization reduces gene flow but not genetic diversity of stream salamander populations in the New York City metropolitan area. *Evolutionary Applications*, 14(1), 99-116. https://doi.org/10.1111/eva.13025

187 Kozakiewicz, C.P., Burridge, C.P., Funk, W.C. *et al*. (2019). Urbanization reduces genetic connectivity in bobcats (lynx rufus) at both intra– and interpopulation spatial scales. *Molecular Ecology*, 28(23), 5068-5085. https://doi.org/10.1111/mec.15274

188 Munshi-South, J. (2012). Urban landscape genetics: canopy cover predicts gene flow between white-footed mouse (peromyscus leucopus) populations in New York City. *Molecular Ecology*, 21(6), 1360-1378. https://doi.org/10.1111/j.1365-294x.2012.05476.x

189 Doherty, T.S., Hays, G.C. & Driscoll, D.A. (2021).Human disturbance causes widespread disruption of animal movement. *Nat Ecol Evol* 5, 513–519. https://doi.org/10.1038/s41559-020-01380-1

190 Ren, Z., He, J. & Yue, Q. (2021). Assessing the impact of urban expansion on surrounding forested landscape connectivity across space and time. *Land*, 10(4), 359. https://doi.org/10.3390/land10040359

191 Egerer, M., Fouch, N., Anderson, E.C. *et al*. (2020). Socio-ecological connectivity differs in magnitude and direction across urban landscapes.

192 Lahoti, S., Dhyani, S., Sahle, M. *et al*. (2024). Exploring the nexus between green space availability, connection with nature, and pro-environmental behavior in the urban landscape. *Sustainability*, 16(13), 5435. https://doi.org/10.3390/su16135435

193 Li, Z., Kong, F., Yin, H. *et al*. (2023). Considering the dynamics of water surface boundaries to measure the evolution of hydrological connectivity in the Yangtze river delta, China. *Progress in Physical Geography: Earth and Environment*, 48(1), 96-112. https://doi.org/10.1177/03091333231213536

194 Delaney, K.S., Riley, S.P.D. & Fisher, R.N. (2010). A rapid, strong, and convergent genetic response to urban habitat fragmentation in four divergent and widespread vertebrates. *PLoS ONE*, 5(9), e12767. https://doi.org/10.1371/journal.pone.0012767

195 Basilio, L.G., Moreno, D.J. & Piratelli, A.J. (2020). Main causes of bird-window collisions: a review. Anais da Academia Brasileira de Ciências, 92, e20180745. https://doi.org/10.1590/0001-3765202020180745

196 Wang, D., Zhang, L., Zhong, Q. *et al*. (2024). Analysis of spatial divergence in bird diversity driven by built environment characteristics of ecological corridors in high-density urban areas. *Land*, 13(9), 1359. https://doi.org/10.3390/land13091359

197 Gong, D., Huang, M. & Lin, H. (2023). Construction of an ecological security pattern in rapidly urbanizing areas based on ecosystem sustainability, stability, and integrity. *Remote Sensing*, 15(24), 5728. https://doi.org/10.3390/rs15245728

198 Wei, W., Wang, S., Li, X. *et al*. (2024). Identification and analysis of ecological corridors in the central urban area of Xuchang based on multi-source geospatial data. *ISPRS International Journal of Geo-Information*, 13(9), 322. https://doi.org/10.3390/ijgi13090322

199 Ament, R., Clevenger, A. & van der Ree, R. (2023). Addressing ecological connectivity in the development of roads, railways and canals. WCPA Technical Report Series No. 5. Gland, Switzerland: IUCN. https://iucn.org/resources/publication/addressing-ecological-connectivity-development-roads-railways-and-canals

200 Tabor, G., Bankova-Todorova, M., Correa Ayram, C. *et al*. (2019). Ecological Connectivity: a bridge to preserving biodiversity.

201 United Nations Convention to Combat Desertification (2017). The Global Land Outlook, first edition. Bonn, Germany. https://www.unccd.int/sites/default/files/documents/2017-09/GLO_Full_Report_low_res.pdf

202 Benítez-López, A., Alkemade, R., Schipper, A.M. *et al. (2017).* The impact of hunting on tropical mammal and bird populations. *Science* 356,180-183(2017). https://doi.org/10.1126/science.aaj1891

203 FIDIC, WWF & AECOM (2023). A Playbook for Nature-Positive Infrastructure Development. Version 1.1. https://files.worldwildlife.org/wwfcmsprod/files/Publication/file/3cv0m8510d_WWF_Playbook_v1_1_Pages_1_.pdf

204 Botelho, J., Costa, S.C.P., Ribeiro, J.G. *et al.* (2022). Mapping Roads in the Brazilian Amazon with Artificial Intelligence and Sentinel-2. *Remote Sensing* 14(15), 3625. https://www.mdpi.com/2072-4292/14/15/3625

205 Skidmore, P. & Wheaton, J. (2022). Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration. *Anthropocene* Vol 38. https://doi.org/10.1016/j.ancene.2022.100334

206 Nyumba, T.O., Sang, C.C., Olago, D.O. *et al*. (2021). Assessing the ecological impacts of transportation infrastructure development: A reconnaissance study of the Standard Gauge Railway in Kenya. *PLoS ONE* 16(1): e0246248. https://doi.org/10.1371/journal.pone.0246248

207 Hou, L., Deng, Y., Wang, X. *et al.* (2024). An analysis of policy transmission flow in the Chengdu plain urban agglomeration in southwest China: towards building an ecological protection network. *Sustainability*, 16(13), 5398. https://doi.org/10.3390/su16135398

208 Benitez-Lopez, A., Alkemade, R. & Verweij, P.A. (2010). The Impacts of Roads and Other Infrastructure on Mammal and Bird Populations: A Meta-Analysis. *Biological Conservation* 143:1307-1316. https://doi.org/10.1016/j.biocon.2010.02.009

209 Hlatshwayo, T., Zungu, M., Collinson Jonker, W. *et al*. (2024). Mainstreaming ecological connectivity and wildlife needs in green road transport infrastructure planning in South Africa. *Journal of Environmental Management*, Volume 371. https://doi.org/10.1016/j.jenvman.2024.123062

210 Bernes, C., Bullock, J.M., Jakobsson, S. *et al*. (2017). How are biodiversity and dispersal of species affected by the management of roadsides? A systematic map. *Environmental Evidence*, 6(1), 1-16. https://doi.org/10.1186/s13750-017-0103-1

211 Phillips, B.B., Wallace, C., Roberts, B.R. *et al.* (2020). Enhancing road verges to aid pollinator conservation: A review. *Biological Conservation*, 250, 108687. https://doi.org/10.1016/j.biocon.2020.108687

212 Son, D., Chu, Y. & Lee, H. (2024). Roads as conduits for alien plant introduction and dispersal: The amplifying role of road construction in Ambrosia trifida dispersal. *Science of The Total Environment*, Volume 912. https://doi.org/10.1016/j.scitotenv.2023.169109.

213 Hatcher, M., Dick, J. & Dunn, A. (2012). Diverse effects of parasites in ecosystems: linking interdependent processes. *Frontiers in Ecology and the Environment*, 10(4), 186-194. https://doi.org/10.1890/110016

214 Zhang, Y., Huang, C., Zhang, W. *et al.* (2021). The concept, approach, and future research of hydrological connectivity and its assessment at multiscales.

215 Tundisi, J.G., Goldemberg, J., Matsumura-Tundisi, T. *et al*. (2014). How many more dams in the Amazon?. *Energy Policy* 74, 703-708. https://doi.org/10.1016/j.enpol.2014.07.013

216 Zhang, Y., Huang, C., Zhang, W. *et al.* (2021). The concept, approach, and future research of hydrological connectivity and its assessment at multiscales.

217 FIDIC, WWF & AECOM (2023). A Playbook for Nature-Positive Infrastructure Development. Version 1.1.

218 Liu, C., Chen, Y., Fang, G. *et al.* (2022). Hydrological Connectivity Improves the Water-Related Environment in a Typical Arid Inland River Basin in Xinjiang, China. *Remote Sens. 14(19), 4977*. https://doi.org/10.3390/rs14194977

219 Ainsworth, R.F., Cowx, I.G. & Funge-Smith, S.J. (2023). Putting the fish into inland fisheries–a global allocation of historic inland fish catch. *Fish and Fisheries*, *24*(2), 263-278. https://doi.org/10.1111/faf.12725

220 Nam, S., Phommakone, S., Vuthy, L.Y. *et al*. (2015). Lower Mekong fisheries estimated to be worth around $17 billion a year. *Catch and Culture*, *21*(3), 4-7. https://www.researchgate.net/publication/350399242_Lower_Mekong_fisheries_estimated_to_be_worth_around_17_billion_a_year

221 Kelleher, K., Westlund, L., Hoshino, E. *et al*. (2012). *Hidden harvest: The global contribution of capture fisheries*. Worldbank; WorldFish. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/515701468152718292/hidden-harvest-the-global-contribution-of-capture-fisheries

222 Hortle, K.G. (2007). Consumption and the yield of fish and other aquatic animals from the Lower Mekong Basin. *MRC technical paper*, *16*, 1-88. https://www.researchgate.net/publication/285504652_Consumption_and_the_yield_of_fish_and_other_aquatic_animals_from_the_Lower_Mekong_Basin

223 Kang, B. & Huang, X. (2022). Mekong fishes: Biogeography, migration, resources, threats, and conservation. *Reviews in Fisheries Science & Aquaculture*, *30*(2), 170-194. https://doi.org/10.1080/23308249.2021.1906843

224 Hughes, K. (2024). The Mekong's Forgotten Fishes and the Emergency Recovery Plan to save them. WWF, Gland, Switzerland. https://wwfasia.awsassets.panda.org/downloads/final-mekong-forgotten-fishes-report--web-version-.pdf

225 Hughes, K. (2024). The Mekong's Forgotten Fishes and the Emergency Recovery Plan to save them. WWF, Gland, Switzerland.

226 Li, M., Sun, J., Baldan, D. *et al*. (2025). Human barriers fragment three-quarters of all rivers in the Mekong basin. *Renewable and Sustainable Energy Reviews*, *210*, 115158. https://doi.org/10.1016/j.rser.2024.115158

227 Soukhaphon, A., Baird, I.G. & Hogan, Z.S. (2021). The impacts of hydropower dams in the Mekong River Basin: A review. *Water*, *13*(3), 265. https://doi.org/10.3390/w13030265

228 Chevalier, M., Ngor, P.B., Pin, K. *et al*. (2023). Long-term data show alarming decline of majority of fish species in a Lower Mekong basin fishery. *Science of the Total Environment*, *891*, 164624. https://doi.org/10.1016/j.scitotenv.2023.164624

229 Ainsworth, R.F., Cowx, I.G., & Funge-Smith, S.J. (2023). Putting the fish into inland fisheries–a global allocation of historic inland fish catch.

230 Hughes, K. (2024). The Mekong's forgotten fishes and the emergency recovery plan to save them.

231 FIDIC, WWF & AECOM (2023). A Playbook for Nature-Positive Infrastructure Development. Version 1.1.

232 Bennun, L., van Bochove, J., Ng, C. *et al*. (2021). Mitigating biodiversity impacts associated with solar and wind energy development. IUCN and The Biodiversity Consultancy, Gland, Switzerland and Cambridge, UK. https://portals.iucn.org/library/node/49283

233 UNEP (2016). Green Energy Choices: The benefits, risks and trade-offs of low-carbon technologies for electricity production. Report of the International Resource Panel. E.G. Hertwich, J. Aloisi de Larderel, A. Arvesen, P. Bayer, J. Bergesen, E. Bouman, T. Gibon, G. Heath, C. Peña, P. Purohit, A. Ramirez, S. Suh, (eds.). https://www.resourcepanel.org/reports/green-energy-choices-benefits-risks-and-trade-offs-low-carbon-technologies-electricity

234 FIDIC, WWF & AECOM (2023). A Playbook for Nature-Positive Infrastructure Development. Version 1.1.

235 Bennun, L., van Bochove, J., Ng, C. *et al*. (2021). Mitigating biodiversity impacts associated with solar and wind energy development.

236 Bonadio, J., Popa, A. & Weiskopf, V. (2021). RESET – Reference Environmental Standards for Energy Techniques Guidance. European Environmental Bureau. https://eeb.org/wp-content/uploads/2021/10/RESET_Guidance.pdf

237 Gasparatos, A., Doll, C.N.H, Esteban, M. *et al*. (2017). Renewable energy and biodiversity: Implications for transitioning to a Green Economy. *Renewable and Sustainable Energy Reviews*, Volume 70, Pages 161-184. https://doi.org/10.1016/j.rser.2016.08.030

238 UNEP (2016). Green Energy Choices: The benefits, risks and trade-offs of low-carbon technologies for electricity production.

239 Yin, J., Wei, Q., Shao, D. *et al.* (2025). The impacts of power transmission and transformation projects on ecological corridors and landscape connectivity: a case study of Shandong province, China. *Sci Rep* 15, 6709. https://doi.org/10.1038/s41598-025-91474-2

240 Tinsley, E., Froidevaux, J.S.P., Zsebők, S. *et al*. (2023). Renewable energies and biodiversity: impact of ground-mounted solar photovoltaic sites on bat activity. *Journal of Applied Ecology*, 60(9), 1752-1762. https://doi.org/10.1111/1365-2664.14474

241 Sawyer, H., Korfanta, N., Nielson, R. *et al.* (2017). Mule deer and energy development—long-term trends of habituation and abundance. *Global Change Biology*, 23(11), 4521-4529. https://doi.org/10.1111/gcb.13711

242 Weinthal, E. & Sowers, J.L. (2020). The water-energy nexus in the middle east: infrastructure, development, and conflict. *WIREs Water*, 7(4). https://doi.org/10.1002/wat2.1437

243 Gasparatos, A., Doll, C.N.H, Esteban, M. *et al*. (2017). Renewable energy and biodiversity: Implications for transitioning to a Green Economy.

244 The Biodiversity Consultancy & WWF (2023). Nature-safe Energy: Linking energy and nature to tackle the climate and biodiversity crises. https://wwfint.awsassets.panda.org/downloads/cleanaction_nature_safe_energy_report.pdf

245 Ott, J.P., Hanberry, B.B., Khalil, M. *et al*. (2021). Energy Development and Production in the Great Plains: Implications and Mitigation Opportunities. *Rangeland Ecology & Management*, Volume 78, Pages 257-272. https://doi.org/10.1016/j.rama.2020.05.003

246 Allred, B.W., Smith, W.K., Twidwell, D. *et al*. (2015). Ecosystem services lost to oil and gas in North America. *Science*: 348(6233): 401-402. https://doi.org/10.1126/science.aaa4785

247 Jaureguiberry, P., Titeux, N., Wiemers, M. *et al*. (2022). The direct drivers of recent global anthropogenic biodiversity loss.

248 Heller, N.E. & Zavaleta, E.S. (2009). Biodiversity management in the face of climate change: A review of 22 years of recommendations.

249 Albright, W., Ament, R., Callahan, R. *et al*. (2021). Connectivity and climate change toolkit.

250 Pitelka, L.F., Gardner, R.H., Ash, J. *et al.*(1997). Plant migration and climate change. *Am. Sci.* 85: 464–473. https://www.jstor.org/stable/27856854

251 Neilson, R.P., Pitelka, L.F., Solomon, A.M. *et al*. (2005). Forecasting regional to global plant migration response to climate change. *Bioscience*. 55(9): 749-759. https://doi.org/10.1641/0006-3568(2005)055[0749:FRTGPM]2.0.CO;2

252 Balzotti, C.S., Asner, G.P., Adkins, E.D. *et al*. (2020). Spatial drivers of composition and connectivity across endangered tropical dry forests.

253 Trauernicht, C. (2019). Vegetation—Rainfall interactions reveal how climate variability and climate change alter spatial patterns of wildland fire probability on Big Island, Hawaii. *Science of the Total Environment*, 650, 459–469. https://doi.org/10.1016/j.scitotenv.2018.08.347

254 Moritz, M.A., Parisien, M., Batllori, E. *et al.* (2012). Climate change and disruptions to global fire activity. *Ecosphere*, 3(6), 1-22. https://doi.org/10.1890/es11-00345.1

255 Keith, D.A., Allen, S., Gallagher, R.V. *et al*. (2022). Fire-related threats and transformational change in Australian ecosystems. *Global Ecology and Biogeography*, 31(10), 2070-2084. https://doi.org/10.1111/geb.13500

256 McLean, C.A., Melville, J., Schubert, J.H. *et al*. (2021). Assessing the impact of fire on spiders through a global comparative analysis. https://doi.org/10.1101/2021.12.20.472855

257 IPBES (2018). The IPBES assessment report on land degradation and restoration.

258 Archibald, S., Staver, A.C. & Levin, S.A. (2011). Evolution of human-driven fire regimes in Africa. *Proceedings of the National Academy of Sciences*, 109(3), 847-852. https://doi.org/10.1073/pnas.1118648109

259 Driscoll, D.A., Armenteras, D., Bennett, A.F. *et al.* (2021). How fire interacts with habitat loss and fragmentation. *Biol Rev*, 96: 976-998. https://doi.org/10.1111/brv.12687

260 Zhang, Y., Huang, C., Zhang, W. *et al.* (2021). The concept, approach, and future research of hydrological connectivity and its assessment at multiscales.

261 Liu, C., Chen, Y., Fang, G. *et al*. (2022). Hydrological Connectivity Improves the Water-Related Environment in a Typical Arid Inland River Basin in Xinjiang, China.

262 IPBES (2023). Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Roy, H.E., Pauchard, A., Stoett, P., and Renard Truong, T. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.7430682

263 Archer, S.R., Andersen, E.M., Predick, K.I. *et al*. (2017). Woody Plant Encroachment: Causes and Consequences. In: Briske D. (eds) Rangeland Systems. Springer Series on Environmental Management, pp 25-84. https://doi.org/10.1007/978-3-319-46709-2_2

264 O'Connor, T.G., Puttick, J.R. & Hoffman, M.T. (2014). Bush encroachment in southern Africa: changes and causes. *African Journal of Range & Forage Science*, 31:2, 67-88. https://doi.org/10.2989/10220119.2014.939996

265 Hare, M.L., Xu, X., Wang, Y. *et al*. (2020). The effects of bush control methods on encroaching woody plants in terms of die-off and survival in Borana rangelands, southern Ethiopia. *Pastoralism* 10, 16 (2020). https://doi.org/10.1186/s13570-020- 00171-4

266 Buyer, J.S., Schmidt-Künzel, A., Nghikembua, M. *et al*. (2016). Soil microbial communities following bush removal in a Namibian savanna. *Soil Journal* 2, 101 - 110. https://doi.org/10.5194/soil-2-101-2016

267 Dannhauser, C. & Jordaan, J. (2015). Practical Veld and Pasture Management for Farmers. Kejafa Knowledge Works, Krugersdorp, ISBN 978-0-620-61125-1

268 Lesoli, M.S., Gxasheka, M., Solomon, T.B. *et al*. (2013). Integrated Plant Invasion and Bush Encroachment Management on Southern African Rangelands. *Herbicides - Current Research and Case Studies in Use*. https://www.intechopen.com/chapters/44961

269 Schimel, J.P. (2018). Life in dry soils: effects of drought on soil microbial communities and processes. *Annual Review of Ecology, Evolution and Systematics*, 49(1), 409-432. https://doi.org/10.1146/annurev-ecolsys-110617-062614

270 Mollot, G., Pantel, J.H. & Romanuk, T.N. (2017). Chapter Two - The Effects of Invasive Species on the Decline in Species Richness: A Global Meta-Analysis. *Advances in Ecological Research*, Academic Press, Volume 56, Pages 61-83. https://doi.org/10.1016/bs.aecr.2016.10.002

271 Balzotti, C.S., Asner, G.P., Adkins, E.D. *et al*. (2020). Spatial drivers of composition and connectivity across endangered tropical dry forests.

272 IPBES (2018). The IPBES assessment report on land degradation and restoration.

273 Tomat-Kelly, G., Dillon, W.W. & Flory, S.L. (2021). Invasive grass fuel loads suppress native species by increasing fire intensity and soil heating. *Journal of Applied Ecology*, 58(10), 2220-2230. https://doi.org/10.1111/1365-2664.13881

274 Freeman, J.P., Stohlgren, T.J., Hunter, M.E. *et al*. (2007). Rapid assessment of postfire plant invasions in coniferous forests of the western united states. *Ecological Applications*, 17(6), 1656-1665. https://doi.org/10.1890/06-1859.1

275 Shackleton, R.T., Shackleton, C.M. & Kull, C.A. (2019). The role of invasive alien species in shaping local livelihoods and human well-being: a review. *Journal of Environmental Management*, 229, 145-157. https://doi.org/10.1016/j.jenvman.2018.05.007

276 IPBES (2018). The IPBES assessment report on land degradation and restoration.

277 Tomalka, J., Hunecke, C., Murken, L. *et al.* (2024). Stepping back from the precipice: Transforming land management to stay within planetary boundaries. Potsdam, Germany: Potsdam Institute for Climate Impact Research. https://doi.org/10.48485/pik.2024.018

278 Kolawole, A.S. & Iyiola, A.O. (2023). Environmental Pollution: Threats, Impact on Biodiversity, and Protection Strategies. In: Izah, S.C. & Ogwu, M.C. (2023). Sustainable Utilization and Conservation of Africa's Biological Resources and Environment. *Sustainable Development and Biodiversity*, Vol 32. Singapore. https://doi.org/10.1007/978-981-19-6974-4_14

279 Salvatierra, D., González, M.P., Blasco, J. *et al.* (2025). Habitat loss and discontinuity as drivers of habitat fragmentation: The role of contamination and connectivity of habitats. *Environ Res*. 266:120609. https://doi.org/10.1016/j.envres.2024.120609

280 Burdon, F.J., Reyes, M., Schönenberger, U. *et al*. (2023). Environmental context determines pollution impacts on ecosystem functioning. *Oikos*, Volume2023, Issue2. https://doi.org/10.1111/oik.09131

281 Golia, E.E. (2023). The impact of heavy metal contamination on soil quality and plant nutrition. sustainable management of moderate contaminated agricultural and urban soils, using low cost materials and promoting circular economy. *Sustainable Chemistry and Pharmacy*, 33, 101046. https://doi.org/10.1016/j.scp.2023.101046

282 Koen, E.L., Minnaar, C., Roever, C. *et al*. (2018). Emerging threat of the 21st century lightscape to global biodiversity. *Global Change Biology*, 24(6), 2315-2324. https://doi.org/10.1111/gcb.14146

283 Lewanzik, D. & Voigt, C.C. (2014). Artificial light puts ecosystem services of frugivorous bats at risk. *Journal of Applied Ecology*, 51(2), 388-394. https://doi.org/10.1111/1365-2664.12206

284 Gaston, K.J., Bennie, J., Davies, T.W. *et al*. (2013). The ecological impacts of nighttime light pollution: a mechanistic appraisal. *Biological Reviews*, 88(4), 912-927. https://doi.org/10.1111/brv.12036

285 Siemers, B.M. & Schaub, A. (2010). Hunting at the highway: traffic noise reduces foraging efficiency in acoustic predators. *Proceedings of the Royal Society B: Biological Sciences*, 278(1712), 1646-1652. https://doi.org/10.1098/rspb.2010.2262

286 Francis, C.D., Kleist, N.J., Ortega, C.P. *et al*. (2012). Noise pollution alters ecological services: enhanced pollination and disrupted seed dispersal. *Proceedings of the Royal Society B: Biological Sciences*, 279(1739), 2727-2735. https://doi.org/10.1098/rspb.2012.0230

287 Kight, C.R. & Swaddle, J.P. (2011). How and why environmental noise impacts animals: an integrative, mechanistic review. *Ecology Letters*, 14(10), 1052-1061. https://doi.org/10.1111/j.1461-0248.2011.01664.x

288 Keyel, A.C., Reed, S.E., Nuessly, K. *et al*. (2018). Modeling anthropogenic noise impacts on animals in natural areas. *Landscape and Urban Planning*, 180, 76-84. https://doi.org/10.1016/j.landurbplan.2018.08.011

289 Brown, C.J., Jupiter, S.D., Albert, S. *et al*. (2019). A guide to modelling priorities for managing land-based impacts on coastal ecosystems. *Journal of Applied Ecology*, 56(5), 1106-1116. https://doi.org/10.1111/1365-2664.13331

290 UNHCR (2022). Global Trends Report. United Nations High Commissioner for Refugees. https://www.unhcr.org/media/global-trends-report-2021

291 Hanson, T. (2018). Biodiversity conservation and armed conflict: a warfare ecology perspective. *Acad Sci* 1429: 50-65. https://doi.org/10.1111/nyas.13689

292 Rist, L., Norström, A. & Queiroz, C. (2024). Biodiversity, peace and conflict: understanding the connections. *Current Opinion in Environmental Sustainability*, Volume 68, 101431. https://doi.org/10.1016/j.cosust.2024.101431

293 Parkinson, S. & Cottrell, L. (2022). Estimating the Military's Global Greenhouse Gas Emissions. Scientists for Global Responsibility (SGR) and the Conflict and Environment Observatory (CEOBS). https://ceobs.org/wp-content/uploads/2022/11/SGR-CEOBS_Estimating_Global_MIlitary_GHG_Emissions.pdf

294 Rist, L., Norström, A. & Queiroz, C. (2024). Biodiversity, peace and conflict: understanding the connections.

295 Wirtu, Y.D. & Abdela, U. (2025). Impact of war on the environment: ecocide. *Front. Environ. Sci*. 13: 1539520. https://doi.org/10.3389/fenvs.2025.1539520

296 Rist, L., Norström, A. & Queiroz, C. (2024). Biodiversity, peace and conflict: understanding the connections.

297 Akhundov, R. (2024). The environmental consequences of military activity. *Vestnik* 29(1):51-58. https://www.researchgate.net/publication/380356613THE

298 Wirtu, Y.D. & Abdela, U. (2025). Impact of war on the environment: ecocide.

299 del Pilar López-Uribe, M. & Torres, F.S. (2024). Ideology and rifles: the agrarian origins of civil conflict in Colombia. *World Development*, *173*, 106387. https://doi.org/10.1016/j.worlddev.2023.106387

300 Landholm, D.M., Pradhan, P. & Kropp, J.P. (2019). Diverging forest land use dynamics induced by armed conflict across the tropics. *Global Environmental Change*, *56*, 86-94. https://doi.org/10.1016/j.gloenvcha.2019.03.006

301 Negret, P.J., Sonter, L., Watson, J.E. *et al.* (2019). Emerging evidence that armed conflict and coca cultivation influence deforestation patterns. *Biological Conservation*, *239*, 108176. https://doi.org/10.1016/j.biocon.2019.07.021

302 Del Río Duque, M.L., Rodríguez, T., Pérez Lora, Á.P. *et al.* (2022). Understanding systemic land use dynamics in conflict-affected territories: The cases of Cesar and Caquetá, Colombia. *Plos one*, *17*(5), e0269088. https://doi.org/10.1371/journal.pone.0269088

303 López, J., Qian, Y., Murillo-Sandoval, P.J. *et al.* (2024). Landscape connectivity loss after the de-escalation of armed conflict in the Colombian Amazon (2011–2021).

304 IPBES (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E.S. Brondizio, J. Settele, S. Díaz, and H.T. Ngo (editors). IPBES Secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.3831673

305 Crooks, K.R. & Sanjayan, M.A. (2006). Connectivity Conservation: Maintaining Connections for Nature.

306 Hallaj, Z., Bijani, M., Karamidehkordi, E. *et al.* (2024). Forest land use change effects on biodiversity ecosystem services and human well-being: A systematic analysis. *Environmental and Sustainability Indicators*, Volume 23, 100445. https://doi.org/10.1016/j.indic.2024.100445

307 Critchley, W., Harari, N. & Mekdaschi-Studer, R. (2021). Restoring Life to the Land: The Role of Sustainable Land Management in Ecosystem Restoration.

308 Critchley, W., Harari, N. & Mekdaschi-Studer, R. (2021). Restoring Life to the Land: The Role of Sustainable Land Management in Ecosystem Restoration.

309 United Nations General Assembly. (2015). Resolution A/RES/70/1 Transforming Our World: the 2030 Agenda for Sustainable Development. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

310 UNCCD (2015). Decision 3/COP.12. https://www.unccd.int/official-documentscop-12-ankara-2015/3cop12

311 Stanturf, J.A. & Callaham, M.A.Jr. (2020). Soils and Landscape Restoration. Academic Press. https://doi.org/10.1016/C2016-0-04571-0

312 Cowie, A.L., Orr, B.J., Sanchez V.M.C. *et al.* (2018). Land in balance: the scientific conceptual framework for land degradation neutrality. *Environ. Sci. Policy* 79,25-35. https://doi.org/10.1016/j.envsci.2017.10.011

313 Orr, B.J., Cowie, A.L., Castillo Sanchez, V.M. *et al.* (2017). Scientific Conceptual Framework for Land Degradation Neutrality. A Report of the Science-Policy Interface. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany. https://www.unccd.int/resources/reports/scientific-conceptual-framework-land-degradation-neutrality-report-science-policy

314 UNCCD (n.d). PRAIS Data Portal – Sustainable Development Goal (SDG) Indicator 15.3.1. Accessed April 2025. https://data.unccd.int/land-degradation

315 Winkler, K., Fuchs, R., Rounsevell, M. *et al.* (2021). Global land use changes are four times greater than previously estimated.

316 Smith, P., Nkem, J., Calvin, K. *et al.* (2019). Interlinkages Between Desertification, Land Degradation, Food Security and Greenhouse Gas Fluxes: Synergies, Trade-offs and Integrated Response Options. In: IPCC (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/srccl/chapter/chapter-6/

317 Critchley, W., Harari, N. & Mekdaschi-Studer, R. (2021). Restoring Life to the Land: The Role of Sustainable Land Management in Ecosystem Restoration.

318 United Nations Convention to Combat Desertification (2022). The Global Land Outlook, second edition. UNCCD, Bonn. https://www.unccd.int/resources/global-land-outlook/glo2

319 Van der Heijden, M., Bardgett, R. & van Straalen, N.M. (2008). The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecol Lett* 11: 296-310. https://doi.org/10.1111/j.1461-0248.2007.01139.x

320 Bardgett, R. & van der Putten, W. (2014). Belowground biodiversity and ecosystem functioning. *Nature* 515, 505–511. https://doi.org/10.1038/nature13855

321 Skidmore, P. & Wheaton, J. (2022). Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration.

322 Saco, P.M., Rodríguez, J.F., Moreno-de las Heras, M. *et al.* (2020). Using hydrological connectivity to detect transitions and degradation thresholds: Applications to dryland systems. *CATENA*, Volume 186, 104354. https://doi.org/10.1016/j.catena.2019.104354

323 Neilson, R.P., Pitelka, L.F., Solomon, A.M. *et al.* (2005). Forecasting regional to global plant migration response to climate change.

324 United Nations Development Programme (2017). Community Approaches to Sustainable Land Management and Agroecology Practices. UNDP, New York. https://www.undp.org/publications/community-approaches-sustainable-land-management-and-agroecology-practices

325 Newbold, T., Hudson, L.N., Arnell, A.P *et al.* (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary?.

326 Reed, J., Van Vianen, J., Foli, S. *et al.* (2020). Integrated landscape approaches for nature, climate and people. *Environmental Science & Policy, 104.* https://www.cifor-icraf.org/publications/pdf_files/articles/AReed1501.pdf

327 Hilty, J.A., Chester, C.C., Wright, P.A. *et al* (2024). Uniting hearts and lands: advancing conservation and restoration across the Yellowstone to Yukon region. *Frontiers in conservation science*, *4*, 1264460. https://doi.org/10.3389/fcosc.2023.1264460

328 Yellowstone to Yukon Conservation Initiative (2025). *Our impact on habitats for biodiversity*. https://y2y.net/our-impact

329 Hebblewhite, M., Hilty, J.A., Williams, S. *et al.* (2022). Can a large-landscape conservation vision contribute to achieving biodiversity targets?. *Conservation science and practice*, *4*(1), e588. https://doi.org/10.1111/csp2.588

330 Hilty, J., Worboys, G.L., Keeley, A. *et al.* (2020). Guidelines for conserving connectivity through ecological networks and corridors.

331 Yellowstone to Yukon (2024). Impact Report 2024. https://y2y.net/blog/every-step-counts-y2ys-2024-impact-report-is-here/

332 Hilty, J. (). Yellowstone to Yukon (Y2Y): Connecting and protecting one of the most intact mountain ecosystems, Conservation Corridor. https://conservationcorridor.org/ccsg/what-we-do/projects-and-activities/guidelines/case-studies/y2y/

333 IPBES (2018). The IPBES assessment report on land degradation and restoration.

334 Mitchell, M.G.E., Bennett, E.M. & Gonzalez, A. (2013). Linking Landscape Connectivity and Ecosystem Service Provision: Current Knowledge and Research Gaps. *Ecosystems* 16, 894–908. https://doi.org/10.1007/s10021-013-9647-2

335 IPBES (2019). Global assessment report on biodiversity and ecosystem services.

336 Suding K.N. (2011). Toward an Era of Restoration in Ecology: Successes, Failures, and Opportunities Ahead. *Annual Review of Ecology, Evolution and Systematics* 2011 42:1, 465-487. https://doi.org/10.1146/annurev-ecolsys-102710-145115

337 Gilby B., Olds, A., Connolly, R. *et al.* (2018). Spatial Restoration Ecology: Placing Restoration in a Landscape Context. *BioScience*. Vol 68, Issue 12, Pages 1007–1019. https://doi.org/10.1093/biosci/biy126

338 Pringle, C.M (2001). Hydrologic connectivity and the management of biological reserves: a global perspective.

339 Mosier, S., Córdova, S. & Robertson, G. (2021). Restoring Soil Fertility on Degraded Lands to Meet Food, Fuel, and Climate Security Needs via Perennialization. Front. Sustain. Food Syst., 5. https://doi.org/10.3389/fsufs.2021.706142

340 Higgs, E.S., Harris, J.A., Heger, T. *et al.* (2018). Keep ecological restoration open and flexible. *Nat Ecol Evol* 2 580. https://doi.org/10.1038/s41559-018-0483-9

341 Falk, D.A., Palmer, M.A. & Zedler, J.B. (2007). Foundations of Restoration Ecology. Island Press, Washington DC. https://link.springer.com/book/10.5822/978-1-61091-698-1

342 Suding K., Higgs, E., Palmer, M. *et al.* (2015). Conservation. Committing to ecological restoration. *Science*. 348. 638-640. https://doi.org/10.1126/science.aaa4216

343 Brennan, A., Naidoo, R., Greenstreet, L. *et al.* (2021). Functional Connectivity of the World's Protected Areas.

344 UNCCD Science Policy Interface (n.d). Science Policy Brief - Sustainable Land Use Systems: The path to collectively achieving Land Degradation Neutrality. https://www.unccd.int/sites/default/files/2024-12/SLUS%20brief.pdf

345 Nekesa, T., Jaquet, S., Sinclair, F.L. *et al.* (2024). Sowing sustainability: Agroecology and Sustainable Land Management in Synergy. Deutsche Gesellschaft für International Zusammenarbeit (GIZ) GmbH, Alliance of Diversity International & CIAT and Center for International Forestry Research and World Agroforestry. https://www.giz.de/en/downloads/giz2024-en-agroecology-wocat.pdf

346 Lal, R. (2020). Regenerative agriculture for food and climate. *Journal of Soil and Water Conservation*. https://functionalfertiliser.co.nz/wp-content/uploads/2020/09/Lal-article-jswc.2020.0620A.full_.pdf

347 State of New South Wales/ Local Land Services (2015). Maintain and improve groundcover. Factsheet. https://www.lls.nsw.gov.au/__data/assets/pdf_file/0004/571846/gmp3-maintain-and-improve-groundcover.pdf

348 GOV.UK (n.d). Blog Farming, Use min-till or no-till farming. https://defrafarming.blog.gov.uk/sustainable-farming-incentive-pilot-guidance-use-min-till-or-no-till-farming/

349 Slavikova, S. (2018). 10 Benefits of Crop Rotation in Agriculture. https://greentumble.com/10-benefits-of-crop-rotation

350 Farooq, M. & Siddique, K. (2015). Conservation Agriculture: Concepts, Brief History, and Impacts on Agricultural Systems. https://mel.cgiar.org/reporting/download/hash/D0ZoiZDt

351 WOCAT (n.d). Glossary. Definitions of terms that are relevant to WOCAT's activities. https://wocat.net/en/glossary/#heading-i

352 WOCAT (n.d). Glossary. Definitions of terms that are relevant to WOCAT's activities

353 Tanveer, A., Ikram, R.M. & Ali, H.H. (2019). Crop Rotation: Principles and Practices. In: Hasanuzzaman, M. (2019). Agronomic Crops. Springer, Singapore. https://doi.org/10.1007/978-981-32-9783-8_1

354 Ding, W., Zvomuya, F., Cao, M. *et al.* (2024). Ground cover management improves orchard soil moisture content–A global meta-analysis. *Journal of Hydrology*. 633. 130710. https://doi.org/10.1016/j.jhydrol.2024.130710

355 Aglasan, S., Rejesus, R.M., Hagen, S. *et al.* (2024). Cover crops, crop insurance losses, and resilience to extreme weather events. *American Journal of Agricultural Economics*, *106*(4), 1410-1434. https://doi.org/10.1111/ajae.12431

356 CIDSE (2018). The Principles of Agroecology Towards Just, Resilient and Sustainable Food Systems. https://www.cidse.org/wp-content/uploads/2018/04/EN_The_Principles_of_Agroecology_CIDSE_2018.pdf

357 Hartmann, L., Walz, Y., Hansohm, J. et al. (2024). Assessing the contribution of land and water management approaches to sustainable land management and achieving land degradation neutrality. Front. Sustain. Resour. Manag. https://doi.org/10.3389/fsrma.2024.1423078

358 Altieri, M. (2015). Agroecology: key concepts, principles and practices. https://agroeco.org/wp-content/uploads/2015/11/Agroecology-training-manual-TWN-SOCLA.pdf

359 HLPE (2019). Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. https://openknowledge.fao.org/server/api/core/bitstreams/ff385e60-0693-40fe-9a6b-79bbef05202c/content
Altieri, M.A., ed. (1995). Agroecology: The Science of Sustainable Agriculture, Second Edition. London: Taylor & Francis. https://www.taylorfrancis.com/books/edit/10.1201/9780429495465/agroecology-miguel-altieri

360 Otieno, M. (2024). Water-Use Efficiency, Water Quality, and Irrigation. In: Sustainable Agroecological Practices in Sub-Saharan Africa in the Face of Climate Change. *Advances in Geographical and Environmental Sciences*. Springer. https://doi.org/10.1007/978-3-031-70472-7_2

361 The Nature Conservancy (2023). Food, Climate and Nature FAQs. https://www.nature.org/en-us/what-we-do/our-priorities/provide-food-and-water-sustainably/food-and-water-stories/climate-friendly-food-faqs-regenerative-ag-101/#agriculture

362 World Economic Forum (2023). 5 benefits of regenerative agriculture – and 5 ways to scale it. https://www.weforum.org/stories/2023/01/5-ways-to-scale-regenerative-agriculture-davos23/

363 Hartmann, L., Walz, Y., Hansohm, J. *et al.* (2024). Assessing the contribution of land and water management approaches to sustainable land management and achieving land degradation neutrality. *Front. Sustain. Resour. Manag.* https://doi.org/10.3389/fsrma.2024.1423078

364 Spratt, E., Jordan, J., Winsten, J. *et al.* (2021). Accelerating regenerative grazing to tackle farm, environmental, and societal challenges in the upper Midwest. *Journal of Soil and Water Conservation*, *76*(1), 15A-23A. https://doi.org/10.2489/jswc.2021.1209A

365 Morris, C. (2021). How biodiversity-friendly is regenerative grazing?. *Front. Ecol. Evol.* Vol. 9. https://doi.org/10.3389/fevo.2021.816374

366 Science Direct (2022). Irrigation Management. https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/irrigation-management

367 Sharma, P.K. & Kumar, S. (2023). Irrigation Management. In: Soil Physical Environment and Plant Growth. Springer. https://doi.org/10.1007/978-3-031-28057-3_3

368 Qin, J., Duan, W., Zou, S. *et al.* (2024). Global energy use and carbon emissions from irrigated agriculture. *Nature Communications*, *15*(1), 3084. https://doi.org/10.1038/s41467-024-47383-5

369 Kuang, W., Gao, X., Tenuta, M. *et al.* (2021). A global meta-analysis of nitrous oxide emission from drip-irrigated cropping system. *Global Change Biology*, *27*(14), 3244-3256. https://doi.org/10.1111/gcb.15636

370 Machado, R.M.A. & Serralheiro, R.P. (2017). Soil salinity: effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. *Horticulturae*, *3*(2), 30. https://doi.org/10.3390/horticulturae3020030

371 Anschütz, J., Kome, A., Nederlof, M. *et al.* (1997). Water Harvesting and Soil Moisture Retention. https://www.cabidigitallibrary.org/doi/pdf/10.5555/20219819942

372 FARMESA (2003). Soil and Water Conservation with a Focus on Water Harvesting and Soil Moisture Retention - A STUDY GUIDE for Farmer Field Schools and Community-based Study Groups. https://www.fao.org/fileadmin/templates/nr/images/resources/pdf_documents/FARMESA_SWC1.pdf

373 Tebeje, A.K., Desta, G., Hussein, M.A. *et al.* (2024). Multi-Scale analysis of the impacts of soil and water conservation practices and landscape on grain yield and return on investment in the sub-humid ethiopian highlands. *Heliyon*, *10*(18). https://doi.org/10.1016/j.heliyon.2024.e37786

374 Utah State University (n.d). Windbreak Benefits and Design. https://extension.usu.edu/forestry/publications/utah-forest-facts/005-windbreak-benefits-and-design

375 WOCAT (n.d). Glossary. Definitions of terms that are relevant to WOCAT's activities.

376 Bekunda, M., Chikowo, R., Claessens, L. *et al.* (2022). Combining multiple technologies: Integrated soil fertility management. In Sustainable agricultural intensification: A handbook for practitioners in East and Southern Africa (pp. 134-144). GB: Cabi. https://www.cabidigitallibrary.org/doi/full/10.1079/9781800621602.0010

377 Liniger, H.P., Mekdaschi Studer, R., Hauert, C. *et al.* (2011). Sustainable Land Management in Practice – Guidelines and Best Practices for Sub-Saharan Africa. TerrAfrica, World Overview of Conservation Approaches and Technologies (WOCAT) and Food and Agriculture Organization of the United Nations (FAO). https://wocat.net/documents/82/SLM_in_Practice_E_Final_low.pdf

378 WOCAT (n.d). Glossary. Definitions of terms that are relevant to WOCAT's activities.

379 Lori, M., Symnaczik, S., Mäder, P. *et al.* (2017). Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-regression. *PloS one*, *12*(7), p.e0180442. https://doi.org/10.1371/journal.pone.0180442

380 Long, Y., Cao, Z., Mao, Y. *et al.* (2023). Research on evaluation elements of urban agricultural green bases: a causal inference-based approach. *Land*, 12(8), 1636. https://doi.org/10.3390/land12081636

381 Irawati, I., Irmawati, D., Permana, M.G.A. *et al*. (2021). Internet of things (iot) in water quality monitoring systems and nutrition in hydroponic plants. *Eduvest - Journal of Universal Studies*, 1(8), 676-684. https://doi.org/10.59188/eduvest.v1i8.139

382 Baganz, G.F.M., Junge, R., Portella, M.C. *et al*. (2021). The aquaponic principle—it is all about coupling. *Reviews in Aquaculture*, 14(1), 252-264. https://doi.org/10.1111/raq.12596

383 Hien, B.T. & Khanh, N.T. (2023). Green innovation in agriculture development: the impact of environment awareness, technology spillover, and social networks. *International Journal of Sustainable Agricultural Management and Informatics*, 9(1), 56. https://doi.org/10.1504/ijsami.2023.127539

384 Grovermann, C., Wossen, T., Müller, A. *et al*. (2019). Eco-efficiency and agricultural innovation systems in developing countries: evidence from macro-level analysis. *Plos One*, 14(4), e0214115. https://doi.org/10.1371/journal.pone.0214115

385 Pamuji, W., Dahliani, L., Jamaludin, J. *et al*. (2024). The development of effective urban farming sales method with hydroponics plantation system to complete instant vegetable supply in urban area. *Indonesian Journal of Contemporary Multidisciplinary Research*, 3(5), 932-939. https://doi.org/10.55927/modern.v3i5.11490

386 Long, Y., Cao, Z., Mao, Y. *et al.* (2023). Research on evaluation elements of urban agricultural green bases: a causal inference-based approach.

387 Liu, N., Hu, M., Liang, H. *et al*. (2022). Physiological, transcriptomic, and metabolic analyses reveal that mild salinity improves the growth, nutrition, and flavor properties of hydroponic chinese chive (allium tuberosum rottler ex spr). *Frontiers in Nutrition*, 9. https://doi.org/10.3389/fnut.2022.1000271

388 Li, L., Liu, Y., Luo, W. *et al.* (2024). Does urban innovation promote rural entrepreneurship? quasi-natural experimental evidence from microdata on new agricultural subjects. *Sustainability*, 16(10), 3981. https://doi.org/10.3390/su16103981

389 Bautista, S. & Mayor, Á. (2021). The role of ecohydrological (dis) connectivity in dryland functioning and management. *Ecosistemas*. 30. 2265. https://www.researchgate.net/publication/357320540_The_role_of_ecohydrological_disconnectivity_in_dryland_functioning_and_management

390 Mayor, Á.G., Bautista, S., Small, E.E. *et al*. (2008). Measurement of the connectivity of runoff source areas as determined by vegetation pattern and topography: A tool for assessing potential water and soil losses in drylands. *Water Resour. Res*., 44, W10423. https://doi.org/10.1029/2007WR006367.

391 Bautista, S. & Mayor, Á. (2021). The role of ecohydrological (dis) connectivity in dryland functioning and management.

392 United Nations Development Programme (2017). Community Approaches to Sustainable Land Management and Agroecology Practices.

393 Strohmeier, S., Fukai, S., Haddad, M. *et al*. (2021). Rehabilitation of degraded rangelands in Jordan: The effects of mechanized micro water harvesting on hill-slope scale soil water and vegetation dynamics. *Journal of Arid Environments*, Volume 185. https://doi.org/10.1016/j.jaridenv.2020.104338

394 Tatsumi, C., Taniguchi, T., Yamanaka, N. *et al*. (2021). Micro-catchment water harvesting-based rehabilitation ameliorated soil microbial abundance, diversity and function in a degraded dryland. *Applied Soil Ecology*, Volume 164. https://doi.org/10.1016/j.apsoil.2021.103938

395 Kiffner, C., Kioko, J., Baylis, J. *et al*. (2020). Long-term persistence of wildlife populations in a pastoral area. *Ecology and Evolution*, 10(18), 10000-10016. https://doi.org/10.1002/ece3.6658

396 Fernández-Giménez, M.E., Allington, G., Angerer, J.P. *et al*. (2018). Using an integrated social-ecological analysis to detect effects of household herding practices on indicators of rangeland resilience in mongolia. *Environmental Research Letters*, 13(7), 075010. https://doi.org/10.1088/1748-9326/aacf6f

397 Waterhouse, H., Aburto, F., Rees, G. *et al*. (2023). Diversified vegetation types on rangelands promote multiple soil-based ecosystem services. *Land Degradation & Development*, 35(3), 1011-1028. https://doi.org/10.1002/ldr.4967

398 Morris, C. (2021). How biodiversity-friendly is regenerative grazing?.

399 Teixeira, H.M., Bianchi, F.J.J.A., Cardoso, I.M. et al. (2021). Impact of agroecological management on plant diversity and soil-based ecosystem services in pasture and coffee systems in the Atlantic Forest of Brazil. *Agriculture, Ecosystems and Environment*, *305*, Article 107171. https://doi.org/10.1016/j.agee.2020.107171

400 UNEP (2020). The State of the World's Forests. https://www.unep.org/resources/state-worlds-forests-forests-biodiversity-and-people

401 Hartmann, L., Walz, Y., Hansohm, J. *et al.* (2024). Assessing the contribution of land and water management approaches to sustainable land management and achieving land degradation neutrality.

402 DGB Group (2023). Reforestation: 10 Amazing benefits of planting trees.https://www.green.earth/blog/reforestation-10-amazing-benefits-of-planting-trees

403 ecolegIT (2024). The environmental benefits of forest conservation and reforestation. https://ecolegit.com/articles/the-environmental-benefits-of-forest-conservation-and-reforestation

404 Ilstedt, U., Bargués Tobella, A., Bazié, H. *et al.* (2016). Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. *Sci Rep* 6, 21930. https://doi.org/10.1038/srep21930

405 Kulbachko, Y.L., Дідур, O.O., Хромых, H.O. *et al*. (2019). Morpho-ecological structure of oribatid mite (acariformes, oribatida) communities in the forest litter of recultivated areas. *Biosystems Diversity*, 27(4), 334-341. https://doi.org/10.15421/011944

406 Clemmensen, K.E., Finlay, R.D., Dahlberg, A. *et al*. (2014). Carbon sequestration is related to mycorrhizal fungal community shifts during long-term succession in boreal forests. *New Phytologist*, 205(4), 1525-1536. https://doi.org/10.1111/nph.13208

407 Liu, M., Liang, G., Wu, Z. *et al*. (2024). Spatiotemporal changes in ecological quality and its response to forest landscape connectivity—a study from the perspective of landscape structural and functional connectivity. *Forests*, 15(7), 1248. https://doi.org/10.3390/f15071248

408 Hartmann, L., Walz, Y., Hansohm, J. *et al.* (2024). Assessing the contribution of land and water management approaches to sustainable land management and achieving land degradation neutrality.

409 DGB Group (2023). Reforestation: 10 Amazing benefits of planting trees.

410 ecolegIT (2024). The environmental benefits of forest conservation and reforestation.

411 Ilstedt, U., Bargués Tobella, A., Bazié, H. *et al.* (2016). Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics.

412 Kulbachko, Y.L., Дідур, O.O., Хромых, H.O. *et al.* (2019). Morpho-ecological structure of oribatid mite (acariformes, oribatida) communities in the forest litter of recultivated areas.

413 Clemmensen, K.E., Finlay, R.D., Dahlberg, A. *et al*. (2014). Carbon sequestration is related to mycorrhizal fungal community shifts during long-term succession in boreal forests.

414 Liu, M., Liang, G., Wu, Z. *et al*. (2024). Spatiotemporal changes in ecological quality and its response to forest landscape connectivity—a study from the perspective of landscape structural and functional connectivity.

415 Liniger, H.P., Mekdaschi Studer, R., Hauert, C. *et al.* (2011). Sustainable Land Management in Practice – Guidelines and Best Practices for Sub-Saharan Africa.

416 Hartmann, L., Walz, Y., Hansohm, J. *et al.* (2024). Assessing the contribution of land and water management approaches to sustainable land management and achieving land degradation neutrality.

417 Mlambo, D., Sebata, A., Chichinye, A. *et al.* (2024). Chapter 5 - Agroforestry and biodiversity conservation. Agroforestry for Carbon and Ecosystem Management. Academic Press. https://doi.org/10.1016/B978-0-323-95393-1.00008-7

418 Global EverGreening Alliance (n.d) Assisted Natural Regeneration. https://www.evergreening.org/anr/

419 Wilson, S.J., Alexandre, N.S., Holl, K.D. *et al.* (2021). Applied Nucleation Restoration Guide for Tropical Forests. Conservation International. https://www.conservation.org/docs/default-source/publication-pdfs/applied_nucleation_full_report_final.pdf?sfvrsn=b371f4d4_2

420 IFC & Conservation International (n.d). Catalogue of Nature-Based Solutions for Infrastructure Projects. Draft for Discussion. https://www.ifc.org/content/dam/ifc/doc/2023/catalogue-of-nature-based-solutions-for-infrastructure-projects.pdf

421 Ilstedt, U., Bargués Tobella, A., Bazié, H. et al. (2016). Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics.

422 Avril, A.L. (2023). Assisted Natural Regeneration, a complementary solution to tree planting to restore degraded forests. Reforest Action. https://www.reforestaction.com/en/magazine/assisted-natural-regeneration-complementary-solution-tree-planting-restore-degraded-forests#anr-is-more-suitable-than-planting-in-certain-situations

423 Lamb, D. (2018). Undertaking large-scale forest restoration to generate ecosystem services. *Restor Ecol*, 26: 657-666. https://doi.org/10.1111/rec.12706

424 Siqueira, F.F., de Carvalho, D., Rhodes, J. *et al*. (2021). Small Landscape Elements Double Connectivity in Highly Fragmented Areas of the Brazilian Atlantic Forest. *Front. Ecol. Evol*. 9:614362. https://doi.org/10.3389/fevo.2021.614362

425 Mitchell, M.G., Suarez-Castro, A.F., Martinez-Harms, M. *et al*. (2015). Reframing landscape fragmentation's effects on ecosystem services. *Trends Ecol Evol*. 30(4):190-8. https://doi.org/10.1016/j.tree.2015.01.011

426 Wang, M.Q., Li, Y., Chesters, D. *et al*. (2019). Multiple components of plant diversity loss determine herbivore phylogenetic diversity in a subtropical forest experiment. *Journal of Ecology*, 107(6): 2697-2712. https://doi.org/10.1111/1365-2745.13273

427 Oliver, T.H., Heard, M.S., Isaac, N.J. *et al.* (2015). Biodiversity and resilience of ecosystem functions. *Trends in Ecology & Evolution*, 30(11), 673-684. https://doi.org/10.1016/j.tree.2015.08.009

428 Perino, A., Pereira, H.M., Navarro, L.M. *et al*. (2019). Rewilding complex ecosystems. *Science* Vol. 364, 6438. https://doi.org/10.1126/science.aav5570

429 JNCC (2021). Nature-based Solutions Triple Win Toolkit – International Climate Finance Evidence Project. JNCC, Peterborough. https://hub.jncc.gov.uk/assets/376d989f-0563-4e7f-b034- c79108f63758

430 Spina, F. *et. al.* (2021). Desertification, progressive extension of ecological barriers and conservation of migratory birds: how the Great Green Wall can potentially contribute to restore ecological connectivity for migratory landbirds crossing the Sahel.

431 UNCCD (2020). The Great Green Wall Implementation Status and Way Ahead to 2030. Climatekos GmbH. https://www.unccd.int/sites/default/files/2024-08/1551_GGW_Report_ENG_Final_040920.pdf

432 Iezzi, M.E., Cruz, P., Varela, D. *et al*. (2018). Tree monocultures in a biodiversity hotspot: Impact of pine plantations on mammal and bird assemblages in the Atlantic Forest. *Forest Ecology and Management*, *424*, 216-227. https://doi.org/10.1016/j.foreco.2018.04.049

433 Mallen-Cooper, M., Atkinson, J., Xirocostas, Z.A. *et al*. (2022). Global synthesis reveals strong multifaceted effects of eucalypts on soils. *Global Ecology and Biogeography*, *31*(8), 1667-1678. https://doi.org/10.1111/geb.13522

434 Prangel, E., Kasari-Toussaint, L., Neuenkamp, L. *et al*. (2023). Afforestation and abandonment of semi-natural grasslands lead to biodiversity loss and a decline in ecosystem services and functions. *Journal of Applied Ecology*, 60(5), 825-836. https://doi.org/10.1111/1365-2664.14375

435 Moyano, J., Dimarco, R.D., Paritsis, J. *et al*. (2024). Unintended consequences of planting native and non-native trees in treeless ecosystems to mitigate climate change. *Journal of Ecology*, 112(11), 2480-2491. https://doi.org/10.1111/1365-2745.14300

436 Yu, P., Tang, H., Sun, X. *et al*. (2024). Afforestation alters soil microbial community composition and reduces microbial network complexity in a karst region of southwest China. *Land Degradation and Development*, 35(8), 2926-2939. https://doi.org/10.1002/ldr.5106

437 Chen, P., Ma, R., Shi, J. *et al.* (2023). Ecological risks arising in the regional water resources in inner Mongolia due to a large-scale afforestation project. *Sustainability*, 15(22), 16091. https://doi.org/10.3390/su152216091

438 Canuel, E., Collier, T., Resh, V. *et al.* (2021). The Science of Non-native Species in a Dynamic Delta. Delta Stewardship Council, Sacramento, California, USA. https://deltacouncil.ca.gov/pdf/isb/products/2021-06-03-isb-non-native-species-review-summary.pdf

439 Albright, M.B.N., Louca, S., Winkler, D.E. *et al*. (2021). Solutions in microbiome engineering: prioritizing barriers to organism establishment. *The ISME Journal* 2021, 1–8. https://doi.org/10.1038/S41396-021-01088-5

440 IPCC (2021). Climate Change 2021: The Physical Science Basis.

441 World Bank (2021). A Catalogue of Nature-based Solutions for Urban Resilience. Washington, D.C. World Bank Group. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/502101636360985715/a-catalogue-of-nature-based-solutions-for-urban-resilience

442 Skidmore, P. & Wheaton, J. (2022). Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration.

443 Fuller, I., Death, R., García, J. *et al*. (2020). An index to assess the extent and success of river and floodplain restoration: recognising dynamic response trajectories and applying a process-based approach to managing river recovery. *River Research and Applications*, 37(2), 163-175. https://doi.org/10.1002/rra.3672

444 Kurth, A., Weber, C. & Schirmer, M. (2015). How effective is river restoration in re-establishing groundwater–surface water interactions? – a case study. *Hydrology and Earth System Sciences*, 19(6), 2663-2672. https://doi.org/10.5194/hess-19-2663-2015

445 Samaritani, E., Shrestha, J., Fournier, B. *et al.* (2011). Heterogeneity of soil carbon pools and fluxes in a channelized and a restored floodplain section (Thur river, Switzerland). *Hydrology and Earth System Sciences*, 15(6), 1757-1769. https://doi.org/10.5194/hess-15-1757-2011

446 Samaritani, E., Shrestha, J., Fournier, B. *et al.* (2011). Heterogeneity of soil carbon pools and fluxes in a channelized and a restored floodplain section (Thur river, Switzerland).

447 World Bank (2021). A Catalogue of Nature-based Solutions for Urban Resilience.

448 Ayers, E.M. & Kangas, P. (2018). Soil layer development and biota in bioretention. *Water*, 10(11), 1587. https://doi.org/10.3390/w10111587

449 World Bank (2021). A Catalogue of Nature-based Solutions for Urban Resilience.

450 World Bank (2021). A Catalogue of Nature-based Solutions for Urban Resilience.

451 IFC & Conservation International (n.d). Catalogue of Nature-Based Solutions for Infrastructure Projects. Draft for Discussion.

452 World Bank (2021). A Catalogue of Nature-based Solutions for Urban Resilience.

453 Griggs, F.T. (2009). California Riparian Habitat Restoration Handbook - Second Edition. River Partners. http://riverpartners.org/documents/Restoration_Handbook_Final_Dec09.pdf

454 FAO/DVWK (2002). Fish passes – design, dimensions and monitoring. Rome, Italy: FAO. https://openknowledge.fao.org/items/024384ba-c171-47ce-87d0-62a0704e6e1e

455 Moore, J.W., Schindler, D.E., Carter, J.L. *et al.* (2007). Biotic control of stream fluxes: Spawning salmon drive nutrient and matter export. *Ecology*, 88(5), 1278-1291. https://doi.org/10.1890/06-0782

456 Poff, N.L. & Hart, D.D. (2002). How dams vary and why it matters for the emerging science of dam removal. *BioScience*, 52(8), 659-668. https://doi.org/10.1641/0006-3568(2002)052[0659:HDVAWI]2.0.CO;2

457 Noonan, M.J., Grant, J.W.A. & Jackson, C.D. (2012). A quantitative assessment of fish passage efficiency. *Fish and Fisheries*, 13(4), 450-464. https://doi.org/10.1111/j.1467-2979.2011.00445.x

458 Bunt, C.M., Castro-Santos, T. & Haro, A. (2012). Performance of fish passage structures at upstream barriers to migration. *River Research and Applications*, 28(4), 457-478. https://doi.org/10.1002/rra.1565

459 Kemp, P.S. (2016). Meta-analyses, metrics and motivation: Mixed messages in the fish passage debate. *River Research and Applications*, 32(10), 2116-2124. https://doi.org/10.1002/rra.3082

460 Lucas, M.C. & Baras, E. (2001). Migration of freshwater fishes. Blackwell Science. https://onlinelibrary.wiley.com/doi/book/10.1002/9780470999653?msockid=3dbd055c438763a23109107c422b626f

461 Skidmore, P. & Wheaton, J. (2022). Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration.

462 Skidmore, P. & Wheaton, J. (2022). Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration.

463 Fairfax, E. & Whittle, A. (2020). Smokey the Beaver: beaver-dammed riparian corridors stay green during wildfire throughout the western USA. *Ecological Applications* 30(8). https://doi.org/10.1002/eap.2225

464 Skidmore, P. & Wheaton, J. (2022). Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration.

465 Randle, T., Helper, T., Edwards, W. *et al*. (2015). Guidelines for dam decommissioning projects. United States Society on Dams, Denver. https://docslib.org/doc/3151814/guidelines-for-dam-decommissioning-projects

466 Skidmore, P. & Wheaton, J. (2022). Riverscapes as natural infrastructure: Meeting challenges of climate adaptation and ecosystem restoration.

467 Tockner, K., Schiemer, F. & Ward, J.V. (1998). Conservation by restoration: the management concept for a river-floodplain system on the Danube River in Austria. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 8(1), 71-86. https://doi.org/10.1002/(SICI)1099-0755(199801/02)8:1%3C71::AID-AQC265%3E3.0.CO;2-D

468 Opperman, J.J., Luster, R., McKenney, B.A. *et al*. (2010). Ecologically functional floodplains: connectivity, flow regime, and scale. *JAWRA Journal of the American Water Resources Association*, 46(2), 211-226. https://doi.org/10.1111/j.1752-1688.2010.00426.x

469 Mouchlianitis, F.A. (2024). Dam Removal Progress 2023. World Fish Migration Foundation. https://damremoval.eu/wp-content/uploads/2024/04/Web-version_DRE-Report-2023.pdf

470 Dam Removal Europe (2024). About Us. https://damremoval.eu/about/

471 Dam Removal Europe (n.d). Danube Delta Dams – Ukraine. https://damremoval.eu/portfolio/danube-delta-ukraine/

472 RESTOR (2023). Restoration Cases Flagship Collection – Case #19 Restoring floodplains and wetland corridors in the Lower Danube River and Danube Delta. https://www.crowtherlab.com/wp-content/uploads/2023/09/Restor_Case_Study_Case-19_Delta_Danube_Low-Rez.pdf

473 Fremier, A., Kiparsky, M., Gmur, S. *et al*. (2015). A riparian conservation network for ecological resilience. *Biological Conservation*. 191. 29-37. https://doi.org/10.1016/j.biocon.2015.06.029

474 European Environment Agency (EEA) (2016). Floodplain management: reducing flood risks and restoring healthy ecosystems. EEA Report No 1/2016. https://www.eea.europa.eu/publications/flood-risks-and-environmental-vulnerability

475 Nuñez, T.A., Lawler, J.J., McRae, B.H. *et al*. (2013). Connectivity planning to address climate change. *Conserv Biol*. 27(2): 407-16. https://doi.org/10.1111/cobi.12014

476 Beier, P. (2012). Conceptualizing and designing corridors for climate change. *Ecological Restoration*, 30(4), 312-319. https://www.researchgate.net/publication/265973565_Conceptualizing_and_Designing_Corridors_for_Climate_Change

477 Fremier, A., Kiparsky, M., Gmur, S. *et al*. (2015). A riparian conservation network for ecological resilience.

478 Hilty, J., Worboys, G.L., Keeley, A. *et al.* (2020). Guidelines for conserving connectivity through ecological networks and corridors.

479 Shin, J. & Lee, I. (2006). Cheong Gye Cheon restoration in Seoul, Korea. *Civil Engineering* 159, Pages 162–170, Paper 14775. https://www.icevirtuallibrary.com/doi/pdf/10.1680/cien.2006.159.4.162

480 Landscape Performance Series (n.d.). Cheonggyecheon Stream Restoration Project – Seoul, South Korea Methodology for Landscape Performance Benefits. https://www.landscapeperformance.org/sites/default/files/Cheonggycheon%20Methodology.pdf

481 Shin, J. & Lee, I. (2006). Cheong Gye Cheon restoration in Seoul, Korea.

482 Seavy, N., Viers, J. & Wood, J. (2009). Riparian bird response to vegetation structure: A multiscale analysis using LiDAR measurements of canopy height. *Ecological applications: a publication of the Ecological Society of America*. 19. https://doi.org/10.1890/08-1124.1

483 IPBES (2019). Global assessment report on biodiversity and ecosystem services.

484 Hunter, D. & Dropuljic, K.Z. (2015). Values And Benefits Of Protected Areas. In: Worboys, G.L., Lockwood, M., Kothari, A. *et al.* (2015). Protected Area Governance and Management. Australian National University Press, Canberra, Australia. https://portals.iucn.org/library/node/45127

485 Hilty, J., Worboys, G.L., Keeley, A. *et al.* (2020). Guidelines for conserving connectivity through ecological networks and corridors.

486 IUCN (2021). The benefits and risks of rewilding. IUCN Issues Brief June 2021. https://iucn.org/sites/default/files/2022-04/rewilding_issues_brief_final.pdf

487 Robinson, S. (2016). Land Degradation in Central Asia: Evidence, Perception and Policy. In: Behnke, R., Mortimore, M. (eds) The End of Desertification?. *Springer Earth System Sciences*. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-16014-1_17

488 Hobbs, R.J. & Norton, D.A. (1996), Towards a Conceptual Framework for Restoration Ecology. *Restoration Ecology*, 4: 93-110. https://doi.org/10.1111/j.1526-100X.1996.tb00112.x

489 Bakker, E.S. & Svenning, J.C. (2018). Trophic rewilding: impact on ecosystems under global change. *Phil. Trans. R. Soc*. B373: 20170432. https://doi.org/10.1098/rstb.2017.0432

490 Carver, S., Convery, I., Hawkins, S. *et al*. (2023). Guiding principles for rewilding. *Conserv Biol*. 35(6):1882-1893. Erratum: *Conserv Biol.* 37(6). https://doi.org/10.1111/cobi.13730

491 Berti, E. & Svenning, J. (2020). Megafauna extinctions have reduced biotic connectivity worldwide. *Global Ecology and Biogeography*, 29(12), 2131-2142. https://doi.org/10.1111/geb.13182

492 Andriuzzi, W.S. & Wall, D.H. (2018). Soil biological responses to, and feedbacks on, trophic rewilding. *Philosophical Transactions of the Royal Society: Biological Sciences*, 373(1761), 20170448. https://doi.org/10.1098/rstb.2017.0448

493 Broughton, R.K., Bullock, J.M., George, C. *et al*. (2021). Long-term woodland restoration on lowland farmland through passive rewilding. *Plos One*, 16(6), e0252466. https://doi.org/10.1371/journal.pone.0252466

494 Karnawat, R. & Gaur, N. (2024). Green Corridor and its Relevance in the Current Scenario. *International Journal of Education, Modern Management, Applied Science & Social Science*, Volume 06, No. 01(I). https://www.inspirajournals.com/uploads/Issues/1987256642.pdf

495 Hilty, J., Worboys, G.L., Keeley, A. *et al*. (2020). Guidelines for conserving connectivity through ecological networks and corridors.

496 Schwandner, I.A., Morrison, T.A., Hopcraft, J.G.C. *et al.* (2025). Predicting the impact of targeted fence removal on connectivity in a migratory ecosystem. *Ecological Applications*. 35. https://doi.org/10.1002/eap.3094

497 Linden, E., Rittenhouse, C., Peel, M. *et al.* (2022). Vegetation Changes Following Large-scale Fence Removal Across a Protected Area Network Within the Kruger to Canyons Biosphere Reserve, South Africa. *Ecosystems*; 26; 1-16. https://doi.org/10.1007/s10021-022-00792-3

498 Hanley, N. & Roberts, M. (2019). The economic benefits of invasive species management. *People Nat*. 1: 124–137. https://doi.org/10.1002/pan3.31

499 Pysek, P. & Richardson, D.M. (2010). Invasive Species, Environmental Change and Management, and Health. *Annu. Rev. Environ. Resour*. 2010. 35: 25–55. https://doi.org/10.1146/annurev-environ-033009-095548

500 Le Maitre, D.C., Forsyth, G.G., Dzikiti, S. *et al.* (2016). Estimates of the impacts of invasive alien plants on water flows in South Africa. *Water Sa*, *42*(4), 659-672. https://doi.org/10.4314/wsa.v42i4.17

501 Raizada, P., Raghubanshi, A.S. & Singh, J.S. (2008). Impact of invasive alien plant species on soil processes: A review. *Proceedings of the National Academy of Sciences India Section B–Biological Sciences*, *78* (PART 4), 288-298. https://www.researchgate.net/publication/225039738_Impact_of_invasive_alien_plant_species_on_soil_processes_A_review

502 Francos, M. & Úbeda, X. (2021). Prescribed fire management. *Current Opinion in Environmental Science & Health*, Volume 21. https://doi.org/10.1016/j.coesh.2021.100250

503 NSW National Parks and Wildlife Service (2024). Fire Management Manual 2024-25 Policy and procedures for fire management. https://www2.environment.nsw.gov.au/sites/default/files/fire-management-manual-2024-25-240268.pdf

504 UNEP-WCMC (2021). Protected Planet Report: Status and Trends of Protected Areas and Other Effective Area-Based Conservation Measures. https://www.cbd.int/protected/2021globalreport.shtml

505 Convention on Migratory Species (2014). UNEP/CMS/COP11/Doc.23.4.1.2 Ecological Networks: A Strategic Review Of Aspects Relating To Migratory Species. https://www.cms.int/sites/default/files/document/COP11_Doc_23_4_1_2_Ecological_network_Strategy_E.pdf

506 Montoya, D. (2019). The restoration of ecological networks: Spatial and temporal scales, stability and global change. *Ecosistemas* Vol. 28 Núm. 2. http://dx.doi.org/10.7818/ECOS.1706

507 Beal, M., Nightingale, J., Belo, J.R. *et al.* (2025). Site-level connectivity identified from multiple sources of movement data to inform conservation of a migratory bird. *Journal of Applied Ecology*, 62, 303–316. https://doi.org/10.1111/1365-2664.14839

508 Keeley A.T.H, Beier, P. & Jenness, J.S. (2021). Connectivity metrics for conservation planning and monitoring. *Biological Conservation*, Volume 255, 109008. https://doi.org/10.1016/j.biocon.2021.109008

509 McRae, B.H., Hall, S.A., Beier, P. *et al*. (2012). Where to restore ecological connectivity? Detecting barriers and quantifying restoration benefits. *PLoS One*. 2012; 7(12). https://doi.org/10.1371/journal.pone.0052604

510 Ament, R., Clevenger, A. & van der Ree, R. (Eds.) (2023). Addressing ecological connectivity in the development of roads, railways and canals.

511 Romão, C., Richard, D. & Jones-Walters, L. (2012). Protected areas in Europe — an overview. European Environment Agency, Copenhagen. 130 pp. https://www.eea.europa.eu/en/analysis/publications/protected-areas-in-europe-2012

512 Moulherat, S., Boileau, J., Chapelier, G. *et al*. (2023). The Mitigation Hierarchy. In: Rosell, C. et al. (Eds.) (2023). IENE Biodiversity and infrastructure. A handbook for action. https://www.biodiversityinfrastructure.org/

513 McInturff, A., Xu, W., Wilkinson, C.E. *et al.* (2020). Fence ecology: Frameworks for understanding the ecological effects of fences. *BioScience* 70 (11), 971–985. https://doi.org/10.1093/biosci/biaa103

514 Zerga, B. (2015). Awash National Park: Its degradation status and protection measures. *Palgo J Agric* 2(3): 57–66. https://www.researchgate.net/publication/281268749_AWASH_NATIONAL_PARK_ITS_DEGRADATION_STATUS_AND_PROTECTION_MEASURES

515 Carver, S., Convery, I., Hawkins, S. *et al*. (2023). Guiding principles for rewilding.

516 Weigand, J. (2012). A landowner's guide to wildlife friendly fences: How to build fences with wildlife in mind. Montana Fish, Wildlife & Parks Department, 2nd edition. https://wildlifefriendly.org/wp-content/uploads/2015/09/fencingwithwildlifeinmind_coloradodow.pdf

517 CMS (2024). Decisions of the Conference of the Parties to CMS in effect after its 14th Meeting. https://www.cms.int/sites/default/files/document/cms_cop14_decisions_e.pdf

518 Huijser, M., McGowan, P., Clevenger, A.P. *et al.* (2007). Wildlife-vehicle collisions and crossing mitigation measures: A Toolbox for the Montana Department of Transportation. https://rosap.ntl.bts.gov/view/dot/48824/dot_48824_DS1.pdf

519 Clevenger, A.P. & Huijser, M.P. (2011). Wildlife crossing structure handbook: design and evaluation in North America (No. FHWA-CFL-TD-11-003). United States. Federal Highway Administration. Central Federal Lands Highway Division. https://www.fhwa.dot.gov/clas/ctip/wildlife_crossing_structures/

520 McGuire, T.M., Clevenger, A P., Ament, R. *et al*. (2020). Innovative strategies to reduce the costs of effective wildlife overpasses. Gen. Tech. Rep. PSW-GTR-267. Albany, CA: US Department of Agriculture, Forest Service, Pacific Southwest Research Station, 267. https://research.fs.usda.gov/treesearch/61443

521 The Economic Times (2024). Complete elevated corridor at Kaziranga National Park at the earliest: Supreme Court. https://economictimes.indiatimes.com/news/india/complete-elevated-corridor-at-kaziranga-national-park-at-the-earliest-supreme-court/articleshow/115485094.cms?from=mdr

522 Cameron, A., Lart, R., Bostock, L. *et al*. (2014). Factors that promote and hinder joint and integrated working between health and social care services: a review of research literature. *Health Soc Care Community*. 22(3): 225-33. https://doi.org/10.1111/hsc.12057

523 Clos, J. (2012). Urbanization Challenges of the 21st Century, Unpublished document. UN-Habitat, Nairobi. https://www.chathamhouse.org/sites/default/files/Clos,%20Joan.pdf

524 World Bank (2021). *A Catalogue of Nature-based Solutions for Urban Resilience*.

525 World Bank (2021). *A Catalogue of Nature-based Solutions for Urban Resilience*.

526 Steenberg, J.W., Millward, A.A., Nowak, D.J. *et al*. (2017). A conceptual framework of urban forest ecosystem vulnerability. *Environmental Reviews*, 25(1), 115-126. https://doi.org/10.1139/er-2016-0022

527 Rossi, L., Menconi, M.E., Grohmann, D. *et al*. (2022). Urban planning insights from tree inventories and their regulating ecosystem services assessment. *Sustainability*, 14(3), 1684. https://doi.org/10.3390/su14031684

528 World Bank (2021). A Catalogue of Nature-based Solutions for Urban Resilience.

529 Mullaney, J., Lucke, T. & Trueman, S.J. (2015). A review of benefits and challenges in growing street trees in paved urban environments. *Landscape and Urban Planning*, 134. https://doi.org/10.1016/j.landurbplan.2014.10.013

530 World Bank (2021). A Catalogue of Nature-based Solutions for Urban Resilience.

531 Tang, P., Yang, X., Sun, X. *et al.* (2023). Correlation between ndvi and pm2.5 concentrations in a small-scale urban area. Research Square. https://doi.org/10.21203/rs.3.rs-3146587/v1

532 World Bank (2021). A Catalogue of Nature-based Solutions for Urban Resilience.

533 MacGregor-Fors, I., Escobar, F., Rueda-Hernández, R. *et al*. (2016). City "Green" Contributions: The Role of Urban Greenspaces as Reservoirs for Biodiversity. *Forests*. 7. https://doi.org/10.3390/f7070146

534 Lepczyk, C.A., Aronson, M.F.J., Evans, K.L. *et al*. (2017). Biodiversity in the City: Fundamental Questions for Understanding the Ecology of Urban Green Spaces for Biodiversity Conservation. *BioScience*, Volume 67, Issue 9, Pages 799–807. https://doi.org/10.1093/biosci/bix079

535 Hernández Romero, P.C., Von Thaden Ugalde, J.J., Muench, C.E. *et al.* (2024). Species richness and ecological connectivity of the mammal communities in urban and peri-urban areas at Mexico City.

536 Wang, P., Yang, Y., Li, H. *et al.* (2022). North China Plain as a hot spot of ozone pollution exacerbated by extreme high temperatures. *Atmos. Chem. Phys.* 22 (7), 4705–4719. https://doi.org/10.5194/acp-22-4705-2022

537 Choe, H. & Thorne, J.H. (2019). Climate exposure of East Asian temperate forests suggests transboundary climate adaptation strategies are needed. *Climatic Change* 156: 51–67. https://doi.org/10.1007/s10584-019-02493-8

538 Thorne, J.H., Gogol-Prokurat, M., Hill, S. *et al*. (2020). Vegetation refugia can inform climate-adaptive land management under global warming *Frontiers in Ecology and the Environment*, Vol. 18:5. https://doi.org/10.1002/fee.2208

539 Egerer, M., Fouch, N., Anderson, E.C. *et al.* (2020). Socio-ecological connectivity differs in magnitude and direction across urban landscapes.

540 Pétremand, G., Chittaro, Y., Braaker, S. *et al*. (2018). Ground beetle (Coleoptera: Carabidae) communities on green roofs in Switzerland: synthesis and perspectives. *Urban Ecosystems*, 21, 119-132. https://doi.org/10.1007/s11252-017-0697-7

541 Climate ADAPT (2016). Case Studies - Green roofs in Basel, Switzerland: combining mitigation and adaptation measures. https://climate-adapt.eea.europa.eu/en/metadata/case-studies/green-roofs-in-basel-switzerland-combining-mitigation-and-adaptation-measures-1

542 Niranjan, A. (2025). Green roofs deliver for biodiversity: how Basel put nature on top. The Guardian. https://www.theguardian.com/environment/2025/feb/28/green-roofs-deliver-for-biodiversity-how-basel-put-nature-on-top

543 Brenneisen, S. (2006). Space for Urban Wildlife: Designing Green Roofs as Habitats in Switzerland. *Urban Habitats*, Volume 4, Number 1. https://www.urbanhabitats.org/v04n01/wildlife_pdf.pdf

544 Green Growth Best Practice (2014). GGBP Case Study Series Sustainable City Singapore. https://www.greenpolicyplatform.org/sites/default/files/downloads/best-practices/GGBP%20Case%20Study%20Series_Singapore_Sustainable%20City%20Singapore.pdf

545 SG Green Plan (n.d.). A City of Green Possibilities. https://www.greenplan.gov.sg/

546 National Parks Singapore (n.d.). City in Nature: key strategies. https://www.nparks.gov.sg/who-we-are/city-in-nature-key-strategies

547 Tan, P.Y. & bin Abdul Hamid, A.R. (2014). Urban ecological research in Singapore and its relevance to the advancement of urban ecology and sustainability. *Landscape and Urban Planning*, Volume 125, Pages 271-289. https://doi.org/10.1016/j.landurbplan.2014.01.019

548 National Parks Singapore (2023). Factsheet: Updates on City in Nature Efforts. https://www.mnd.gov.sg/docs/default-source/default-document-library/city-in-nature-efforts.pdf

549 Egerer, M., Fouch, N., Anderson, E.C. *et al.* (2020). Socio-ecological connectivity differs in magnitude and direction across urban landscapes.

550 Hou, D., Al-Tabbaa, A., O'Connor, D. *et al.* (2023). Sustainable remediation and redevelopment of brownfield sites. *Nat Rev Earth Environ* 4, 271–286. https://doi.org/10.1038/s43017-023-00404-1

551 Chulliparambil, V.R., Shearer, H., Cortes-Ramirez, J. *et al.* (2024). Identifying the potential for ecological rehabilitation of landfills in Queensland: A spatial analysis. *Australasian Journal of Environmental Management*, *31*(1), 64–82. https://doi.org/10.1080/14486563.2024.2306342

552 Environmental Protection Agency (2023). Resilient Brownfields Redevelopment - Understanding the financial risks of our changing climate. https://www.epa.gov/system/files/documents/2023-08/OBLR_Climate-Risk_FactSheet_FINAL_080323.pdf

553 Proteus (2021). Brownfield Sites - Achieving net gain through the biodiversity potential of brownfield sites. UNEP-WCMC Technical Briefing. https://www.proteuspartners.org/content//uploads/2021/09/Proteus-Technical-Brief-Brownfield-Sites.pdf

554 IFC & Conservation International (n.d). Catalogue of Nature-Based Solutions for Infrastructure Projects. Draft for Discussion.

555 Bull, J.W., Gordon, A., Law, E.A. *et al.* (2016). Importance of baseline specification in evaluating conservation interventions and achieving no net loss of biodiversity. *Conservation Biology*, 30(3), 12-423. https://doi.org/10.1111/cobi.12243

556 Bogner, J., Pipatti, R., Hashimoto, S. *et al.* (2008). Mitigation of Global Greenhouse Gas Emissions from Waste: Conclusions and Strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation). *Waste management & research: the journal of the International Solid Wastes and Public Cleansing Association, ISWA*. 26, 11-32. https://www.researchgate.net/publication/5513043_Mitigation_of_Global_Greenhouse_Gas_Emissions_from_Waste_Conclusions_and_Strategies_from_the_Intergovernmental_Panel_on_Climate_Change_IPCC_Fourth_Assessment_Report_Working_Group_III_Mitigation

557 Mulligan, C.N., Yong, R.N. & Gibbs, B.F. (2001). Remediation technologies for metal-contaminated soils and groundwater: An evaluation. *Engineering Geology*, 60(1-4), 193-207. https://doi.org/10.1016/S0013-7952(00)00101-0

558 Zheng, H., Wang, X., Yuan, M. *et al.* (2025). Differential response of ecosystem service to restoration methods and restoration time in shallow landslide-prone areas. *Land Degradation & Development*, 36(9), 3051-3062. https://doi.org/10.1002/ldr.5550

559 Cundy, A.B., Hopkinson, L. & Whitby, R.L.D. (2013). Use of iron-based technologies in contaminated land and groundwater remediation: A review. *Science of the Total Environment*, 400(1-3), 42-51. https://doi.org/10.1016/j.scitotenv.2008.07.002

560 Bowler, D.E., Buyung-Ali, L., Knight, T.M. *et al.* (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, 97(3), 147-155. https://doi.org/10.1016/j.landurbplan.2010.05.006

561 Haniger, K., Ma, L. & Timmins, C. (2017). Estimating the value of brownfield remediation. *Journal of the Association of Environmental and Resource Economists*, 4(1). https://www.journals.uchicago.edu/doi/abs/10.1086/689743?journalCode=jaere

562 Landrigan, P.J., Fuller, R., Acosta, N.J., *et al.* (2018). The Lancet Commission on pollution and health. *The Lancet*, 391(10119), 462-512. https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(17)32345-0/abstract

563 IFC & Conservation International (n.d). Catalogue of Nature-Based Solutions for Infrastructure Projects. Draft for Discussion.

564 Blanchette, M.L. & Lund, M.A. (2016). Pit lakes are a global legacy of mining: An integrated approach to achieving sustainable benefit. *Current Opinion in Environmental Sustainability*, 23, 28-34. https://doi.org/10.1016/j.cosust.2016.11.012

565 Salgueiro, P.A., Prach, K., Branquinho, C. *et al.* (2020). Enhancing biodiversity and ecosystem services in quarry restoration – challenges, strategies, and practice. *Restor Ecol*, 28: 655-660. https://doi.org/10.1111/rec.13160

566 Vorovencii, I. (2021). Changes detected in the extent of surface mining and reclamation using multitemporal Landsat imagery: a case study of Jiu Valley, Romania. *Environ Monit Assess* 193, 30. https://doi.org/10.1007/s10661-020-08834-w

567 IFC & Conservation International (n.d). Catalogue of Nature-Based Solutions for Infrastructure Projects. Draft for Discussion.

568 IFC & Conservation International (n.d). Catalogue of Nature-Based Solutions for Infrastructure Projects. Draft for Discussion.

569 Misrahi, P.P., Marais, C. & Varoli, I. (2024). Clean Energy as a Catalyst for a Nature-Positive Transition. World Economic Forum. https://www3.weforum.org/docs/WEF_Clean_Energy_2024.pdf

570 WWF & BCG (2023). Building a Nature-Positive Energy Transformation: Why a low-carbon economy is better for people and nature. WWF, Washington, DC. https://www.worldwildlife.org/publications/building-a-nature-positive-energy-transformation--2

571 Vincevica-Gaile, Z., Burlakovs, J., Fonteina-Kazeka, M. *et al.* (2023). Case Study-Based Integrated Assessment of FormerWaste Disposal Sites Transformed to Green Space in Terms of Ecosystem Services and Land Assets Recovery. *Sustainability* 2023, 15, 3256. https://doi.org/10.3390/su15043256

572 Sydney Olympic Park (2020). 20 years of healing: Delivering the ecological legacy of the Green Games. https://www.sydneyolympicpark.nsw.gov.au/sites/default/files/2023-11/2021%20Biodiversity%20Ebook.pdf

573 Sydney Olympic Park (2015). Fact Sheet – Restoring Ecosystems. https://www.sydneyolympicpark.nsw.gov.au/sites/default/files/2023-11/fact_sheet_restoring_ecosystems.pdf

574 Sydney Olympic Park (2020). 20 years of healing: Delivering the ecological legacy of the Green Games. https://www.sydneyolympicpark.nsw.gov.au/sites/default/files/2023-11/2021%20Biodiversity%20Ebook.pdf

575 Deshaies, M. (2024). Mines, the Environment, and Mining Landscapes in Germany. Encyclopédie d'histoire numérique de l'Europe. https://ehne.fr/en/node/21499

576 Internationale Bauaustellungen (n.d). IBA Emscher Park – Future for an Industrial Region. https://www.internationale-bauausstellungen.de/en/history/1989-1999-iba-emscher-park-a-future-for-an-industrial-region/

577 ARUP (n.d). Using regenerative land management techniques to provide natural landscaping around the A30. https://www.arup.com/projects/keyn-glas-a30-environmental-designated-funds/#:~:text=Working%20with%20National%20Highways%2C%20Arup%20has%20designed%20Keyn,risks%20of%20climate%20change%20impacts%20such%20as%20flooding.

578 Oakman, B. & Woods, P. (2022). A green legacy: A groundbreaking project setting new standards for infrastructure providing environmental growth on private land at scale. *The Arup Journal*, Issue 1. https://www.arup.com/globalassets/downloads/arup-journal/the-arup-journal-2022-issue-1.pdf

579 Quintero, J.D. (n.d). A Guide to Good Practices for Environmentally Friendly Roads. Latin America Conservation Council. https://www.nature.org/content/dam/tnc/nature/en/documents/latin-america/Friendlyroads.pdf

580 Krueger, L., Willingshofer, A., McKenney, B. *et al.* (2023). Forging a Nature Positive Energy Transition. T20 Policy Brief. https://www.nature.org/content/dam/tnc/nature/en/documents/2023-India-G20-Forging-a-Nature-Positive-Energy-Transition.pdf

581 Misrahi, P.P., Marais, C. & Varoli, I. (2024). Clean Energy as a Catalyst for a Nature-Positive Transition.

582 BirdLife (n.d.). Birds and Power Lines within the rift valley/red Sea Flyway. https://www.cms.int/en/publication/guidance-power-lines-birds-and-power-lines-within-rift-valleyred-sea-flyway

583 UN Environment Programme (2024). Addressing the impact of linear infrastructure on migratory species. https://www.cms.int/cami/sites/default/files/publication/infrastructure_fact_sheet_dec2024_part2.pdf

584 BirdLife (n.d.). Birds and Power Lines within the rift valley/red Sea Flyway.

585 BirdLife (2024). Online Tool Prevents Bird Collisions in Flyways Across the World. https://www.birdlife.org/news/2024/09/17/online-tool-prevents-bird-collisions-in-flyways-across-the-world/

586 Martin, D. (2017). Ecological restoration should be redefined for the twenty-first century. *Restoration Ecology*, 25. https://doi.org/10.1111/rec.12554

587 Sapkota, R.P., Stahl, P.D. & Rijal, K. (2018). Restoration governance: An integrated approach towards sustainably restoring degraded ecosystems. *Environmental Development*, Vol 27: 83-94. https://doi.org/10.1016/j.envdev.2018.07.001

588 Higgs, E.S. (1997). What is Good Ecological Restoration?. *Conservation Biology*, 11(2), 338–348. http://www.jstor.org/stable/2387608

589 Sapkota, R.P., Stahl, P.D. & Rijal, K. (2018). Restoration governance: An integrated approach towards sustainably restoring degraded ecosystems.

590 Wiegant, D., Van Oel, P. & Dewulf, A. (2022). Scale-sensitive governance in forest and landscape restoration: a systematic review. *Reg Environ Change* 22**,** 25. https://doi.org/10.1007/s10113-022-01889-0

591 Key, I., Smith, A., Turner, B. *et al*. (2021). Can Nature-Based Solutions Deliver a Win-Win for Biodiversity and Climate Change Adaptation?. Preprints. https://doi.org/10.20944/preprints202110.0336.v1

592 Hu, B., Zhang, Z., Han, H. *et al.* (2021). The grain for green program intensifies trade-offs between ecosystem services in midwestern Shanxi, China. *Remote Sensing*, 13(19), 3966. https://doi.org/10.3390/rs13193966

593 Lloret, F. (2017). Trade-offs in high mountain conservation. *Advances in Global Change Research*, 37-59. https://doi.org/10.1007/978-3-319-55982-7_2

594 Vasilijević, M., Zunckel, K., McKinney, M. *et al*. (2015). Transboundary Conservation: A systematic and integrated approach. Best Practice Protected Area Guidelines Series No. 23, Gland, Switzerland: IUCN. xii + 107pp. https://iucn.org/resources/publication/transboundary-conservation-systematic-and-integrated-approach

595 Grumbine, R.E., Dore, J. & Xu, J. (2012). Mekong hydropower: Drivers of change and governance challenges. *Frontiers in Ecology and the Environment*, 10(2), 91-98. https://doi.org/10.1890/110146

596 Middleton, N. & Kang, U. (2017). Sand and dust storms: Impact mitigation. *Sustainability*, 9(6), 1053. https://doi.org/10.3390/su9061053

597 Benjaminsen, T.A. & Ba, B. (2019). Why do pastoralists in Mali join jihadist groups? A political ecological explanation. *The Journal of Peasant Studies*, 46(1), 1-20. https://doi.org/10.1080/03066150.2018.1474457

598 Torney, C.J., Hopcraft, J.G.C., Morrison, T.A. *et al*. (2018). From single steps to mass migration: the problem of scale in the movement ecology of the Serengeti wildebeest. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *373*(1746), 20170012. https://doi.org/10.1098/rstb.2017.0012

599 Catry, T., Ventura, F., Dias, M.P. *et al*. (2021). Estimating the conservation cost of the projected new international lisbon airport for migratory shorebirds of the tagus estuary, portugal. *Bird Conservation International*, 32(2), 232-245. https://doi.org/10.1017/s0959270921000125

600 Demony, C. & Waldersee, V. (2020). Don't kill our national bird: Dutch object to new Lisbon airport. Reuters. https://www.reuters.com/article/business/environment/dont-kill-our-national-bird-dutch-object-to-new-lisbon-airport-idUSKBN20C2A4/

601 ClientEarth (2024). Portugal abandons plans to build new airport on nature reserve following lawsuit. https://www.clientearth.org/latest/press-office/press-releases/portugal-abandons-plans-to-build-new-airport-on-nature-reserve-following-lawsuit/

602 Metternicht, G. (2017). Global Land Outlook Working Paper – Land Use Planning. https://www.unccd.int/sites/default/files/2018-06/6.%20Land%2BUse%2BPlanning%2B__G_Metternicht.pdf

603 UNCCD/Science-Policy Interface (2022). The Contribution of Integrated Land Use Planning and Integrated Landscape Management to Implementing Land Degradation Neutrality. Science-Policy Brief No: 07. May 2022. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany. https://www.unccd.int/resources/reports/contribution-integrated-land-use-planning-and-integrated-landscape-management

604 Gurrutxaga, M. (2011). The management of the landscape ecological connectivity in Spain: Initiatives and challenges. *Boletín de la Asociación de Geógrafos Españoles*, 56, 443-448. https://www.researchgate.net/publication/287185070_The_management_of_the_landscape_ecological_connectivity_in_Spain_Initiatives_and_challenges

605 GEF (n.d.). Ridge to Reef. https://www.thegef.org/what-we-do/topics/ridge-reef

606 Pacific Ridge to Reef (n.d.). What is Ridge to Reef?. https://www.pacific-r2r.org/help/faq/what-ridge-reef

607 Reed, J., Ickowitz, A., Chervier, C. *et al*. (2020). Integrated landscape approaches in the tropics: A brief stock-take.

608 Pérez-Cirera, V., Cornelius, S. & Zapata, J. (2021). Powering Nature: Creating the Conditions to Enable Nature-based Solutions. WWF. https://www.wwfca.org/en/powering_nature/

609 IPBES (2018): The IPBES assessment report on land degradation and restoration.

610 Scolozzi, R. & Geneletti, D. (2012). Assessing habitat connectivity for land-use planning: A method integrating landscape graphs and Delphi survey. *Journal of Environmental Planning and Management* Vol. 55. Issue 6. https://doi.org/10.1080/09640568.2011.628823

611 Pascual, U., Balvanera, P., Anderson, C.B. et al. (2023). Diverse values of nature for sustainability. Nature 620, 813–823. https://doi.org/10.1038/s41586-023-06406-9

612 Critchley, W., Harari, N. & Mekdaschi-Studer, R. (2021). Restoring Life to the Land: The Role of Sustainable Land Management in Ecosystem Restoration.

613 Castillo-Mandujano, J. & Smith-Ramirez, C. (2022). The need for holistic approach in the identification of priority areas to restore: A review. *Restoration Ecology*, 30. https://doi.org/10.1111/rec.13637

614 Aronson, J., Clewell, A.F., Blignautd, J.N. *et al.* (2006). Ecological restoration: A new frontier for nature conservation and economics. *Journal for Nature Conservation* 14: 135–139. https://doi.org/10.1016/j.jnc.2006.05.005

615 Keeley, A.T.H., Beier, P., Creech, T. *et al.* (2019). Thirty years of connectivity conservation planning: an assessment of factors influencing plan implementation. *Environ. Res. Lett*. 14: 103001. https://iopscience.iop.org/article/10.1088/1748-9326/ab3234

616 Desmet, P.G., Holness, S., Skowno, A. *et al.* (2013) Limpopo Conservation Plan v.2: Technical Report. Contract Number EDET/2216/2012. Report for Limpopo Department of Economic Development, Environment & Tourism (LEDET) by ECOSOL GIS. https://conservationcorridor.org/cpb/Desmet_et_al_2013.pdf

617 Castillo-Mandujano, J. & Smith-Ramirez, C. (2022). The need for holistic approach in the identification of priority areas to restore: A review.

618 IPBES (2018). The IPBES assessment report on land degradation and restoration.

619 Staccione, A., Candiago, S. & Mysiak, J. (2022), Mapping a Green Infrastructure Network: a framework for spatial connectivity applied in Northern Italy. *Environmental Science & Policy*, Vol 131: 57-67. https://doi.org/10.1016/j.envsci.2022.01.017

620 Estreguil, C., Dige, G., Kleeschulte, S. *et al*. (2019). Strategic Green Infrastructure and Ecosystem Restoration - Geospatial methods, data and tools. EU Publications Office. https://data.europa.eu/doi/10.2760/06072

621 Hilty, J., Worboys, G.L., Keeley, A. *et al.* (2020). Guidelines for conserving connectivity through ecological networks and corridors.

622 Critchley, W., Harari, N. & Mekdaschi-Studer, R. (2021). Restoring Life to the Land: The Role of Sustainable Land Management in Ecosystem Restoration.

623 Critchley, W., Harari, N. & Mekdaschi-Studer, R. (2021). Restoring Life to the Land: The Role of Sustainable Land Management in Ecosystem Restoration.

624 Agrawal, A. & Gibson, C.C. (1999). Enchantment and disenchantment: The role of community in natural resource conservation. *World Development*, 27(4), 629-649. https://doi.org/10.1016/S0305-750X(98)00161-2

625 IPBES (2022). Summary for Policymakers of the Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Pascual, U., Balvanera, P., Christie, M., Baptiste, B., González-Jiménez, D., Anderson, C.B., Athayde, S., Barton, D.N., Chaplin-Kramer, R., Jacobs, S., Kelemen, E., Kumar, R., Lazos, E., Martin, A., Mwampamba, T.H., Nakangu, B., O'Farrell, P., Raymond, C.M., Subramanian, S.M., Termansen, M., Van Noordwijk, M., and Vatn, A. (eds.). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.6522392

626 Kettunen, H. & Cuxil, A. (2021). Indigenous People, National Parks,and Biodiversity in the Maya Region - Chapter 5. In: Andersson, R., Cothran, B. & Kekki, S. (eds.). Bridging Cultural Concepts of Nature. Helsinki University Press.

627 FAO (2019). Governance of tenure: Making it happen. FAO. https://www.fao.org/fileadmin/user_upload/nr/land_tenure/pdf/VG_tenure_brochure_EN.pdf

628 Robinson, B.E., Masuda, Y.J., Kelly, A. *et al*. (2018). Incorporating land tenure security into conservation. *Conservation Letters*, 11(2), e12383. https://doi.org/10.1111/conl.12383

629 Meinzen-Dick, R., Quisumbing, A., Doss, C. *et al*. (2019). Women's land rights as a pathway to poverty reduction: Framework and review of available evidence. *Agricultural Systems*, 172, 72-82. https://doi.org/10.1016/j.agsy.2017.10.009

630 Add ref: Termansen, M., Jacobs, S., Mwampamba, T.H. et al. (2022). Chapter 3: The potential of valuation. In: Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. P. Balvanera, U. Pascual, M. Christie, B. Baptiste, and D. González-Jiménez (eds). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.6521298

631 Sneed, A. (2019). What conservation efforts can learn from indigenous peoples. *Scientific American* 331(6). https://www.scientificamerican.com/article/what-conservation-efforts-can-learn-from-indigenous-communities/

632 Schuster, R., Germain, R.R., Bennett, J.R. *et al*. (2019). Vertebrate biodiversity on indigenous-managed lands in Australia, Brazil and Canada equals that in protected areas. *Environ. Sci. Policy* 101, 1–6. http://dx.doi.org/10.1016/j.envsci.2019.07.002

633 IPBES (2019): Global assessment report on biodiversity and ecosystem services.

634 Sneed, A. (2019). What conservation efforts can learn from indigenous peoples.

635 Nganso, B.T., Kyerematen, R. & Obeng-Ofori, D. (2012). Review of biodiversity in sacred groves in Ghana and implications on conservation. *Current Trends in Ecology*, 3, 1-10. https://www.researchgate.net/publication/235701263_Review_of_biodiversity_in_sacred_groves_in_Ghana_and_implications_on_conservation

636 Collantes, V., Kloos, K., Henry, P. *et al*. (2018). Moving towards a twin-agenda: Gender equality and land degradation neutrality. *Environmental Science & Policy*, Volume 89, 2018, Pages 247-253. https://doi.org/10.1016/j.envsci.2018.08.006

637 Mor, T. (2018). Towards a Gender-Responsive Implementation of the United Nations Convention to Combat Desertification. http://www.unwomen.org/en/digitallibrary/publications/2018/2/towards-a-gender-responsive-implementation-of-the-unconvention-to-combat-desertification

638 Gender in conservation and climate policy. *Nat. Clim. Chang.* 9, 255 (2019). https://doi.org/10.1038/s41558-019-0448-2

639 Kettunen, H. & Cuxil, A. (2021). Indigenous People, National Parks,and Biodiversity in the Maya Region.

640 Bennett, M.T. (2008). China's sloping land conversion program: Institutional innovation or business as usual?. *Ecological Economics*, 65(4), 699-711. https://doi.org/10.1016/j.ecolecon.2007.09.017

641 Pagiola, S. (2008). Payments for environmental services in Costa Rica. *Ecological Economics*, 65(4), 712-724. https://doi.org/10.1016/j.ecolecon.2007.07.033

642 Porras, I. & Neves, N. (2006). Honduras – Jesus de Otoro. Markets for Watershed Services -Country Profile. IIED & Watershed Markets. https://watershedmarkets.org/documents/Honduras_Jesus_de_Otoro.pdf

643 World Bank Group (2022). Enhancing ecological connectivity in the projects of the Amazon Sustainable Landscapes and Global Wildlife Programs. https://www.worldbank.org/en/news/feature/2022/10/05/enhancing-ecological-connectivity-in-the-projects-of-the-amazon-sustainable-landscapes-program-and-the-global-wildlife-p

644 Puppim de Oliveira, J., Cadman, T., Hwan, A. *et al.* (2013). Governing the Forests: An Institutional Analysis of REDD+ and Community Forest Management in Asia Governing the Forests: An Institutional Analysis of REDD+ and Community Forest Management. UNU-IAS Policy Report. https://collections.unu.edu/view/UNU:2876

645 World Bank (2015). What Are Green Bonds?. https://www.worldbank.org/en/topic/climatechange/brief/what-are-green-bonds

646 Mirova (2021). Mirova's Land Degradation Neutrality Fund exceeds $200m of commitments for its final close. https://www.mirova.com/en/news/ldn-land-degradation-neutrality-fund-exceeds-200-million-dollars-commitments-for-final-close

647 NATIXIS (2025). Mirova mobilises a blended finance coalition for its second-generation fund dedicated to sustainable land use in the global south. https://www.im.natixis.com/en-intl/about/investment-manager-news/2025/mirova-mobilises-a-blended-finance-coalition-for-its-second-generation-fund-dedicated-to-sustainable-land-use-in-the-global-south

648 The Nature Conservancy (2022). Restoring Degraded Landscapes in the Cerrado. https://www.nature.org/en-us/about-us/where-we-work/latin-america/brazil/stories-in-brazil/restoring-degraded-landscapes-in-the-cerrado/

649 Liverpool City Region – Investing in Nature (n.d.). Case Study 2: The Wyre Catchment Natural Flood Management Project. https://investinginnaturelcr.com/case-studies/#case-study-2

650 Green Finance Institute (n.d.). Milestone 4: The Wyre Catchment Natural Flood Management Project - Identify and Work with Buyers. https://hive.greenfinanceinstitute.com/gfihive/toolkit/identify-and-work-with-buyers/the-wyre-river-natural-flood-management-project/

651 Payne, L.L., Zimmermann, J.A.M., Mowen, A.J. *et al*. (2013). Community size as a factor in health partnerships in community parks and recreation. 2007. *Preventing Chronic Disease*, 10. https://doi.org/10.5888/pcd10.120238

652 Cao, S., Zheng, X., Chen, L. *et al.* (2017). Using the green purchase method to help farmers escape the poverty trap in semiarid China. *Agronomy for Sustainable Development*, 37(2). https://doi.org/10.1007/s13593-017-0420-3

653 Aronson, J., Blignaut, J., Milton, S.J. *et al*. (2010). Are socioeconomic benefits of restoration adequately quantified? a meta-analysis of recent papers (2000-2008) in restoration ecology and 12 other scientific journals. *Restoration Ecology*, 18(2), 143-154. https://doi.org/10.1111/j.1526-100x.2009.00638.x

654 Mirzabaev, A., Vakulchuk, R. & Øverland, I. (2024). Economic potential of land restoration for climate change mitigation. Research Square. https://doi.org/10.21203/rs.3.rs-5094446/v1

655 Rahman, S.A., Baral, H., Sharma, R. *et al.* (2019). Integrating bioenergy and food production on degraded landscapes in Indonesia for improved socioeconomic and environmental outcomes. *Food and Energy Security*, 8(3). https://doi.org/10.1002/fes3.165

656 Yusop, A., Yahaya, I., Kadis, G. *et al*. (2017). Hybrid micro-hydro power generation development in Endau Rompin national park Johor, Malaysia. *MATEC Web of Conferences*, 135, 00007. https://doi.org/10.1051/matecconf/201713500007

657 Ain, Q.U., Yousaf, T. & Tahir, M.A. (2024). Decentralization policies and sustainable rural development: a path to eradicating poverty (sdg 1) and hunger (sdg 2). *Sustainable Development*, 33(1), 700-716. https://doi.org/10.1002/sd.3147

658 Bakchan, A. & White, K.D. (2024). Sustainable development in rural underserved communities through improved responsible management of decentralized wastewater infrastructure: a focus on the Alabama black belt. *Environmental Science & Technology*, 58(42), 18671-18685. https://doi.org/10.1021/acs.est.4c01170

659 Behrendt, G., Peter, S., Sterly, S. *et al.* (2019). Community financing in the German organic food sector: a key for sustainable food systems?. *CIRIEC Working Papers* 1918, CIRIEC - Université de Liège. https://www.ifls.de/fileadmin/user_upload/Abbildungen/Publikationen/2019/WorkingPaper_CommunityFinancing.pdf

660 Lebos, J.L. (2022). How Kiva works with Lending Partners. https://www.kiva.org/blog/how-kiva-works-with-lending-partners

661 Kiva (n.d.). How does Kiva work?. https://www.kiva.org/about/how

662 Root Capital (n.d.). Access to Finance. https://rootcapital.org/our-approach/access-to-finance/

663 Root Capital (n.d.). Root Capital's 2021-2025 Strategy. https://rootcapital.org/wp-content/uploads/2024/06/Summary-of-Five-Year-Strategy.pdf

664 Belote, T., Beier, P., Creech, T. *et al*. (2020). A Framework for Developing Connectivity Targets and Indicators to Guide Global Conservation Efforts. *Bioscience*, 70, 122-125. https://doi.org/10.3390/land11101670

665 Keeley, A.T.H., Faselt, J., Oppler, G. *et al.* (2025). Monitoring Ecological Corridors for Nature and People. *Ecoevorixiv*. https://doi.org/10.32942/X25K82

666 Grantham, H.S., Duncan, A., Evans, T.D. *et al.* (2020). Anthropogenic modification of forests means only 40% of remaining forests have high ecosystem integrity. *Nat Commun* 11, 5978. https://doi.org/10.1038/s41467-020-19493-3

667 Wu, J., Zhang, S., Luo, Y. *et al.* (2022). Assessment of risks to habitat connectivity through the stepping-stone theory: A case study from Shenzhen, China. *Urban Forestry & Urban Greening*, Volume 71. https://doi.org/10.1016/j.ufug.2022.127532

668 Walters, C.J. (1986). Adaptive management of renewable resources. New York: Macmillan Publishing Company. 374 p. https://pure.iiasa.ac.at/id/eprint/2775/1/ER-86-012.pdf

669 Keeley, A.T.H., Faselt, J., Oppler, G. *et al.* (2025). Monitoring Ecological Corridors for Nature and People.

670 Wilkinson, M., Dumontier, M., Aalbersberg, I. *et al.* (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Sci Data* 3, 160018. https://doi.org/10.1038/sdata.2016.18

671 Cooke, S., Bennett, J. & Jones, H. (2019). We have a long way to go if we want to realize the promise of the "decade on ecosystem restoration". *Conservation Science and Practice*, 1(12). https://doi.org/10.1111/csp2.129

672 Dawson, S.K., Kingsford, R.T., Berney, P. *et al.* (2017). Contrasting influences of inundation and land use on the rate of floodplain restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27(3), 663-674. https://doi.org/10.1002/aqc.2749

673 Berkes, F. (1999). Sacred Ecology: Traditional Ecological Knowledge and Resource Management. https://archive.org/details/sacredecologytra0000berk

674 Tengö, M., Hill, R., Malmer, P. *et al.* (2017). Weaving knowledge systems in IPBES, CBD and beyond—lessons learned for sustainability. *Current Opinion in Environmental Sustainability,* Volumes 26–27. https://doi.org/10.1016/j.cosust.2016.12.005

675 Aydin, B., Tezer, A., Türkay, Z. *et al.* (2018). Resilience through participatory planning for the integrated ecological risks in Düzce. *Resilience*, 2(2), 105-121. https://doi.org/10.32569/resilience.484946

676 Fink, G., Schmid, M. & Wuest, A. (2014). Large lakes as sources and sinks of anthropogenic heat: Capacities and limits. *Water Resour. Res.*, 50, 7285–7301. https://doi.org/10.1002/2014WR015509

677 Zakharova, O., Kucher, D.E., Mashkova, E.I. *et al.* (2021). Land reclamation and the possibility of its digitalization. *Prirodoobustrojstvo*, (4), 31-37. https://doi.org/10.26897/1997-6011-2021-4-31-37

678 Cordell, S., Questad, E.J., Asner, G.P. *et al.* (2016). Remote sensing for restoration planning: how the big picture can inform stakeholders. *Restoration Ecology*, 25(S2). https://doi.org/10.1111/rec.12448

679 Reis, B.P., Martins, S.V., Filho, E.I.F. *et al.* (2019). Management recommendation generation for areas under forest restoration process through images obtained by UAV and Lidar. *Remote Sensing*, 11(13), 1508. https://doi.org/10.3390/rs11131508

680 Quintero-Uribe, L.C., Pereira, H.M., Dunn-Capper, R. *et al.* (2025). Finding space for rewilding: participatory scenarios reveal ecological opportunities based on plural values of nature. *bioRxiv*. https://doi.org/10.1101/2025.03.05.641619

681 Pereira, L., Davies, K.K., Belder, E.D. *et al.* (2020). Developing multiscale and integrative nature–people scenarios using the nature futures framework. *People and Nature*, 2(4), 1172-1195. https://doi.org/10.1002/pan3.10146

682 SMART (n.d.). How we use SMART. https://smartconservationtools.org/en-us/SMART-in-Practice/How-we-use-SMART

683 Graham, L. (n.d.). Handling big data across the Eastern Cape of South Africa. SMART Website. https://smartconservationtools.org/en-us/SMART-Community/Your-stories/Case-Study?CaseStudyID=23

684 Shepel, I. (2025). Organization of land plot document management: problems and ways of improvement. *Scientific Opinion: Economics and Management*, (1(89)). https://doi.org/10.32782/2521-666x/2025-89-6

685 McGovern, A., Ebert-Uphoff, I., Gagne, D. *et al.* (2022). Why we need to focus on developing ethical, responsible, and trustworthy artificial intelligence approaches for environmental science. *Environmental Data Science*, 1. https://doi.org/10.1017/eds.2022.5

686 Rolnick, D., Donti, P.L., Kaack, L.H. *et al.* (2022). Tackling climate change with machine learning. *ACM Computing Surveys*, 55(2), 1-96. https://doi.org/10.1145/3485128

687 Rolnick, D., Donti, P.L., Kaack, L.H. *et al.* (2022). Tackling climate change with machine learning.

688 Elliott, S. (2016). The potential for automating assisted natural regeneration of tropical forest ecosystems. *Biotropica*, 48(6), 825-833. https://doi.org/10.1111/btp.12387

689 Altieri, M. (2015). Agroecology: key concepts, principles and practices.

690 CBD (2011). Convention on Biological Diversity : text and annexes. https://www.cbd.int/doc/legal/cbd-en.pdf

691 CMS (2024). UNEP/CMS/Resolution 14.16 – Ecological Connectivity. https://www.cms.int/sites/default/files/document/cms_cop14_res.14.16_ecological-connectivity_e.pdf

692 Hilty, J. *et al.* (2020). Guidelines for conserving connectivity through ecological networks and corridors. IUCN, Gland. https://iucn.org/resources/publication/guidelines-conserving-connectivity-through-ecological-networks-and-corridors

693 Parrish, J.D., Braun, D.P. & Unnasch, R.S. (2003). Are we conserving what we say we are? Measuring ecological integrity within protected areas. *BioScience*, 53(9), 851-860. https://academic.oup.com/bioscience/article-abstract/53/9/851/311604

694 Hilty, J. *et al.* (2020). Guidelines for conserving connectivity through ecological networks and corridors.

695 UNCCD (1994). Convention Text. https://www.unccd.int/resource/convention-text

696 UNCCD (2015). Decision 3/COP.12 - Integration of the Sustainable Development Goals and targets into the implementation of the United Nations Convention to Combat Desertification and the Intergovernmental Working Group report on land degradation neutrality. https://www.unccd.int/sites/default/files/inline-files/dec3-COP.12eng.pdf

697 UNCCD (2022). The Global Land Outlook, second edition.

698 Metternicht, G. (2018). Land use and spatial planning: Enabling sustainable management of land resources. Springer. https://www.unccd.int/sites/default/files/2018-06/6.%20Land%2BUse%2BPlanning%2B__G_Metternicht.pdf

699 UNEA (2022). Nature-based Solutions for supporting sustainable development. UNEP/EA.5/Res.5. https://www.unep.org/environmentassembly/unea5/unea-5.2/outcomes-resumed-session-unea-5-unea-5.2

700 CBD (2018). CBD Decision 14/8 - Protected areas and other effective area-based conservation measures. https://www.cbd.int/doc/decisions/cop-14/cop-14-dec-08-en.pdf

701 IUCN (n.d). Our Work. https://iucn.org/our-work/topic/effective-protected-areas

702 Carver, S. *et al.* (2021). Guiding principles for rewilding.

703 Joint Research Centre of the European Commission (2025). The Digital Observatory for Protected Areas (DOPA) Explorer 4.1, Accessed: June 2025, Ispra, Italy. Available at: http://dopa-explorer.jrc.ec.europa.eu

704 Lindsey, R. (2002). The Migrating Boreal Forest. NASA Earth Observatory. https://earthobservatory.nasa.gov/features/BorealMigration/boreal_migration3.php

705 Peller, T. & Altermatt, F. (2024). Invasive species drive cross-ecosystem effects worldwide. *Nature Ecology & Evolution*, 8, 1087-1097. doi:10.1038/s41559-024-02380-1

706 López-Calderón, C., Martín-Vélez, V., Blas, J. *et al.* (2023). White stork movements reveal the ecological connectivity between landfills and different habitats. *Mov Ecol.* 11(1): 18. https://doi.org/10.1186/s40462-023-00380-7

707 Hartmann, L., Walz, Y., Hansohm, J. *et al.* (2024). Assessing the contribution of land and water management approaches to sustainable land management and achieving land degradation neutrality.

708 KAZA TFCA (n.d.). Livelihoods Diversification Strategy. https://www.kavangozambezi.org/publications-2/

709 WWF (2019). Nur wer genug zu essen hat, interessiert sich auch für Naturschutz. https://www.wwf.de/themen-projekte/projektregionen/kavango-zambesi-kaza/landwirtschaft-in-kaza/

710 WWF (2023). Zukunft für Wildtiere durch bessere Lebenschancen für Menschen. https://www.wwf.de/themen-projekte/projektregionen/kavango-zambesi-kaza/zukunft-fuer-wildtiere

711 Namibia Nature Foundation (2022). Press Release - Food Security and Habitat Protection in KAZA – KAZA ARISE. http://the-eis.com/elibrary/sites/default/files/downloads/literature/Food%20Security%20and%20Habitat%20Protection%20in%20KAZA_KAZA%20ARISE.pdf

712 Mulela, T. (2025). Conservation Namibia. Agroecology: A path to resilient farming in Namibia. https://conservationnamibia.com/blog/resilient-farming-namibia.php

713 Pers. Comms. (Email) Mareike Voigts, Senior Technical Advisor – Sustainable Agriculture, Namibia Nature Foundation.

714 Sistema Nacional de Áreas de Conservación (SINAC) (2018). Plan Estratégico 2018-2025 del Programa Nacional de Corredores Biológicos de Costa Rica (Informe Final). Programa Nacional de Corredores Biológicos. San José-Costa Rica. https://enbcr.go.cr/sites/default/files/sinac_2018_planestrategico_programa_nacional_de_corredores_biologicos_costa_rica.pd

715 Bernal Herrera, F., Chassot, O., Monge, G. *et al.* (2016). Technical Guidelines for the design and management of participatory connectivity conservation and restoration projects at the landscape scale in Latin America. Tropical Agricultural Research and Higher Education Center (CATIE), Technical Series Technical Bulletin no.82. https://portals.iucn.org/library/sites/library/files/documents/2016-059.pdf

716 Beita, C.M., Murillo, L.F.S. & Alvarado, L.D.A. (2021). Ecological corridors in Costa Rica: An evaluation applying landscape structure, fragmentation-connectivity process, and climate adaptation. *Conservation Science and Practice*, 3(8), e475. https://doi.org/10.1111/csp2.475

GLOBAL LAND OUTLOOK

The United Nations Convention to Combat Desertification (UNCCD) recognizes that addressing and reversing land degradation is one of the key sustainable development priorities for many countries, particularly in the developing world. In response, the UNCCD secretariat produces strategic communications publications under the brand of the Global Land Outlook (GLO) to facilitate insights, debate, and discourse on a transformative vision for land management policy, planning and practice at various scales.

The aim of the GLO is to communicate and raise awareness of evidence-based, policy-relevant information and trends to a variety of stakeholders, including national governments formulating their responses to commitments to better manage and restore land resources, including the SDGs and associated targets, such as Land Degradation Neutrality (LDN). The evidence presented in the GLO reports demonstrates that informed and responsible decision making can if more widely adopted help to reverse the current worrying trends in the state of our land resources.

All GLO reports and working papers, can be found at:
https://www.unccd.int/resources/global-land-outlook/overview

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