Biodiversity evidence for integrative policy and collaborative governance: nexus mechanisms across climate, food, water, energy, transport and health

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Abstract

Biodiversity loss and ecosystem degradation, exacerbated by climate change, represent one of the most urgent governance challenges of our time. Effective policy responses remain constrained by fragmented understanding of how biodiversity interacts simultaneously with climate, food, water, energy, transport, and health systems. This study addresses this gap through an evidence synthesis of 194 European studies examining biodiversity interactions across terrestrial, freshwater, marine, and multi-realm contexts. An impact archetype analysis was conducted with a causality visualisation tool to classify systems interactions according to their structure and complexity, including unidirectional influences, bidirectional reinforcing or balancing feedbacks, and multidirectional cascading or compounding effects, and to assess their direction (positive, negative, mixed) across seven nexus sectors. The findings show that biodiversity functions as an active component of the nexus, both as mediums and mediators through which other sectors interact in diverse forms of feedbacks and pathways. Positive-reinforcing feedbacks linking biodiversity conservation, ecosystem health, human behaviour, and cross-sectoral co-benefits are widespread but understudied and underleveraged. Conversely, negative cascades associated with agricultural intensification, fossil fuel consumption, land-use change, and transport infrastructure propagate across sectoral and realm boundaries, generating risks that cannot be effectively anticipated or managed through single-sector governance approaches. Biodiversity governance therefore requires coherent and integrative cross-sectoral policy that deliberately amplifies positive feedbacks, interrupts harmful cascades, and embeds co-benefits and trade-off analysis into policy planning and adaptive management. Biodiversity demands to be governed not as a sectoral externality, but as a dynamic nexus component central to achieving nature- and people-positive futures.

1. Introduction

Recent assessments by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC) have alarmed the global community about accelerating biodiversity loss and ecosystem degradation, exacerbated by climate change (Calvin et al., 2023; IPBES, 2019). The European Union's Green Deal, the Kunming-Montreal Global Biodiversity Framework (KMGBF), and the Sustainable Development Goals (SDGs) collectively promote nature and biodiversity conservation and sustainable development as foundational to human security and planetary health. Yet despite growing political objectives and commitment, translating these goals into coherent cross-sectoral policies and action remains constrained, in part, by a fundamental evidence gap. While interactions between biodiversity and individual sectors are well documented (IPBES 2024; Kim et al., 2024), there is limited understanding of the mechanistic pathways through which biodiversity interacts simultaneously and over time across multiple sectors, how these interactions generate biodiversity outcomes, and how associated cross-sectoral risks can be mitigated.

Understanding biodiversity nexus interactions entails unravelling complexity into a structured understanding of social-ecological systems dynamics and emergent outcomes (Cumming et al., 2017; Estoque, 2023). This mechanistic lens is essential for identifying leverage points and designing policy responses that amplify synergies and dampen trade-offs (Chan et al., 2020; Meadows, 2009). However, these interactions are context-specific, varying across terrestrial, freshwater, and marine realms as well as biospheric, atmospheric, and biogeochemical systems across social, ecological, economic, and geopolitical contexts. Capturing this complexity requires disaggregating broad categories such as 'biodiversity' into more precise dimensions and measures – spanning genetics, species, ecosystems, ecosystem services – and tracing the directionality, magnitude, and conditionality of impacts that generate systemic effects. Understanding changes within the biodiversity nexus therefore requires a contextualised analytical framework in which interactions can be conceptualized, assessed and acted upon by both scientists and policymakers (Ferraro et al., 2019; Schrodt et al., 2025).

The sectors at the heart of this challenge are deeply interconnected. Biodiversity underpins climate regulation through carbon sequestration in forests, peatlands, blue carbon ecosystems, among others, while climate change in turn drives biodiversity loss through temperature rise, altered precipitation, and phenological disruption (Birkel et al., 2017; Hochman et al., 2018; Pullens et al., 2018). Interactions between biodiversity and food production and consumption – through pollination, soil health, pest control, and land use – are increasingly documented, as are the consequences for water availability and quality through nutrient runoff, hydrological alteration, and ecosystem degradation (Baattrup-Pedersen et al., 2014; Klante et al., 2021; Wessel et al., 2004). Ecosystem and human health are similarly intertwined: biodiversity mediates disease transmission, shapes air and water quality, and generates physical and mental health benefits through contact with green and blue spaces, while human health systems demand resource use and put pressure on the environment (Di Giulio et al., 2009; Hulme, 2020; Robinson et al., 2024; Sula et al., 2020). The energy and transport sectors, meanwhile, represent a particular governance challenge: as major components of national development and economic security, they exert large-scale, direct pressure on nature and climate across all realms – through habitat conversion and fragmentation, pollution, and species collision – yet these interactions remain systematically underrepresented in sectoral policy (Apoznański et al., 2018; Buekers et al., 2014; Simkins et al., 2023; Wilkinson et al., 2007). Given that some of these dynamics pose compounding risks to human security and economic viability, identifying synergistic solutions is an urgent scientific and governance priority (Pörtner et al., 2023).

In this context, three knowledge gaps constrain the ability of science to inform policy. First, feedback loops – both reinforcing and balancing – that generate emergent outcomes when interventions target multiple nexus elements remain poorly understood (Meadows, 2009; Pichon et al., 2026). Second, cascading and compounding effects that propagate across sectoral boundaries remain understudied, making it difficult to anticipate and mitigate unintended consequences (Reduction, 2022; Rocha et al., 2018). Third, the context dependence of these interactions – varying by spatial scale, ecosystem realm, taxonomic group, and socio-economic conditions – is poorly characterised, limiting our ability to tailor interventions to local contexts (Kim et al., 2024). Without this understanding, identifying interventions that generate synergies, mitigate trade-offs, and account for biodiversity outcomes in the planning of climate, food, water, energy, transport, and health systems remains difficult (IPBES 2024).

The evidence synthesis presented in this paper addresses these gaps through an impact archetype analysis and causality visualisation approach that analyses biodiversity interaction mechanisms across seven nexus sectors and in marine, terrestrial, and freshwater realms in Europe and explores their policy implications. The paper responds to three central research questions: *(RQ1) How do feedback loops, cascading and compounding effects generate emergent interaction mechanisms across the biodiversity-climate-food-water-energy-transport-health nexus? (RQ2) Which interventions have the potential to enhance co-benefits and reduce trade-offs across multiple nexus elements, and under what contextual conditions? (RQ3) What are the implications for coherent cross-sectoral policy, and what research and evidence gaps remain?*

2. Materials and methods

This study employs a four-stage methodological approach progressing from quality assurance of the evidence base, through the development and application of an impact archetype analysis, to evidence and policy analyses, and, finally, synthesis of results into sectoral and intersectoral recommendations for biodiversity governance. This section describes each stage and how they collectively contribute to the final evidence synthesis.

2.1 Data quality assurance of indicators and impact relations

This study builds on the review database compiled by Kim et al. (2024), further analysing recorded impact relations between seven nexus elements: biodiversity, climate, food, water, energy, transport and health. The database comprises causal loop diagrams (CLDs) for each of the 194 reviewed studies, 932 quantitative and qualitative indicator records describing nexus elements, and descriptions of impact relations between nexus elements across all interlinkages represented in each CLD. In this review database, impact relations were defined as interlinkages between two nexus elements and did not necessarily imply causality, but rather an observed and evidenced influence between them. As the reliability of all subsequent stages of this evidence synthesis depends on the integrity of these recordings, quality assurance (QA) was the first necessary step. As Kim et al. (2024) did not analyse the indicator records or CLDs directly, the QA process established a new evidence base for this paper.

We conducted a comprehensive QA in which new reviewers verified indicator records of nexus elements and descriptions of relations between nexus elements in each CLD. A verification template was used to confirm or correct indicator and influence records, ensuring that all entries were substantially evidenced by expert knowledge, peer-reviewed literature, experimental evidence, or other sources of evidence in the article. If this was not the case, the entry was removed. Additionally, we verified each recorded influence for: direction (positive, negative, or mixed), magnitude (scale 0–5), type of measure (indicator vs. proxy; direct vs. indirect), and type of evidence (quantitative, qualitative, or mixed). Review coordinators conducted a final consistency check before the next stage of analysis and visualisation.

2.2 Design of impact archetype and visualisation tool

This stage involved developing an analytical framework to classify and visualise the diversity of causal mechanisms identified across the 194 studies. This directly addresses RQ1 by providing the structural means to identify and distinguish feedback loops and cascading and compounding effects within the biodiversity nexus. An impact archetype analysis of diverse causal mechanisms was developed to understand biodiversity impact relationships.

The resulting archetypes were classified into three main categories anchored on biodiversity (Fig. 1, see the Supplementary Material I (SM I) for definitions). Unidirectional impacts are either from biodiversity to another nexus element or from another nexus element to biodiversity, and are classified as positive, negative, or mixed. Bidirectional impact relations operate between biodiversity and another nexus element: when both directions are either positive or negative, they form reinforcing feedback loops; when directions differ, they form balancing feedback loops. Identifying reinforcing and balancing feedback loops required contextualized analysis of the indicators used and the descriptions of the relations between the indicators as not all bi-directional interactions were directly linked but influential within the broader nexus context and scope. Multidirectional impacts involve interactions between biodiversity and two or more nexus elements, and these impacts may be overall positive, negative, or mixed. Cascading impacts describe a chain of sequential impacts from, to, or through biodiversity across multiple nexus elements, while compounding impacts describe the convergence of impacts on or from biodiversity from or to two or more nexus elements simultaneously. Both cascading and compounding impacts can be positive or negative if all impact relations share the same directionality (i.e. positive or negative), or they are considered mixed if both directional interactions are observed.

Based on this archetype classification, a ShinyApp was developed to visualise the CLDs from the database, catalogued by archetype category and filterable by realm (freshwater, marine, terrestrial, mixed), ecosystem, species group, regional scale, and the literature ID. This enabled parts of CLDs from each study or multiple studies to appear under each relevant impact archetype, allowing reviewers to evaluate, analyse, and synthesize evidence.

2.3 Archetype-based impact analyses and policy recommendations

The third stage applied the archetype definitions and the ShinyApp visualisation to systematically analyse biodiversity nexus evidence across the database. To respond to RQ2, the evidence analyses were extended to assess policy implications and suggest recommendations that navigating co-benefits and trade-offs.

Evidence analyses was conducted for each archetype category (unidirectional from or to biodiversity; bidirectional reinforcing or balancing feedback; multidirectional cascading or compounding impact) by realm (terrestrial, freshwater, marine, multi-realm) and direction of impact (positive, negative, mixed), using the archetype definitions (Fig. 1, SM I) and the CLD visualisation in the ShinyApp, recorded in a standard template (SM II). The ShinyApp displayed structured and classified impact archetypes with indicators describing each nexus element and the impact relations between elements with directionality (positive, negative, mixed). This enabled reviewers to partition relevant archetypes from each study's CLD to examine impact relations across nexus elements, with the overall CLD as a reference source.

Following this evidence analysis, reviewers inferred policy implications and proposed recommendations for each nexus element considered as a sector, drawing on the evidence analysis results and reflecting on findings reported in the original studies. This extended interpretation was necessary because a substantial proportion of studies did not include policy contexts, apply policy frameworks, analyse policy implications, or make policy recommendations (Kim et al., 2024). Recommendations were designed to be forward-looking and action-oriented, with the aim of improving coherence between sectoral priorities and biodiversity outcomes.

2.4 Evidence synthesis and policy coherence analyses

Evidence analyses and policy recommendations resulting from the impact archetype analysis were subsequently synthesised to identify key underlying mechanisms to inform the design of integrative and coherent policy in biodiversity governance. This addressed RQ3 by identifying key evidence gaps, governance priorities for implementing policy coherence, and directions for future research. We used an expert-knowledge driven synthesis, supported by a Large Language Model (Claude version Sonnet 4.6), to organise and aggregate reviewed evidence effectively (see SM III for an example prompt and table). The use of the LLM was modest, enabling a large text-based dataset that is partitioned by archetype categories and other attributes such as direction of impact, realm, and nexus sector (the full set of SM II) to be concisely tabulated and summarized for higher level synthesis. Outputs were validated against the original dataset and through additional prompts -- e.g. differentiating recorded vs. inferred summaries, primarily using the former and only using the latter to draw insights.

Evidence was further synthesized by sector to make recommendations for cross-sectoral policy coherence. The sectoral recommendations categorized synthesized evidence into 1) leveraging positive feedbacks and cascades, 2) mitigating negative feedbacks and cascades, and 3) navigating co-benefits and trade-offs with this third category considering both uni-directional and compounding effects. This enabled an integrated assessment of all archetype categories analyzed with context-dependent effects focusing on amplifying benefits and mitigating risks.

For cross-sectoral policy coherence analyses, overarching recommendations were made on integrated policy design, collaborative governance, ex-ante co-benefit and trade-off policy analyses and ex-post monitoring and adaptive management. Finally, research and evidence gaps were identified with directions for future research.

3. Results

The evidence review results are presented according to the overall direction of nexus impact (positive, negative, mixed) in this section, organised by realm (terrestrial, freshwater, marine, multi-realm) and by impact archetype (unidirectional influence, bidirectional reinforcing or balancing feedbacks, and multi-directional cascading or compounding effects). Figure 2 presents the frequency of uni-directional evidence records by realm, position of biodiversity, and direction of impact with indicators describing different dimensions and roles of biodiversity aligned with the CBD Kunming-Montreal Global Biodiversity Framework (SM IV).

3.1 Terrestrial realm

3.1.1 Terrestrial: positive biodiversity nexus influence

Terrestrial biodiversity generates multiple positive influences across the nexus. Forest and soil conservation reduce carbon emissions (Irabien and Darton, 2016), while peatlands serve as critical carbon sinks contributing to climate change mitigation (Birkel et al., 2017; Pullens et al., 2018). Low-intensity cultivation and diverse bee nectar-providing plants enhance crop pollination (Maskell et al., 2013), and alley cropping systems increase yields (Tsonkova et al., 2012). Agricultural and forest biomass residues contribute to carbon dioxide removal and energy generation (Perišić et al., 2022; Sacchelli et al., 2013). Transport corridor verges and semi-natural land provide habitats and support the recovery of red-listed and ecosystem-specialist species (Brown and Sawyer, 2012; Elo et al., 2021; Helldin et al., 2015). Green infrastructure expands green roofs and public spaces (Pasimeni et al., 2019), and forested and protected areas reduce socioeconomic and environmental vulnerability to heat (Grigorescu et al., 2021). Active and green transport modes can improve human health (Hunter et al., 2021; Khreis et al., 2016), and reduced traffic prevents wildlife-vehicle collisions (Raymond et al., 2023). Natural and green areas also absorb atmospheric pollutants and deliver physical and mental health benefits through improved air quality and recreation (Barrios-Crespo et al., 2021; Di Giulio et al., 2009; Jevtic et al., 2022; Zorić et al., 2022).

Cascading and compounding effects can further amplify benefits. Biodiversity conservation linked to healthier lifestyles shifts consumer preferences toward local food, reducing frozen food demand, transport needs, and GHG emissions (Guiné et al., 2021). Bat populations can reduce mosquito density and crop pests, reducing human health risks (Xavier et al., 2020). Willow riparian buffer strips mitigate nutrient-rich agricultural runoff, improving downstream water quality (Livingstone et al., 2021). Urban green spaces and ecosystem restoration can simultaneously deliver carbon sequestration, cooling, and recreational health benefits (Pasimeni et al., 2019; Romanello et al., 2022). Vegetation in green spaces can buffer the emission of particulate matter, improving air quality and public health (Fusaro et al., 2015; Pallozzi et al., 2020).

3.1.2 Terrestrial: negative biodiversity nexus influence

Terrestrial systems also experience significant negative nexus interactions. In some cases, nature directly harms other nexus elements: wild boar can damage crops (Mauri et al., 2019), Miscanthus can spread fungal disease to cereal crops (Glynn et al., 2015), and badger-cattle interactions can cause bovine tuberculosis with human health implications (Madden et al., 2021). Invasive mosquitoes can transmit zoonotic pathogens to humans (Medlock et al., 2012). Conversely, other nexus elements can negatively affect biodiversity. Agricultural intensification and the abandonment of traditional land use can erode semi-natural habitats and their associated species (Whitmee et al., 2015), compounded by pesticide and fertilizer use that alters ecosystem functioning (Irabien and Darton, 2016; Whitmee et al., 2015) and EU policies driving shrub encroachment and grassland habitat degradation (Mihók et al., 2017). Fossil fuel and renewable energy systems can generate ecological costs through emissions and habitat disturbances, respectively (Bielecki et al., 2020; Fuller et al., 2022), with energy demand driving land conversion, monoculture, and soil quality deterioration (Garnier et al., 2020; Haines et al., 2007; Perišić et al., 2022; Sacchelli et al., 2013; Sutherland et al., 2015). Wind farms fragment steppe landscapes, reducing avifauna abundance (Laiolo and Tella, 2006), and bioenergy infrastructure on biodiversity hotspots causes habitat conversion, fragmentation, and species collision (Simkins et al., 2023). Herbicides impose acute and chronic toxicity on bees, birds, and invertebrates and persist as active harmful ingredients in the environment (Cech et al., 2022), while unchecked deforestation and soil degradation risk ecosystem collapse (Takaes Santos, 2020).

These impacts often cascade and compound. Warming-induced drought reduces plant stomatal conductance, impairing ozone mitigation and degrading air quality and public health (Fusaro et al., 2015; Lei et al., 2022; Lin et al., 2020). Fossil fuel combustion pollutes air and degrades natural ecosystems, plant biomass, and carbon balances (Fuller et al., 2022; Schulze, 2006; Wilkinson et al., 2007). Human land use alters biomass distribution, productivity, nutrient pathways, and carbon balance (Schulze, 2006), while intensive agriculture reduces farmland biodiversity in species richness and abundance (Bourke et al., 2014). Transport and energy infrastructure collectively impose habitat conversion, fragmentation and disturbance, and species mortality (Apoznański et al., 2018; Biasotto and Kindel, 2018; Nazir et al., 2020; Simkins et al., 2023), with transport-sourced carbon dioxide driving acidification, eutrophication, and biodiversity loss (Buekers et al., 2014), and infrastructure increasing flood risk and thermal loading (Hunter et al., 2019).

3.1.3 Terrestrial: mixed biodiversity nexus influence

Mixed interactions in terrestrial systems are particularly evident in the energy sector, where the type and management of renewable energy sources generate divergent outcomes for species and habitats (Bourke et al., 2014; Holma et al., 2018). Short rotation coppice biomass plantations offer an alternative energy source but produce variable ecological outcomes depending on location and management intensity (Livingstone et al., 2021; Petzold et al., 2014). Large-scale renewable energy production reduces GHG emissions but yields mixed effects on nature (Gasparatos et al., 2017). Biofuel crops can improve soil quality on degraded land yet simultaneously drive deforestation and intensify competition for land (Takaes Santos, 2020). Scale and spatial configuration strongly influence outcomes: small Miscanthus blocks provide suitable habitat for the brown hare (*Lepus europaeus*), while large-scale blocks offer poor habitat due to distance from feeding sites (Petrovan et al., 2017). High-intensity bioenergy harvesting ranges from negative to neutral in its ecological impact depending on the resilience threshold of the surrounding landscape (Giuntoli et al., 2022). Woody biomass from forest residue can substitute for fossil fuels in district heating, though with trade-offs for soil properties and species traits (Sacchelli et al., 2013). Similarly, wind farms generate mixed outcomes, threatening bird populations through noise and collision risk while altering the microclimate in ways that benefit some plant species (Nazir et al., 2020).

Mixed cascading and compounding interactions are also evidenced. Green transport infrastructure reduces human disease risks but can fragment and destroy wildlife habitat (Khreis et al., 2016). Roads and railways lower local species richness, yet green spaces surrounding transport corridors create microhabitats that partially offset these losses (Toffolo et al., 2021). Transport infrastructure and traffic present barriers to wildlife movement and increase roadkill, while habitat clearance for energy infrastructure can incidentally benefit certain species with appropriate management (Biasotto and Kindel, 2018). Co-locating solar panel facilities with food production reduces overall environmental pressure but also reduces land available for agriculture and livestock (Hernandez et al., 2014). More broadly, transport and energy demands are embedded within food production and consumption chains – spanning processing, packaging, storage, and distribution – which can either moderate or intensify environmental pressures depending on the systems involved (Gallo et al., 2017).

3.2 Freshwater realm

3.2.1 Freshwater: positive biodiversity nexus influence

In freshwater systems, positive biodiversity influences operate across hydrological and ecological dimensions. Hydrological flow supports biodiversity (Irabien and Darton, 2016), and improved waste treatment enhances water quality to benefit freshwater biota (Urban and Hametner, 2022). Wetlands and estuaries function as carbon sinks, contributing to climate change mitigation (Barrios-Crespo et al., 2021). Pond presence and connectivity increase species richness, including amphibian populations (Bounas et al., 2020réghino et al., 2008; Sun et al., 2019b). Minimum discharge mandates generate positive effects on aquatic biota while simultaneously delivering economic and recreational co-benefits through increased fish species diversity, creating reinforcing feedbacks (Göthe et al., 2019). At smaller scales, mini hydropower plants can improve the ecological state of river systems, regulate flooding, and benefit downstream ecosystems and biodiversity (Comino et al., 2020).

Cascading and compounding interactions can amplify freshwater biodiversity benefits. The diversity and abundance of bivalves can reduce bacterial concentrations and lower metal and chemical pollutant levels in freshwater, improving the quality and quantity of trout as a food source (Zieritz et al., 2022). Coastal wetlands can act as natural buffers, simultaneously reducing flood risks and improving water quality, with compounding benefits for human security and health (Möller et al., 2022). Urban blue space amenities provide habitat for biodiversity while delivering a suite of ecosystem services – carbon sequestration, urban heat mitigation, and recreation – that benefit both ecosystems and human wellbeing (Thornhill et al., 2022).

3.2.2 Freshwater: negative biodiversity nexus influence

Negative interactions in freshwater systems arise from multiple nexus pressures. Extreme weather events alter the biological attributes of wetland ecosystems (Möller et al., 2022), while pesticide concentrations suppress algae growth and negatively impact benthic invertebrates (Foy et al., 2001; Pérez et al., 2010). Sinkhole ponds can facilitate the spread of alien snail species (Krodkiewska et al., 2019), and altered hydrological regimes can harm freshwater biodiversity (Yoshida et al., 2020). Transport infrastructure disrupts habitat connectivity, with road density significantly reducing amphibian species richness (Bounas et al., 2020; Lambdon et al., 2008; Šigutová et al., 2022). Agricultural intensification elevates nitrate concentrations and dissolved inorganic nitrogen in groundwater, adversely affecting dependent vegetation through negative reinforcing feedbacks (Baattrup-Pedersen et al., 2014).

Cascading impacts further amplify these pressures. Climate-driven heatwaves increase cyanobacteria in freshwater, triggering cyanotoxin episodes with toxic effects on animals, plants, invertebrates, and humans (Moreira et al., 2023). Road traffic and polycyclic aromatic hydrocarbon pollutants degrade stormwater and sediment pond water quality, reducing macroinvertebrate species richness (Meland et al., 2020; Sun et al., 2019a). Road de-icing salts and livestock together raise chloride concentrations to levels harmful to aquatic species (Nava et al., 2020), while pollutants accumulating in sediment ponds elevate contaminant levels in plants, dragonfly larvae, and fish (Grung et al., 2021).

Negative compounding influences in freshwater systems include altered river discharge, hydropower fragmentation, sediment loads, thermal changes, and nutrient transfers collectively harming migratory fish, amphibians, reptiles, and macroinvertebrates (Bakanos, 2019; Crnobrnja-Isailović et al., 2021; Dopico et al., 2022; Göthe et al., 2019). Road networks and agricultural fields reduce green frog abundance, while pollutant exposure degrades their condition (Conan et al., 2022). Combined exposure to hypoxia, pesticides, and PCBs disrupts the biochemistry, physiology, and morphology of fish and shellfish, elevating stress through metabolic and endocrine pathways with implications for human health through consumption (Burada et al., 2017; Giubilato et al., 2016; Sula et al., 2020).

3.2.3 Freshwater: mixed biodiversity nexus influence

In freshwater systems, mixed nexus influences depend largely on the type, scale, and quality of water infrastructure and management. Pond type and water quality contribute to species richness (Meland et al., 2020; Šigutová et al., 2022), and pond connectivity benefits amphibian occurrence while increased road density can reduce their richness (Bounas et al., 2020). Hydropower dams can reduce overall fish species diversity while enabling opportunistic species to persist in variable flow conditions (Göthe et al., 2019). Mini hydropower systems have comparatively lower environmental impacts but still fragment habitat and affect vegetation and fish populations (Comino et al., 2020). Electrical conductivity from hydropower systems impacts aquatic biodiversity despite companies' legal obligations and preferences for renewable energy (Kellner, 2023; Niedrist et al., 2021). In urban settings, the quality of water bodies determines whether they function as ecosystem service providers or disservices for human wellbeing

(Thornhill et al., 2022), and urban fishing delivers social and recreational benefits while enhancing knowledge about nature, but raises public health concerns around exposure to contaminants through fish consumption (Joosse et al., 2021). Operationally, hydropeaking from variable hydropower output disrupts stream ecosystem functioning, although these effects can be mitigated through electricity storage and technological solutions (Román et al., 2019).

3.3 Marine realm

3.3.1 Marine: positive biodiversity nexus influence

In marine systems, positive biodiversity nexus influences are primarily associated with offshore wind energy infrastructure. Offshore wind farms create alternative biotopes functioning as artificial reefs, producing reinforcing and compounding benefits – including increased local biomass, enhanced ecosystem dynamics, greater species diversity, and improved food supply in surrounding marine ecosystems (Maar et al., 2009). This demonstrates how energy infrastructure, when appropriately sited, can generate incidental positive co-benefits for marine biodiversity alongside its primary function for energy.

3.3.2 Marine: negative biodiversity nexus influence

Marine systems face significant negative biodiversity impacts from nexus interactions. Climate change drives cascading and compounding effects through sea temperature rise, ocean acidification, altered fish migration patterns, and broader ecosystem disruptions (Pellens et al., 2023). Increases in solar irradiance and temperature elevate dinoflagellate abundance in seagrass meadows, intensifying toxic algal blooms that disrupt ecosystem composition and structure (Leiva-Dueñas et al., 2020). Marine microplastic litter from food packaging harbours antibiotic-resistant bacteria, threatening both aquatic ecosystems and human health (Moore et al., 2020).

Transport and energy infrastructure impose substantial additional pressures. Offshore wind farms, combined with associated vessel traffic and noise, affect the size and location of resting and breeding sites and reduce the survival and conservation status of species including loons, long-tailed ducks, and herring gulls (Busch et al., 2013; Fliessbach et al., 2019; Mendel et al., 2019; Mercker et al., 2021). Ship presence and vessel traffic more broadly displace and disturb bird and marine species, altering distribution, abundance, behaviour, and habitat characteristics (Gasparatos et al., 2017; Mendel et al., 2019). Marine transport can also facilitate the introduction of invasive alien species through ballast water, enabling them to dominate native species and restructure food webs (Bax et al., 2003; Katsanevakis et al., 2013). Ballast water additionally transports viral and bacterial pathogens, contributing to algal blooms and fish poisoning events (Bax et al., 2003). Together, these interactions highlight the vulnerability of marine systems to the compounding risks of climate change, energy infrastructure, and transport pressures.

3.3.3 Marine: mixed biodiversity nexus influence

In marine and aquatic environments, mixed biodiversity nexus influences reflect the tensions inherent in energy policy and infrastructure. While energy policies broadly support climate change adaptation and mitigation, they can unintentionally result in undesirable ecosystem impacts (Lloret et al., 2022). Hydropower, while a renewable energy alternative, stresses salmon life cycles through elevated water temperatures, altered precipitation regimes, and exacerbated acid deposition (Wright et al., 2017). Underwater noise disturbance from offshore wind turbines produces mixed outcomes across species groups, with some demonstrating an ability to adapt to altered acoustic environments while others remain adversely affected (Serpetti et al., 2021).

3.4 Multiple realms

3.4.1 Multi-realm: positive biodiversity nexus influence

Positive cross-realm biodiversity influences operate through multiple pathways. Anaerobic digestion with food waste disposal technology improves ecotoxicity, eutrophication, and acidification conditions across freshwater, marine, and terrestrial systems (Salemdeeb et al., 2017).

Cascading positive influences can extend across realms. Reducing fertilizer and pesticide use in agricultural land can improve habitat quality and increase aquatic species abundance (Mihók et al., 2017). Willow riparian buffer strips support biodiversity while moderating agricultural nutrient runoff, benefiting downstream water quality (Livingstone et al., 2021). Trees cultivated for biomass in alley cropping systems increase species richness and abundance while reducing water erosion and agricultural pollutant leaching (Tsonkova et al., 2012). Childhood contact with nature generates wide-ranging health benefits – including joy, recreation, and growing familiarity with natural environments – contributing to long-term wellbeing and sustained engagement with nature (Vitale et al., 2022).

3.4.2 Multi-realm: negative biodiversity nexus influence

Negative biodiversity nexus influences extend across realms through interconnected pressures. Water stress harms both freshwater and terrestrial species (Elshout et al., 2019), while wildlife diseases can present risks to human health (Hulme, 2020). Renewable energy expansion requires new infrastructure and space, driving land and sea use change that degrades natural capital and ecosystem services (Logan et al., 2023). Rising carbon dioxide in the atmosphere elevates water body temperatures, reducing oxygenation and productivity across aquatic systems with reinforcing negative feedback on biodiversity (Romanello et al., 2022).

Negative multi-realm cascading influences are wide-ranging. Increased forest cover can paradoxically cause brownification of lakes, degrading water quality and reducing fish composition, longevity, and productivity (Klante et al., 2021). Declining soil organic matter reduces water retention and nitrate concentration, diminishing groundwater quality (Wessel et al., 2004). Phenological shifts increase fire occurrences and constrain water availability, threatening agricultural production and human security (Hochman et al., 2018). Invasive alien species introduced through transport compete with native grassland plants, displacing communities and increasing the risk of transmissive diseases such as malaria (Peyton et al., 2019).

Compounding multi-realm influences include the combined effect of climate change and biofuel habitat conversion, which disrupts ecological processes and Earth system cycles across whole ecosystems (Whitmee et al., 2015). Agricultural intensification negatively affects carnivore habitat and habitat selection (Mayer et al., 2023; Papp et al., 2022), while elevated sediment loads reduce macroinvertebrate diversity (Kuglerová et al., 2021). Fossil fuel-based energy consumption drives carbon emissions, temperature rise, and altered biogeochemical cycles, with cascading consequences for biodiversity and ecosystems across terrestrial, freshwater, and marine realms (Romanello et al., 2022; Schulze, 2006).

3.4.3 Multi-realm: mixed biodiversity nexus influence

Mixed multi-realm biodiversity nexus influences illustrate the challenges in managing ecosystems for multiple objectives simultaneously. Hydropower exerts variable impacts on terrestrial biodiversity, though strategic site selection can limit adverse outcomes (Dorber et al., 2020). Peatland soils simultaneously act as critical carbon sinks for climate mitigation and release dissolved organic carbon that degrades aquatic systems through water pollution (Birkel et al., 2017). Forest ecosystems regulate water availability and quality with benefits for ecological and human health, yet both are threatened by climate change and can be harnessed to mitigate climate change through bioenergy (Hazarika and Jandl, 2019). At the landscape level, lower-intensity cultivation with diverse nectar-providing species enhances bee and butterfly pollination, while higher-intensity land use reduces plant diversity and freshwater quality, with cascading negative influences on macroinvertebrates (Maskell et al., 2013).

Mixed cascading and compounding influences are also prevalent across realms. Alley cropping biomass systems can increase organism diversity and reduce water erosion and pollutant leaching, although effects on crop yields are variable (Tsonkova et al., 2012). Hydropower negatively affects aquatic ecosystems but simultaneously supports water supply regulation and flood and drought control (Gasparatos et al., 2017). Offshore wind farm construction and operation increase vessel traffic and harm bird, and marine species yet may offset more severe environmental impacts from alternative energy systems (Gasparatos et al., 2017). Childhood contact with blue spaces offers long-term health benefits but also presents immediate risks including waterborne diseases (Vitale et al., 2022).

3.5 Synthesis of underlying mechanisms

This section synthesises the underlying mechanisms for biodiversity nexus interactions across sectors with illustrative examples. As presented in Fig. 3, some articles in the evidence database included more than one interaction mechanism within a study (e.g. reinforcing feedback with cascading effects, both cascading and compounding effects).

Biodiversity underpins the provision and regulation of ecosystem services on which other nexus elements or sectors depend, including carbon sequestration, pollination, water filtration, and air purification. Peatlands and forests absorb carbon; bee-plant diversity sustains crop yields; bivalves reduce bacterial and chemical loads in freshwater; and wetlands buffer floods. However, these mechanisms depend on ecosystem integrity and thresholds: once the provisioning species or habitat is degraded, the service reduces and may collapse (Folke et al., 2004; Scheffer et al., 2001). This mechanism explains why habitat loss from agricultural intensification, land conversion or energy infrastructure, appears consistently as a negative mechanism with downstream effect on food security, water quality, and human health.

Where interactions become more dynamic, feedback mechanisms emerge. **Balancing feedbacks** act as regulatory buffers, moderating changes rather than amplifying them. Hydropower plants, for instance, can regulate water flow and reduce flood risk while simultaneously fragmenting aquatic habitat – two opposing pressures that partially offset each other depending on scale and management. Peatlands similarly both sequester carbon and release dissolved organic carbon under certain conditions, creating a self-regulating dynamic where the same system can function as sink and source simultaneously. These balancing interactions suggest that many biodiversity nexus relationships are conditional rather than stable equilibria.

Reinforcing feedbacks, where changes amplify themselves either positively or negatively, are the most frequently observed mechanism. Fossil fuel combustion, for instance, raises atmospheric carbon dioxide, warming water bodies, reducing oxygenation, and impairing aquatic productivity, which in turn diminishes the biological capacity of ecosystems to absorb further emissions. Agricultural nitrate loading increases dissolved inorganic nitrogen in groundwater, which degrades groundwater-dependent vegetation, reducing the natural filtration function that buffers against further nitrate input. In these cases, biodiversity loss does not simply remove a service – it removes the mechanism that would otherwise slow further deterioration. The interaction becomes self-reinforcing, and the nexus system loses its capacity for self-regulation to mitigate further effects into other interconnected systems.

Cascading effect mechanisms extend influences across multiple domains and systems, where an initial change in one nexus element triggers a sequential chain of effects through intermediate systems. As an example, a warming climate increases drought frequency, which reduces stomatal conductance in vegetation, which diminishes the plant-based uptake of ozone and particulate matter, which degrades air quality and increases likelihood of respiratory disease risks in human populations. Each step is mediated by a different biological or physical process, creating considerable distance between the initial driver and its eventual outcome. This structural distance between cause and effect is what makes cascading mechanisms difficult to anticipate and govern. The same mechanistic logic applies positively: reducing pesticide use can improve habitat quality, increasing species abundance and enhancing natural pest control and pollination functions, which reduces agricultural input and environmental loading.

Compounding effect mechanisms highlight how simultaneous interactions among multiple drivers, operating within or across systems, can generate outcomes that no single driver could produce independently. For instance, urban green spaces can sequester carbon, mitigate the urban heat island effect, remove particulate matter through stomatal uptake, provide recreational opportunities for people, and create habitat for species, thereby delivering climate, health and biodiversity benefits through the same physical infrastructure. The compounding mechanism can also generate negative effects when transport infrastructure, agricultural intensification and energy production interact to fragment habitats, increase chemical pollution, raise temperatures, and facilitate the spread of invasive species. In these cases, no single driver is sufficient to collapse a system, but their simultaneous compounding influence presents risks to ecological resilience.

Across all mechanisms, common patterns and principles emerge: biodiversity can function as both the recipient and the driver and moderator of nexus interactions. It is the substrate through which food is produced, water is cleaned, energy flows, and human health is sustained or threatened. Whether outcomes are positive, negative or mixed depends less on biodiversity itself than on how human systems interact with and manage it. Mechanisms that preserve ecological integrity, ecosystem stability and resilience tend to generate positive self-reinforcing feedbacks; those that degrade it tend to trigger cascading and compounding risks and losses that extend far beyond the initial point of disturbance.

4. Discussion

This section summarizes sector-specific recommendations for coherent and integrative biodiversity governance based on the key biodiversity nexus mechanisms emerged from the evidence synthesis. Research and evidence gaps are discussed along with limitations of the study and directions for future research.

4.1 Sector-specific implications based on biodiversity nexus mechanisms

Sector-specific recommendations are made for policy planning in this section, accounting for biodiversity mechanisms in leveraging positive feedbacks and cascades, mitigating negative feedbacks and cascades, and navigating co-benefits and trade-offs (Table 1). Figure 4 shows the frequency of evidence by direction of impact, nexus sector, and position of biodiversity with measures describing different dimensions and roles of biodiversity.

4.1.1 Biodiversity

Biodiversity co-benefits across terrestrial, freshwater, and marine systems can be embedded in spatial planning frameworks and monitoring frameworks across sectors (Elo et al., 2021; Maar et al., 2009; Pasimeni et al., 2019) and in risk-prevention frameworks for climate change, pandemics, and food security (Mihók et al., 2017). Biodiversity policies can regulate ecosystem service delivery within ecological boundaries (Maskell et al., 2013), mitigate negative cascades from key sectors such as agriculture and energy (Whitmee et al., 2015), and promote conservation behavior through nature-contact programs such as active transport and outdoor education (Hunter et al., 2021; Vitale et al., 2022).

4.1.2 Climate

Climate policies can reinforce feedbacks between ecosystem restoration and climate mitigation by restoring carbon-rich ecosystems – forest, mangroves, seagrasses (Fusaro et al., 2015; Schulze, 2006). Joint monitoring of biospheric and atmospheric change helps intercept cascades from droughts and phenological shifts (Lin et al., 2020). Biodiversity and health policies can be integrated into climate adaptation planning, while synergies and trade-offs of renewable infrastructure assessed before implementation (Lloret et al., 2022; Romanello et al., 2022).

4.1.3 Food

Food policies can reinforce biodiversity-food feedbacks (Guiné et al., 2021; Maskell et al., 2013) by regulating pesticide use and disincentivizing forest to agriculture conversion to interrupt intensification cascades (Bourke et al., 2014; Garnier et al., 2020). Agroecological transitions and drought-tolerant crops should be incentivized (Kropf et al., 2021), and biofuel trade-offs – especially land conversion – assessed before implementation (Takaes Santos, 2020).

4.1.4 Water

Water policies can maintain aquatic biodiversity through discharge mandates and connectivity investment, preventing pollutant and fragmentation cascades through integrated monitoring (Apoznański et al., 2018; Dorber et al., 2020). Hydropower trade-offs need pre-implementation assessment and adaptive management of ecosystem and community impacts (Göthe et al., 2019; Möller et al., 2022).

4.1.5 Energy

Energy policies can integrate green infrastructure to benefit marine and terrestrial systems while mitigating habitat-conversion cascades (Pasimeni et al., 2019). Site-level assessment of synergies and trade-offs is needed for all renewable options before deployment, including biofuels siting on degraded rather than forested land (Gasparatos et al., 2017; Takaes Santos, 2020).

4.1.6 Transport

Transport policies can reinforce biodiversity-health feedbacks through active transport incentives, mitigating pollution and fragmentation cascades via ecological corridors (Buekers et al., 2014; Sovacool et al., 2021). Strict frameworks on vessel traffic and ballast water are needed to protect marine ecosystems from invasive species cascades (Bax et al., 2003; Katsanevakis et al., 2013).

4.1.7 Health

Health policies can reinforce biodiversity feedbacks through green/blue space access and a One Health approach, preventing zoonotic and chemical exposure cascades through systematic monitoring (Hulme, 2020; Sula et al., 2020). Public health can be embedded in environmental and marine planning to capture co-benefits while managing risks (Jevtic et al., 2022; Möller et al., 2022; Thornhill et al., 2022).

Table 1

Summary of sector-specific policy recommendations based on key biodiversity nexus mechanisms.

Biodiversity	Leverage positive feedbacks and cascades	Mitigate negative feedbacks and cascades	Navigate co-benefits and trade-offs

	Greater contact with nature through active transport, outdoor education, urban gardening, nature-based therapies, and environmental advocacy can foster pro-environmental behaviour and support biodiversity conservation (Hunter et al., 2021; Vitale et al., 2022; White et al., 2020). **Protecting high-diversity habitats reinforces ecosystem service delivery (Maskell et al., 2013), while biodiversity conservation shifts consumer preferences toward local food, reducing transport and energy demands and further easing pressure on ecosystems (Guiné et al., 2021).** **Willow riparian buffer strips provide an example of reinforcing spatial feedback: supporting biodiversity while mitigating nutrient-rich agricultural runoff improves water quality, sustaining the aquatic ecosystems that underpin biodiversity (Livingstone et al., 2021).** **Investment in green spaces to enhance human health can generate social and political support for continued environmental conservation (Vitale et al., 2022).**	**Expanding protected areas and providing adaptive agri-environment schemes with research and monitoring can reduce the cascading impacts of agricultural intensification on semi-natural habitat and species (Mihók et al., 2017).** **In the terrestrial realm, assessing and preventing ecosystem-specific risks to habitats and species – e.g. microbial communities to generalist and specialist species in forests, peatlands, and farmland systems – is necessary to maintain ecosystem stability and services before cascading effects reach irreversible thresholds (Birkel et al., 2017; Di Giulio et al., 2009; Khreis et al., 2016; Pullens et al., 2018; Sacchelli et al., 2013; Zorić et al., 2022).** **In the freshwater realm, monitoring and regulating agricultural pollution and discharges can prevent pollutant cascades and compounding risks across organisms and people (Foy et al., 2001).** **In the marine realm, regular monitoring of marine biodiversity and blue space health can enable the early detection and interruption of cascades that threaten long-term ecosystem resilience (Lloret et al., 2022; Pellens et al., 2023).**	**Implementing green measures for energy performance and increasing access to green space simultaneously benefit biodiversity, energy efficiency, and human health (Elo et al., 2021; Helldin et al., 2015; Pasimeni et al., 2019).** **Deepening knowledge of biodiversity nexus interactions – such as the trade-off between carbon sequestration and soil retention when replacing grassland with shrubland – is essential for designing synergistic policies (Wessel et al., 2004).** **In freshwater, protecting farm ponds (Céréghino et al., 2008), conserving interconnected water bodies (Bounas et al., 2020), and evaluating the effectiveness of enforcement laws on hydropower dam impacts (Göthe et al., 2019; Kellner, 2023) can minimize ecological risks with multiple co-benefits.** **In the marine realm, conservation strategies synergizing climate regulation and renewable energy can compound benefits: offshore wind infrastructure can simultaneously enhance marine biodiversity through artificial reef creation, support climate regulation, and provide clean energy (Maar et al., 2009).**
Climate	Restoring ecosystems with high carbon sequestration potential	Monitoring climate-driven droughts, water scarcity, and phenological shifts is critical	Integrating green space restoration into urban climate adaptation and

	– forests and soils (terrestrial), mangroves, seagrasses, and saltmarshes – creates reinforcing loops where sequestration reduces warming, stabilizing the very ecosystems that sustain it (Fusaro et al., 2015; Hochman et al., 2018; Lei et al., 2022; Schulze, 2006; Wessel et al., 2004). Biodiversity-driven shifts towards local food consumption can further reinforce this loop by reducing transport and energy demand, thereby lowering GHG emissions and pollution (Guiné et al., 2021).	for interrupting cascading effects from reduced plant stomatal conductance impairing ozone mitigation, degrading air quality and public health (Fusaro et al., 2015; Hochman et al., 2018; Lei et al., 2022; Lin et al., 2020; Wessel et al., 2004). Potential unintended consequences of climate policies – particularly hydropower-driven changes in water regimes – must be assessed before implementation to prevent cascading impacts on terrestrial and freshwater ecosystems (Crnobrnja-Isailović et al., 2021; Elshout et al., 2019).	health policies maximises simultaneous co-benefits of carbon sequestration, urban cooling, and public health (Pasimeni et al., 2019). Offshore wind farms compound clean energy and marine ecosystem benefits, provided unintended ecological consequences are assessed prior to implementation and actively monitored and prevented (Maar et al., 2009).
Food	Preserving biodiversity drives consumer preferences toward local food consumption, reducing transport and energy demand, easing environmental pressure, and further supporting ecosystem health (Guiné et al., 2021). Supporting biodiversity-rich, low-intensity farming landscapes reinforces pollination services that can increase crop yields (Maskell et al., 2013), while wild wastelands that provide edible plants can reinforce feedbacks between food systems knowledge, nature awareness, and conservation behaviour (Fischer et al., 2019).	Reducing chemical inputs (Mihók et al., 2017), regulating pesticides (Irabien and Darton, 2016; Whitmee et al., 2015), and disincentivising forest-to-agriculture conversion (Garnier et al., 2020) are essential to interrupt cascades from agricultural intensification to biodiversity loss, collapse of natural pest control, and further intensification dependency. Monitoring disease risks in food provisioning – bovine TB, fungi, crop pathogens – prevents harmful cascades through dairy, meat, egg, and cereal supply chains (Glynn et al., 2015; Madden et al., 2021; Mauri et al., 2019).	Biofuel policies must carefully weigh synergies such as improved soil quality on degraded land against trade-offs including deforestation risk and land competition before implementation (Takaes Santos, 2020). Transitioning to agroecological practices protects landscape stability, prevents toxicity in key functionally mediative species such as pollinators and worms, and supports food security while delivering wider co-benefits (Bourke et al., 2014; Cech et al., 2022; Helldin et al., 2015). In marine systems, offshore wind farms can enhance food sources for ecosystems and people through increased

			species diversity with changed habitat (Maar et al., 2009).
Water	Minimum discharge mandates generate reinforcing loops through positive effects on aquatic biota, generating economic and recreational co-benefits through increased fish species diversity (Göthe et al., 2019). Bivalve abundance reduces bacterial and chemical pollutants in freshwater, improving water quality that supports further bivalve reproduction and trout as example food sources (Zieritz et al., 2022). Pond connectivity increases species richness, strengthening the ecosystem function that sustains pond health (Bounas et al., 2020réghino et al., 2008; Sun et al., 2019b).	Regulating agricultural nitrate inputs can interrupt cascades linking agricultural intensification to groundwater degradation (Baattrup-Pedersen et al., 2014; Wessel et al., 2004). Monitoring peatland dissolved organic carbon, sediment loads, and traffic emissions can prevent harmful cascades on aquatic ecosystems (Birkel et al., 2017; Kuglerová et al., 2021). Strategic hydropower site selection is essential to prevent cascades from habitat fragmentation that harm migratory fish, amphibians, and macroinvertebrates (Crnobrnja-Isailović et al., 2021; Dopico et al., 2022; Dorber et al., 2020).	Hydropower management should balance water supply and flood control benefits against ecological impacts. Smaller scale hydropower may provide a lower impact alternative to large dams, which can reduce disruptions in aquatic ecosystem (Comino et al., 2020; Göthe et al., 2019). The quality of urban blue space can determine whether ecosystem services benefit or disserve human wellbeing, requiring quality monitoring along with access (Thornhill et al., 2022).
Energy	Offshore wind farms can act as artificial reefs generating reinforcing marine loops. Increased species diversity, biomass, and ecosystem functioning can complement clean energy benefits such as reduced pollution and climate impacts (Maar et al., 2009). Integrating green infrastructure such as green roofs into energy performance measures reinforces synergies between energy efficiency and	Accelerating decarbonisation reduces cascading impacts linking air pollution, ecosystem degradation, carbon imbalance, and further warming (Fuller et al., 2022; Schulze, 2006; Wilkinson et al., 2007). Avoiding renewable infrastructure on biodiversity hotspots reduces habitat conversion, fragmentation, and species collision cascades (Apoznański et al., 2018; Köppel et al., 2014; Simkins et al., 2023). Avoiding bioenergy monocultures and enforcing sustainable agricultural practices mitigates cascades	Renewable energy infrastructure should avoid areas of high biodiversity value, with comprehensive assessment of synergies and trade-offs (Gasparatos et al., 2017). Biofuel policies can improve soil quality if implemented on degraded land against direct deforestation of healthy forest (Haines et al., 2007; Takaes Santos, 2020). Solar co-location with food production can reduce environmental

	biodiversity outcomes (Pasimeni et al., 2019). Promoting small-scale bioenergy crops and trees grown alongside other crops can leverage biodiversity co-benefits while reducing water erosion and agricultural pollutant leaching (Petrovan et al., 2017; Tsonkova et al., 2012).	from soil erosion and forest loss (Glynn et al., 2015; Sacchelli et al., 2013; Sutherland et al., 2015).	pressure but competes for agricultural land and requires deliberate spatial planning (Hernandez et al., 2014).
Transport	Active and green transport can generate reinforcing biodiversity-health feedbacks, with improved health encouraging further uptake of active travel. Reduced traffic decreases wildlife-vehicle collisions and pollution, improving ecosystem health (Hunter et al., 2021; Khreis et al., 2016; Raymond et al., 2023). Reducing transport demand through local food production and consumption can reduce transport and energy-related pressure on nature (Guiné et al., 2021).	A shift towards low-emission public transport can interrupt cascades linking transport emissions to acidification, eutrophication, and biodiversity loss (Buekers et al., 2014). Improving ecological corridors in road and rail planning can mitigate cascades of habitat fragmentation, invasive species spread, and wildlife collision mortality (Medlock et al., 2012d-Eriksen et al., 2020; Sovacool et al., 2021; Zhang et al., 2021). Strict management of vessel movement and ballast water is essential to control the spread of invasive alien species and pathogen cascades in marine systems (Bax et al., 2003; Fliessbach et al., 2019; Katsanevakis et al., 2013).	Green transport infrastructure can improve human health but may also fragment wildlife habitat, requiring integrated planning that accounts for both outcomes (Khreis et al., 2016). Roads and railways reduce local species richness, but surrounding non-institutionalised green spaces can create compensating microhabitats (Toffolo et al., 2021). Habitat connectivity, wildlife collision potential, and polluting impact on water quality need to be considered in infrastructure design and monitoring (Nava et al., 2020; Šigutová et al., 2022; Sun et al., 2019a).
Health	Access to green and blue spaces can generate reinforcing feedbacks whereby physical and mental health benefits foster pro-environmental behaviour and conservation values, which contributes to sustaining the ecosystems that deliver health benefits (Di Giulio et al., 2009;	Managing wildlife-related disease transmission is critical for reducing zoonotic risks to human health (Hulme, 2020; Peyton et al., 2019). Monitoring and controlling contaminants such as PCBs and heavy metals in fish and shellfish interrupts chemical exposure cascades with documented implications on human health through consumption (Burada et al.,	Access to blue space delivers long-term health benefits but presents immediate risks of drowning and waterborne infection, requiring access and quality monitoring (Joosse et al., 2021; Vitale et al., 2022). Integrating marine biodiversity conservation, energy

	Vitale et al., 2022; White et al., 2020).	2017; Giubilato et al., 2016; Sula et al., 2020).	transition, and climate policies can generate multiple co-benefits for ecosystem and human health beyond climate regulation (Lloret et al., 2022; Maar et al., 2009; Pellens et al., 2023).
	Green healthcare teams that use nature-based remedies reduce the ecological footprint of medical equipment, reinforcing environmental health that supports human health (Kurth, 2017).	Protecting coastal wetlands as natural buffers can reduce flooding and water degradation cascades that impact human security and health (Möller et al., 2022).	

4.2 Implications for cross-sectoral biodiversity governance

Evidence synthesised across terrestrial, freshwater, and marine realms and across the biodiversity, climate, food, water, energy, transport and health policy sectors shows that policies planned in isolation are prone to generating unintended consequences for biodiversity and other nexus sectors. The prevalence of reinforcing and balancing feedbacks, as well as cascading and compounding effects reported throughout this synthesis, suggests that cross-sectoral policy design is fundamental for reducing cumulative risks across the environment and society.

4.2.1 Integrative policy

This study finds that integrative policy is essential for biodiversity conservation, sustainable development, and human wellbeing. Three recommendations emerge as key considerations for policy. First, the direction of interaction mechanisms matters; positive reinforcing feedbacks and cascades can be deliberately amplified rather than left to emerge unaided. Second, mitigating negative feedbacks and cascades requires early, targeted intervention at the initiating mechanism rather than remediation of downstream effects. Breaking the cascade is frequently more efficient and less expensive than repairing ecosystems only after ecological thresholds have been crossed. Third, co-benefits are most effectively realized when they are deliberately integrated into policy from the outset rather than evaluated only retrospectively.

The energy and transport sectors warrant particular attention given their large-scale, economy-wide footprint and their highly mixed, often underappreciated interactions with biodiversity across all realms (Apoznański et al., 2018; Buekers et al., 2014; Simkins et al., 2023; Wilkinson et al., 2007). In addition, viewed through a One Health lens, health functions as a critical integrative bridge across the biodiversity nexus (Keune et al., in review). Its deep interconnections with biodiversity, food systems, water quality, and ecosystem condition create opportunities to use health co-benefits as a tangible entry point for cross-sectoral policy coherence (Ricketts et al., 2024). Realising this potential requires treating health not as a downstream outcome of environmental policy but as an active co-determinant of nexus outcomes (Hulme, 2020; Keune et al., in review; Jevtic et al., 2022; Sula et al., 2020).

4.2.2 Collaborative governance

Translating these findings into coherent policy requires governance mechanisms that operate across scales and institutional boundaries. At the strategic level, nexus governance frameworks should move beyond sector-by-sector impact assessment towards integrated monitoring and evaluation systems that evaluate proposed policies against their cross-sectoral interaction effects – including second and third-order implications across biodiversity, climate, food, water, energy, transport, and health. The IPBES Nexus Assessment provides a critical reference point here, identifying nexus governance requiring deliberate institutional architecture: shared problem framings, cross-ministerial coordination mechanisms, and governance roadmaps that sequence action across sectors in a manner consistent with reinforcing synergies and resolving trade-offs (McElwee et al., 2026)

At the operational level, interventions such as protected area frameworks can be reformed to manage watersheds and transboundary ecosystems effectively, extending beyond static boundaries to dynamic connectivity of terrestrial, freshwater, and marine systems (Bounas et al., 2020; Dorber et al., 2020; Mihók et al., 2017). Adaptive agri-environment schemes with built-in monitoring and revision mechanisms can help maintain the biodiversity outcomes that underpin food and water security across changing conditions (Mihók et al., 2017; Whitmee et al., 2015). Economic instruments – including payment for ecosystem services, biodiversity net gain requirements, and carbon pricing linked explicitly to ecosystem health – can be integrated and streamlined across sectors to prevent the competing economic agendas that result in policy silos and accelerate cumulative risk (Urban and Hametner, 2022). International collaboration can be particularly critical for transboundary systems: offshore wind governance (Busch et al., 2013), ballast water regulation (Bax et al., 2003; Katsanevakis et al., 2013), and marine biodiversity monitoring (Lloret et al., 2022; Mendel et al., 2019) will benefit from coordinated multilateral or regional regulatory frameworks and cooperation mechanisms.

4.2.3 Co-benefit and trade-off analyses *(ex-ante)*

Across sectors, a consistent pattern of intervention is identified: reinforcing loops between ecosystem restoration and climate regulation, between biodiversity and food security, between green infrastructure and public health, represent co-benefit opportunities that remain underexploited when policy is developed within disciplinary silos. Conversely, cascading risks from habitat fragmentation, chemical pollution, invasive species dispersal, and land use conversion routinely propagate across sectoral boundaries in ways that isolated governance instruments are structurally ill-equipped to intercept. Coherent cross-sectoral planning therefore requires both a forward-looking agenda, centred on the deliberate amplification of reinforcing synergies, and a precautionary one, centred on the identification and mitigation of cascading harms before implementation rather than after (Kim et al., 2023; Pörtner et al., 2023).

Institutionally, this demands embedding pre-implementation synergy and trade-off assessment as non-negotiable procedural requirement across energy, transport, food, and water policy; the integration of biodiversity and health indicators into climate adaptation frameworks; and the development of collaborative spatial planning mechanisms capable of reconciling competing sectoral claims on land, water, and coastal systems. Conservation institutions have a critical enabling role, not only in generating the evidence base for cross-sectoral risk assessments, but also in anchoring biodiversity within the risk prevention frameworks through which governments respond to climate change, pandemic threats, and food insecurity. Without such structural integration, harnessing the reinforcing and cascading dynamics between planetary and human health will remain aspirational rather than realised policy outcomes.

4.2.4 Monitoring and adaptive management *(ex-post)*

Effective cross-sectoral governance requires integrated monitoring systems capable of tracking nexus interactions at policy-relevant spatial and temporal scales. Adaptive management frameworks should be institutionalised rather than implemented solely at the project level, with the capacity to revise policy instruments as monitoring data reveal unintended cross-sectoral effects. Policies with demonstrated co-benefits across multiple nexus sectors can serve as priorities for adaptive governance. The IPBES Nexus Assessment's roadmap for nexus action provides a structured basis for this – sequencing near-term capacity building in integrated assessment, medium-term development of cross-sectoral policy coherence mechanisms, and long-term institutional reform toward integrated nexus governance (IPBES 2024).

This synthesis identifies several priority monitoring requirements. Cross-realm ecological monitoring – spanning biospheric, atmospheric, and biogeochemical cycles – is needed to detect cascade initiation before thresholds are crossed, for example, early-warning indicators for cyanobacteria proliferation (Moreira et al., 2023), peatland carbon flux dynamics (Birkel et al., 2017), lake brownification from increasing forest cover (Klante et al., 2021), and phenological shifts driving fire and water stress (Hochman et al., 2018) are particularly policy-relevant. Contaminant monitoring in food chains – particularly PCBs, heavy metals, and pesticide residues in freshwater and marine food sources – can be systematically integrated into public health surveillance frameworks (Burada et al., 2017; Giubilato et al., 2016; Sula et al., 2020). Connectivity metrics for habitat networks across terrestrial, freshwater, and marine realms can be developed and standardised to assess the effectiveness of ecological corridor policies in transport and energy planning (Apoznański et al., 2018; Bounas et al., 2020; Sovacool et al., 2021). Spatial monitoring of green and blue space access and quality can be embedded within urban planning systems to track health and wellbeing co-benefits alongside ecological condition (Di Giulio et al., 2009; Thornhill et al., 2022; Vitale et al., 2022).

4.3 Research and evidence gaps

Evidence synthesised for the biodiversity nexus highlights the potential of integrated and cross-sectoral planning across realms. However, achieving this potential is constrained by chronic evidence gaps that limit coherent cross-sectoral policy design in Europe. These gaps include measurement deficiencies, methodological limitations, geographic and taxonomic biases, and lack of alignment with policy frameworks.

Measurement gaps undermine the ability to monitor and act on the critical policy-relevant nexus interactions. Biodiversity to health feedbacks remain poorly quantified: while the benefits of green and blue space for physical and mental health are increasingly studied (Di Giulio et al., 2009; Vitale et al., 2022), evidence on how improved human health influences attitudes and behaviours towards nature and biodiversity conservation remains limited. Similarly, habitat-climate interactions, such as the simultaneous role of peatlands as carbon sinks and sources of dissolved organic carbon affecting aquatic systems (Birkel et al., 2017), or the mixed effects of forest cover on lake brownification and water quality (Klante et al., 2021), are rarely captured within single monitoring frameworks. Connectivity metrics across terrestrial, freshwater, and marine realms remain underdeveloped, constraining the ability to assess how habitat fragmentation from transport and energy infrastructure propagates across realms and species groups (Apoznański et al., 2018; Bounas et al., 2020; Sovacool et al., 2021). Monitoring plans based on integrated spatial planning and ecological data, including fluxes across air, water, and land, are needed to address these gaps and track the condition of organisms and ecosystems at the resolution required for policy-relevant inference.

Methodological gaps prevent the evidence base from supporting the causal and threshold-based understanding that cross-sectoral policy and regulations require. Causality frameworks linking nexus sector pressures to biodiversity outcomes are largely absent from the literature; most evidence in this synthesis is associative, limiting the ability to attribute observed change to specific policy-driven results and mechanisms to design interventions with predictable outcomes. Integrated monitoring systems that simultaneously monitor outcomes across sectors and scales remain absent, impeding the assessment of cross-sectoral cascading and compounding effects. Critically, threshold identification – the capacity to determine at what point stressor accumulation triggers irreversible ecological change, such as ecosystem collapse from deforestation and soil degradation (Takaes Santos, 2020) or cyanotoxin episodes from heatwave-driven cyanobacteria proliferation (Moreira et al., 2023) – is understudied across all realms. Building institutional capacity to assess, forecast, and mitigate unintended short- to long-term consequences of nexus interactions across sectoral policies – considering biospheric, atmospheric, and biogeochemical cycles – will be essential to address these methodological constraints.

Geographic and taxonomic biases further limit the generalisability and policy relevance of the evidence base. The evidence base is heavily skewed towards temperate terrestrial systems, with freshwater and particularly marine realms underrepresented (Kim et al., 2024). Taxonomic coverage favours vertebrates and vascular plants, leaving microbial communities, invertebrates, and functionally critical species such as soil organisms, as well as aquatic macroinvertebrates poorly represented despite their central role as mediators of ecosystem services. These biases have important implications: they risk generating policy recommendations calibrated to well-studied systems and species that may not translate to the ecosystems and organisms that are themselves the focus of important monitoring and governance gaps.

Weak alignment with policy frameworks further contributes to these evidence gaps. Many studies do not measure policy-relevant change across the biodiversity nexus. Energy and transport sector assessments rarely incorporate biodiversity or health co-benefits with measurable indicators, despite the large-scale and highly mixed nature of their interactions with ecosystems (Apoznański et al., 2018;

Buekers et al., 2014; Wilkinson et al., 2007). The prioritisation of energy and transport as dominant economic sectors, composed of large-scale pressures on nature and climate with cumulative risks to human security, further results in siloed monitoring systems that obscure critical cross-sectoral influence. Health represents a particularly significant alignment gap: although it has strong potential to generate policy bridges with co-benefits between biodiversity and the remaining nexus sectors (Ricketts et al., 2024), health-biodiversity interlinkages are not yet mainstreamed into policy monitoring frameworks. Furthermore, the interaction between the seven nexus sectors and synergies and trade-offs with the broader economy can be assessed more transparently within a centrally-supported accountability system for implementation efficacy (Urban and Hametner, 2022).

4.4. Limitations and future research

The evidence analysed in this synthesis is grounded in the frameworks and measures used in the reviewed studies, which were designed across a range of disciplinary perspectives and subsequently interpreted for synthesis. The synthesis reflects the disciplinary, socioeconomic and geographic biases of the available literature rather than the full complexity of the biodiversity nexus. Interlinkages are evidenced with quantitative, qualitative or mixed measures with variable degrees of rigour, confidence, and methodological transparency. Accordingly, the term 'influence' and 'interaction impact' are used throughout this paper as broader terms to describe the directionality and characteristics of interlinkages between nexus elements rather than to assert a causally established or statistically robust effect.

Further, this study synthesized evidence of biodiversity nexus mechanisms observed in Europe. While the findings may be generalizable to other regions, it is worth recognizing the potential displacement of environmental pressures across regions through shifts in international trade and resource supply chains (Liu et al., 2018; Meyfroidt et al., 2013). Incorporating a telecoupling perspective into future biodiversity nexus research would offer important insight into the global consequences of regional policy decisions (Liu et al., 2015).

The methodology employed in this study was intentionally iterative as the complexity of nexus interactions became apparent across realms and sectors. The categories of impact archetype – unidirectional, reinforcing and balancing feedbacks, cascading, and compounding – relied on reviewer understanding and interpretation of studied evidence. In many cases, the original studies did not explicitly state the hypothesis being tested or employ the archetype category used in this study. This study represents a meaningful step forward in analysing patterns and characteristics of complex system interactions in the biodiversity nexus.

Looking ahead, LLM-assisted systematic review may offer a promising avenue for advancing the science of evidence synthesis with improved consistency, accuracy, reproducibility, and efficiency (Gartlehner et al., 2024; Lieberum et al., 2025). Realising this potential will demand improved standardization in the research design across studies, ensuring that computational tools draws upon rigorous and aggregable evidence (Haddaway et al., 2018). The methodological approaches applied in this synthesis and the emerging tools available for future research may suggest how nexus evidence review and synthesis can be completed more systematically and routinely for integrated and adaptive biodiversity governance.

Future studies on the biodiversity nexus can address limitations through targeted methodological improvements. Most critically, developing a clear causality framework at the study design phase – with pre-specified quantitative and qualitative measures capable of associating changes in drivers and response options with measurable changes in nature – can substantially improve the accuracy and rigour of nexus evidence. The choice of measures for positive impact studies is particularly underdeveloped: causal evidence on synergistic interactions and co-benefits remains weak and less established than evidence on harmful interactions and risks. Targeted research support in this area would improve understanding of how synergistic cross-sectoral policies can be designed and implemented. Future studies can also embed policy frameworks more explicitly from the design stage and extend the analyses to draw policy implications from the results. This would enable findings to better serve both scientific and policy communities and bridge the translation gap that currently limits the availability, usability and uptake of nexus evidence in governance contexts.

5. Conclusion

Given the complexity of nexus dynamics across ecological, social, and geopolitical systems, nexus studies will become increasingly relevant for developing and implementing effective policy and practice. With growing volumes of digitized evidence accumulating amid the uncertainty of rapid global environmental change, systematic evidence synthesis will be instrumental in enabling strategic, informed decision-making to safeguard biodiversity, human livelihoods and security. Realising this potential will, however, require overcoming epistemic and ontological differences across disciplines and sectors through sustained inter- and transdisciplinary research and practice that places policy-relevant science and science-policy collaboration at its centre. Ultimately, the scale and urgency of cumulative nexus risks – from biodiversity loss and climate extremes to food and water insecurity and health vulnerability – demand that cross-sectoral policy coherence move from a governance aspiration to a structural requirement for implementation. The evidence in this synthesis demonstrates both the risks of policy misalignment and the benefits of integrated approaches. The mechanisms are identifiable, the co-benefits are evidenced, and the governance architecture is within reach if there is sufficient political will to support a sustainability transition.

Declarations

Author contribution

HyeJin Kim: conceptualization, methodology, data curation, investigation, validation, writing – original draft preparation, project administration. **Paula A. Harrison**: conceptualization, investigation, funding acquisition, writing – review & editing. **George Linney**: methodology, data curation, software, investigation, validation, writing – review & editing. **Andy Sier**: investigation, validation, visualization. **Elizabeth Díaz-General**, **Alejandrina Viesca-Ramirez, Alexandra Ioannou, Dorothea Kasiteropoulou, Hans Keune, Chrysi Laspidou, Anita Lazurko, Soile Kulmala, Joanna Louise Raymond, Arnoutvan Soesbergen, Simeon Vaňo**: data curation, investigation, validation, writing – review & editing.

Data availability

The biodiversity nexus evidence analyses data and indicator and unidirectional impact record database that were used in this study are accessible on Zenodo: 10.5281/zenodo.21891813

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Figures

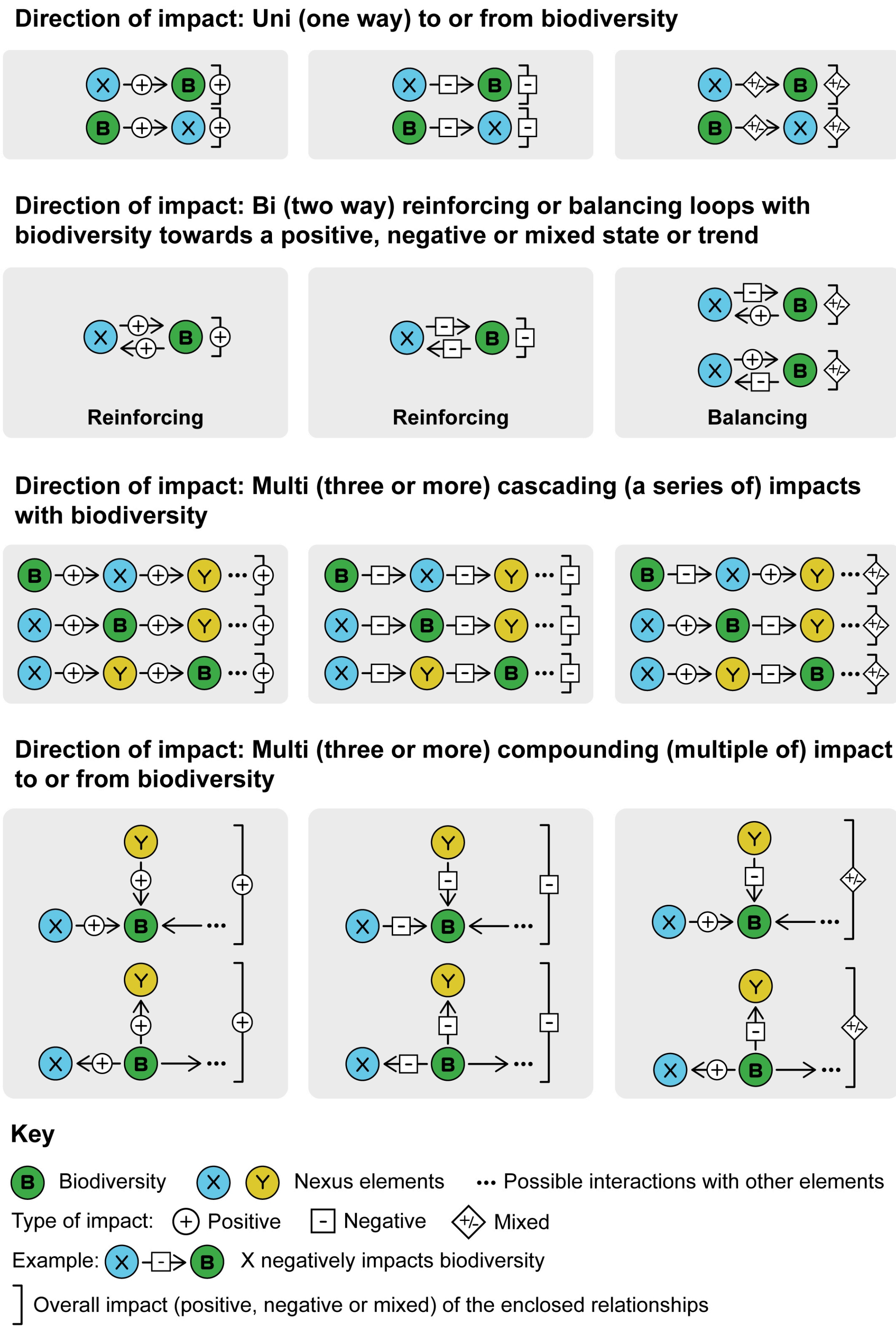

Figure 1

Impact archetypes of biodiversity nexus mechanisms from unidirectional to bidirectional (reinforcing and balancing feedback) and multidirectional (cascading and compounding effects). Nexus elements are shown in coloured circles. B (green circle) = Biodiversity nexus element. X and Y (blue and yellow circles respectively) = Other (unspecified) nexus elements. An ellipsis (…) represents possible interactions with other elements. Arrow direction indicates the direction of impact of one element on another. Type of impact, either positive, negative or mixed, is indicated by the +, - and +/- symbols on each arrow. The overall impact (positive, negative or mixed) of a set of relationships is shown by the symbols in square brackets.

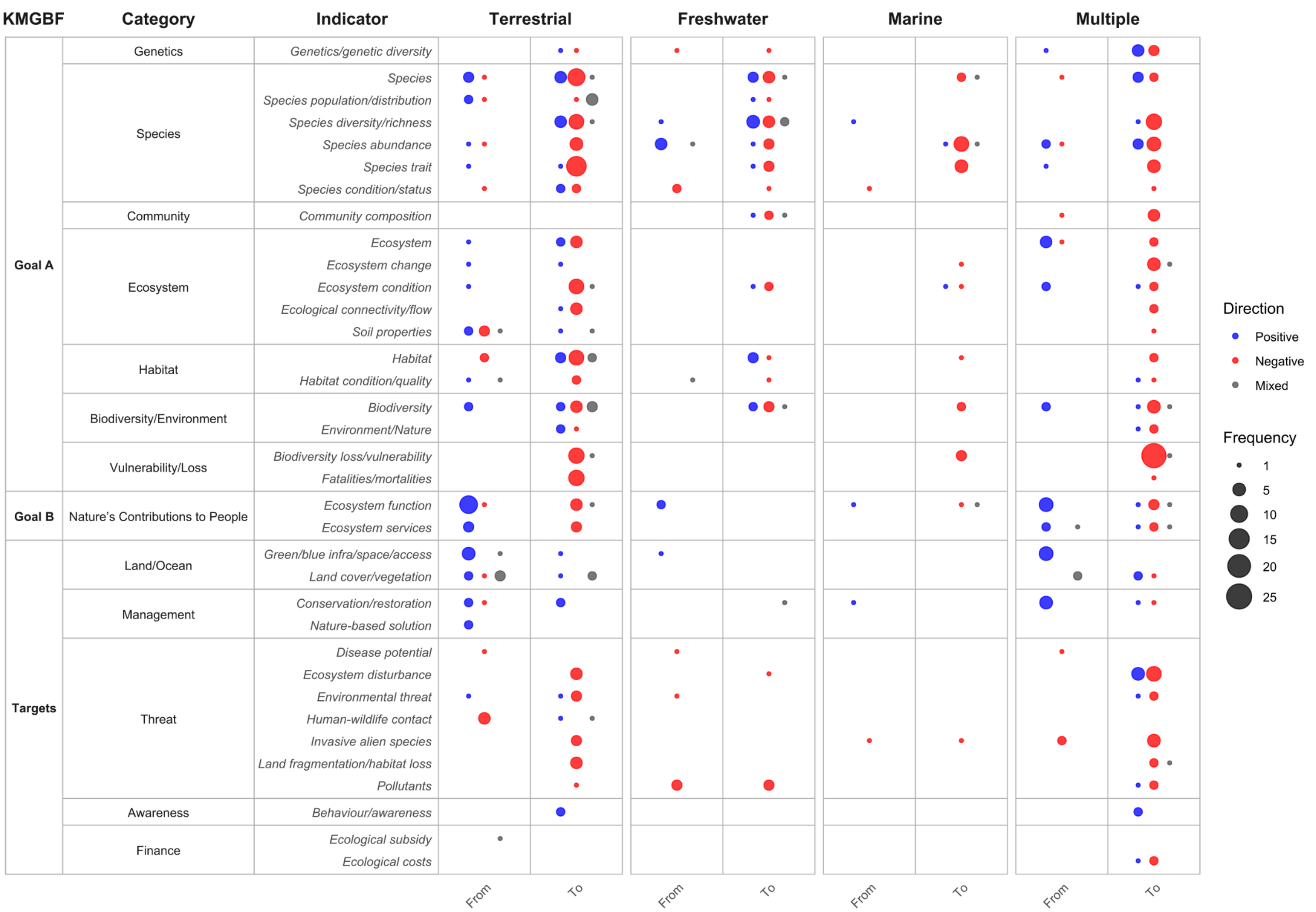

Figure 2

Frequency of positive, negative and mixed/neutral influence from or to biodiversity by classes of biodiversity metrics across terrestrial, freshwater, marines and multiple realms (See SI V for frequency data table). Positive influence refers to beneficial for biodiversity and negative influence harmful for biodiversity with mixed/neutral influence either beneficial or harmful depending on context. Only uni-directional evidence between two nexus elements is represented in this figure. The figure shows more substantial evidence in terrestrial and multi-realm than freshwater and marine realm from 194 studies in the database, and more harmful effects on biodiversity from other sectors and more beneficial effects from biodiversity to other sectors. There is more evidence to inform harmful effects on KMGBF Goal A at species and ecosystem level and beneficial effect on Goal B nature's contributions to people.

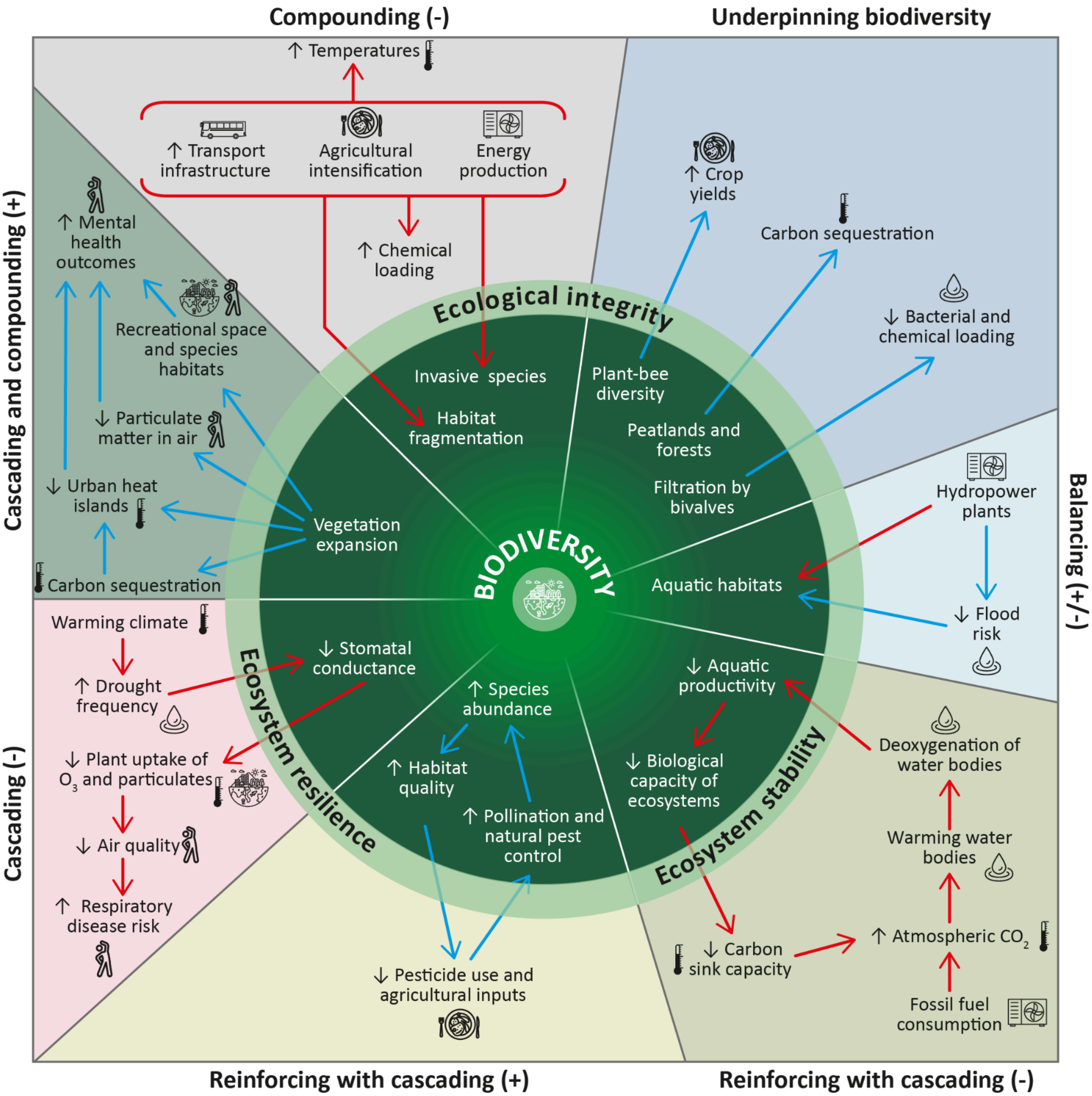

Figure 3

Underlying mechanisms in biodiversity nexus interactions across sectors, presented by impact archetype categories with illustrative examples. When the loss and degradation in biodiversity crosses thresholds and loses ecological integrity, ecosystem stability and ecosystem resilience, further disruptions are made on ecosystem functioning and services across sectors in society through a diverse range of complex interactions. The central circle groups various dimensions of biodiversity across levels across realms. The different examples are shown in the coloured outer sections. Titles around the edge of the figure indicate the underlying mechanisms that each example represents. Arrows denote the direction of the impact of one node on another. Blue = positive (beneficial) interactions; red = negative (detrimental) ones. Icons denote the seven nexus elements: half-globe + landscape = biodiversity; thermometer = climate; plate = food; droplet = water; air conditioner unit = energy; bus = transport; active person = health. In node labels, upward-pointing arrows denote ‘increased’ or ‘enhanced’, downward arrows denote ‘decreased’ or ‘deteriorated’.

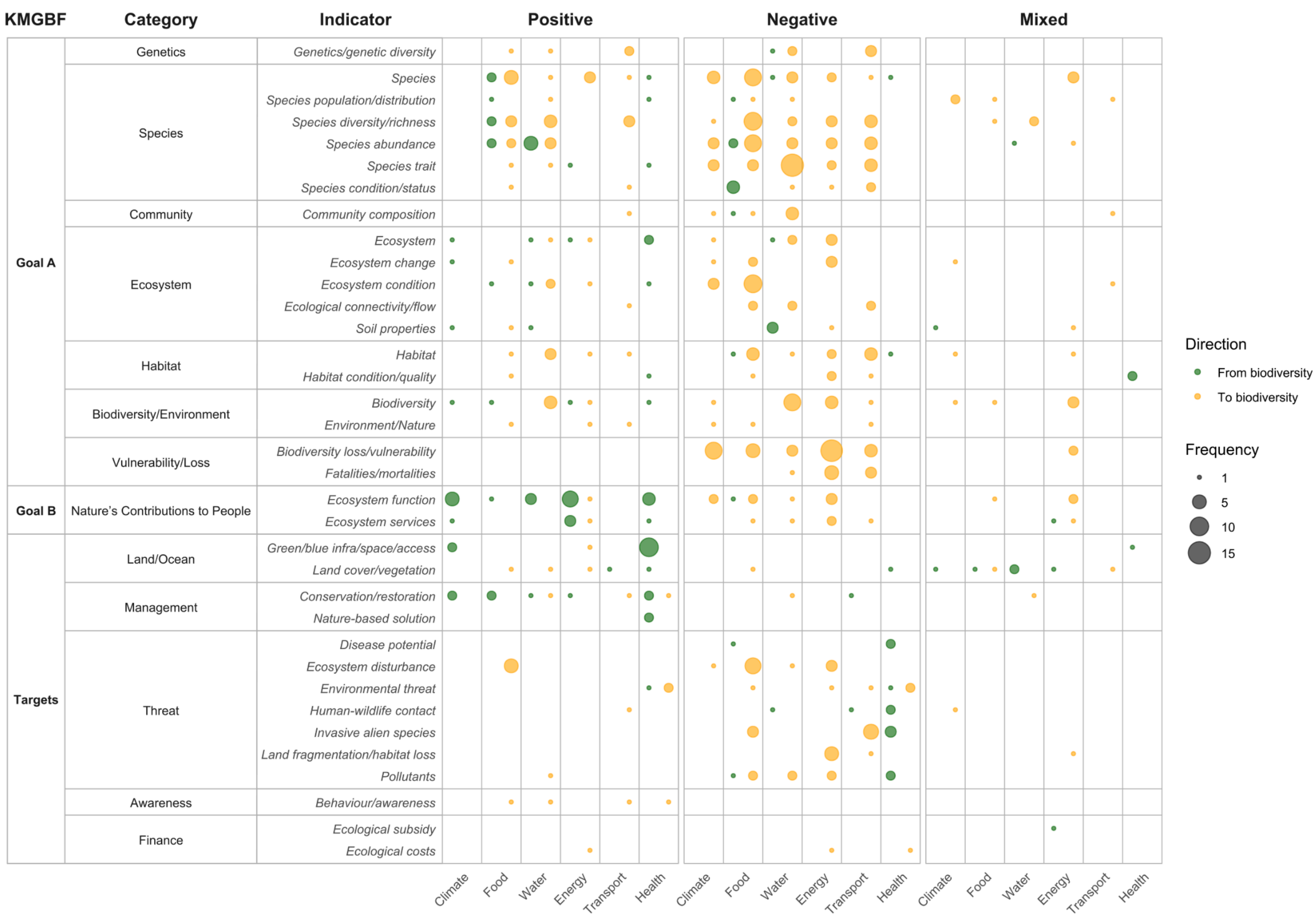

Figure 4

Frequency of evidence between biodiversity metrics and the nexus evidenced by the articles, displayed by nexus element (sector) and direction of influence (positive, negative, mixed) (See SI V for frequency data table). Positive influence refers to beneficial for biodiversity and negative influence harmful for biodiversity with mixed influence either beneficial or harmful depending on context. Only uni-directional evidence between two nexus elements is represented in this figure. The figure shows more evidence of harmful effects on biodiversity from other sectors to inform KMGBF Goal A species and ecosystems and Targets on threats from 194 studies in the database. There are also more beneficial effects from biodiversity to other sectors to inform Goal B nature’s contributions to people and Targets related to spatial planning, conservation and restoration actions.

Supplementary Files

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