Science of the Total Environment 925 (2024) 171692

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Understanding the role of biodiversity in the climate, food, water, energy, transport and health nexus in Europe

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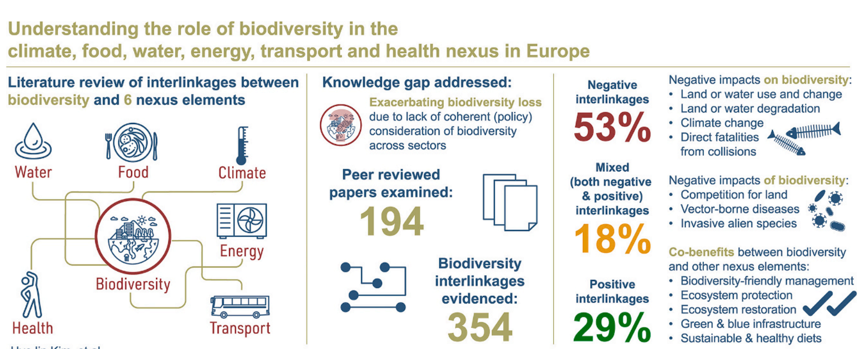
HIGHLIGHTS

- Biodiversity underpins the climate, food, water, energy, transport and health nexus.
- Negative impact studies on biodiversity outnumber positive impact studies.
- Biodiversity has mostly positive impacts on the nexus, but more evidence is needed.
- Nexus studies inform the development of holistic policy and management options.
- Biodiversity nexus is context-dependent, and evidence needs to be contextualized.

GRAPHICAL ABSTRACT



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https://doi.org/10.1016/j.scitotenv.2024.171692
Received 11 December 2023; Received in revised form 10 March 2024; Accepted 11 March 2024
Available online 12 March 2024

ARTICLE INFO

Editor: Manuel Esteban Lucas-Borja

Keywords:
Biodiversity
nexus
Conservation
Sustainability
Policy coherence
Europe

ABSTRACT

Biodiversity underpins the functioning of ecosystems and the diverse benefits that nature provides to people, yet is being lost at an unprecedented rate. To halt or reverse biodiversity loss, it is critical to understand the complex interdependencies between biodiversity and key drivers and sectors to inform the development of holistic policies and actions. We conducted a literature review on the interlinkages between biodiversity and climate change, food, water, energy, transport and health ("the biodiversity nexus"). Evidence extracted from 194 peer-reviewed articles was analysed to assess how biodiversity is being influenced by and is influencing the other nexus elements. Out of the 354 interlinkages between biodiversity and the other nexus elements, 53 % were negative, 29 % were positive and 18 % contained both positive and negative influences. The majority of studies provide evidence of the negative influence of other nexus elements on biodiversity, highlighting the substantial damage being inflicted on nature from human activities. The main types of negative impacts were land or water use/change, land or water degradation, climate change, and direct species fatalities through collisions with infrastructure. Alternatively, evidence of biodiversity having a negative influence on the other nexus elements was limited to the effects of invasive alien species and vector-borne diseases. Furthermore, a range of studies provided evidence of how biodiversity and the other nexus elements can have positive influences on each other through practices that promote co-benefits. These included biodiversity-friendly management in relevant sectors, protection and restoration of ecosystems and species that provide essential ecosystem services, green and blue infrastructure including nature-based solutions, and sustainable and healthy diets that mitigate climate change. The review highlighted the complexity and context-dependency of interlinkages within the biodiversity nexus, but clearly demonstrates the importance of biodiversity in underpinning resilient ecosystems and human well-being in ensuring a sustainable future for people and the planet.

1. Introduction

Biodiversity supports and sustains life on Earth and underpins the functioning of ecosystems and the diverse benefits that nature provides to people (Brauman et al., 2020; Cardinale et al., 2012; IPBES, 2019). It plays a crucial role in the achievement of sustainability outcomes related to food and water security, health and wellbeing, and climate change mitigation and adaptation, among others (Moreno Vargas et al., 2023; Newell, 2023; Ortiz et al., 2021; Sietz and Neudert, 2022; Stoy et al., 2018). Ranging in organismal levels from genes to species and ecosystems, biodiversity contributes directly or indirectly to the achievement of all 17 Sustainable Development Goals (SDGs), encompassing a broad range of ecological and societal wellbeing ambitions set to be achieved by 2030 (Blicharska et al., 2019; Liu et al., 2018; Petersson and Stoett, 2022; Robinson, 2017). Yet, biodiversity is declining worldwide at unprecedented rates due to human activities, with more than one million species threatened by extinction (Bellard et al., 2022; Hochkirch et al., 2023; IPBES, 2019).

The Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES), established in 2010, has raised attention to the importance of biodiversity and the urgent need to halt and reverse biodiversity loss. However, although the biodiversity crisis is now widely recognized, policy has been unable to arrest the decline, with much of this failure being attributed to a lack of mainstreaming of biodiversity in public policy across sectors (Rounsevell et al., 2020). Recent assessments and workshop reports from IPBES – Global Assessment (IPBES, 2019), Biodiversity and Pandemics report (IPBES, 2020), and Biodiversity and Climate Change report (Pörtner et al., 2021) – all point to the importance of holistic policy and governance that addresses challenges across sectors in an integrated way to identify opportunities for synergistic actions that benefit both nature and people. This has been recognized by IPBES in the initiation of the Nexus Assessment focusing on the interlinkages among biodiversity, water, food, health and climate change, which is scheduled to be published in 2024. In addition, a cross-sectoral approach for achieving conservation and sustainability is being increasingly embedded in regional and global policy frameworks, e.g. the SDGs of the United Nations (UN) (Blicharska et al., 2019; Carmona-Moreno et al., 2021); the Kunming-Montreal Global Biodiversity Framework (KMGBF) of the Convention on Biological Diversity (CBD) (CBD Secretariat, 2022; Leadley et al., 2022) and the European Green Deal of the European Union (EU) (European Commission DG Environment, 2021; Paleari, 2024).

Nexus studies provide evidence that is essential for transforming governance away from typically siloed decision-making, where single sector policies are developed and implemented in isolation, towards holistic decision-making that aims to foster synergies and co-benefits across sectors, whilst minimizing or avoiding trade-offs or unintended consequences (Müller et al., 2015; Pascual et al., 2022). Recognising and understanding the underpinning role of biodiversity in nexus studies is key to mainstreaming biodiversity across sectors and improving policy coherence. This would be essential in implementing the CBD KMGBF so that "*biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people*", in line with its 2050 vision of living in harmony with nature. To do this, nexus research and practice need to be diversified to provide evidence on how policies and actions oriented towards biodiversity restoration and conservation can provide co-benefits for other sectors, and whether policies and actions in other sectors impact on biodiversity positively or negatively (Kim et al., 2023; Pascual et al., 2022).

The scientific literature on nexus studies has grown rapidly over the last few decades (Estoque, 2023). Many previous nexus studies focused on two-way nexus interactions, such as food-energy (Sachs and Silk, 1990) or water-energy (Malik, 2002) or on three-way nexus interactions, with the water-energy-food nexus being particularly dominant (Bian and Liu, 2021; Carvalho et al., 2022; Lucca et al., 2023). However, the complexity and diversity of applications of the nexus approach has recently expanded (Estoque, 2023). These studies tend to expand upon the water-energy-food nexus by adding new elements, including climate change (Adeola et al., 2022; Ioannou and Laspidou, 2022), land use (Jaroenkietkajorn and Gheewala, 2021; Kati et al., 2021; Laspidou et al., 2019; Sietz and Neudert, 2022), and health (Hirwa et al., 2021; Newell, 2023; One Health High-Level Expert Panel (OHHLEP) et al., 2022). The inclusion of biodiversity and its interlinkages with other sectors (i.e., the biodiversity nexus) has also started to gain traction more recently in terms of studies focused on the water-energy-food-ecosystem nexus (Carmona-Moreno et al., 2021; Cristiano et al., 2021; UNECE, 2015), the water-energy-food-biodiversity nexus (Moreno Vargas et al., 2023; Stoy et al., 2018; Subedi et al., 2020) or more broadly in terms of the water-energy-food-environment nexus (Hellegers et al., 2008). Despite these recent extensions of nexus applications, studies covering greater than three-way nexus interactions, and studies focusing on three-way nexus interactions other than water-energy-food, remain relatively rare.

The nexus studies that do incorporate some consideration of biodiversity, review evidence using diverse frameworks, approaches, methods and sources from a broad range of disciplines. These include studies with a specific focus on a local area (e.g., resilience of the land-water-biodiversity nexus in a coastal city of China, Wang et al., 2021), a country (e.g., impacts of land use in the GHG-water-land-biodiversity nexus in Thailand, Jaroenkietkajorn and Gheewala, 2021), a region (e.g., water-energy-food-ecosystem nexus in the Mediterranean, Lucca et al., 2023), a realm (e.g., effects of marine system pressure on the food-energy-water nexus in China, Zhu et al., 2021), an ecosystem (e.g., implications of maiz irrigation in water-energy-food-ecosystem nexus in the Nanube River Basin, Probst et al., 2024), a sectoral or cross-sectoral system (e.g., water-energy-food nexus for consideration in biodiversity conservation in agricultural system transition, Moreno Vargas et al., 2023), a land type (land-energy-water nexus on bioenergy from abandoned cropland, Næss et al., 2021) or an intervention type (e.g., urban greenroofs in the water-energy-food nexus, Cristiano et al., 2021). These reviews show the new and emerging research on the biodiversity nexus, but also highlight that it is currently limited to a few regions, systems and topics, and highly focused on slight augmentations or interpretations of the water- energy-food nexus. In addition, other nexus studies have focused on negative sectoral impacts on biodiversity (Green et al., 2019; Sonter et al., 2020) and negative climate impacts on a range of sectors, including biodiversity (Adeola et al., 2022; Ioannou and Laspidou, 2022; Pereira et al., 2020). However, few studies demonstrate the potential of the nexus approach for understanding the positive influence of biodiversity on other sectors, which will be vital for mainstreaming biodiversity considerations across sectors and providing evidence on how biodiversity can support transformative pathways towards sustainable futures.

Amid growing attention to nexus thinking in research and policy, there is a need for more comprehensive and integrated evidence on the biodiversity nexus to understand the role biodiversity plays in nexus interactions across sectors or domains of relevance to conservation, climate change, sustainability and human wellbeing. This review responds to this research gap and aims to synthesize evidence on the current state of knowledge on the nexus between biodiversity and six other elements – climate, food, water, energy, transport and health – focusing on Europe as a geographic region. It poses the research question: how is biodiversity influencing and influenced by climate, food, water, energy, transport and health? The review synthesises information on multiple directions and types of influences (i.e., influencing and influenced, positive and negative) across the seven nexus elements to improve understanding of the complex system dynamics represented by higher-order interlinkages (i.e. beyond two-way) within the biodiversity nexus.

2. Methods

2.1. The literature review database

A literature review was conducted to identify peer-reviewed studies that consider three-way interlinkages between biodiversity and at least two other nexus elements, with a focus on literature regarding Central and Western Europe. The literature included in this review, however covered countries in the broader European region, including Belarus, Georgia, Russian Federation and Ukraine, in cases where these countries participated in regional or global studies. Ten combinations of three-way nexus interlinkages with biodiversity were considered: Biodiversity-Energy-Food (BEF), Biodiversity-Energy-Health (BEH), Biodiversity-Energy-Transport (BET), Biodiversity-Energy-Water (BEW), Biodiversity-Food-Health (BFH), Biodiversity-Food-Transport (BFT), Biodiversity-Food-Water (BFW), Biodiversity-Health-Transport (BHT), Biodiversity-Health-Water (BHW), and Biodiversity-Transport-Water (BTW).

We used the Web of Science online literature search engine and the R package LitsearchR to identify potentially relevant key terms for each of the seven nexus elements (biodiversity, climate change, food, water, energy, transport, health) and for terms related to "nexus". These were subsequently ranked using expert elicitation by the author team and combined with terms representing the geographical region (i.e., Central and Western Europe) to derive a set of search strings (see Table 1 for standard search terms used, and Supplementary Material A, Tables S1, S2 for further details). Climate change was not explicitly included in the searches associated with the ten three-way nexus interlinkages as it was anticipated that climate change would be considered in many of the articles identified. This was found to be the case, with climate change being part of about half (49 %) of the 194 studies included in the review.

The search revealed 2633 articles from the Web of Science, of which 1185 articles passed an initial screening focused on title and abstract and 122 passed a second screening of the full articles. Criteria for both screenings were that the study should contain a clear link to biodiversity and between biodiversity and at least two other nexus elements, as well as information on the direction and magnitude of the interlinkages. We aimed to identify 20 articles per three-way nexus interlinkage to ensure consistent coverage of the ten three-way nexuses. Hence, additional refined searches were undertaken for those three-way interlinkages for which <20 eligible articles were found from the standard search (see Supplementary Material A). The final literature database included 200 studies; 20 for each nexus, with exceptions of 22 for Biodiversity-Health-Water and 18 for Biodiversity-Transport-Water. The former was due to over-submission and the latter due to lack of literature. The 200 reviews were based on 194 articles with six articles that were relevant for two of the three-way nexus interlinkages and hence are counted twice in the total (see Supplementary Material A Fig. S1 and Table S1 for details on the literature count, the eligibility steps and selection criteria). In addition, we searched for literature that integrates Indigenous knowledge through both a standard search using Web of Science and a refined search using additional sources (see Additional literature searches section of the Supplementary Material A. Methodology).

The selected articles were reviewed using a common template (see Supplementary Material B for review questionnaire, Supplementary Material C for the list of literature). An annotated Causal Loop Diagram was drawn for each article to provide an overview of all nexus interlinkages covered in the study under consideration, including and beyond the three-way interlinkage (i.e., biodiversity and two other nexus elements). In addition, the following information was recorded for each article: 1) spatial scale of the nexus described in the study, 2) temporal scale over which the impacts from the nexus interlinkages manifested, 3) realm (i.e., freshwater, marine, terrestrial), 4) species group, 5) ecosystems, 6) inclusion of climate in the study, 7) additional nexus elements, drivers or intermediaries beyond biodiversity, climate, food, water, energy, transport and health (e.g., pollution), 8) direct or indirect bi-directional impacts between two nexus elements, 9) positive or negative direction of these impacts, 10) magnitude of these impacts (scale of 1 to 5), 11) indicators used to assess these impact relationships,

Table 1
Standard search terms used in literature search strings across nexus elements.

Nexus	Nexus, Interlink*, Interact*, Trade$off*, Synerg*, Cross-sect*, Inter $dependen*, Coupled
Biodiversity	Biodiversity, Habitat, Species, Nature, Ecosystem
Climate	Climate change, Climate regulation, Climate mitigation, Climate adaptation, Carbon sequestration, GHG, Greenhouse gas emission
Food	Food, Land$use, Agricultur*, Crop*, Farm*, Food production, Food consumption
Water	Water quality, Water quantity, Flood regulation, Irrigation, Catchment*, Drought, Water security
Energy	Energy, Renewable*, Bioenergy, Fossil fuel*, Solar, Wind, Hydropower, Wave energy, Nuclear power, Hydrogen energy
Transport	Transport, Infrastructure, Rail*, Road, Ship*, Automobile, Electric vehicle, Aviation, Cycling, Walk, Hydropower transport
Health	Human health, Public health, Physical health, Mental health, One health, Infectious disease, Zoonotic disease, health AND well$being

12) overall outcome of the nexus interlinkages including synergies and trade-offs, 13) drivers mentioned in the study, 14) engagement of stakeholders and Indigenous knowledge, 15) mention of policy goals including the Sustainable Development Goals (SDGs), the Kunming-Montreal Global Biodiversity Framework, the Paris Agreement and others, and 16) strength of evidence (scale of 1 to 5). Items (8) to (11) were repeated for all bi-directional impacts specified in the Causal Loop Diagram to capture the complexity of higher-order (beyond two-way) interactions. Detailed methodological steps, including the quality assurance of the review, are described in the Supplementary Material A.

2.2. Analyzing the literature database

2.2.1. Bi-directional interlinkages

The review resulted in a database of bi-directional interlinkages (e.g., Biodiversity to Food, Food to Water, Water to Health) evidenced in each article with information on the direction (positive, negative) and magnitude (scale of 1 to 5) of impact and the type of methods (quantitative, qualitative) and measures (indicators, surrogates/proxies). These bi-directional interlinkages were recorded across all of the seven nexus elements as well as for additional nexus elements or drivers (e.g., pollution) considered beyond the three-way nexus interlinkages. This bi-directional impact database was used as a basis for the subsequent analyses on three-way nexus interlinkages and synthetic network pathways.

2.2.2. Three-way interlinkages

The impact relations across the three nexus elements were analysed in terms of the direction and magnitude of bi-directional impacts and visualised in a 3-dimensional space, which we refer to as a triplet. Ten triplets were created by plotting the information from the approximately 20 articles as triangles, with biodiversity and two nexus elements at each vertex (see Figs. 4–6). In addition, five triplets were produced that highlighted interlinkages between biodiversity, climate and one other nexus element. The triplets show the influence of biodiversity on the other two nexus elements as well as their influence on biodiversity. The magnitude of bi-directional impact is plotted on the sides of the triangle, separately for positive (blue) and negative values (red) on a scale of 0 to 5. The geometric centroid is calculated and plotted in the 3-dimensional triangular space. The position and magnitude of the centroid indicate the predominance in influenced strength among the three interlinked elements: (i) position—the closest it is to one of the corners, the more this element is influenced by the other elements; (ii) magnitude—the size of the circle where the centroid is marked indicates the strength of influence. The size of the centroid is calculated by taking an average of all values (absolute values) of the magnitude of impact. This visual presentation of the three-way interlinkage was used in analyzing the impact relations across the three nexus elements and their estimated cascading and reinforcing effects based on the selected 20 articles.

2.2.3. Synthetic network pathways

The bi-directional evidence (direction and magnitude of impact) from all the articles in the review database was synthesized to identify all possible pathways between biodiversity and other six nexus elements. For example, a systematic pathway across the Energy-Transport-Food-Biodiversity nexus was constructed based on all of the studies that identify an interlinkage between energy and transport, all of the study that identify an interlinkage between transport and food, and all of the studies that identify an interlinkage between food and bodiversity. The synthetic network pathways were created using the "all_simple_paths()" function in the "igraph" package (Csardi and Nepusz, 2006) in R (R Core Team, 2022). We filtered these synthetic pathways to two groups: (i) pathways formed of only positive linkages that start with one of the seven nexus elements; (ii) pathways formed of only negative interlinkages that start with one of the seven nexus elements (please see Fig. 7). Each pathway group consisted of one nexus element as a start with the other six nexus element as ends. For example, the positive network pathways starting with biodiversity consist of all possible pathways of the following combinations: Biodiversity to Climate, Biodiversity to Energy, Biodiversity to Food, Biodiversity to Health, Biodiversity to Transport, Biodiversity to Water. The overall impact of the pathways was calculated by first taking the mean of the magnitudes for each of the bi-directional interlinkages that make up the pathway. Then the impact of the pathways was generated by calculating the sum of the mean magnitudes of the bi-directional interlinkages that make up each pathway. For these, we generated scores for positive and negative pathways both from biodiversity to the other nexus elements and from the other nexus elements to biodiversity (see Supplementary Material A, *Data Visualization and Analysis* for more details on the calculation methods).

3. Results

3.1. Descriptive statistics

The majority of studies were at sub-national (between local and national; 28 %), national (22 %) or global (22 %) scales. Local scale studies (single land parcel, farm, sub-catchment or city) made up 18 % of the database with continental and sub-continental studies making up the rest (4 % and 6 %, respectively). The studies covered all realms with the largest number of studies focusing on the terrestrial realm (50 %), followed by freshwater (34 %) then marine (16 %). In total, 45 countries in the European region were covered in the review with Germany, United Kingdom, Europe and Italy with the most coverage (over 6 % each). The countries studied in the 194 articles are shown with study counts on the map in Fig. 1.

Information on biodiversity was captured in terms of species and ecosystem type (Fig. 2). Plants were the most frequently represented species type (26 %) with birds, mammals, fish, and invertebrates similarly represented (11–12 %) and amphibians slightly lower (6 %). Invertebrates is a broad category to describe many different taxa and a considerable portion was undefined (15 %). Rivers and lakes, cropland, urban/peri-urban, grassland, woodland and forest were the most frequently recorded ecosystem types (10–13 %). Wetland, coastal, heathland, open ocean, marine inlet and transitional waters, and sparsely vegetated land were also studied but in a lower proportion of

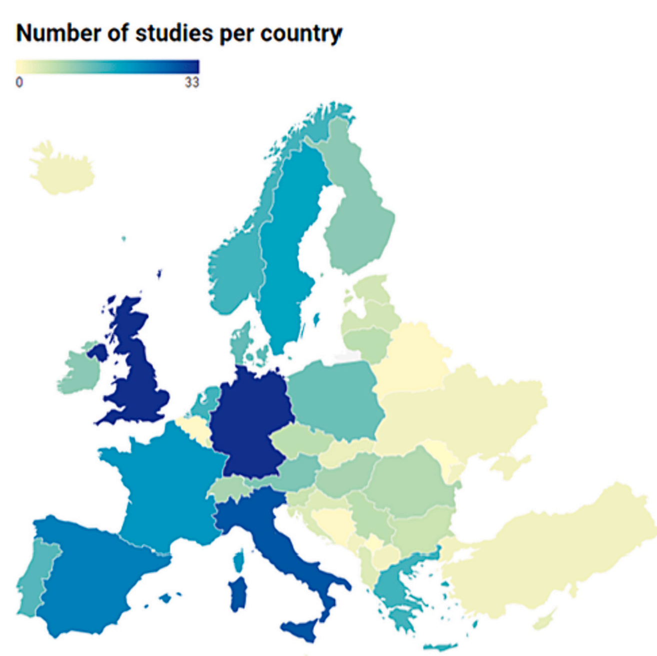

Fig. 1. Number of studies included in the review per country.

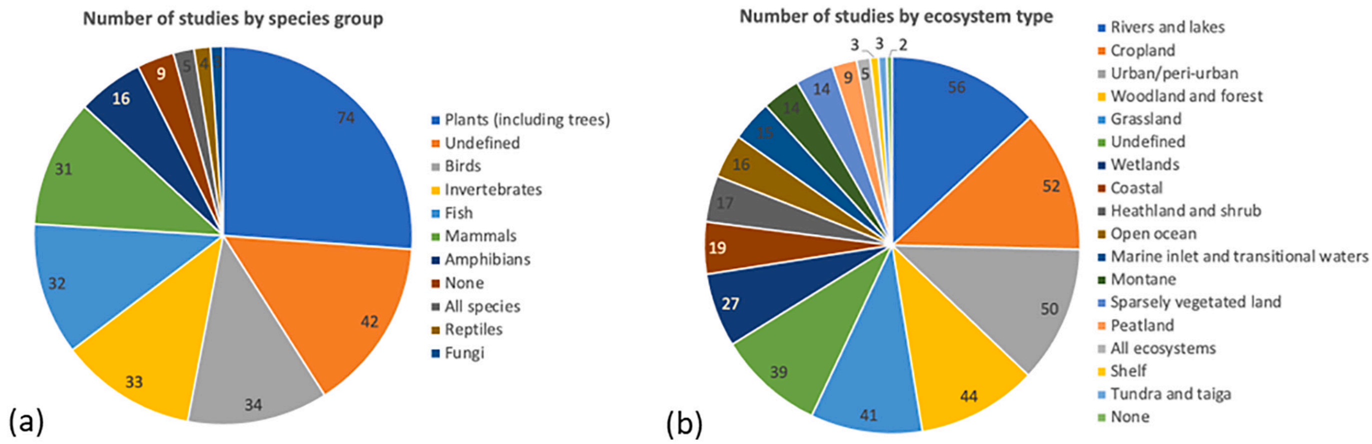

Fig. 2. Number of studies by (a) species group and (b) ecosystem type.

the records (<7 %).

The estimated timeframe of impacts to be manifested in the nexus interlinkages studied tended to be short term (1–5 years 47 %, < 1 year 27 %) with studies using longer time frames ranging from 6 to 20 years less common (24 %). Land use (18.6 %), climate change (13 %), economy (11.9 %), pollution (10.6 %), policy, institutions and governance (8.6 %), direct exploitation (8.5 %), technology (7.2 %), health (6 %), sociocultural (4.6 %), invasive alien species (3.4 %), sea use (3.3 %), and conflict (2.5 %) were direct or indirect drivers impacting nexus interlinkages.

The most frequently used method of research was indicator/data analysis (26 %), then literature review (17 %), modelling/simulation/computation (16 %), observation (10 %), experiment (6 %), meta-analysis (5 %), synthesis (5 %), survey (4 %), focus group/workshop (4 %), interview (4 %) and other (4 %). Stakeholder knowledge was included in 19 % of the studies with barely 1 % on Indigenous knowledge. Concerning policy and legal frameworks, the Paris Agreement was mentioned in 15 % of the studies whilst 10 % mentioned the SDGs and 8 % biodiversity goals, more broadly. In terms of strength of evidence, 42 % of the studies were rated as very strong, 9 % strong, 38 % reasonably supported, 11 % weak and 0.5 % very weak evidence (see Supplementary Material A for the description of the scale).

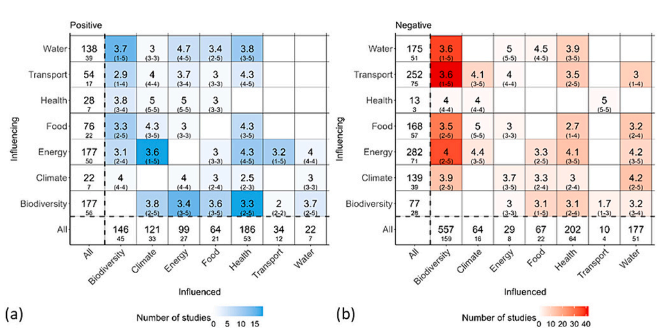

Fig. 3. Heatmaps of (a) positive and (b) negative impact scores between the seven nexus elements where the nexus element in the row direction is influencing the nexus element in the column. The colour intensity indicates the number of studies evidencing each linkage, ranging from 1 to 37. The number in each coloured cell refers to the mean magnitude of each bi-directional impact, with the range across the studies shown in brackets underneath. The total sum of the mean magnitude of impact across all other nexus elements is shown in the first column and the last row, with the count of studies upon which this is based shown underneath.

3.2. Bi-directional impact score

Bi-directional impacts between nexus elements are shown in Fig. 3. The heatmaps show the relatively large number of studies evidencing a negative impact on biodiversity. The largest number of studies describe the negative impacts of transport, energy and water on biodiversity, but the highest mean magnitude of impact is from energy and climate change. Conversely, there are far fewer studies showing negative influences from biodiversity to the other nexus elements and the mean magnitude of impact is also lower. Overall, fewer studies describe positive bi-directional impacts than negative across the nexus elements. Among these studies, a large proportion provides evidence of positive biodiversity influence on health and energy. The highest mean magnitude of influence from biodiversity to the other nexus elements was found for climate and food. Alternatively, the greatest proportion of studies provide evidence of positive influence from food and water to biodiversity, whilst the highest mean magnitude of influence was from climate (based on a single study) and health.

Looking at bi-directional interlinkages among all the nexus elements based on the total sum of the mean magnitudes of impact (first column in Fig. 3), we find that biodiversity and energy had the highest positive influence on the other nexus elements, whilst energy and transport has the highest negative influence. Alternatively, the greatest positive impacts from nexus elements was on health, whilst by far the greatest negative impact was on biodiversity (final row in Fig. 3). The heatmaps show the complexity of interlinkages among the nexus elements, with evidence showing that one element can provide both positive and negative impacts on another element. This is reflected in differences in the indicators used in each study to represent the nexus elements, which we elaborate below using specific examples from the literature database for some of the key bi-directional linkages.

The positive bi-directional linkages with the highest number of studies were between water influencing biodiversity, energy influencing climate, biodiversity influencing energy, and biodiversity influencing health. The mean magnitude of these links was 3 to 4, i.e., between moderate and substantial, although the magnitude could range from 1 to 5 within each category. Demonstrative examples of these interlinkages include water quality positively influencing the functioning of local unique biotopes rich in biodiversity (Kropf et al., 2021); renewable energy replacing fossil fuels positively influencing climate by reducing greenhouse gas emissions (Livingstone et al., 2021); biodiversity positively influencing energy through the sustainable harvesting of above ground biomass in riparian ecosystems as a fuel source (Cartisano et al., 2013); biodiversity positively influencing health in terms of forest walks promoting cardiovascular relaxation compared to walks in urban environments (Zorić et al., 2022); and natural ecosystems absorbing atmospheric pollutants, which improves air quality and benefits health (Barrios-Crespo et al., 2021).

The negative bi-directional linkages with the highest number of studies were for transport, energy, water and food, all influencing biodiversity. The mean magnitude of these links was 3 to 4, i.e., between moderate and substantial, although the magnitude could range from 1 to 5 within each category. Demonstrative examples of these interlinkages include negative impact of roads on species mortality, movement and genetic diversity (Johansson et al., 2005; Mayer et al., 2023); ballast water for shipping transport negatively impacting biodiversity through the release of non-native species (Barrios-Crespo et al., 2021); dam construction for hydropower generation causing loss of biodiversity (Donadi et al., 2021; Göthe et al., 2019; Yoshida et al., 2020); degraded water quality from peat extraction for energy negatively influencing habitat quality and biodiversity (Juutinen et al., 2020); acidification of freshwater resulting in loss of fish populations (Wright et al., 2017); and negative impacts of crop production on ecosystem quality (Todorović et al., 2018) and habitat loss (Eiter and Potthoff, 2007).

3.3. Three-way nexus interlinkages

The analysis of three-way interlinkages (triplets) offers insights into more complex interactions within the biodiversity nexus. Results for Biodiversity-Energy-Water (BEW), Biodiversity-Health-Transport (BHT) and Biodiversity-Climate-Food (BCF) are shown in Figs. 4 to 6, respectively, as illustrative examples. Results for the eight other triplets focused on biodiversity and four other triplets focused on biodiversity-climate are provided in the Supplementary Materials D and E. Looking across all 15 sets of three-way nexus interlinkages, the evidence from the review indicates that biodiversity receives overall positive influences from the other two nexus elements within the BFT, BFW and BTW triplets. In contrast, biodiversity receives overall negative influences from the other two nexus elements within the BEF, BET, BEW, BFT, BCE and BCT triplets. Biodiversity plays a more active role in other nexus interlinkages, exerting negative influences on the other two nexus elements within the BFH and BCH triplets and positive influences within the BEF, BET, BCE and BCH triplets.

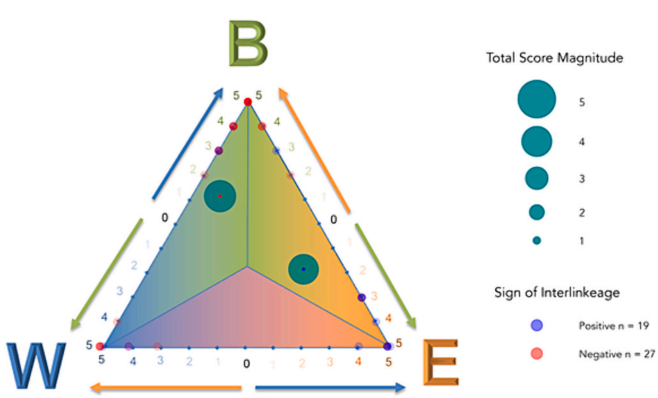

Fig. 4. Three-way interlinkages between biodiversity (B), energy (E) and water (W). The locations of the centroids (blue: positive, red: negative) in the triangular space indicate the degree to which one nexus element is influencing or influenced by another nexus element (i.e., the closer it is to one of the corners, the more this element is influenced by the other elements). The larger the centroid, the stronger the average magnitude of the interlinkage (i.e., on a scale of 1 to 5). The number of studies reporting positive or negative influences is indicated in the legend at the lower panel (i.e., Positive $n = 19$, Negative $n = 27$).

The location and size of the centroids in the Biodiversity-Energy-Water (BEW) triplet (Fig. 4) show that biodiversity and water have a positive influencing role on energy, and energy has a negative influencing role on water and biodiversity. Our evidence indicates that the magnitude of these influences is scored relatively high at about 4.

Biodiversity is negatively impacted by energy and water in the case of energy-producing peat extraction, resulting in eutrophication and brownification (Juutinen et al., 2020). This can affect fisheries in nearby freshwater bodies causing a negative impact on the longitudinal dispersal of fish species which hinders the colonization of migrating species (Göthe et al., 2019) and leads to significant decline in the abundance of trouts, diatoms, seagrass and rhodophytes (Donadi et al., 2021). Water infrastructure for energy production, such as dams and hydropower, causes river fragmentation, alters river flow significantly (Dopico et al., 2022; Pittock, 2011; Yoshida et al., 2020) and creates stressors on river regulation and excess loadings of nutrients and sediments (Bakanos and Katsifarakis, 2019; Donadi et al., 2021). This in turn impacts water quality, aquatic life and habitat conditions, resulting in loss of biodiversity. In addition, dams can alter biophysical attributes like water depth which can have a direct effect, for example, on the abundance of diatoms, seagrass and rhodophytes (Leiva-Dueñas et al., 2020).

Water is shown to affect biodiversity positively with higher water availability improving vegetation (Eriksson et al., 2018; Irabien and Darton, 2016) and the ecological status of rivers with benefits for local ecosystems (Comino et al., 2020). Water is also shown to affect energy positively with direct contributions to bioenergy generation from forests (Eriksson et al., 2018; Franzaring et al., 2015; Irabien and Darton, 2016), higher yields of bioenergy plants (Cartisano et al., 2013; Palacios-Abrantes et al., 2022) and hydropower plants as a renewable energy source (Comino et al., 2020; Dopico et al., 2022). In turn, bioenergy production can positively impact biodiversity when delivered using a variety of tree species, which has the knock-on effect of reducing carbon emissions and mitigating climate change (Cartisano et al., 2013). In addition, forest residue and other forms of woody above ground biomass can be used as a natural source of energy, such as in district heating systems (Sacchelli et al., 2013). However, bioenergy production can have negative consequences on water and biodiversity if undertaken in a way that increases irrigation use and risks to ecosystem integrity and resilience (Bakanos and Katsifarakis, 2019; Donadi et al., 2021; Pittock, 2011; Sacchelli et al., 2013; Wright et al., 2017). For example, support for bioenergy production has been shown to have strong negative effects on the habitat suitability for farmland birds (Glemnitz et al., 2015).

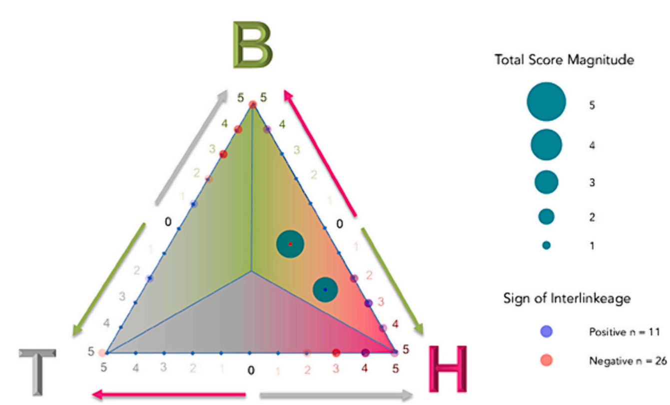

Fig. 5. Three-way interlinkage between biodiversity (B), health (H) and transport (T). See caption of Fig. 4 for an explanation of the structure of the figure.

The Biodiversity-Health-Transport (BHT) triplet depicted in Fig. 5 offers a contrasting example. The negative centroid shows how transport has a negative influencing role on biodiversity and health. Conversely, the positive centroid shows that transport also has a strong positive influence on biodiversity and health.

Transport negatively influences biodiversity through species killed by vehicles (Di Giulio et al., 2009; Puodziukas et al., 2016; Raymond et al., 2023) and habitat loss and degradation from transport infrastructure (Di Giulio et al., 2009; Hunter et al., 2019; Khreis et al., 2016; Simkins et al., 2023). Transport negatively influences health through road accidents, air pollution from fossil fuel transport (Buekers et al., 2014; Khreis et al., 2016; Pallozzi et al., 2020; Rupcic et al., 2023; Weerakkody et al., 2017) and traffic-related noise (Khreis et al., 2016; Puodziukas et al., 2016). Transport has been shown to facilitate the spread of invasive species, pathogens, parasites and disease vectors causing zoonotic diseases that negatively influence health and biodiversity (Bax et al., 2003; Hulme, 2020; Medlock et al., 2012; Peyton et al., 2019). Control measures (e.g., on mosquitoes) may also damage non-target species (Medlock et al., 2012). Biodiversity, through wildlife and provision of habitat, enables the reproduction and spread of vectors, invasive alien species and pathogens that can impact human health directly or indirectly through damages to food supplies (Bax et al., 2003; Hulme, 2020; Medlock et al., 2012; Peyton et al., 2019). The production of electric vehicles negatively influences biodiversity through resource use and the manufacturing footprint (Dall-Orsoletta et al., 2022).

However, transport through green infrastructure can enhance local biodiversity (Hunter et al., 2019, 2021), mitigate air and noise pollution (Toffolo et al., 2021) and positively influence mental and physical health (Di Giulio et al., 2009; Hunter et al., 2021; Khreis et al., 2016; Zijlema et al., 2018; Zorić et al., 2022). Raymond et al. (2023) shows that as a result of the global health pandemic, the reduction in transport was so profound that a global 'quietening' was detected, called the 'anthropause' (Lecocq et al., 2020). As the interlinkage between transport and biodiversity is usually negative, the pause in transport reduced wildlife vehicle collisions, having a positive effect on biodiversity (Raymond et al., 2023). There are mixed effects of transport on health because battery powered electric vehicles can cause further exploitation of natural resources, pollution and human health issues (e.g., cobalt mining, respiratory hazards of Li ion battery particles), yet there are also benefits in human health and urban environments (e.g., reduced pollution in air) (Buekers et al., 2014; Dall-Orsoletta et al., 2022). Hence, there are mixed effects on the climate as although electric vehicles have the potential to mitigate climate change, this is dependent on the methods and sources of productions of electricity and greenhouse gas emissions throughout the whole lifecycle being less than that of the fossil fuel counterpart. There is also disparity in socio-environmental impact geographically by, for example, global south vs. north (Dall-Orsoletta et al., 2022).

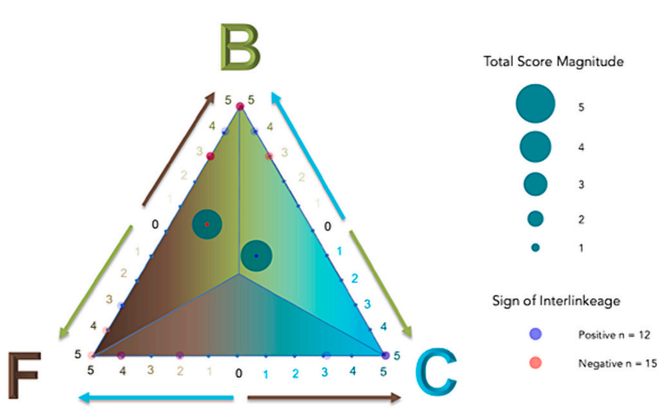

Fig. 6. Interlinkages between biodiversity (B), climate (C) and food (F). See caption of Fig. 4 for an explanation of the structure of the figure.

Fig. 6 shows an example of the triplets focused on the Biodiversity-Climate-Food (BCF) nexus. The location and size of the negative centroid show that climate change has a strong negative influence on both biodiversity and food. For example, hydropower plants, built as infrastructure for alternative energy sources from the water system, not only affect species in aquatic food webs but also their neighboring terrestrial foodwebs through interactions and affect local communities as well as highly threatened vertebrate groups such as amphibians and reptiles (Crnobrnja-Isailović et al., 2021). Climate change can exacerbate other negative influences on biodiversity within food systems, such as agricultural intensification, further contributing to a loss of species richness and abundance (Andriamanantena et al., 2022; Bourke et al., 2014; Wagner, 2020). Climate change can also reduce the productivity of food production, for example, making the rainfed cultivation of olive crops no longer economically feasible due to the increasing demand for water (Fotia et al., 2021). In addition, more frequent and severe flood events related to climate change can affect the recovery phase of microbenthic assemblages from eutrophication, which in turn impacts bivalves for fishers who rely on estuarine resources (Cardoso et al., 2008).

In contrast, the location and size of the positive centroid shows that the positive influences between these three nexus elements are relatively balanced and moderate. Biodiversity mitigates climate change as forest restoration and other biodiversity conservation measures contribute to carbon storage (Eriksson et al., 2018; Schulze, 2006). The food system can also positively influence biodiversity and climate change. Changing agricultural practices such as reducing livestock production reduces greenhouse gas emissions from the agricultural sector (Westhoek et al., 2014), and agronomic management of grasslands can serve to maintain habitats for grassland species and prevent the encroachment of other species such as shrubs (Dibari et al., 2021). Similarly, conversion from monocropping to alley cropping systems increases plant diversity (Tsonkova et al., 2012) and provides enhanced niche space for multiple speces. In some regions, changing climate conditions can have a positive influence on biodiversity vulnerability and food production, such as in northern Europe (Harrison et al., 2015).

3.4. Evidence on the biodiversity nexus from Indigenous knowledge and related sources

The additional search of peer-reviewed and grey literature sources on Indigenous knowledge and perspectives on the biodiversity nexus found that Indigenous People's food systems are often intimately linked to biodiversity and climatic conditions (see Supplementary Material A. *Literature identification from Web of Science* and *Additional literature searches* for more details on the literature search). This means that changes in these nexus elements can disproportionately impact Indigenous People's access to food, high-quality nutrition and livelihood, especially in the Arctic regions of Europe where the Sámi and Greenlandic Inuit live (IWGIA, 2023). Reindeer herding is an important livelihood activity and a food source for the Sámi and reindeers are semi-domesticated and rely on the availability of natural forage, especially lichens which act as the primary food source during winter (Jaakkola et al., 2018). Climate change is projected to lead to a decline in lichen ecosystems in high latitudes, which is associated with reduced reindeer meat production, nutritional quality and changes in traditional herding practices (Jaakkola et al., 2018; Ocobock et al., 2023). Furthermore, the Sámi and Greenlandic Inuit rely on wild food sources, including wild plants, game and fish, and the reliance on wild fish increases the vulnerability of these communities to the negative impacts of environmental pollutants (Bjerregaard et al., 2021; Nilsson, 2018). For Indigenous People, declines in biodiversity can negatively affect food security and human health, since many direct harvests from nature are often the main sources of vitamins and minerals.

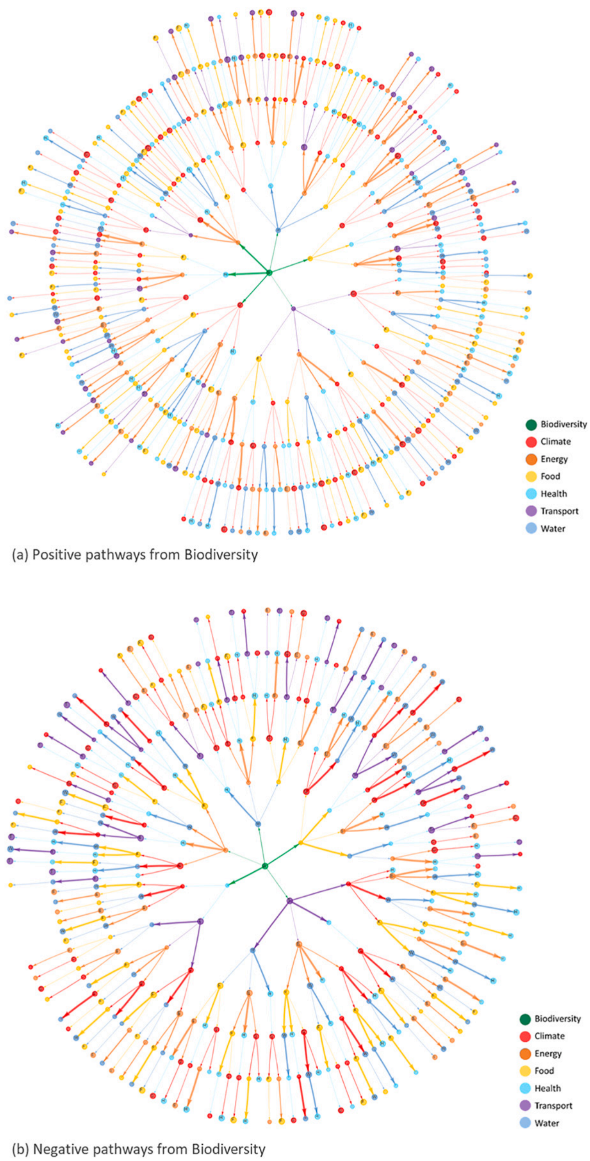

Fig. 7. Synthetic network trees showing (a) 526 positive pathways between biodiversity and all other nexus elements and (b) 388 negative pathways between biodiversity and all other nexus elements. The thickness of the links is proportional to the number of studies evidencing the link and the size of each nexus element is proportional to the mean magnitude of its incoming link.

3.5. Synthetic network pathways

Synthetic network diagrams showing the full complexity of the interlinkages represented in the review database are shown in Fig. 7 for all pathways through which biodiversity can positively or negatively influence the other six nexus elements. These pathways represent the number of studies that evidence the pathway as well as the magnitude of the pathway. Our review database shows that there are 526 possible positive pathways and 388 possible negative pathways through which biodiversity can influence the other six nexus elements. See Supplementary Material F for the remaining 12 positive and negative synthetic network pathway figures with the other six nexus elements as a start.

The complexity and magnitude of the influence of biodiversity on the six nexus elements (as visualised in Fig. 7) is summarised in Table 2(a), whilst the influence of the six nexus elements on biodiversity is summarised in Table 2(b).

The high complexities displayed in Table 2 highlight the central role that biodiversity plays in the nexus with 914 paths involving biodiversity having an influence on at least one of the other nexus elements, and 984 paths involving biodiversity being influenced by the other nexus elements. These are split between positive and negative impacts, with a similar number of positive influences from and to biodiversity, but a greater number of negative influences of other nexus elements on biodiversity than from biodiversity to other nexus elements (458 vs 388). Overall, biodiversity is shown to have a higher positive than negative impact on the other nexus elements (1877 vs 1424).

Table 2
Summary of the (a) positive, negative and overall influence of biodiversity on the six nexus elements and (b) positive, negative and overall influence of the six nexus elements on biodiversity. The "Complexity" metric is calculated as the number of pathways from biodiversity to the nexus element. The "Impact" metric is generated by calculating the means of the bi-directional magnitudes that make up each pathway that goes from biodiversity to the nexus element and then summing these means. The "Overall" columns in the table show the total complexity (sum of the number of positive and negative pathways) and the overall impact (calculated by subtracting the negative impact from the positive impact indicator). The coloured bar within each cell indicates the numeric value proportional to the maximum value for each metric. These are indicative measures of the complexity and impact of nexus pathways.

(a) Overall influence of biodiversity on the six nexus elements

Nexus element	Positive		Negative		Overall	
	Complexity	Impact	Complexity	Impact	Complexity	Impact
Climate	92	340.8	75	281.7	167	5.7
Energy	70	252.2	60	220.6	130	3.7
Food	122	429.0	64	236.5	186	9.7
Health	122	427.0	79	276.4	201	9.4
Transport	44	157.5	39	152.6	83	-2.3
Water	76	270.8	71	255.7	147	0.2
All	526	1877.4	388	1423.5	914	26.5

(b) Overall influence of the six nexus elements on biodiversity

Nexus element	Positive		Negative		Overall	
	Complexity	Impact	Complexity	Impact	Complexity	Impact
Climate	65	228.7	70	268.7	135	-6.1
Energy	70	253.3	69	270.7	139	-4.4
Food	57	214.8	78	308.8	135	-9.6
Health	57	212.1	58	234.4	115	-5.2
Transport	163	603.8	120	459.5	283	4.8
Water	114	417.4	63	255.0	177	4.7
All	526	1930.1	458	1797.1	984	-15.7

Complexity and impact are closely linked in Table 2 as we have assumed that the magnitude of impact is passed through all connected links in a pathway without diminishing in strength. Table 2(a) shows that food, health and climate stand out as being most positively impacted by biodiversity (through various paths), followed by water and energy, then finally transport as the least positively impacted by biodiversity. Biodiversity supports ecosystem services crucial to various dimensions of human health and has positive impacts on food systems such as wild food plants (Quave and Pieroni, 2015), functional agrobiodiversity (Dibari et al., 2021), wild game (Bjerregaard et al., 2021), and landraces (Scartazza et al., 2020) to ensure long-term food security. Negative influences from biodiversity are more even (but with a lower impact) across climate, health, water, food and energy, with transport again the least impacted. An example of the negative impacts from biodiversity are nature-related health risks such as infectious diseases and allergies (Hulme, 2020; Medlock et al., 2012).

Impacts on biodiversity are almost the opposite with transport standing out as having comparatively both stronger negative and positive impacts than the other nexus elements (see Table 2(b)). Negative impacts of transport on biodiversity include roadkill and habitat fragmentation and loss (Di Giulio et al., 2009; Puodziukas et al., 2016) whereas positive impacts of transport are cited where green infrastructure has been promoted (Buekers et al., 2014; Hunter et al., 2019) or where the form of transport presented is 'active' such as cycling and walking (Hunter et al., 2019; Khreis et al., 2016; Zijlema et al., 2018). After transport, food has the largest negative impact on biodiversity, for example, land clearance for food and intensive agriculture causing biodiversity loss (Maskell et al., 2013). Water has the second largest positive impact on biodiversity, such as where streams act as humid dispersal corridors (Haugen et al., 2020) and studies highlighting the hydroperiod as one of the most important drivers of species richness (Couto et al., 2017).

4. Discussion and conclusions

The results of this review show an intricate set of relationships by which biodiversity influences and is influenced by climate change, food, water, energy, transport and health. Overall, it adds weight to other studies that highlight how biodiversity plays a critical role in nexus interlinkages as it underpins ecosystem state and functioning, which are essential for the delivery of nature's contributions to people and human well-being (Brauman et al., 2020; Cardinale et al., 2012; IPBES, 2019).

The analyses demonstrate the immense complexity of the interdependencies in the biodiversity nexus. Nevertheless, some dominant trends emerge in the impact relationships between biodiversity and the other nexus elements (Fig. 8). Out of the 354 interlinkages evidenced between biodiversity and six other elements in the review, 53 % were negative, 29 % were positive and 18 % contained both positive and negative influences. 260 of these interlinkages provided evidence for how biodiversity is influenced by the other nexus elements, with 61 % representing negative, 17 % positive, and 21 % both positive and negative impacts on biodiversity (see Fig. 8(a)). The remaining 94 interlinkages provided evidence for how biodiversity influences the other nexus elements, with 30 % representing negative, 60 % positive, and 10 % both positive and negative impacts (see Fig. 8(b)).

Thus, about half of the interlinkages involving biodiversity in the database were negative influences of other nexus elements on biodiversity, highlighting the substantial damage being inflicted on nature from human activities in these sectors. This evidence can be classified into six main types related to (i) land use/land use alteration, such as habitat destruction for expansion of food production (Wagner, 2020), competition for land from land-based renewable energy (bioenergy, solar, wind) (Perišić et al., 2022), and habitat fragmentation from transport and energy infrastructure (Simkins et al., 2023); (ii) water use/water course alteration, such as alteration of water flows and river fragmentation due to dams and reservoirs related to hydropower (Bakanos and Katsifarakis, 2019; Dopico et al., 2022), water demand for energy and irrigation reducing environmental flows (Pittock, 2011), and dredging affecting coastal and marine ecosystems (Dolmer and Frandsen, 2002); (iii) land degradation affecting habitat quality and species diversity and richness, such as from agricultural intensification (Glemnitz et al., 2015), peat extraction for energy (Juutinen et al., 2020), and mining for renewable energy (Simkins et al., 2023); (iv) degradation of water quality affecting freshwater, coastal and marine ecosystems and species, such as through euthrophication, acidification, brownification and sedimentation (Klante et al., 2021); (v) climate change impacts on species and ecosystems, such as through changes in heat or water stress, seasonality and floods (Cardoso et al., 2008; Leiva-Dueñas et al., 2020; Wright et al., 2017); and (vi) direct species fatalities, such as collisions with wind turbines and traffic (road, rail, shipping) (Busch et al., 2013; Mayer et al., 2023; Raymond et al., 2023; Simkins et al., 2023).

By contrast, the review found only limited evidence of the negative influence of biodiversity on the other nexus elements through impacts related to (i) competition for land (Eiter and Potthoff, 2007); (ii) disease transmission from a small set of species triggered by habitat gain or loss and climate change (Hulme, 2020; Milićević et al., 2016); or (iii) the introduction and expansion of invasive alien species (Bax et al., 2003; Medlock et al., 2012).

About one third of interlinkages in the database demonstrate positive impacts between biodiversity and the other nexus elements. This evidence can be classified into five main types: (i) biodiversity-friendly management of the nexus elements, such as through agro-biodiversity or agroecological practices (Dibari et al., 2021; Fischer et al., 2019), sustainable management of bioenergy cropping systems (Tsonkova et al., 2012), integrated management of water landscapes (Eriksson et al., 2018), and management of habitats on road verges and railway embankments (Galantinho et al., 2020); (ii) restoration of ecosystems, such as forests and peatlands for climate mitigation (Eriksson et al., 2018; Pasimeni et al., 2019) and biomass energy production (Sacchelli et al., 2013; Pullens et al., 2018; Voortman et al., 2015), riparian forests for flood control (Cartisano et al., 2013), and remediation of water courses for improving water quality (Comino et al., 2020); (iii) protection of species and ecosystems for providing ecosystem services such as water filtration (Dolmer and Frandsen, 2002) and water retention (Voortman et al., 2015); (iv) urban green and blue infrastructure, including nature-based solutions, such as green roofs for improving energy performance in buildings (Pasimeni et al., 2019), greening of transport infrastructure for pollution control through promotion of active transport (walking, cycling) (Hunter et al., 2021), and the creation of urban green space for health benefits (Khreis et al., 2016); and (v) dietary change involving lower meat consumption to reduce livestock for climate mitigation (Westhoek et al., 2014). The studies that evidence positive interlinkages to and from biodiversity, although fewer in number, provide valuable information on how the nexus approach can

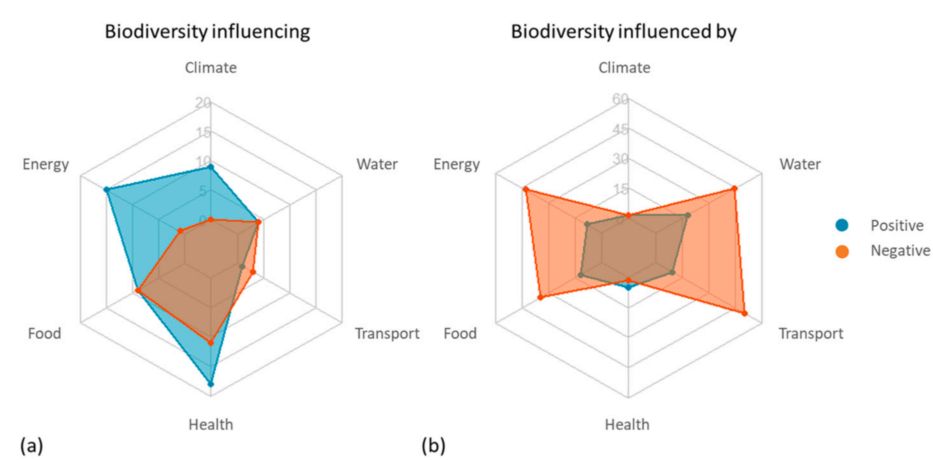

Fig. 8. Number of studies demonstrating positive or negative interlinkages of (a) the influence of biodiversity on the other nexus elements and (b) the influence of the other nexus elements on biodiversity.

support the development of coherent biodiversity policies across sectors for realising multiple co-benefits.

Interpretations of these dominant trends in interlinkages should consider that the study was limited to evidence sourced from 194 scientific peer-reviewed articles written in English for practical reasons. Hence, it does not capture knowledge from other regional and local languages, or include a systematic review on Indigenous knowledge, which can provide diverse framings and unique insights on the biodiversity nexus (IPBES, 2021). In addition, there was considerably more literature on terrestrial and freshwater than the marine realm (Zhu et al., 2021). Further, to help attain sufficient literature for each of the ten three-way interlinkages, biodiversity was defined broadly, but in line with the IPBES glossary (Díaz et al., 2015) as "...living organisms from all sources including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part". Thus, some studies discuss specific species or habitats, whilst others discuss the role of nature, natural areas, or green infrastructure more generally. In addition, information in some articles were ambiguous and required interpretation by the reviewers. Finally, the direction and magnitude of nexus interlinkages are often context-dependent and thus can vary depending on the ecosystem type, spatial and temporal scale, geographical location, and study method (Gasparatos et al., 2017; Linney et al., 2020). Therefore, caution is required when interpreting and applying findings in different contexts.

Despite these limitations and uncertainties, we believe the broad findings of the review are robust and clearly demonstrate the importance of biodiversity in underpinning resilient ecosystems and human well-being in ensuring a sustainable future for people and the planet. The review database consolidates and extends the nascent and fragmented evidence base on the role of biodiversity in complex, higher-order (i.e., three-way and beyond) nexus studies. This is particularly important for supporting the growing number of policies that are embracing a nexus (or systems) approach, such as the European Green Deal, which require a better understanding of the cascading and compounding impacts of multi-order nexus interlinkages to prevent trade-offs and maximise synergies across sectors (Arneth et al., 2023; European Environment Agency., 2022; Habibullah et al., 2022). This includes evidence on how conservation and restoration of biodiversity can contribute to the goals and targets of policies across sectors by delivering nexus-wide benefits (Paleari, 2024).

Identifying appropriate holistic interventions and actions for specific contexts may require evidence from nexus studies to be filtered and analysed in more detail with local practitioners and experts to inform the design, planning and implementation of decision processes (Sutherland et al., 2004; Walsh et al., 2015). Further research is also needed on quantifying positive interlinkages between biodiversity and other nexus elements to inform future decisions on conservation and sustainable development (Clark et al., 2014; Rook, 2013; Sandifer et al., 2015). This is particularly critical given the current dominance in the literature on negative interlinkages among biodiversity and other nexus elements, reflecting past and current trends. Integrative and systemic approaches are needed to address the underlying causes of biodiversity loss as represented in these negative nexus interlinkages. Furthermore, reviews such as this one can be replicated in other world regions to better understand regional, environmental, economic and socio-political similarities and differences in the evidence base on the biodiversity-nexus for informing decision processes. Evidence from comprehensive nexus studies highlights the urgent need for policy coherence across sectors to foster synergistic interlinkages across nexus elements. Such evidence is critical in moving towards sustainable futures where "*biodiversity is valued, conserved, restored and wisely used while sustaining a healthy planet and delivering benefits essential for all people*", in line with the 2050 Vision of the Convention for Biological Diversity.

CRediT authorship contribution statement

HyeJin Kim: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Anita Lazurko:** Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **George Linney:** Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Lindsay Maskell:** Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Elizabeth Díaz-General:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Romana Jungwirth Březovská:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Hans Keune:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Chrysi Laspidou:** Data curation, Formal Analysis, Methodology, Visualization, Writing – review & editing. **Henna Malinen:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Soile Oinonen:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Joanna Raymond:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Mark Rounsevell:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Simeon Vaňo:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Marina Demaria Venâncio:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Alejandrina Viesca-Ramirez:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Ayesha Wijesekera:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Katie Wilson:** Data curation, Formal Analysis, Investigation, Methodology, Writing – review & editing. **Konstantinos Ziliaskopoulos:** Data curation, Formal Analysis, Methodology, Visualization, Writing – review & editing. **Paula A. Harrison:** Conceptualization, Formal Analysis, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This work is supported by the EU Horizon Europe BIONEXT project No. 101059662, which is co-funded by UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee 10039588. We thank Claire Brown and Zuzana Harmáčková for their input to the set-up of this review and two annonymous reviewers for their time and comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171692.

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