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

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## Abstract

Biodiversity holds the fabric of life on earth and underpins the functioning of ecosystems and diverse benefits nature provides to people. As the earth is a complex social-ecological system with dynamic interactions across air, water, food, infrastructure, humans health, among others, it is of a paramount importance that the role of biodiversity is understood well for sustainable planetary and human wellbeing. For this, we conducted a literature review on the interactions within the biodiversity nexus by identifying and analysing literature that addresses three-way interlinkages between biodiversity and two other nexus elements from climate, food, energy, water, transport, and health. We posed two research questions: How is biodiversity being influenced by and is influencing climate, food, water, energy, transport and health? We identified 194 peer reviewed articles and used bi-directional impact information to understand the interactions on ten three-way nexus interlinkages and analyzed the complexity of these interactions across the seven nexus elements using pathway analyses. Our results show that while more studies have been conducted on negative impacts of nexus elements on biodiversity, biodiversity has more positive than negative impacts on other nexus elements. Further, while a broad range of evidence exist on how biodiversity impacts other nexus elements, the evidence on biodiversity nexus interlinkages is fragmented as biodiversity has only recently been considered in nexus studies. This paper provides a methodological approach towards identifying, reviewing and analyzing the critical knowledge necessary to preventing adverse effect on and to implement effective strategies for biodiversity conservation, climate change, and human wellbeing.

## 1. Introduction

Biodiversity plays a crucial role in the achievement of a wide range of sustainability outcomes related to food and water security, health and wellbeing, and climate change mitigation and adaptation (Moreno Vargas et al., 2023; Ortiz et al., 2021; Sietz & Neudert, 2022; Stoy et al., 2018). The recent IPBES Global Assessment (2019), Biodiversity and Pandemic report (2020), and Biodiversity and Climate report (2021) point to the complex and critical interactions between biodiversity and other sectors, biodiversity and health, and biodiversity and climate respectively (IPBES, 2019, 2020; Pörtner et al., 2021). This led to the recognition by the 145 government members of IPBES to assess the nexus interlinkage across biodiversity, climate, food, water and health. Further, biodiversity, ranging from organismal levels from genes to species and ecosystems, contribute directly or indirectly to the achievement of all 17 sustainable development goals (SDGs), which covers a broad range of ecological and societal wellbeing ambitions set to be achieved by 2030 (Blicharska et al., 2019).

The importance of understanding cross-sectoral interlinkages have been acknowledged and studied from a nexus perspective in a wide range of studies in the past decades (Estoque, 2023). Many of these studies have focused on the water-energy-food nexus (Bian & Liu, 2021; Carvalho et al., 2022; Lucca et al., 2023), with the role of biodiversity and its interlinkages to other sectors (i.e., the biodiversity nexus) only gaining more traction recently (Cristiano et al., 2021; Moreno Vargas et al., 2023; Stoy et al., 2018; Subedi et al., 2020), in addition to links to climate change and land use (Adeola et al., 2022; Jaroenkietkajorn & Gheewala, 2021; Laspidou et al., 2019) and to health (Hirwa et al., 2021). These nexus studies have reviewed evidence from studies that use a diverse range of frameworks, approaches, and methods with focus on different regions and scales and on specific topics or ecosystems. Yet, each has limitations: for example, a review of land-biodiversity-food-climate nexus interlinkages highlights regional knowledge gaps, inadequately captured social dimensions of the nexus, and general methodological shortcomings (Sietz & Neudert, 2022, p. 202). The studies and reviews to date also tended to focus on the negative climate impact on other sectors (Adeola et al., 2022; Ioannou & Laspidou, 2022) or negative sectoral impact on biodiversity (Green et al., 2019; Sonter et al., 2020) with research gap on the positive impact of biodiversity cross-sectorally using the nexus approach.

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). Moreover, stakeholders are increasingly interested in how nexus approaches can support sustainability transitions (Lucca et al., 2023) and enhance policy coherence to collectively achieve global goals such as the SDGs (Liu et al., 2020), the Kunming-Montreal Global Biodiversity Framework (Wanger et al., 2020) and the Paris Agreement (Gomez-Echeverri, 2018). Biodiversity is central to the Kunming-Montreal Global Biodiversity Framework and underpins many other global and regional policy frameworks, such as the SDGs (Blicharska et al., 2019) and European Green Deal (European Commission DG Environment, 2021). Nexus toolboxes 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., 2021; Pascual et al., 2022).

Given the significant interactions between biodiversity loss and climate change, integrative and latest evidence will be key to identifying the interventions that can prevent future risks and adverse effects and maximize synergies across sectors that can contribute to both biodiversity conservation and climate mitigation. For example, nature-based solutions like afforestation are considered to have multiple benefits including carbon sequestration, but the expansion of monoculture afforestation can have adverse effects on biodiversity (Seddon et al., 2021). Identifying synergistic solutions that minimize such trade-offs and maximize co-benefits can be identified through reviewing the evidence from science and practice. For example, agroforestry that integrates tree planting as well as shrubs and hedges in farming systems enhances farm productivity, increases wildlife, improves soil health, boost livestock welfare, manage water flow, and mitigate climate change (Mbow et al., 2014). Optimizing the use of such evidence would help halt and reverse biodiversity loss, mitigate and adapt to climate change, and achieve sustainable outcomes overall, which in turn, improves human wellbeing (Baldwin-Cantello et al., 2023). To date, the evidence on biodiversity nexus interlinkages is fragmented as biodiversity has not been previously included in a comprehensive way in nexus studies that include climate change, health, and transport as well as the usual water-energy-food nexus elements.

Amid growing attention to the nexus approach in research and policy frameworks, there is a need for new evidence regarding the interlinkages of the biodiversity nexus, i.e., the role biodiversity plays in nexus interactions across food, water, energy, transport, and health, in addition to the role of climate change as a broad context that is influencing and influenced by the biodiversity nexus. Thus, this review aims to synthesize evidence on the current state of interlinkages between biodiversity and six other sectors (energy, food, health, transport, water, and climate change, referred to as nexus elements) in Europe. The review asks: how is biodiversity influencing, and influenced by, water, food, health, energy, and transport, in the context of climate change? The review considers multiple directions and types of influences – influencing and influenced, positive and negative. The review also moves beyond bi-directional interlinkages (i.e., impacts between two nexus elements) to consider the complex interactions across three or more nexus elements, as these higher-order interlinkages reveal more extensive network dynamics across elements and systemic tendencies within the biodiversity nexus as a complex system.

## 2. Methods

### 2.1 The literature review database

A literature review was conducted to respond to the research question by identifying and analysing literature that considers three-way interlinkages between biodiversity and two other nexus elements. This included ten combinations of three-way nexus interlinkages with biodiversity: Biodiversity-Food-Health, Biodiversity-Food-Water, Biodiversity-Health-Water, Biodiversity-Energy-Food, Biodiversity-Energy-Health, Biodiversity-Energy-Water, Biodiversity-Energy-Transport, Biodiversity-Food-Transport, Biodiversity-Health-Transport, and Biodiversity-Water-Transport. 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, water, food, health, energy, transport and climate change) 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., Europe) to derive a set of search strings (see Supplementary Material I). 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 included in many of the articles identified. This was found to be the case with climate change being part of about half (49%) of the 200 studies included in the review.

Twenty articles were reviewed for each of the nexus interlinkages, with the exception of 22 articles for Biodiversity-Health-Water and 18 articles for Biodiversity-Transport-Water. The former was due to over-submission and the latter due to lack of literature. The final database contains a total of 200 reviews, of which the analysis is based on 194 articles. Six articles were found to be relevant to two of the three-way nexus interlinkages and hence are counted twice in the total (see SM I Figure S1 and Table S3 for details on the literature count).

Each article was reviewed according to a common template. An annotated Causal Loop Diagram was drawn to provide an overview of all nexus interlinkages covered in the study, including and beyond the three-way interlinkage (i.e., biodiversity + two other nexus elements) that was the target of the search. In addition, the following information was captured 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 beyond food, water, health, energy, transport and climate (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, 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 SDGs, biodiversity, Paris agreement, and others, and 16) strength of evidence (scale of 1 to 5). Notes 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 are described in the Supplementary Material I and the review questionnaire is found in Supplementary Material II.

This review conducted an additional literature search with indigenous search terms to identify articles that incorporate indigenous knowledge. However, the Web of Science alone found very few articles that met the criteria and therefore, we conducted a further search of literature through other sources such as Google Scholar, UNESCO and IPBES, through which six peer reviewed and grey literature were identified.

## 2.2 Analysing the literature database

### 2.2.1 Three-way interlinkages

The ten three-way nexus interlinkages were investigated by plotting the information from the approximately 20 articles as triangles, with biodiversity and two nexus elements at each vertex. The triangle shows the influences of biodiversity on the other two nexus elements as well as their influence on biodiversity. The magnitude of bi-directional interlinkages 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 indicates 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).

### 2.2.2. Synthetic network pathways

The evidence from all the articles together was used to create synthetic higher-order nexus pathways (i.e., beyond three-way interlinkages). Using the information on bidirectional linkage (direction, magnitude of impact), we identified all possible pathways between biodiversity and the six nexus elements and the six nexus elements and biodiversity. The pathways were created either using only positive bidirectional interlinkages or negative bidirectional interlinkages. This gave the four path groups: positive from biodiversity, negative from biodiversity, positive to biodiversity and negative to biodiversity. Each path group consisted of six start and end element combinations. For example, the pathway group positive from biodiversity consists of the following six start and end element combinations: Biodiversity to Climate, Biodiversity to Energy, Biodiversity to Food, Biodiversity to Health, Biodiversity to transport, Biodiversity to Water. Pathways were identified using the "all_simple_paths()" function in the "igraph" package (Csardi and Nepusz, 2006) in R (Version: R Core Team, 2022). Impact was generated by calculating the means of the bidirectional magnitudes that make up each pathway that goes from biodiversity to the nexus element and then summing these means.

## 3. Results

### 3.1 Descriptive statistics

The majority of studies were at a sub-national scale (between local and national; 28%) with national (22%) and global (22%) scales being the next most frequent. 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 Europe were covered in the review with Germany, UK, Europe and Italy with the most coverage (over 6%). Only five countries in Eastern Europe and Central Asia had no coverage of studies: Armenia, Azerbaijan, Kazakhstan, Kosovo and Moldova (Figure 1).

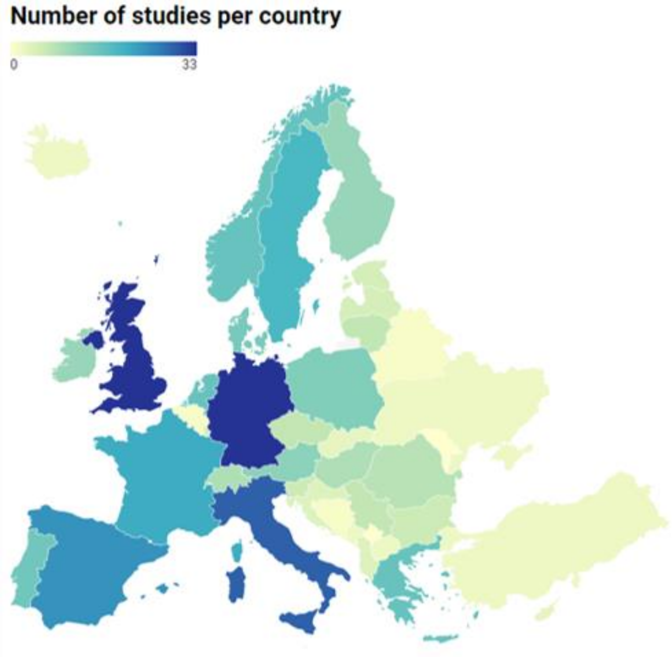

**Figure 1**. Number of studies included in this review per country.

Information on biodiversity was captured in terms of species and ecosystem type (Table 1). 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 obviously a broad category to describe many different taxa. 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 the sample (<7%).

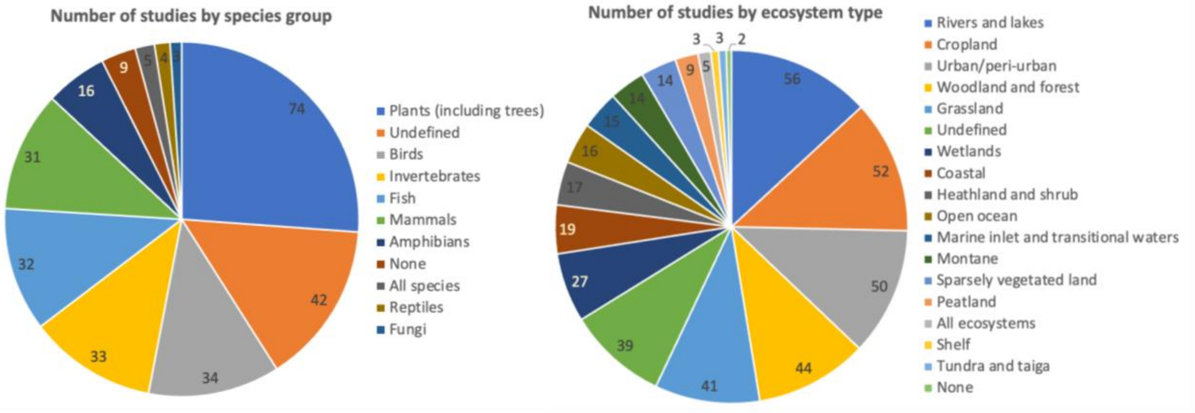

**Figure 2.** Number of studies by species group and ecosystem type

The estimated timeframe of impacts in the nexus studies tended to be short term (1-5 years 47%, < 1 year 27%) with studies using longer time frames ranging from 6 to greater than 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 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. The Paris Agreement was mentioned in 15% of the studies while 10% mentioned the SDGs and 8% biodiversity goals. In terms of strength of evidence[1], 42% of the studies were rated as very strong, 9% strong, 38% reasonably supported, 11% weak and 0.5% very weak evidence; noting that studies with weak and very weak evidence were avoided where better evidence was available as part of the review design.

### 3.2 Bidirectional impact score

Bi-directional impacts between nexus elements are shown in Figure 3. The positive bidirectional linkages with the highest numbers of studies were between water influencing biodiversity, energy influencing climate, biodiversity influencing energy, and biodiversity influencing health. The mean magnitude of these links was 3-4, i.e., between moderate and substantial, although magnitude could range from 1- 5 within each category.

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[1] Definition of evidence strength: **Very strong evidence** based on well-design empirical research and on synthesis (e.g., systematic review, meta-analysis); agrees with stakeholder knowledge or findings of other studies; **Strong evidence** based on multiple observations, well-designed experiments, modelling, indicator analysis or systematic literature review; with hypothesis and conclusion of the paper, well supported by stakeholder knowledge or findings of other studies; **Reasonably supported evidence** based on observations, experiment, modelling, indicator analysis or literature review, supported by stakeholder knowledge or findings of other studies; **Weak evidence** based on single observation, experiment, modelling, limited stakeholder engagement, indicator analysis or literature review, not as rigorously supported by findings of other studies; **Very weak evidence** based on author's expert or stakeholder opinion only, with no further corroboration by other citations in the discussion.

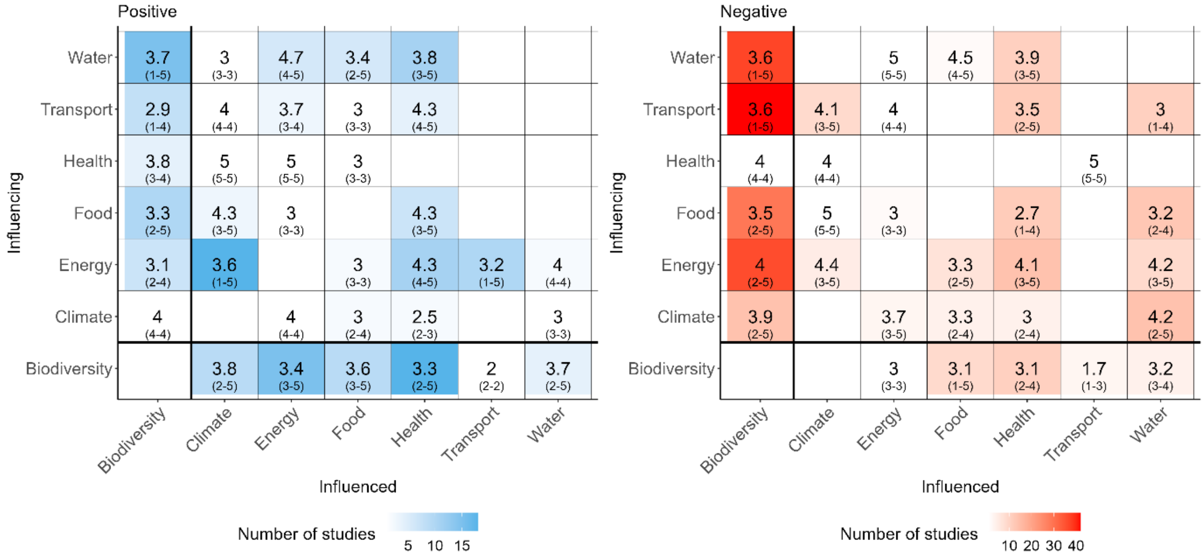


**Figure 3. Heatmaps of positive (left) and negative (right) impact scores between seven nexus elements where the** nexus element in the row direction is influencing the nexus element in the column. The colour indicates the number of studies evidencing each linkage, ranging from 1 to 37. The large number refers to the mean magnitude of the linkage and the range of magnitudes of the studies is shown in brackets.

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); and biodiversity positively influencing health in terms of forest walks promoting cardiovascular relaxation compared to walks in urban environments (Zorić et al., 2022a); and natural ecosystems absorbing atmospheric pollutants, which improves air quality and benefits health (Barrios-Crespo et al., 2021).

Negative bidirectional linkages were found for water influencing biodiversity (which also had a high numbers of positive links), and transport, food, and energy all influencing biodiversity. The mean magnitude of these links was 3-4, i.e., between moderate and substantial, although magnitude could range from 1- 5 within each category. Demonstrative examples of these interlinkages include poor water quality due to energy-producing peat extraction negatively influencing biodiversity (Juutinen et al., 2020); acidification of fresh water resulting in loss of fish populations (Wright et al., 2017); ballast water for shipping transport negatively impacting biodiversity through the release of non-native species (Barrios-Crespo et al., 2021); negative impact of roads on mortality, movement, and genetic diversity (Johansson et al., 2005; Mayer et al., 2023); negative impacts of food crops on ecosystem quality (Todorović et al., 2018) and and habitat loss (Eiter & Potthoff, 2007); peat extraction for energy reducing habitat quality (Juutinen et al., 2020); and dam construction for hydropower generation causing loss of biodiversity (Donadi et al., 2021; Göthe et al., 2019; Yoshida et al., 2020).

Other positive and negative bidirectional linkages were found with a high magnitude of impact, but a low number of studies that might indicate important interlinkages with the potential to have strong impacts but requiring further research.

### 3.3 Three-way nexus interlinkage

The analysis of three-way interlinkages offers insight into more complex interactions within the biodiversity nexus. Results for Biodiversity-Energy-Water (BEF) and Biodiversity-Health-Transport

(BHT) are shown in Figures 4 and 5, respectively. Results for the other eight three-way interlinkages are provided in the Supplementary Material III. Looking across all ten sets of three-way interlinkages, the evidence in our review shows that biodiversity receives generally positive influences from the other two nexus elements within the BWT, BWF, and BTF triplets. In contrast, biodiversity receives negative influences within the BWT, BWH, BTE, BTH, BFE, and BWE triplets. Biodiversity plays a more active role in other interlinkages, exerting negative influences within the BHE and BFH triplets and exerting positive influences in the BWH, BTE, BTH, and BWE triplets.

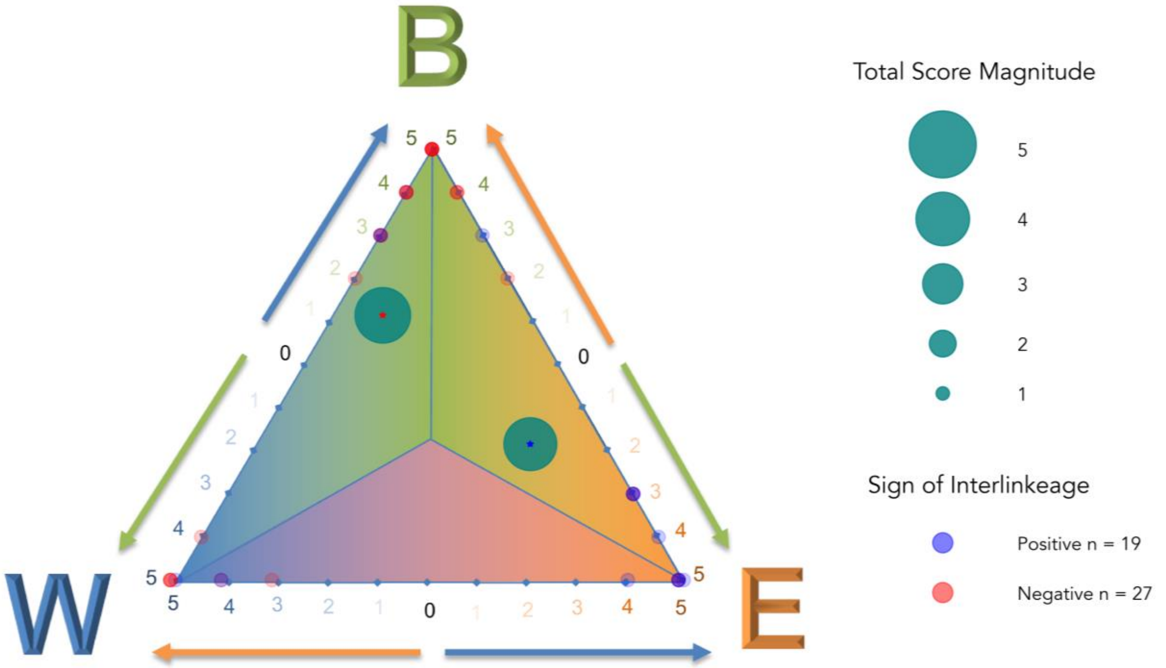


**Figure 4.** Three-way interlinkage between biodiversity (B), energy (E) and water (W). Each corner of the triangle represents a nexus element and the edges of the triangle represent the degree to which one nexus element is influencing or influenced by another nexus element on a scale of 0 to 5. The locations of the centroids in the triangular space indicate stronger receiving influences (i.e., the closer it is to one of the corners, the more this element is influenced by the other elements). The positive (purple) and negative (red) influences are reported separately as two different centroids. 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 bottom right of each diagram (i.e., n=X).

Energy impacts biodiversity positively with the growth of variable tree species, thereby creating a strong forest bioenergy potential (Cartisano et al., 2013). Forest residue, or other forms of woody above ground biomass can be used as an energy source (Cartisano et al., 2013), with district heating being such an example (Sacchelli et al., 2013). Also, water impacts the carbon balance of peatlands that are important energy sources (Pullens et al., 2018). In dry dune ecosystems, moss vegetation can play a role in increasing groundwater recharge due to energy requirements and emitted radiation that plays a role in evapotranspiration dynamics (Voortman et al., 2015). Water is shown to affect biodiversity positively with higher water availability yielding higher bioenergy plants and forest and riparian vegetation (Cartisano et al., 2013; Franzaring et al., 2015) and higher water quality and chemistry improving the vegetation and biodiversity (Eriksson et al., 2018; Irabien & Darton, 2016) and the ecological status of rivers with benefits for local ecosystems (Comino et al., 2020). Water and energy have positive reinforcing impacts on each other with water directly contributing to forest bioenergy generation (Comino et al., 2020; Eriksson et al., 2018; Franzaring et al., 2015) and hydropower plants as a renewable energy source (Comino et al., 2020; Dopico et al., 2022).

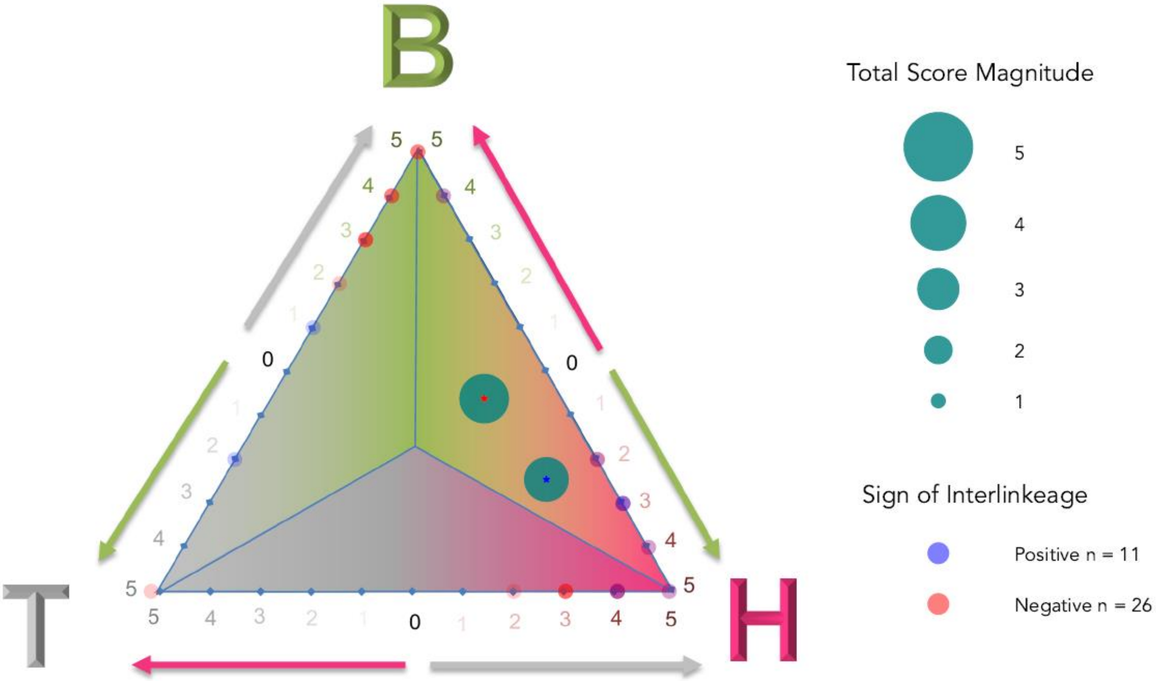


**Figure 5.** Three-way interlinkage between biodiversity (B), health (H) and transport (T). See caption of figure X for an explanation of the structure of the figure.

The Biodiversity-Health-Transport (BHT) nexus interlinkage depicted in Figure 5 offers a contrasting example. The location and size of the negative centroid (red) shows how transport has a negative influencing role on biodiversity and health. Conversely, the location and size of the positive centroid (purple) shows that transport also has a strong positive influence on biodiversity and health.

Transport negatively influences biodiversity through species killed by vehicles (Seddon et al., 2021) and habitat loss and degradation from transport infrastructure (Di Giulio et al., 2009; Hunter et al., 2019; Khreis et al., 2016; Puodziukas et al., 2016). 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; 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 (e.g. mosquitoes) causing zoonotic diseases that negatively influence health and biodiversity. Control measures may also damage non-target species. Biodiversity, through wildlife and provision of habitat, enables the reproduction and spread of vectors, invasive species and pathogens that can impact directly on human health or indirectly through damage 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, green infrastructure can enhance local biodiversity (Buekers et al., 2014; Hunter et al., 2019), mitigate air and noise pollution (Toffolo et al., 2021) and positively influence mental and physical health (Hunter et al., 2019; Khreis et al., 2016; Zijlema et al., 2018; Zorić et al., 2022b). 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'. Although usually the interlinkage between transport and biodiversity is negative the pause in transport reduced wildlife vehicle collisions showing a positive relationship with biodiversity (Raymond et al., 2023). There are mixed effects of transport on health because battery powered electric vehicles can cause pollution and human health issues (cobalt mining, respiratory hazards of Li ion battery particles), yet there are improvements in human health in urban environments (Buekers et al., 2014; Dall-Orsoletta et al., 2022). There are then mixed relationships with climate because although electric vehicles have the potential to positively influence climate this is dependent on electricity production methods and greenhouse gas emissions throughout the whole lifecycle may not be less than the fossil fuel counterpart. This study also suggested disparity in impact geographically by, for example, global south vs north (Dall-Orsoletta et al., 2022).

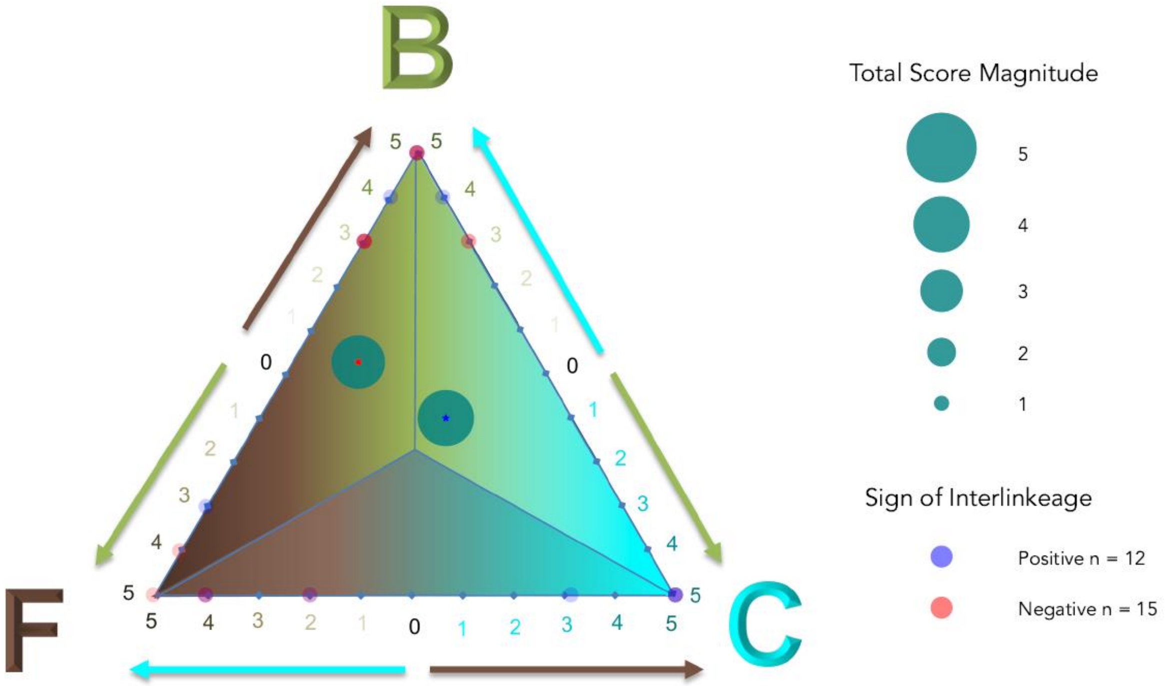


**Figure 6.** Interlinkages between biodiversity (B), climate(C), food (F). See caption of figure X for an explanation of the structure of the figure.

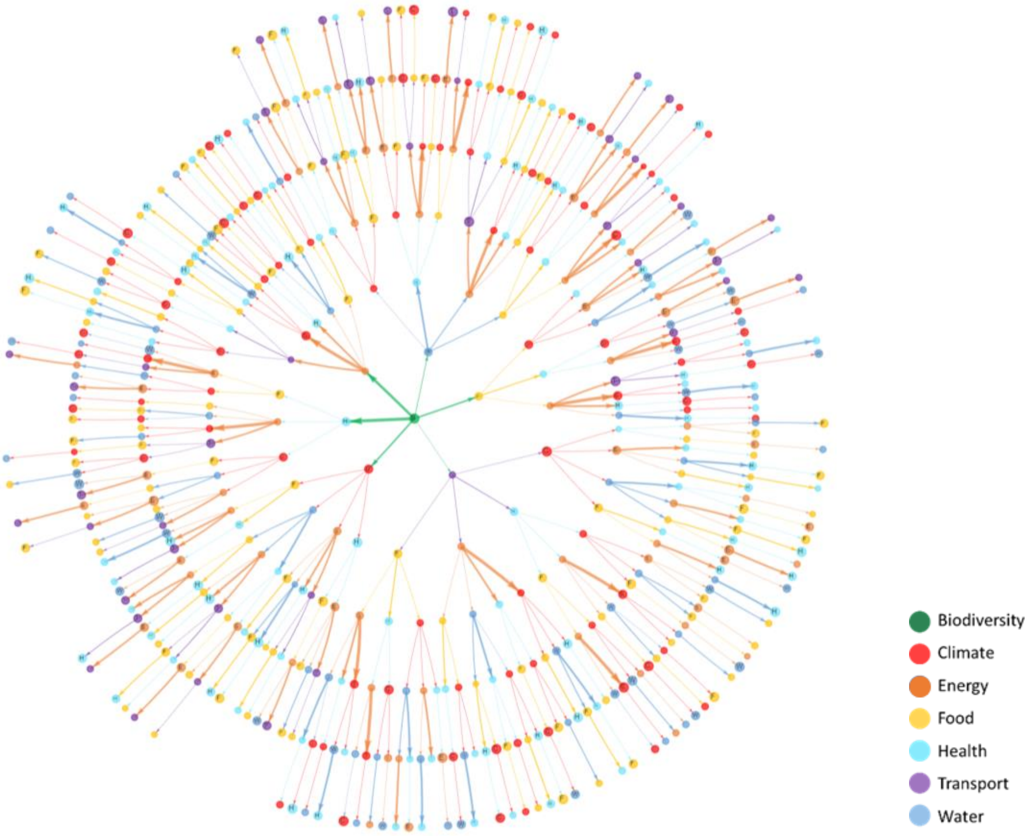
Five additional triangle diagrams were created including climate change as a node in three-way interlinkages with biodiversity and one other nexus element. Figure 6 shows an example of this analysis for the Biodiversity-Climate-Food (BCF) triplet. Results for the other four triplets are provided in Supplementary Material IV. The location and size of the negative centroid show that climate change has a strong negative influencing role in this three-way-interlinkage. For example, fossil fuel burning releases atmospheric nitrites that negatively impact species (e.g., butterflies), and wood fuel leads to deforestation that contributes to biodiversity loss (Wagner, 2020). Climate change impacts like aridification can negatively impact amphibian and reptile reproductive sites and habitats, which reduces food availability for other trophic levels in the food web (Crnobrnja-Isailović et al., 2021). Climate change can exacerbate other negative influences on biodiversity within the food system, 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 also influences habitat condition directly, with ripple effects to the food system. For example, higher temperatures and relative humidity can improve the growing conditions of mycotoxin producing fungi, which can infect food crops and livestock, thereby reducing agricultural and livestock productivity (Milićević et al., 2016). Similarly, more frequent and severe flood events 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). Climate change can also directly impact food production, reducing food production in regions like southern Europe (Harrison et al., 2015), such as by increasing water demand in ways that make the rainfed cultivation of olive crops no longer economically feasible (Fotia et al., 2021).

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 influences climate change as forest restoration and other biodiversity conservation measures contribute to carbon storage and climate mitigation (Eriksson et al., 2018; Schulze, 2006). The food system can 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 like shrubs (Giubilato et al., 2016). Similarly, conversion from monocropping to alley cropping systems increases plant diversity (Tsonkova et al., 2012). 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).

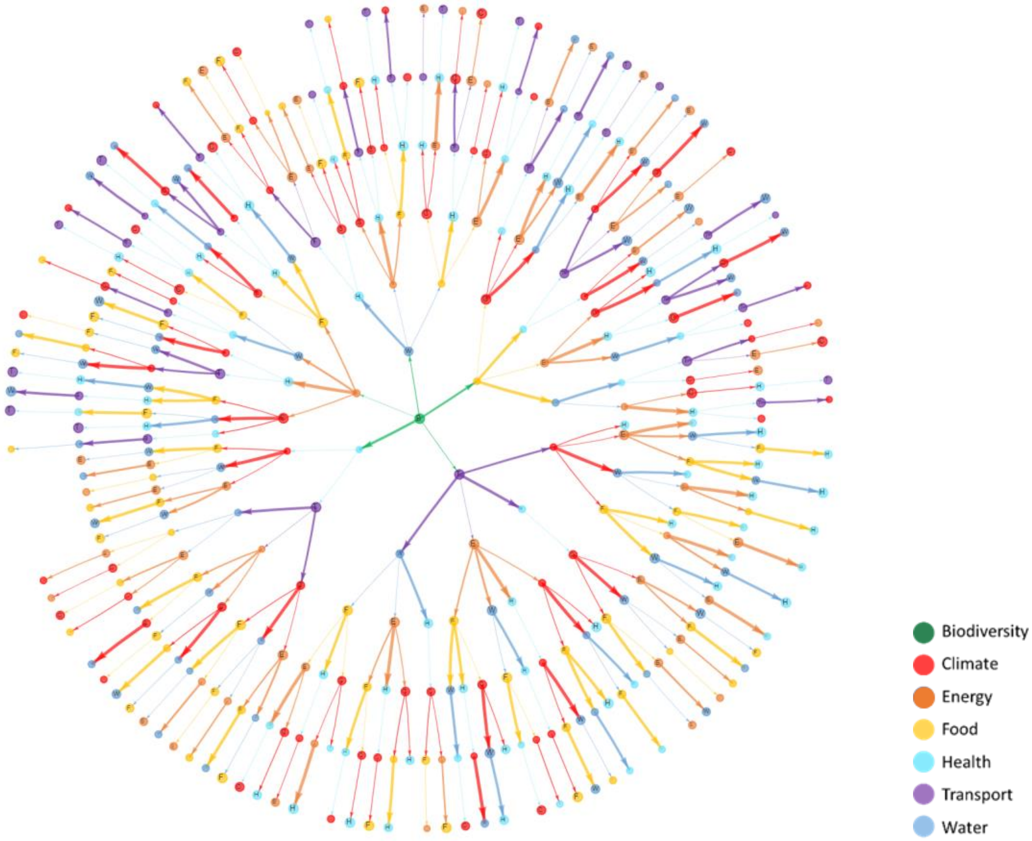
Further, based on Indigenous Knowledge and perspectives from the peer reviewed and grey literature sources, we find that indigenous food systems were often intimately linked to biodiversity and climatic conditions. This means that changes in these nexus elements can disproportionately impact Indigenous 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). Further, articles identified were on reindeer herding and wild food harvesting. Reindeer herding is an important livelihood activity and a food source for the Sámi. 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 (Jaakkola et al., 2018; Ocobock et al., 2023). The decrease in lichen availability is associated with reduced reindeer meat production, nutritional quality and changes in traditional herding practices (Jaakkola et al., 2018; Ocobock et al., 2023). Both the Sámi and Greenlandic Inuit rely on wild food sources. This includes wild plants, game and fish (Bjerregaard et al., 2021; Nilsson, 2018). For these groups, declines in biodiversity can negatively affect food security and health, since many of these food sources are key sources of vitamins and minerals. Furthermore, the reliance on wild fish increases the vulnerability of these communities to the negative impacts of environmental pollutants on their health and food security fish (Bjerregaard et al., 2021; Nilsson, 2018).

### 3.4 Synthetic network pathways

Network diagrams showing the full complexity of the interlinkages represented in our review database are show in Figure 7 for all pathways by 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. Figure 6 shows that there are 526 possible positive paths and 388 possible negative paths by which biodiversity can influence the six nexus elements. These synthetic network pathways demonstrate the great complexity in influence that biodiversity has on the rest of the nexus.



(a) Positive pathways

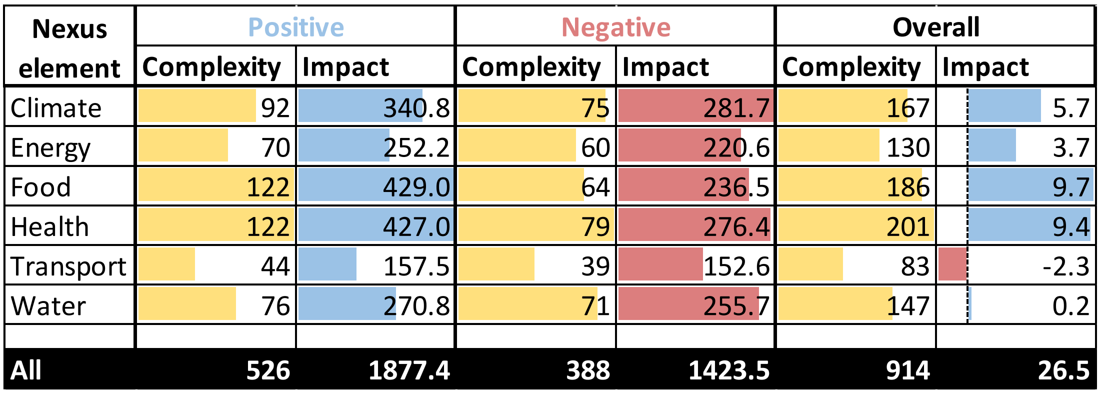


(b) Negative pathways

**Figure 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. The nexus elements shown are Biodiversity (green), Climate change (red), Energy (orange), Food (yellow), Health (sky blue), Transport (purple) and Water (light blue).

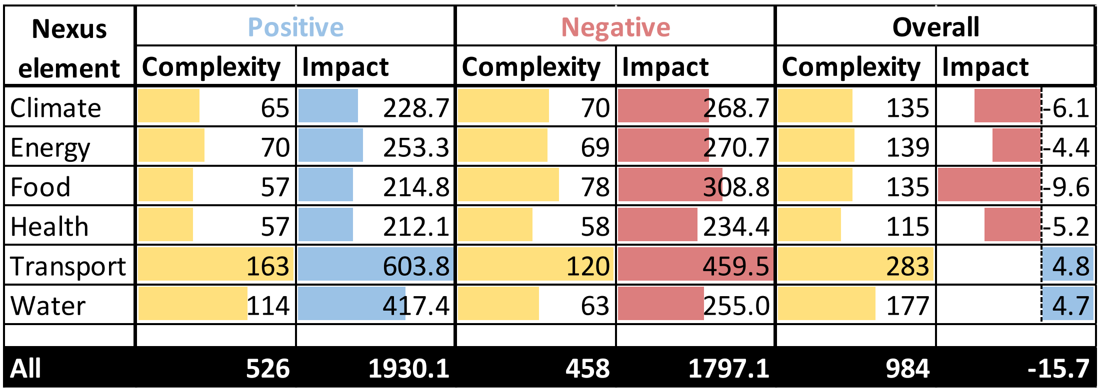
The complexity and magnitude of the influence of biodiversity on the six nexus elements (as visualised in Figure 6) is summarized in Table 2.

(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** |

**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 bidirectional 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.

The high complexities displayed in Table 2 shows the central role 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 nexus elements on biodiversity than from biodiversity to other nexus elements (458 vs 388). Furthermore, biodiversity is shown to have a higher overall positive than negative impact on nexus elements (1877 vs 1424).

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 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 biodiversity has positive impacts on food systems such as the importance of conserving wild food plants (Quave & Pieroni, 2015), wild game (Flis, 2012) and landraces (Scartazza et al., 2020) to ensure long-term food security. Negative influences by biodiversity are more even (but lower impact) across climate, health, water, food and energy with transport again being the least impacted. For example, nature related health risks such as infectious diseases and allergies (Johnson et al., 2015; Ostfeld, 2017).

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. Negative impacts of transport on biodiversity include roadkill, fragmentation of habitat and habitat loss (Hunter et al., 2019; Khreis et al., 2016; Quave & Pieroni, 2015) 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 consists of ‘active’ transport such as cycling and walking (Hunter et al., 2019; Khreis et al., 2016; Zijlema et al., 2018). After transport, food also has quite a large negative impact on biodiversity, whilst water has quite a large positive impact. Land clearance for food and intensive agriculture can cause drastic biodiversity loss, whereas streams act as humid dispersal corridors (Haugen et al., 2020) and the hydroperiod was one of the most important drivers of species richness (Couto et al., 2017).

## 4. Discussion

### 4.1 Wider implications for research and practice

This review builds the evidence on the “biodiversity nexus” focusing on the role of biodiversity plays in complex interlinkages with food, water, energy, transport, health and climate. We find that biodiversity plays different roles in the nexus in relation to different nexus elements, in some cases receiving significant negative influences from sectors like transport (Di Giulio et al., 2009; Hunter et al., 2019; Khreis et al., 2016; Puodziukas et al., 2016; Seddon et al., 2021) and energy (Bakanos & Katsifarakis, 2019; Donadi et al., 2021; Glemnitz et al., 2015) and in other cases positively influencing sectors like health (Linard et al., 2009; Quave & Pieroni, 2015; Scartazza et al., 2020). These interactions become even more complex when considering three-way and higher-order interlinkages: for example, there are also many different combinations and sequences of pathways through which biodiversity can influence and be influenced by the other six nexus elements with different directions and significance of impacts. These findings together offer a roadmap to navigate the complexities of the biodiversity nexus and point toward important areas for future research. More research is needed on the positive impact biodiversity has across nexus elements as more studies to date have looked at the negative impact of these nexus elements on biodiversity.

Using the knowledge and evidence will be key to addressing biodiversity nexus issues and this review reveals that rich information exists in the literature and practice. It will be critical that this information is made available for use in decision processes. This review included studies that are specific to certain ecosystems, regions, climate regime, or societal system and therefore, requires caution when interpreting and applying findings in different contexts. For this reason, designing and conducting nexus studies that are relevant for each region, system, question or issue at stake will be essential in assessing the complex dynamics of impact relations accurately and in identifying interventions that can mitigate risks on biodiversity, climate and other sectors for that particular context.

We also lack understanding on how specific interventions for biodiversity conservation or climate mitigation contribute to other nexus elements. Further, our analysis focused on interactions between nexus elements, supported by specific examples, but further analysing interactions between specific indicators within each element would offer insights relevant for implementation in policy and practice.

### 4.2 Literature gap and limitations

This review revealed that while many studies at the European level look at nexus issues in its complex dynamics, some focus on bidirectional linkages independently of each other or without specific links to biodiversity. Also, positive and negative bidirectional linkages were found with a high magnitude of impact, but with a low number of studies. Further research is needed to investigate whether these bidirectional linkages have strong impacts.

Very limited studies analysed consider more than three or four nexus elements in their analysis and many of them do not have a specific nexus approach or systems thinking. Involving seven elements in this review as an overall analysis added more complexity to the nature of the three-way interlinkages. Further, most studies do not mention or make explicit links to policy frameworks or goals, potentially reducing the usability of information for decision-making processes. Participation of stakeholders is rarely considered despite the importance of co-created analyses and decisions. Transport was found to be under-studied in this review while health was defined or scoped in a very broadly defined way (including both human and environmental health), making the interpretation of results difficult. Nevertheless, the One Health orientation given in the analyses allowed to identify clear positive and negative impacts on this element.

Like Health, the definition of biodiversity was very variable within the evidence. Definitions included individual species- presence and abundance, both positive and adverse (e.g. invasive species, disease vectors), biodiversity metrics, the extent and condition of habitat, ecosystem integrity and resilience, pollution, processes or functions and cultural aspects such as wild food, recreation. Whilst many of the studies are based on precise definitions of species and habitats, others use generalised definitions such as green infrastructure, nature or habitat area which makes it more difficult to understand the mechanisms operating and to implement findings. This may particularly be the case when work is interdisciplinary e.g. research on the positive benefit of biodiversity on health does not always deconstruct the quality of the habitat although this research is advancing rapidly. Understanding and identifying the aspects of biodiversity that form positive or negative interlinkages is critical to progress nexus research (Clark et al., 2014; Rook, 2013; Sandifer et al., 2015).

### 4.3 Integration of indigenous knowledge

Many Indigenous Peoples hold detailed knowledge of the environment with which they interact, which has been passed down through generations given their sustained and close relationships with their lands and natural resources (IPBES, 2021). This knowledge can provide unique insights into the types of interactions between biodiversity and other nexus elements, which can complement western scientific literature to provide a more holistic picture of the biodiversity nexus.

While scientific journal-based literature reviews may not provide a good representation of all the written information available on Indigenous Knowledge (IPBES, 2021), we suggest targeted methods to identify Indigenous Knowledge given the unique perspectives on the biodiversity nexus that Indigenous Peoples and Indigenous Knowledge can provide. This could include: 1) Refining search terms through consultations with Indigenous Knowledge holders, Indigenous Knowledge experts from Indigenous groups in Europe, and experts on Indigenous Knowledge, to identify the most relevant keywords to run additional searches, 2) Carrying out searches for grey literature, such as *inter alia*, technical and community reports, compilations of case studies, essays and policy briefs. These sources can include large amounts of information on Indigenous Peoples and Indigenous Knowledge and should increase the likelihood of capturing materials written by Indigenous Peoples (IPBES, 2021), 3) Developing mechanisms to engage with non-English materials as part of systematic and non-systematic literature reviews. Among other approaches, this could include having multilingual teams, with Indigenous language speakers or speakers of national languages in the countries in which Indigenous groups live (IPBES, 2021), 4) Consulting Indigenous Knowledge holders, Indigenous Knowledge experts and experts on Indigenous Knowledge to help identify the most relevant sources of Indigenous Knowledge which may be less obvious or accessible to non-experts (IPBES, 2021), 5) Conducting dialogues with Indigenous Knowledge holders and Indigenous Knowledge experts to document Indigenous Knowledge which is not recorded in written formats (IPBES, 2021).

## 5. Conclusions

Understanding the role of biodiversity in food production and consumption, water quality and availability, climate regulation and mitigation, human and ecosystem health, energy production and means of transportation provides critical evidence towards improving biodiversity, climate change and human wellbeing. This is particularly important in the context of complex systems dynamics in today's telecoupled world with cross-regional impact and fast-changing cultural practices (e.g. lifestyle, consumption patterns). The first step in assessing these cascading and compounding impact of multi-order nexus interlinkages is collecting, reviewing and synthesizing existing evidence from a wide range of credible knowledge systems that can provide insights to the type and magnitude of impacts. Identifying location- and context-specific interventions requires further scoping and in-depth analyses of the evidence with local practitioners and experts for relevant evidence to inform the design, planning and implementation of decision processes. This review provides a methodological approach towards synthesizing biodiversity nexus issues across food, water, energy, transport and health in climate context. More contextualized analyses on causal and feedback loops across these nexus elements using indicators and proxy measures will give further insights to how the current knowledge systems are assessing these nexus interactions, what they inform us on how adverse effects can be mitigated or prevented, and where the gaps are in research and practice.

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