Chapter **2**

STATUS AND PAST TRENDS OF INTERACTIONS IN THE NEXUS[1]

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Note

The Nexus Assessment chapters share a common thread of case studies highlighting Indigenous Peoples' and local communities' (IPLC) food systems. **Chapters 1** to **4**, **5.1** to **5.5** and **6** include one or more of these case studies. The case studies are presented in boxes and are distinguished by *box titles in italicized font*. Lessons learned from the common case studies are presented in **Chapter 7**, online **Suplementary material 7.1**.

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EXECUTIVE SUMMARY

Biodiversity continues to decline, leading to significant cascading impacts on health, food, water and climate systems, and influencing human well-being and environmental sustainability *(well established)* {2.2, 2.4, 2.5}. The relative abundance of the global wildlife population has declined on average 69 per cent between 1970 and 2018, with a greater decline for Latin America (94 per cent) when compared to other regions of the world. Likewise, freshwater species also show greater overall decline (83 per cent) than terrestrial and marine species *(well established)* {2.3.3}. Biodiverse ecosystems regulate the hydrological cycle, ensuring water supply and purification which is crucial for human consumption, agriculture and maintaining natural habitats. Forests, grasslands, wetlands and mountains play pivotal roles in this process, but their degradation compromises water quality and availability *(well established)* {2.4.1}. In the food system, biodiversity supports the resilience and productivity of agriculture through pollination, pest control and soil health *(well established)* {2.4.1}. However, modern (i.e., conventional) agricultural practices and climate change drive biodiversity loss, leading to reduced nutritional diversity and food security, especially for smallholder farmers who form the backbone of global food production. Monocultures and the over-reliance on a few crop species exacerbate these issues, impacting both human health and ecosystem stability, with diet-related non-communicable diseases a major cause of the global burden of disease *(well established)* {2.4.1}. Biodiversity also directly influences human health through better mental health outcomes, natural products used in traditional and modern medicine and through the regulation of air and water quality *(well established)* {2.4.3}. The loss of biodiversity increases the risk of zoonotic diseases as human activities encroach on natural habitats, disrupting the balance of ecosystems and increasing human exposure to pathogens *(established, but incomplete)* {2.4.3}. Climate change further stresses biodiversity, altering species distributions and ecosystem functions, leading to the extinction of vulnerable species and the spread of invasive species *(well established)* {2.4.4}. This creates feedback loops that exacerbate climate impacts, highlighting the critical need for biodiversity conservation to sustain nature's contributions to people and mitigate and adapt to climate change effects *(well established)* {2.4.4}.

Indirect drivers such as economic growth, population dynamics, urbanization and institutional policies underpin trends in direct drivers, thereby impacting biodiversity, water, food, health and climate change *(well established)* {2.3.2}. Economic expansion and increased trade drive changes in land and resource use, intensifying exploitation and pollution while at the same time fostering prosperity and poverty alleviation. However, this growth often correlates with higher greenhouse gas emissions and environmental degradation *(well established)* {2.3.2.1}. Population growth and urbanization increase the demand for housing, food and energy, leading to further land- and sea-use changes, pollution, and resource extraction *(well established)* {2.3.2.2}. Institutional drivers, including environmental policies and regulations, can mitigate or exacerbate these impacts *(well established)* {2.3.2.3}. Effective policies and regulations have succeeded in reducing pollution in some regions but have often fallen short globally *(well established)* {2.3.2.3}. Additionally, cultural drivers, such as increasing per-capita consumption, intensify the demand for resources, leading to further exploitation and environmental degradation *(well established)* {2.3.2.4; 2.3.2.5}. Finally, in addition to resulting in the loss of human lives, destruction of nature, loss of agricultural land, water supply and pollution, the increasing number of armed conflicts in various places of the world diverts political capacity from fostering engagement in fighting climate change and biodiversity decline *(established but incomplete)* {2.3.2}.

Direct drivers of biodiversity loss—land- and sea- use changes, unsustainable exploitation of species and resources, climate change, pollution and invasive alien species—have significant but varying impacts across different world regions and ecosystems. These direct drivers influence multiple nexus elements and thus human well-being by altering nature's contributions to people that are essential for food security, clean water and health *(well established)* {2.3.1}. Land- and sea-use changes, including deforestation and expansion of agricultural lands, are major contributors to biodiversity decline, particularly in tropical regions where forests and savannas are converted for cattle ranching and crop cultivation *(well established)* {2.3.1.1}. This transformation reduces biodiversity and contributes to climate change by increasing greenhouse gas emissions (*well established*) {2.3.1.1, 2.4.4}. Unsustainable agricultural practices and land degradation have led to a loss of nature's contributions to people, with an associated cost of $6.3 trillion/year in the first decade of the 21st century {2.3.1.1}. Urban expansion affects local climates and exacerbates health issues due to pollution and reduced green spaces. Direct exploitation, such as overfishing and resource extraction, exacerbates biodiversity loss while providing resources for the growing human population *(well established)* {2.3.1.1}. However, this leads to ecological degradation and greenhouse gas emissions, further impacting climate change and health *(well established)* {2.3.1.2}. Pollution from fertilizers and pesticides used in agriculture contaminates water sources and soils, posing risks to both ecosystems and human health *(well established)* {2.3.1.3}. Additionally, invasive alien species disrupt local ecosystems, leading to significant biodiversity loss and affecting food supplies *(well established)* {2.3.1.4}.

The expansion of agriculture and direct exploitation of resources have strong impacts on biodiversity, water, food, health and climate change. Agriculture is essential for food production but related greenhouse gas emissions, including methane from livestock, significantly contribute to global emissions. Land-use changes, such as deforestation for cropland, disrupt local and global water cycles, increasing runoff and reducing precipitation. These changes exacerbate climate change and contribute to extreme weather conditions, affecting agricultural productivity, biodiversity and health *(well established)* {2.5.2.1}. Monocultures and habitat fragmentation increase the risk of zoonotic diseases by disrupting ecosystems and increasing human-wildlife interactions *(established but incomplete)* {2.5.2.1}. Overexploitation of marine resources through industrial fishing and aquaculture leads to pollution and biodiversity loss, hampering the ability of marine environments to continue their crucial role in global food security *(well established)* {2.5.2.1}. Intensive resource use accelerates biomass turnover, depleting carbon stocks and nature's contributions to people. Irrigation and inappropriate fertilizer use further degrade soil health and water quality, while the high-water footprint of animal-based diets puts pressures on freshwater resources *(well established)* {2.5.2.1}. Indigenous Peoples face compounded health and food security challenges due to these environmental changes *(established but incomplete)* {2.5.2.1}.

Climate change has significant negative impacts on biodiversity, water, food and health. Biodiversity loss due to climate change weakens ecosystem resilience, amplifying climate-related disturbances and feedback loops on land and in the oceans. Ocean acidification threatens coral reefs, essential to marine ecosystems and human livelihoods. Increased heat and drought reduce carbon sinks in natural ecosystems, sometimes turning them into carbon sources *(well established)* {2.5.2.2}. Wildfires, exacerbated by climate change, not only release vast amounts of carbon but also cause deaths and health issues due to air pollution *(well established)* {2.5.2.2}. Urban areas, home to over 50 per cent of the global population, experience intensified heat and altered precipitation patterns, leading to increased mortality during heatwaves *(well established)* {2.5.2.2}. Climate change also exacerbates the spread of infectious diseases by altering the habitats and behaviours of vectors like mosquitoes *(established but incomplete)* {2.5.2.2}. High-altitude regions face increased hazards like avalanches and landslides, affecting water supplies and biodiversity. These changes disrupt food production and access, with warmer temperatures sometimes extending growing seasons but also causing water shortages or extreme events *(well established)* {2.5.2.2}.

Pollution, involving harmful substances such as chemicals and particulate matter, disrupts vital land and marine ecosystems, reduces biodiversity, and poses severe risks to human health and food security *(well established)* {2.5.2.3}. Air pollution, from sources such as fossil fuel combustion and wildfires, is a leading cause of diseases including heart disease, lung cancer and strokes, contributing to 9 million premature deaths globally in 2019. In some countries, over 25 per cent of deaths are pollution-related, with the majority occurring in low- and middle-income countries *(well established)* {2.5.2.3}. Water and soil pollution, driven by agricultural practices and industrial waste, introduce toxins like heavy metals and pesticides, harming aquatic life and contaminating food and water supplies. Eutrophication, caused by nutrient runoff, creates dead zones in water bodies, killing marine life *(well established)* {2.5.2.3}. Pesticides and industrial livestock practices further degrade biodiversity and human health through contamination and the spread of antibiotic-resistant bacteria *(established but incomplete)* {2.5.2.3}. Poor water quality leads to significant health issues, causing over 1.4 million deaths annually and substantial economic losses, particularly in poorer regions *(well established)* {2.5.2.3}.

Invasive alien species, introduced through human activities, pose significant threats to biodiversity, human health, food security, water quality and climate stability. There are over 37,000 documented invasive alien species globally, with approximately 200 new species identified annually, affecting nature's contributions to people, with many serving as vectors of infectious diseases *(well established)* {2.5.2.4}. Invasive alien species have proven detrimental to native species and ecosystems, particularly on islands where alien plants often outnumber natives. These species disrupt terrestrial and aquatic environments, with major impacts reported in the Americas, Europe, Asia and Africa *(well established)* {2.5.2.4}. They have driven 16 per cent of existing global animal and plant extinctions and pose risks to Indigenous Peoples and local communities by threatening livelihoods and cultural identities and damaging crops and fisheries, exacerbating food insecurity *(well established)* {2.5.2.4}. Invasive plants and animals also contribute to the spread of diseases, including invasive mosquitoes able to transmit dengue and Zika viruses *(well established)* {2.5.2.4}. Interactions between invasive alien species and environmental changes, such as habitat degradation and climate change, can amplify their impacts, leading to more severe outcomes such as increased wildfire frequency *(well established)* {2.5.2.4}.

Changes in biodiversity, health, food, water and climate significantly impact people worldwide *(well established)* {2.5.3}. Approximately 65 per cent of the global population resides in areas with beneficial hotspots of at least one nexus element: areas with high biodiversity, sufficient groundwater volume, high food production or high life expectancy. On the contrary, 52 per cent of people live in degradation hotspots faced either with severe declines in biodiversity, water scarcity, malnutrition, health burdens or climate change impacts. Low- and middle-income countries bear the brunt of this degradation *(well established)* {2.5.3}. Nearly three quarters of the population of low-income countries experience at least one, and 17-18 per cent two or more degraded conditions of nexus elements *(well established)* {2.5.3.2}. Lower middle-income countries have the lowest values for food production and volumes of accessible groundwater *(well established)* {2.5.3.2} **(Figure 2.31)**. People in sub-Saharan Africa live on average 17 years less than people in wealthy countries and yet wealthy countries still support practices that cause harm, such as harmful fishing in lower-income countries' waters *(established but incomplete)* {2.3.3; 2.5.3.2} **(Box 2.13)**. Seventy-two percent of low income and 31-68 per cent of lower middle-income populations experience degraded conditions of multiple nexus elements. In contrast, only 12-15 per cent of people in high-income countries face similar challenges, while 64-67 per cent benefit from at least one nexus element in favourable condition *(established but incomplete)* {2.5.3.2}.

Indigenous Peoples and local communities perceive more negative trends than positive ones in local biodiversity, water, food, health and climate change (*well established*) {2.5.4}. These environmental challenges lead to food security problems and negative health outcomes (*established but incomplete*) {2.5.4}. A systematic review of 87 studies on the interactions and relationships of Indigenous Peoples and local communities and their Indigenous and local knowledge systems with nexus elements revealed that Indigenous Peoples and local communities perceive more cases of negative than positive trends for nearly all nexus elements and all regions, with negative biodiversity trends being the most prominent across regions, particularly in Asia and North America, while in Africa negative food trends predominate. Indigenous Peoples and local communities-identified local indicators for these trends are reported most frequently for biodiversity, water and climate change, followed by food and then health. Climate change is perceived as the most important direct driver of biodiversity loss to Indigenous Peoples and local communities, in contrast to global trends that usually point to land and sea-use change as the major driver. The most important indirect drivers of biodiversity loss and other environmental changes for Indigenous Peoples and local communities include cultural, economic and institutional or governance drivers, with demographic drivers being more important for Asia relative to other regions {2.5.4}.

Policy frameworks such as the Sustainable Development Goals, the Kunming-Montreal Global Biodiversity Framework and the Paris Agreement address outcomes related to biodiversity, health, food, water and climate change, yet currently only 18-20 per cent of Sustainable Development Goals are on track for 2030, with major challenges related to biodiversity, food, water and climate change *(well established)* {2.6.2.1}. These frameworks, while addressing various aspects of sustainability, highlight the complex interconnections between different policy goals and the need to balance synergies and trade-offs. High-income countries tend to externalize environmental costs, impacting global justice and sustainability *(well established)* {2.6.2}. Effective implementation can be gained by integrating justice issues and recognizing the interconnected impacts of policies on different sustainability dimensions, for example by emphasizing the rights of Indigenous Peoples and local communities {2.6.2.2}.

2.1 INTRODUCTION

Over the past 50 years, people have transformed ecosystems more rapidly and extensively than in any comparable period in human history (Millennium Ecosystem Assessment, 2005). Rapidly growing demands for goods and services have increased production and consumption globally, particularly affecting food, freshwater, timber, fibre and fuel (IPBES, 2019a). Indirect drivers such as changes in demography and lifestyles, population growth and continually increasing income have expanded economic pressures on natural systems (IPBES, 2019a).

Previous assessments and reviews have established that well-functioning, stable and resilient ecosystems crucially rely on biodiversity to provide goods, services and physical, spiritual and mental nourishment essential to human health and well-being (IPBES, 2019a; Romanelli *et al.,* 2015; Sandifer *et al.,* 2015; Secretariat of the Convention on Biological Diversity, 2020). However, these assessments have focused on assessing historical trends in biodiversity, water systems, food systems, the climate system and health individually, or their two-way interactions, ignoring the complexity and interconnections between these different elements (FAO, 2018, 2020b, 2022b; FAO, IUFRO & USDA, 2021; UNEP, 2002; UNESCO, 2018; WHO, 2022; WWF, 2022). This chapter examines the trends and interlinkages between biodiversity, water, food and health and their drivers, including drivers of climate change in relation to mitigation and adaptation. This chapter addresses the following policy-relevant questions for the assessment **(Section 1.1.3)**:

- What are the current status and past trends in interactions among biodiversity, water, food, health and climate change (the nexus)?
- How have past drivers, actions and policies affected these nexus elements in positive and negative ways?
- What are the most important interactions that should be taken into account for decision-making?

The chapter synthesizes evidence on the interactions that have shaped past and current trends in and among the different nexus elements, including identifying those that are most relevant to designing response options to respond to these trends (see **Chapters 4** to **7**). Different world views, values and knowledge systems, including science and Indigenous and local knowledge (ILK), are considered in assessing evidence to capture diverse perspectives on how the complexity of the nexus is understood and managed. Throughout the chapter, boxes provide case studies to demonstrate how changes in drivers or one nexus element can affect several other nexus elements and thus either positively or negatively impact communities, including Indigenous Peoples and local communities (IPLC). By assessing understanding of the complexity of the nexus and contextualizing past actions, decisions and policies in relation to this complexity, the chapter provides evidence to manage and balance biodiversity and development issues more effectively.

2.2 CONCEPTUAL FRAMING FOR THE CHAPTER

Multiple possible combinations exist of cause-and-effect between biodiversity, water, food, health and climate change and the most important direct and indirect drivers affecting these nexus elements. **Figure 2.1** provides an overview of this complexity by mapping some of the main interactions on to the components of the IPBES conceptual framework (Díaz *et al.,* 2015): nature, nature's contributions to people, quality of life, direct and indirect drivers, and anthropogenic assets.

Biodiversity provides nature's contributions to people in the following three main ways: (i) through the role of individual species in the production of food and materials, medical services, and the control of pests and natural foci of disease, as well as the direct impact of biodiversity on human perception, enjoyment and other intangible benefits from nature (arrow 1 in **Figure 2.1**); (ii) through ecosystem functioning (arrow 3 in **Figure 2.1**), which in turn depends on diversity of genes, species and ecosystems (arrow 2 in **Figure 2.1**) (IPBES, 2018c, 2019a), with different ecosystem functions being important for different nature's contributions to people; and (iii) through the area of ecosystems, which denotes the area covered, size and location (arrow 4).

Regulating nature's contributions to people, in turn, have a feedback effect on the state of biodiversity (arrow 5, **Figure 2.1**). Biodiversity also affects climate and other environmental parameters regardless of impact on nature's contributions to people (arrow 6). Nature's contributions to people ensure food (arrow 7), water security (arrows 8) and health benefits (arrows 9). Food and water security in turn can affect health in both positive and negative pathways (arrows 10 and 11). Quality of life influences indirect drivers (arrow 12) which affect direct drivers (arrow 13).

Biodiversity and ecosystem functioning are determined by direct drivers (see **Section 2.3.1**). Natural drivers (e.g., climatic conditions, topography, soils) determine the typical undisturbed levels of biodiversity (arrow 14, **Figure 2.1**). Anthropogenic drivers (arrow 16) usually lead to the loss of biodiversity and its functions, except in cases of conservation, restoration and management programmes or as a result of some practices associated with IPLC (e.g., use of fire as a management tool). Combined natural-anthropogenic drivers, i.e., climate change and invasive species (arrow 15, **Figure 2.1**), are also harmful to biodiversity (see **Sections 2.3.1.2** and **2.3.1.4**), as seen for example in the dependence of many IPLCs living in polar and boreal regions on food collection and provisioning from these ecosystems (see **Box 2.20**). All three groups of drivers also directly affect food and water security and human health (arrows 17-19). Additionally, all direct drivers affect the direction and strength of the selection of phenotypes (and so genotypes) within species, and ultimately their evolution (not shown in the diagram) (IPBES, 2019a).

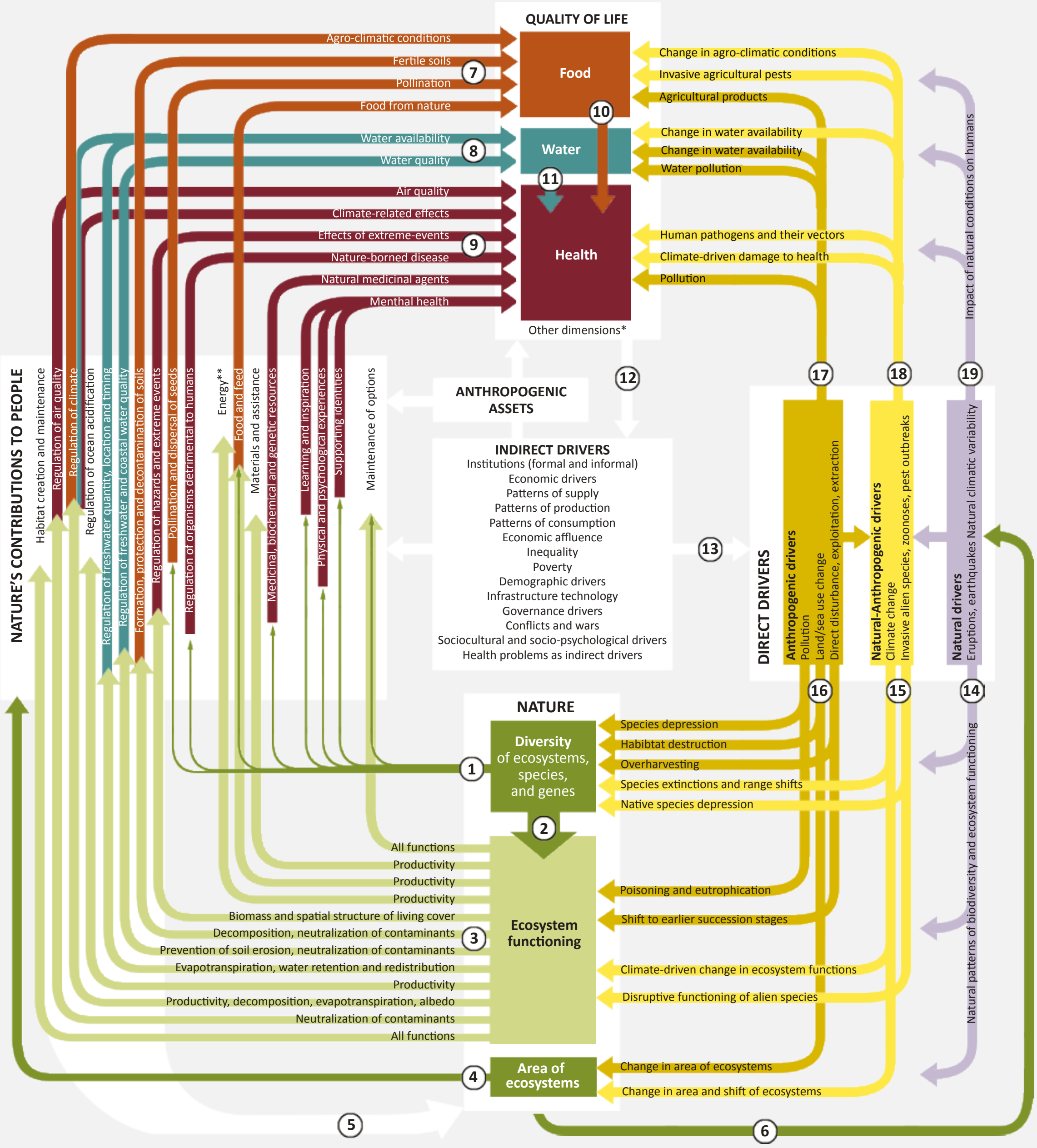


Figure 2 1 **Interactions between biodiversity and the different nexus elements mapped onto the IPBES conceptual framework.**

Arrows marked with numbers (1-19) are named in the text. Food, water and health are included in the "quality of life" box and named as *other dimensions, while biodiversity is in the "nature" box. Climate is included as a direct driver (arrow 15). **nature's contributions to people "Energy" includes only the functions of living organisms. A more simplified mapping of the nexus elements to the IPBES conceptual framework is given in **Chapter 1 (Figure 1.4)**.

Table 2 1 **Impacts of direct drivers of biodiversity loss on the nexus elements.**

This table summarizes some important direct drivers of biodiversity loss and how these affect the nexus elements of biodiversity, water, food and health as well as the climate system. Health refers to human health.

Direct driver	Biodiversity	Water	Food	Health	Climate
Land/sea-use change	Loss and degradation of natural habitat reduces or fragments species range, limits key processes such as pollination, reduces mean species abundance and can disproportionally impact biodiversity hotspots. Land use might impact pollution (see below)	Water abstraction for irrigation, dams or drainage of wetlands affects the provision of water-related nature's contributions to people such as freshwater supply, inflow of freshwater into estuaries and nutrient and sediment transport, along with potential pollution (see below)	Enhances or decreases food supply and quality, affecting the provision of food-related nature's contributions to people. Impacts such as extensive use of agrochemicals may be detrimental to food supply or quality (see below)	Loss of native habitats can affect physical as well as mental health: e.g., reduces disease regulation services, recreational use and diversity of natural medicines. It can also (via enhanced calorie supply) reduce malnutrition. Extensive use of agrochemicals may be detrimental to health (see below)	Biophysical processes affect climate change via increase or decrease of surface temperatures and precipitation, depending on where these taken place. Transforming (semi) natural ecosystems into managed ecosystems typically results in a loss of CO_2 sink capacities
Direct Exploitation	Overexploitation of fishing, hunting, grazing, extraction of wood, aromatic species, fruits, seeds or medicinal species as well as mining for sand or minerals reduces species diversity and abundances	Exploitation, especially in large quantities, can lead to groundwater depletion, reduction of streamflow, disappearance of wetlands and decreased water quality	Enhances food supply (but not necessarily nutritional quality), however harvested species can be over exploited	Reduces under-/malnutrition but harvested species can be over exploited and species trade may be a source of infectious diseases	Logging, deforestation and other exploitative actions can have a direct impact on climate change through increasing use of resources and energy and associated emissions
Climate change	Shifts (and often reduces) species ranges, changes structure and composition of species communities and their connectivity, imposes direct physiological stress (e.g., for ectotherms, in coral reefs, or via drought in forests), can support the spread of invasive species, affects ecosystem stocks of carbon and the carbon sink, and ocean acidification stresses marine species	Altered precipitation and evapotranspiration patterns lead to complex changes in floods or droughts, increase the occurrence of river drying and alter inflow to estuaries. They can also affect freshwater and marine ecosystems e.g., through acidification, salinization, turbidity and clarity, as well as the storage of carbon and methane. Affects the cryosphere (water in solid form such as glaciers, snow permafrost, ice)	Reduces yields in some regions while enhancing in others; increases uncertainty for farming practices; can impact food nutritional quality (via CO_2)	Extreme events such as heat waves, wildfires and floods cause physical and mental stress and mortality. Heat can decrease or increase the range of hosts and vectors species; affects viral replication and extrinsic incubation period in vectors; may increase zoonotic transmission risk by increasing contacts between hosts, vectors and pathogens	Affects precipitation, temperature and the frequency and duration of extreme events. Leads to climate-feedbacks via biophysical (e.g., snow albedo) or biogeochemical (e.g. carbon cycle) processes
Pollution	Toxic and nutrient pollution alters habitat quality, genetic diversity, community composition and food webs, usually leading to declining species diversity	Reduces water quality. Can accumulate in sediments and be transported downstream to estuaries, wetlands and coastal areas	Reduces crop yields and fisheries and may accumulate to pollute food sources	Decreases physical fitness and can be toxic to individuals. Increases multiple diseases (cardiovascular, diarrhoeal, respiratory or neurological, causes cancer, hormonal disruption, etc)	Air pollutants such as soot or ozone are also climate change forcers. Other particles lead to negative forcing and alter cloud types and precipitation
Invasive alien species	Threatens species composition in native food-webs and biotic interactions, e.g., through predation, competition or by carrying pathogens, impacting function and distributions	Reduces water quality through invasive algae species or if water carries, e.g., pathogens. Invasive bivalves alter water quality also by their filtration (increasing water transparency)	Impacts fisheries and crop yields, e.g., through predation, competition or by carrying pathogens	Negative impacts on health have been found related to allergies or by invasive species acting as disease vectors	Reduces the resilience of natural habitats, agricultural systems and urban areas to climate change

2.3 STATUS AND TRENDS OF DIRECT AND INDIRECT DRIVERS AFFECTING NEXUS ELEMENTS

The five most important direct drivers (land- and sea-use, direct exploitation via harvesting/extracting (wild) species and abiotic resources, climate change, pollution and invasive alien species) that drive biodiversity loss are well established. Which of these dominate in terms of their impacts differs between world regions and between terrestrial, freshwater and marine realms (IPBES, 2019a; Jaureguiberry *et al.,* 2022). The IPBES Global Assessment Report on Biodiversity and Ecosystem Services (Global Assessment) investigated the impacts of these direct drivers on biodiversity. Their importance for the remaining nexus elements is evident, with varying degrees of confidence regarding the strength and direction of the impact.

Trends in direct drivers are underpinned by a multitude of economic, demographic, cultural, institutional and technological indirect drivers, many of which have accelerated over the 20th and into the 21st century (Steffen *et al.,* 2018). These indirect drivers are assessed using several indicators, selected based on their importance and data availability **(Box 2.1; Figure 2.6; Table 2.2)**.

Box 2 1 Methodology: Knowledge synthesis on drivers and nexus elements.

The analyses and figures shown in **Section 2.3** represent a synthesis of knowledge on the most important indirect drivers, the corresponding direct drivers and their joint influence on nexus elements. It also presents time series data of selected indicators of these drivers and nexus elements.

Direct and indirect drivers: Direct drivers were selected based on previous IPBES assessments (e.g., IPBES, 2019a): land- and sea-use change, resource exploitation, climate change, invasive alien species and pollutants. The indirect drivers, which provide the underlying causes for changes in the direct drivers, have also been identified in previous IPBES assessments (IPBES, 2019a), and cover five broad groups: economic, demographic, institutional, cultural and technological.

Selection of indicators: Indicators for indirect and direct drivers, and trends in the nexus elements, were selected based on their representativeness and contingent on the availability of long-term, and preferably nationally explicit, time series data from credible sources. The time series allows quantitative and qualitative analysis of global and regional trends. For detailed information on the selected indicators and respective data sources see the associated data management report: **(Figure 2.4, Figure 2.6, Figure 2.13, Figure 2.14)** [2] and **(Table 2.2; Figure 2.10, Figure 2.11, Figure 2.12)**.[3]

Temporal trend plots: Figure 2.4, Figure 2.6 and Figure 2.14 display temporal trends between 1970 and 2022 of direct drivers, indirect drivers and the five nexus elements. Trends are based either on global or national-level indicator data that have been aggregated for four different income levels (as specified by World Bank (2023b)) and globally. Therefore, income levels are not purchasing power parity corrected (World Bank, 2023n). Unless indicated otherwise data shown are *means.* For detailed information see the associated data management report[2].

Quantitative trend analysis: Table 2.2 shows the results of the quantitative trend analysis of indicators of indirect drivers. Where data availability allowed, linear regression analysis against time as well as the Mann-Kendall test were conducted for the period 1981-2021 (long-term) as well as for the period 2000-2021 (recent) to assess trends. Columns 'Trend' depict significant annual rates of change. Significance of the trend was assessed using the t-test in the linear regression (p-value < 0.05) and the Mann-Kendall test (absolute value of 'Kendall's tau' > 0.3). The resulting trends were used as input data for the knowledge synthesis figures on drivers and nexus elements **(Figure 2.10, Figure 2.11, Figure 2.12).** For detailed information on the selected indicators and respective data sources see the associated data management report[3].

Knowledge synthesis on drivers and nexus elements: Figure 2.11 synthesizes established knowledge from a global perspective on the most important indirect drivers, their recent trends **(Table 2.2; Figure 2.6)**, how these affect direct drivers **(Figure 2.10)** and how this is affecting each nexus element. The impacts of these trends in indirect drivers on direct drivers and subsequently on nexus elements have been assessed based on an extensive literature review. This included (a) a synthesis of the impact of the indirect drivers on the trend in direct drivers (with confidence statement) and how these broadly affect nexus elements; and (b) a more detailed assessment of how the trend in direct drivers affects the status and trend in the nexus element (with confidence statements) (see the associated data management report[3] for detailed documentation). For the nexus element "food", food quantity and food quality have been assessed separately. Likewise, "water" has been assessed separately as freshwater quantity and quality and "health" as physical and mental human health. Climate change is considered as a driver in this analysis rather than a nexus element.

The analysis showed that some indicators of indirect drivers in some cases also act as important direct drivers in the nexus, such as poverty or armed conflicts (as depicted in **Figure 2.12**). This figure displays the information from **Figure 2.11** as a Sankey diagram. As the assessment was made from a global perspective large regional variation could not be depicted.

Box 2 1

Assessments at regional scales would in some cases result in a different outcome. For detailed information on the methods used to assess impacts on direct driver and nexus elements, including the trend analysis and level of evidence statements, see the associated data management report[3].

Regional differences of nexus element indicators: For **Figure 2.14** mean nexus element indicator values for the time period 2005-2014 were calculated for each income level group (World Bank, 2023m) as well as globally. To ease comparison of the different mean values per income level group with the global mean value, data was scaled such that the global mean value is zero. Data was subsequently displayed as bar plots. For detailed information on indicators and income levels, see the associated data management report[2].

2.3.1 Status and trends of direct drivers

2.3.1.1 Land/sea-use and direct exploitation

The terms "land-use", "sea-use", and "resource extraction" are not always used unambiguously. Sea-use, still a relatively novel concept, refers to changes over a certain area of ocean water. Land-cover and land-use changes are often treated as separate categories (IPCC, 2023a), but some use the term land-use change to either refer to both changes in area and in management intensity. Extraction of non-biological material is also an important driver, so changes in area are separated here, both for land (which corresponds to land-cover changes) and marine ecosystems, from changes in resource extraction. The IPBES Global Assessment Report on Biodiversity and Ecosystem Services (Global Assessment) (IPBES, 2019a) focussed on the extraction of wild species, but this is broadened in this assessment to fisheries and harvesting in land ecosystems of both wild and domesticated species **(Box 2.2)** and also includes resource extraction for non-biological materials through mining.

Globally, land- and sea-use together with direct exploitation of biological resources and other materials were identified as the most prominent drivers of past biodiversity loss (IPBES, 2019a, 2023).

2. The data management report for assessing trends in nexus elements (https://doi.org/10.5281/zenodo.13913118).
3. The data management report for assessing trends in indirect drivers (https://doi.org/10.5281/zenodo.13913136).

Box 2 2 **Successful reductions in commercial whaling.**

Whales have been hunted for subsistence use for millennia, but commercial hunting massively increased in the 20th century for meat, oil, blubber and cartilage, industrial, pharmaceutical and health supplement use (Parsons & Rose, 2022). The ecological importance of whales includes mitigating global warming through the sequestration of atmospheric carbon dioxide, fertilisation of global marine ecosystems and enabling food web regeneration for bigger fisheries with higher abundance, based on the regeneration of krill and plankton populations (Durfort *et al.,* 2022; Nicol *et al.,* 2010; Pershing *et al.,* 2010). However, the populations of these long-lived, slow reproducing animals collapsed due to industrial hunting (Parsons & Rose, 2022; Tulloch *et al.,* 2018).

The subsequent cessation of commercial whaling can be attributed to a series of international policies and agreements aimed at protecting whale populations and preserving marine ecosystems, along with changing attitudes. One of the most pivotal agreements was the International Whaling Commission's implementation of a moratorium on commercial whaling in 1986. This moratorium, initially intended to be temporary, was extended indefinitely due to concerns over the declining populations of several whale species (Parsons & Rose, 2022). Additionally, the establishment of whale sanctuaries in various regions, such as the Southern Ocean Whale Sanctuary and the Indian Ocean Whale Sanctuary, may have further reinforced conservation efforts (Cook *et al.,* 2019). The growing public awareness of the ecological importance of whales and the ethical considerations surrounding their unsustainable hunting led to public pressure on governments and industries to end commercial whaling practices, while some Indigenous communities for whom whaling is a sacred act and important for subsistence food provisioning, continue hunting practices in limited areas (Doubleday, 1989).

Together, these policies and initiatives and changes in values have contributed to the significant reduction in commercial whaling activities and the gradual recovery of many whale populations worldwide, positively affecting biodiversity and other nexus elements (Parsons & Rose, 2022).

Box 2 2

Figure 2 2 **Humpback whale with a calf in the South Pacific (Tonga).**

Photo credit: Paula R. Prist under license CC BY-NC-ND 4.0.

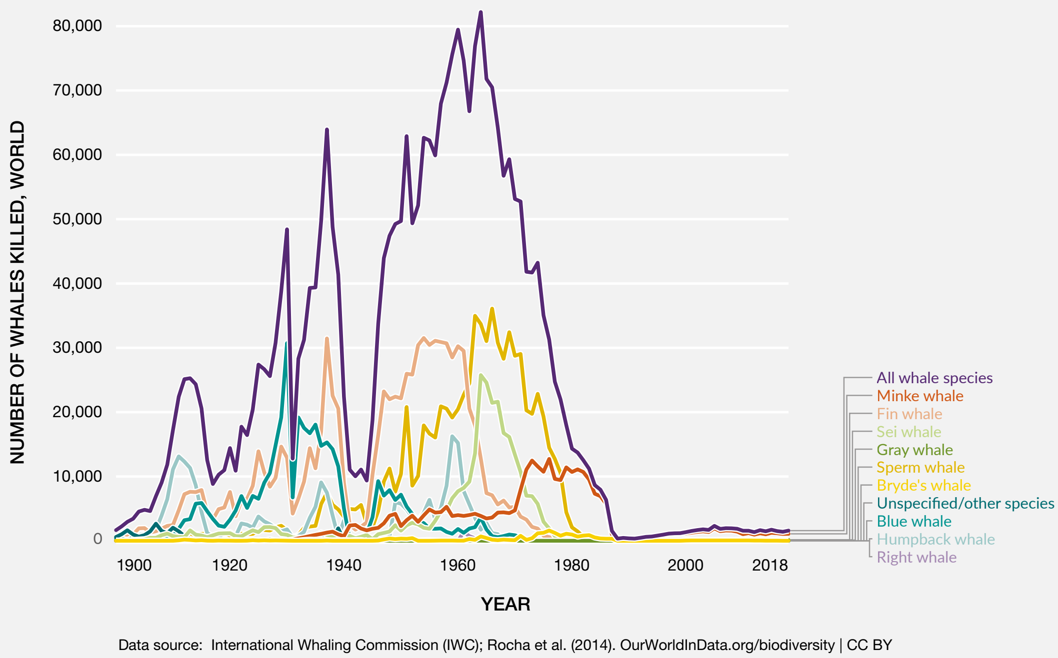


Figure 2 3 **Global number of whales killed.**

From Rocha *et al.* & IWC – processed by Our World in Data (2023) under license CC BY.

The need to increase crop and fisheries yields to provide food to a globally growing population and the associated use of agro-chemicals has resulted in a global agricultural system heavily dependent on fossil fuels, in many regions massively subsidised, with detrimental impacts on biodiversity as well as being a large source of greenhouse gas (GHG) emissions (IPBES, 2019a; IPCC, 2019c; Pörtner *et al.,* 2023; Seppelt *et al.,* 2023) **(Figure 2.1, Figure 2.4; Table 2.1; Section 2.5.2.1)**. Cropland and pastures expanded by 1.9 million km^2 into both forested and non-forested ecosystems over the period 1960-2019, whereas the area of primary forest worldwide has decreased by over 80 million hectares

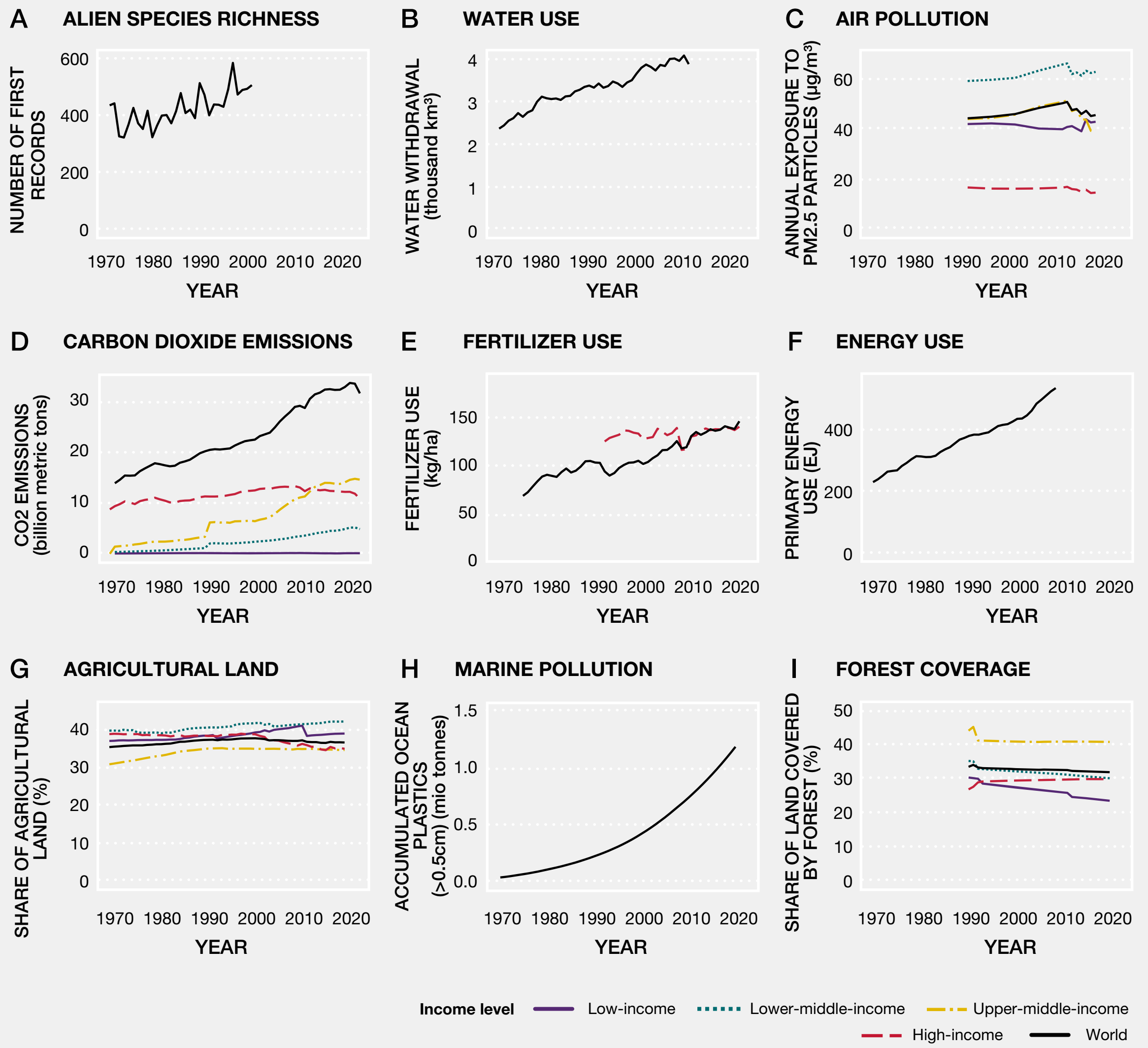


Figure 2.4 **Changes over time in indicators for the most important direct drivers affecting the nexus elements.**

Data cover period 1970-2022, where available. Time series are based either on global data or on country-level data that has been aggregated for four different income levels (World Bank, 2023m) and globally. Unless indicated otherwise, data shown are mean values. For detailed information on the indicators and income levels used, see the associated data management report[2] and **Box 2.1. (A)** Alien species richness: annual number of alien species first records (Seebens *et al.,* 2017); **(B)** Water use: water withdrawal for irrigation, livestock, domestic, manufacturing and electricity (thousand km³) (Alcamo *et al.,* 2003; Aus Der Beek *et al.,* 2010; Flörke *et al.,* 2013); **(C)** Air pollution: mean annual exposure to concentrations of suspended particles measuring less than 2.5 microns in aerodynamic diameter (µg/m³) (World Bank, 2023j); **(D)** Carbon dioxide (CO_2) emissions (summed totals): gross direct emissions from fuel combustion (million tons) (OECD, 2022a); **(E)** Fertilizer use: fertilizer consumption (kg/ha of arable land) (World Bank, 2023d); **(F)** Energy use: primary energy use (EJ) (T. B. Johansson *et al.,* 2012); **(G)** Agricultural land: share of land area used for agriculture (crop & pasture) (per cent) (World Bank, 2023a); **(H)** Marine pollution: accumulated macroplastic (diameter > 0.5 cm) in surface ocean (tonnes) (Lebreton *et al.,* 2019); **(I)** Forest coverage: share of land area covered by forest (per cent) (FAO, 2023b).

since 1990 (FAO & UNEP, 2020; Winkler *et al.,* 2021) **(Figure 2.4G)**. Large losses of natural ecosystems in the tropics, which are generally species-rich tropical forests and savannas (as well as tropical coral reefs), are still occurring, driven mostly by cattle ranching and cultivation of soya bean and palm oil (FAO & UNEP, 2020; Feng *et al.,* 2022; Pugh *et al.,* 2019) **(Figure 2.4I)**. Unsustainable agricultural practices have not only environmental but also economic and societal consequences: agricultural losses from degradation as a result of crop and pasture land mismanagement have been calculated to cost $231 billion per year (2007 values); Nkonya *et al.* (2016) and others estimated the loss of total ecosystem service value from unsustainable agricultural practices and land degradation as $6.3 trillion/year for the first decade of the 21st century (Sutton *et al.,* 2016).

Approximately 50 per cent of the past extent of coastal wetlands (including mangroves, tidal marshes and seagrasses) have been lost, releasing ancient carbon back into the atmosphere and limiting their contribution to carbon sequestration (Duarte *et al.,* 2013; Macreadie *et al.,* 2021) **(Box 2.8)**. World marine and freshwater fisheries catch increased from ca. 111 million tonnes in the 1990s to close to 178 million tonnes in 2020 (FAO, 2022b). Other human activities include the expansion of aquaculture, accidental oil spills, increased area under bottom trawling, expansion of ports, coastal development, and offshore wind turbines (Duarte *et al.,* 2013; Langlois *et al.,* 2014; Macreadie *et al.,* 2021). Like on land, many of these have negative impacts on marine ecosystems, such as coral reefs (2.4.1), except for some submerged infrastructures that also serve as artificial reefs (Langlois *et al.,* 2014; Pörtner *et al.,* 2021, 2023). Land-use change also cascades into marine food-webs via altered flows of water and nutrients (e.g., dams, freshwater withdrawals) (Maavara *et al.,* 2020; Shi & Qin, 2023; X. Wang *et al.,* 2022) **(Section 2.5.2.1)**.

Intensification of crop production and the extraction of aquatic and terrestrial species have helped to feed the growing human population and continue to do so. Still, some 800 million people remain undernourished (i.e., suffer from nutrient deficiency) (FAO *et al.,* 2022), while substantial quantities of food are lost each year (Arneth *et al.,* 2019; Mbow *et al.,* 2019). Energy and material use **(Figure 2.4F)** for buildings and industry is also increasing and can be an important cause of biodiversity loss, pollution – and related health issues – and water abstraction. The benefits of proximity to both diverse land- and seascapes for people's physical and mental health are now well established such that the increasing lack of green spaces, sealing and homogenisation of coastal and terrestrial environments over recent decades have reduced human well-being (Barton & Rogerson, 2017; Nishi & Subramanian, 2023; Romanelli *et al.,* 2015). Moreover, land-use change can also act as a driver of infectious disease emergence (Bardosh *et al.,* 2017; Gottdenker *et al.,* 2014) (2.4.3, 2.5.2.1).

Finally, while making an important contribution to decarbonizing the economy and reducing the detrimental impacts of mining for fossil fuels, the increasing demand for minerals and ores, such as copper, lithium and rare minerals, required for the green transition necessitates mining activities, which in turn demand water and energy. The impacts of materials extraction, unsustainable food production and overharvesting reverberate through the entire nexus (IPBES, 2019a; IPCC, 2019c, 2022b; Romanelli *et al.,* 2015) **(Figure 2.10)**.

2.3.1.2 Climate change

As a consequence of continued anthropogenic emissions of GHGs (**Figure 2.4D** for CO_2) and other climate forcing agents, the global mean temperature in 2022 was 1.15°C above pre-industrial levels (WMO, 2023a), accompanied by intensified and more frequent extreme weather events due to human activities and GHG emissions (IPCC, 2023b). Likewise, the manifold, mostly negative, impacts on biodiversity and human well-being are also well established (IPBES, 2019a; Pörtner *et al.,* 2023). As a driver of biodiversity loss, climate change until now has been of lesser importance compared to land-/sea-use change and exploitation of resources, but will likely become more prominent in the future (IPBES, 2019a; Pörtner *et al.,* 2023) **(Section 3.2)**. Climate change effects on biodiversity and all other nexus elements are diverse and operate both via increasing atmospheric CO_2 and changes in climate, principally temperature and precipitation. For instance, although warming trends and increasing CO_2 concentration can be beneficial to yields in some parts of the world, a decline in yields due to climate change is expected stemming from increasing extreme events, shorter vegetation periods or higher herbivory (Seppelt *et al.,* 2023), with yield losses already observed in response to weather extremes (Lesk *et al.,* 2016; C. Zhao *et al.,* 2017). Carbon dioxide alters woody-grass competition in the tropics **(Section 2.4.4)** and is thought to reduce food protein and micro-nutrient levels (Fanzo & Downs, 2021; Mozny *et al.,* 2023; Zhu *et al.,* 2022). Food production is also a source of GHG emissions, with animal-based proteins, and especially proteins from red meat, a particularly high source because of high land area requirements and poor production efficiencies for primary feed crops (Alexander *et al.,* 2016; Poore & Nemecek, 2018).

From 1901 to 2018, global sea level rose by 0.20 [confidence interval: 0.15 to 0.25] m, with an accelerating rate since 1960 to 3.7 [confidence interval: 3.2 to 4.2] mm/yr for the period 2006–2018 (IPCC, 2021). This rate of sea-level rise is faster than any century over at least the last three millennia (IPCC, 2021). Since the late 1980s, open ocean surface pH in response to the dissolution of atmospheric CO_2 has declined by approximately 0.017–0.027 pH units per decade (IPCC, 2019b) and current ocean acidity is above levels experienced since at least over 800,000 years ago (IPBES, 2019a). Continued ocean warming and climate change-related acidification, as well as changes in ocean salinity, are negatively impacting marine organisms and function, and hence also fisheries yield **(Section 2.5.2.2)**. In coastal environments, increased loadings of nutrients and organic matter from agriculture and sewage have exacerbated deoxygenation (Breitburg *et al.,* 2018), with negative impacts on biodiversity and local fishing communities.

Health impacts of anthropogenic climate change include the negative responses of the human body to heat episodes, and the mortality caused by wildfires or floods, all of which are attributed to extremes caused by climate change (Mitchell, 2021; Vicedo-Cabrera *et al.,* 2021). There is still limited understanding regarding the full range of mental health impacts caused by climate change and the underlying physiological processes, but stress, anxiety and depression have been related to climate change, either worsening the situation for people already having these, but also leading to the development of new conditions (Cianconi *et al.,* 2020) **(Section 2.5.2.2)**.

2.3.1.3 Pollution

Other forms of pollution other than GHG emissions remain an important driver within the nexus, with well-established detrimental effects on freshwater and marine habitats, biodiversity, health and the food system (IPBES, 2019a) **(Section 2.5.2.3)**. These impacts are local (i.e., close to pollution sources, including those affecting Indigenous Peoples and local communities (Prist *et al.,* 2023), and transboundary (Caswell *et al.,* 2018; Groh *et al.,* 2022; Naidu *et al.,* 2021; Sigmund *et al.,* 2023).

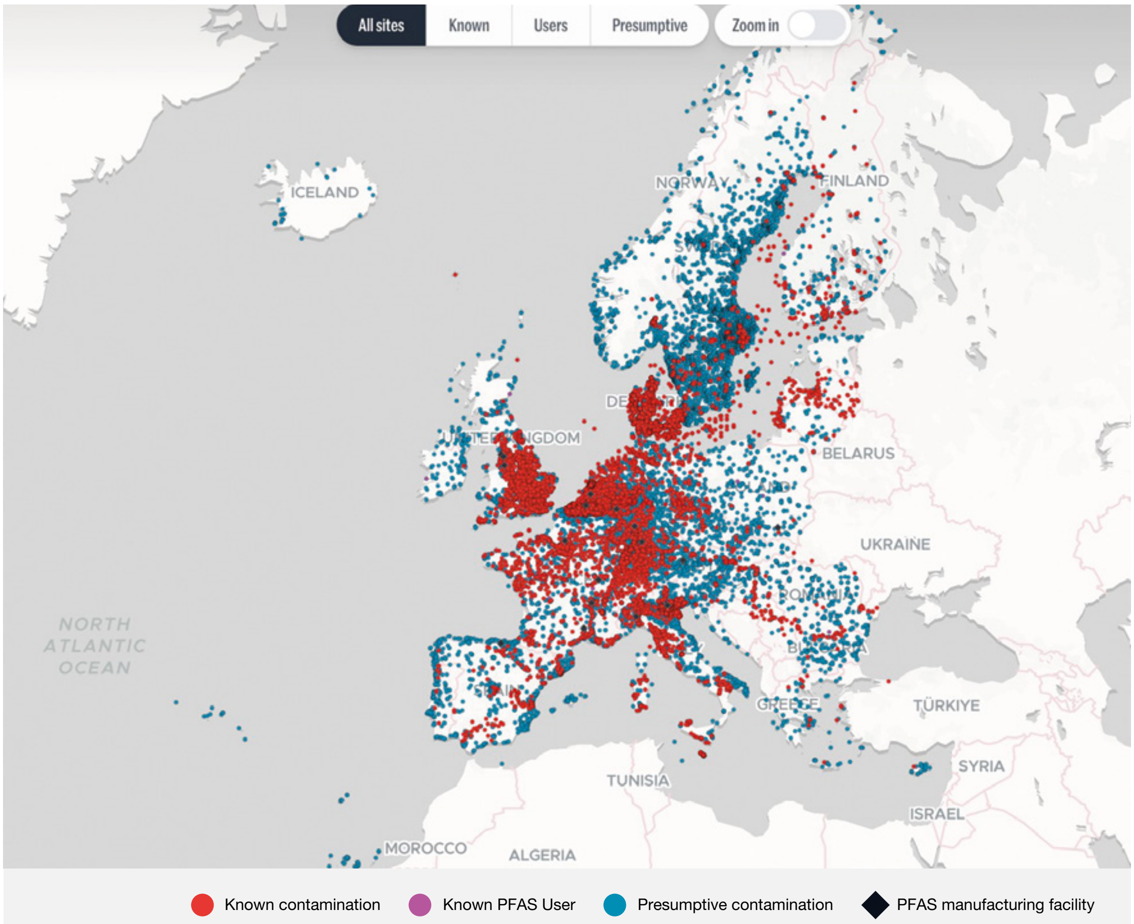
While massive increases in the use of fertilizers (e.g., increase nearly nine-fold since 1961 (IPCC, 2019c) **(Figure 2.4E)** and agro-chemicals (approximately 2 million tonnes of pesticides are used globally; A. Sharma *et al.,* 2019) have ensured the calorific demands of a growing population are met (Gu *et al.,* 2023; IPCC, 2019c; Springmann *et al.,* 2018), their side-effects on ecosystems and humans are well established (Beaumelle *et al.,* 2023; Caswell *et al.,* 2018; Klingelhöfer *et al.,* 2022; Rashid *et al.,* 2023) **(Section 2.5.2.3)**. For example, total anthropogenic emissions of nitrous oxide, a potent GHG whose emissions are dominated by mineral fertilizer application, increased by 30 per cent over the past four decades (Tian *et al.,* 2020), while agricultural nitrogen losses also act as pre-cursors of particulates and tropospheric ozone – both of which are also climate change forcers, and affect human and ecosystem health (Springmann *et al.,* 2018; Tian *et al.,* 2020). Ozonesondes have measured increases in tropospheric ozone of 1.9 ± 1.7 parts per billion by volume per decade from 1995-2017 (H. Wang *et al.,* 2022) on average. Ozone has been estimated to reduce crop yields in the first decades of the 21[st] century by between approximately 3-7 per cent for important staple crops (maize, rice, soybean, wheat), with some metrics indicating yield losses of possibly >10 per cent (Tai *et al.,* 2021) **(Box 2.5)**.

Multiple other forms of pollutants exist that interfere with human health and biodiversity **(Box 2.3, Section 2.5.2.3)**. Among these, light and noise pollution have received less attention in the scientific literature but given human population increases and trends towards rapid urbanization, their impacts on biodiversity and human health (particularly mental health) are increasingly being examined (Cao *et al.,* 2023; Tortorella *et al.,* 2020). Plastic pollution **(Figure 2.4H)** is also increasingly the focus of research: plastic production has grown 20-fold in the past 50 years (T. R. Walker & Fequet, 2023) **(Box 2.4)**. Products from plastic break down have been found in all ecosystems, including the poles (Kibria *et al.,* 2023; Morrison *et al.,* 2022; T. R. Walker & Fequet, 2023), and have entered thousands of species (including humans) via the food web (Allen *et al.,* 2022).

Box 2 3 **Forever chemicals affect biodiversity and health: Massive pollution throughout Europe.**

Pollutants known as forever chemicals do not break down in the environment and can remain permanently in the air, soil and water, as well as in the human body and animals. These include per- and polyfluoroalkyl substances (PFAS), a family of about 10,000 chemicals, valued for their non-stick and detergent properties. Many non-stick cooking pans and some baking pans are coated with a polymer form of PFAS called PTFE (polytetrafluoroethylene), best known by the brand name Teflon (Herzke *et al.,* 2012). Also, food packaging, waterproof clothes, firefighting foam and some cosmetics can contain PFAS.

Box 2 3



Data source: Forever Pollution Project

Figure 2 5 **Polyfluoroalkyl substances (PFAS) contamination map in Europe.**

PFAS have caused and continue to cause harmful pollution that is extremely difficult and expensive to clean up, as they are resistant to biodegradation and can persist for millennia (Sonne *et al.,* 2023). They can be found in surface water, groundwater, soil and sediments, as well as in the air. PFAS accumulation in the ocean and marine food chains and contamination of groundwater persist over long timescales (Sunderland *et al.,* 2019). The production and use of PFAS has contaminated drinking water supplies in several European countries (EEA, 2019).

Recently, the Forever Pollution Project (2023) – a cross-country media investigation on PFAS contamination around Europe – published a map of over 17,000 contaminated sites identified in Europe, based on the methodology of Salvatore *et al.* (2022) **(Figure 2.5)**. The project shows that there are 20 manufacturing facilities and more than 2,100 sites in Europe that can be considered PFAS hotspots – places where contamination reaches levels considered to be hazardous to the health of exposed people.

One such hotspot is a manufacturing plant in Zwijndrecht, near Antwerp, Belgium (Paul *et al.,* 2009). Here, the PFAS pollution is mainly from perfluorooctanesulfonic acid (PFOS), a so-called 'long-chain' PFAS that accumulates in people and other organisms (EEA, 2023). The plant recently decided to stop producing PFAS in Zwijndrecht by the end of 2025 and pledged €571 million to remediate Zwijndrecht and the surrounding areas. PFAS were found in the blood of people living near the site with levels the highest that scientists have ever seen in a human being. Those living within 15km of the site have been told not to eat any eggs laid in their gardens and to avoid homegrown vegetables. Meanwhile, 70,000 people living within a 5km radius of the plant have been offered a blood test to look for the presence of PFAS in a campaign starting in May 2023.

PFAS has multiple effects on human health (Sunderland *et al.,* 2019). They are carcinogenic, endocrine disruptive and immunotoxin chemicals (Sonne *et al.,* 2023). It was estimated that PFAS put a burden of between 52 and 84 billion euros on

Box 2 3

European health systems each year (Goldenman *et al.,* 2019). PFAS pollution also threatens ecosystems worldwide (Sonne *et al.,* 2023). PFAS bioaccumulates in animal organisms, including fish and seafood (thereby posing an additional risk to human health when consumed), and have been found in over 330 species across the globe (EWG, 2023). Studies in animals have found similarly harmful health effects as for humans, but more research is needed to understand the full impact on various species and their environments. Marine PFAS pollutants adversely affect the growth and photosynthesis of phytoplankton and the development and reproduction of zooplankton (Mahmoudnia, 2023).

Box 2 4 **Increasing plastic pollution of the global seas: A threat to marine ecosystems, food systems, human health and the climate system.**

Global plastic production has steadily risen over the last decades, from about 2 million tonnes (Mt) in 1950 to 393 Mt in 2016 (Lebreton *et al.,* 2019) and 460 Mt in 2019 (OECD, 2022b), with an average annual growth rate of 8.4 per cent. Geyer *et al.* (2017) estimated that only 9 per cent of all cumulative virgin plastic produced had been recycled, 12 per cent was incinerated and 79 per cent was accumulated in landfills or the natural environment, as of 2015. If current production and waste management trends continue, roughly 12,000 Mt of plastic waste will be in landfills or in the natural environment by 2050 (Geyer *et al.,* 2017). Thus, the accumulation of mismanaged plastic waste in the environment is a global growing concern. The land surface is the main source of plastic pollution in the oceans. Jambeck *et al.* (2015) calculated that 275 million Mt of plastic waste was generated in 192 coastal countries in 2010, with 4.8 to 12.7 million Mt entering the ocean (generated by 2 billion people living within 50 km from the coast). Rivers also bring substantial plastic pollution to the ocean, which ranges between 0.8 and 2.7 Mt per year, with small urban rivers among the most polluting (Meijer *et al.,* 2021).

Plastics in the oceans have a direct impact on biodiversity, as many species swallow or can be entangled by them (Jepsen & De Bruyn, 2019). Most plastics in the ocean break up into very small particles called microplastics, which have been detected in marine organisms from plankton to whales. Microplastics accumulate in the food system through seafood including fish, invertebrates and mussels (M. Smith *et al.,* 2018), through drinking water or through baby feeding bottles (D. Li *et al.,* 2020). Microplastics have been found in human blood (Leslie *et al.,* 2022) and faeces (J. Zhang *et al.,* 2021). They likely have negative consequences for human health (Danopoulos *et al.,* 2022), although more research is needed to confirm this.

In addition, the production of plastics has a huge carbon footprint, thereby contributing to climate change. Zheng & Suh (2019) calculated that the global life cycle GHG emissions of conventional plastics were 1.7 Gt of CO_2-equivalent in 2015. If the trend of plastic production were to continue, the GHG emissions from plastics would reach 15 per cent of the global carbon budget by 2050.

2.3.1.4 Invasive alien species

Invasive alien species (IAS) have multiple negative effects on biodiversity and food webs and have been emerging as important impediments to nexus elements, with more than 3,500 IAS being introduced by diverse human activities to various regions of the world (IPBES, 2023) **(Section 2.5.2.4)**. The number of new recordings of IAS have increased consistently worldwide over the last 200 years, but more than a third of all first introductions were recorded between 1970 and 2014, costing over $423 billion in 2019 (IPBES, 2023) **(Figure 2.4A)**. By affecting agricultural systems as well as wild foods, IAS have well established negative impacts on food supplies that local communities rely on, and their rapid increase implies – similar to climate change – that they will become more prominent drivers in the future of global biodiversity loss (IPBES, 2019a, 2023). Of the documented impacts, 85 per cent of IAS negatively affect human well-being, ranging from being vectors for infectious zoonotic diseases to altering cultural landscapes (IPBES, 2023). Interactions between IAS and other global changes have been exacerbating past invasions and facilitating new ones, thereby escalating the extent and impacts of invaders (Pyšek *et al.,* 2020).

2.3.2 Status and trends of indirect drivers

In the Regional and Global Assessments (IPBES, 2018a, 2018b, 2018c, 2018d, 2019a), IPBES established the concept of causal relationships between trends in indirect drivers impacting direct drivers, which in turn impact biodiversity. Trends in indirect drivers are more difficult to quantify than direct drivers as the diversity of possible indicators is large and new indicators are emerging, hence, a comprehensive picture is difficult to obtain **(Figure 2.6; Table 2.2).** Moreover, indirect driver indicators can also act as direct drivers on some nexus elements.

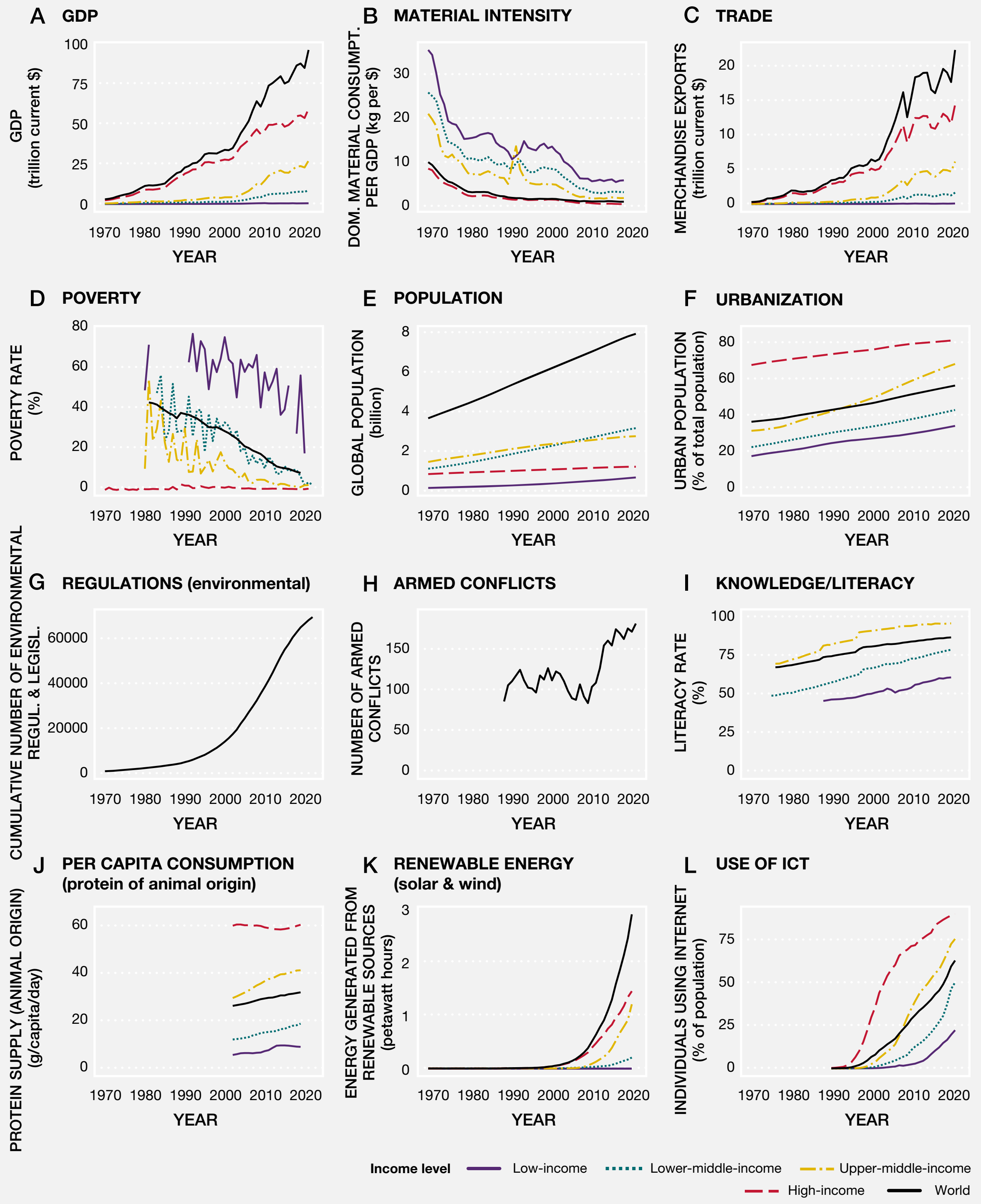


Figure 2 6 **Changes over time in indicators for important indirect drivers affecting the nexus elements.**

Data cover the period 1970 to 2022, where available. Time series shown are based either on global data or country-level data that has been aggregated for four different income levels (World Bank, 2023m) and globally. Unless indicated otherwise, data shown are mean values. For detailed information on used indicators and income levels, see the associated data management report[2] and **Box 2.1** Panel **(A)** Gross domestic product (GDP) (trillion current USD), global/regional total (World Bank, 2023e); **(B)** Material intensity: domestic material consumption per unit of GDP (UNEP, 2023; World Bank, 2023e); **(C)** Trade: merchandise exports (trillion current $), global/regional total (World Bank, 2023h); **(D)** Poverty: poverty rate (per cent) (World Bank, 2022); **(E)** Population: global/regional total

Figure 2.6

population (World Bank, 2023k); **(F)** Urbanization: urban population (per cent of total population) (World Bank, 2023l); **(G)** Regulations and legislations (environmental): total number of environmental regulations and legislations (FAO, 2023a); **(H)** Armed conflicts: total number of armed conflicts (UDCP & PRIO, 2023a, 2023b, 2023b, 2023c, 2023d – processed by Our World in Data); **(I)** Literacy (knowledge): literacy rate (per cent) (World Bank, 2023g) (note: data not available for high income level countries); **(J)** Per-capita consumption (protein): protein supply of animal origin per capita and day (g/cap/day) (FAO, 2020a); **(K)** Renewable energy: energy generated from renewable sources (Petawatt hours), global/regional total (BP p.l.c., 2022); **(L)** Use of information and communications technology (ICT): individuals using the internet (per cent of population) (World Bank, 2023f).

Table 2.2 **Trend analysis of indicators of important indirect drivers affecting the nexus elements.**

Where data allowed, linear regression analysis against time and the Mann-Kendall test were conducted for a long-term (1981-2021, according to data availability) as well as for a more recent (2001-2021 according to data availability) period to assess trends. Trend columns depict significant annual growth rates. Significance of the trend was assessed using the t-test in the linear regression (p-value < 0.05) and the Mann-Kendall test (absolute value of 'Kendall's tau' > 0.3) including a Bonferroni correction. **Figure 2.6** provides time series plots of the indicators. For detailed information on used indicators and methods as well as exact p-values, see the associated data management report[3] and **Box 2.1**.

INDICATOR OF INDIRECT DRIVER		Trend			Data availability
		Since 1981	Since 2001		
Economic	GDP	5.46%	4.82%	↑	1981–2021
	Material intensity	–3.00%	–2.33%	↘	1981–2019
	Trade	6.91%	5.33%	↑	1981–2021
	Poverty	–4.30%	–6.97%	↓	1981–2019
Demographic	Population	1.38%	1.20%	↗	1981–2021
	Urbanization	0.89%	0.91%	↗	1981–2021
Institutional	Regulations (environmental)	8.95%	7.43%	↑	1981–2021
	Armed conflicts	1.39%	3.05%	↑	1989–2021
Cultural	Knowledge/literacy	0.59%	0.36%	↗	1981–2020
	Per capita consumption	-	1.40%	↗	2000-2021
Technology	Renewable energy (solar and wind)	29.24%	21.70%	↑	1981–2021
	Use of ICT	20.76%	9.46%	↑	1990–2021

Trend characterization, annual growth rate since 2001

↑ > +3.0%   ↗ 0.3 to 3.0%   → –0.3 to 0.3%   ↘ –0.3 to –3.0%   ↓ < –3.0%

2.3.2.1 Economic drivers

The global economy grew by 3.5 per cent on average per year since 2001, but with the impacts of the financial crisis in 2008 and the COVID-19 pandemic clearly visible **(Figure 2.6; Table 2.2)**. Trade and GDP growth are correlated **(Figure 2.6)**: trade is a driver of economic growth, but also stimulated by it. GDP growth and trade are important for further increasing prosperity in many world regions and helping to alleviate poverty – although many other aspects that determine wealth distribution, such as inequality, governance and education, also play a decisive role (Piketty & Saez, 2014).

The continuing strong correlation between GDP growth and GHG emissions underpins the long-standing call to decouple the world's economy from its reliance on fossil fuels (IPBES, 2019a; IPCC, 2022b). Increasing GDP and trade have had a strong impact on past trends in all direct drivers, in particular land- and sea-use, resource extraction, climate change and pollution – with associated negative, variable or – in case of food provisioning – also positive impacts on nexus elements

(Figure 2.11). Given the strong correlation, it is not possible to clearly differentiate between nexus impacts caused by trends in trade *versus* those caused by trends in GDP, apart from IAS for which the movement of goods through trade has been a dominant driver. Trade and international travel also move organisms and animal products that include infection hosts and vectors, increasing the risk of zoonoses and other infectious diseases (Fisher *et al.,* 2012; Harvey *et al.,* 2023; IPBES, 2020).

Improving efficiency, such that the same economic value is created from less resources, of energy, water or material inputs is considered one of the levers towards slowing GHG emissions and over-extraction and is regarded as an important factor to foster environmentally sustainable growth in poor societies (Papież *et al.,* 2022; Ringler *et al.,* 2013). Declining trends in material intensity over the last decades **(Figure 2.6; Table 2.2)** may have contributed to the observed decline in the annual growth of GHG emissions in some regions (Friedlingstein, O'Sullivan, *et al.,* 2022) **(Figure 2.10)**. This, however, must be treated with caution, as material intensity is measured as domestic material consumption per unit of GDP, which also captures income generation by service-oriented societies. Literature to assess the impact of improved material intensity on direct drivers of the nexus, and on the nexus elements themselves, is scarce. With the exception perhaps of food provisioning (i.e., improved harvest index of cereals; M. Liu *et al.,* 2022), global impacts so far are likely to have been insubstantial **(Figure 2.11, Figure 2.12).** Trends in material intensity observed over the last decade have levelled-off **(Figure 2.6)**, but rebound effects may be at play, whereby increasing resource use efficiency is generating an increase in resource consumption (Thiesen *et al.,* 2008).

Eradicating poverty has been one of the foremost priorities in the 2030 Agenda for Sustainable Development. Poverty has declined **(Figure 2.6)**, but trends have slowed since 2015, and the combined impacts of the COVID-19 pandemic, inflation and price increases following recent conflicts have impeded – or even reversed – progress **(Box 2.6)** (UN, 2023a). Within the nexus, declining poverty has had and will have mixed impacts. Rural populations in poorer countries rely disproportionally on direct, often unsustainable, resource extraction from ecosystems for sustaining their livelihoods (an estimated 3.5 billion people, or 45 per cent of the human population (Bailis *et al.,* 2015; Cawthorn & Hoffman, 2015; IPBES, 2022). However, per-capita consumption of area- and input-intensive goods correlates with income (IPCC, 2019b), with the use of land and sea areas, materials and energy rising as people have higher incomes. There is considerable inequitable distribution of resource-use, as evidenced by a small high-income proportion of the world's population being responsible for a large share of GHG emissions (Chancel *et al.,* 2023). Given both increases and decreases of poverty can lead to increased use of different types of resources combined with the mixed trends in poverty, little overall effect on direct drivers of the nexus elements is expected globally.

2.3.2.2 Demographic drivers

Even though population growth itself has slowed in recent years, the world's population continues to grow and in 2022 reached 8 billion. This growth is unequal among countries and tends to be concentrated among the lowest per capita regions. A growing population requires food, housing and energy, and consequently, land- and sea-use change, resource extraction, GHG emissions and pollution all continue to correlate with human population growth, while the associated nexus impacts are assessed to be broadly similar **(Figure 2.11, Figure 2.12, Figure 2.13)**.

Urbanization is an additional key indicator of demographic drivers, with more the 50 per cent of the world's population now living in urban environments and the wildland-urban interface globally covering nearly 5 per cent of the land surface (Schug *et al.,* 2023). Impacts of urbanization on direct driver trends have been in some respects similar (but smaller) to those of population growth, but differences need to be considered. Urban land is often co-located with land suitable for agriculture and/or in coastal areas, such that despite urban area being small globally, notable impacts on nexus elements in the immediate vicinity of cities are increasingly taking place (e.g., van Vliet *et al.,* 2017). At the same time, urban growth and people's lifestyles affect land- and sea-use, food provisioning and freshwater supply and quality far beyond the cities' boundaries (Güneralp *et al.,* 2020). Similarly, the extraction of resources from land and marine systems for urban infrastructure impacts local climate and pollution, thereby intensifying the effect of these other direct drivers on biodiversity, food and health **(Box 2.14)**.

2.3.2.3 Institutional drivers

Laws, policies and regulations that target important indirect drivers are among the best measures for effectively reducing the effects of direct drivers on biodiversity and the other nexus elements **(Box 2.2, Box 2.5)**. However, the increasing number of national environmental regulations (i.e., ca. 1990-2010, **Figure 2.6**) and important international agreements, such as the Kunming-Montreal Global Biodiversity Framework and the Paris Agreement, have not had the desired effects globally **(Figure 2.4, Figure 2.11, Figure 2.13)**, given the continued increase of direct drivers and their negative impacts within the nexus. Moreover, the number of environmental regulations has increased more slowly over the last 10 years (see UN, 2019a).

Some policy measures have been an exception and led to reduced levels of some pollutants in some regions (e.g., levels of aerosol particles or sulphate in the atmosphere and rainwater in Europe and the U.S., and levels of some heavy metals (Y. Li *et al.,* 2019; Sicard *et al.,* 2023) **(Box 2.5)**. There is also evidence that the effectiveness of protected area implementation is a key factor for its success in protecting biodiversity (Arneth *et al.,* 2023), with co-benefits for other nexus elements. In some regions, progress has been made regarding upstream/downstream water access and reduction of conflicts over dams through international and transboundary treaties and agreements (Y. Zhao *et al.,* 2022). Overall, however, effective environmental and social legislation and policy that takes into consideration the concerns of local actors as part of inclusive and integrated governance systems have shown limited implementation (see **Chapter 4**) or not had detectable impacts on trends. Accordingly, improvements in governance across the nexus are a necessary step towards just and sustainable futures (c.f. **Chapter 7**).

The importance of stable institutional environments for addressing nexus challenges is also demonstrated by the indirect driver of armed conflicts, which have increased over the last years. Demonstrating a clear link between weakened institutional capacity and direct drivers is challenging and thus its understanding remains mostly inconclusive or unresolved, although individual case studies provide compelling arguments **(Box 2.6)**. The literature points to complex relationships regarding resource extraction in which weakened capacity to enforce regulations can both increase or decrease unsustainable uses and/or lead to displacement effects. Likewise, emissions arising from

Box 2 5 Successful policy implementation to reduce atmospheric pollution.

In the late 20th century, concerns over environmental degradation led to significant policy decisions aimed at mitigating acid rain from sulphur dioxide (SO_2) and nitrogen oxides (NOx), the primary precursors of acid rain, and ozone depletion caused by chlorofluorocarbons (CFCs) (Grennfelt *et al.,* 2020; Montzka *et al.,* 2021; NOAA, 2023). These chemicals were causing severe ecological and atmospheric damage and were considered serious transboundary environmental problems. Acid deposition affects the survival of trees and forests by removing vital nutrients from the soil and by destroying the outer coating of leaves; the acidity in the water leads to biodiversity loss **(Figure 2.7)**, affecting food supply and water quality, and consequently, human health. Moreover, acid particles can directly affect human health causing respiratory problems (Grennfelt *et al.,* 2020).

Figure 2 7 **Effects of acid rain on forests, Jizera Mountains, Czech Republic.**

From: Lovecz, (2006), under license PDM (public domain mark).

The successful control of acid rain was through a combination of strong environmental policies and technological advancements. Key policies include the Clean Air Act in the United States, the National Emission Ceilings Directive in the European Union, the Convention on Long-Range Transboundary Air Pollution and the 1985 Helsinki Protocol on the Reduction of Sulphur Emissions, which set strict limits on emissions from industrial facilities and power plants. As a result of these policies and collaborative initiatives, many regions have witnessed a remarkable decline in acid rain deposition, leading to improved environmental quality and ecosystem health.

Box 2 5

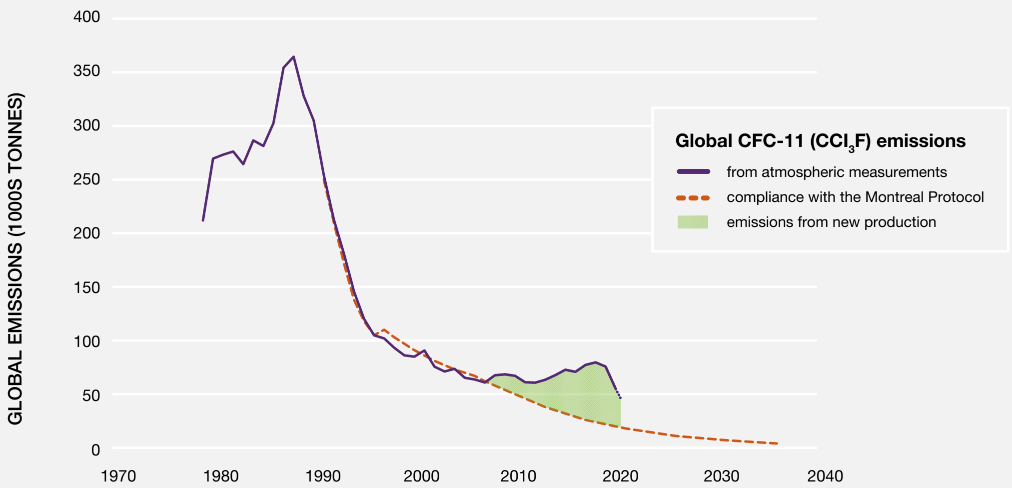


Figure 2 8 **Global CFC-11 (trichlorofluoromethane) emissions.**

The data is based on atmospheric measurements from the AGAGE global network, compared to expected emissions under the Montreal Protocol. From CSIRO (2021) based on data from Montzka *et al.* (2021), copyright CSIRO Australia and AGAGE (2024), one-time use of figure permission granted.

CFCs were found in many products, such as aerosol sprays and packing materials, and used as solvents and refrigerants for food preservation. The Montreal Protocol was a landmark international treaty, signed in 1987, which aimed to phase out the production and consumption of ozone-depleting substances (ODS), including CFCs, through establishing a timeline for the reduction, replacement and eventual elimination of these chemicals. Continuous monitoring of atmospheric ozone levels and strict enforcement mechanisms ensured adherence to the Montreal Protocol's regulations, with periodic revisions to strengthen its effectiveness, along with greater public awareness and education. The IPCC Sixth Assessment Report found that global stratospheric ozone levels underwent rapid decline in the 1970s and 1980s before showing signs of recovery, although they have not yet returned to preindustrial levels (IPCC, 2021).

Both of these situations were remedied by international cooperation and national policy decisions, backed by scientific research, leading to significant reductions in acid rain and the mitigation of ozone depletion and demonstrating the effectiveness of global agreements and efforts in addressing environmental challenges.

Box 2 6 War as a catastrophic driver of all nexus elements.

Since World War II, hundreds of national and international armed conflicts and hostilities have ravaged the globe, most of which have occurred within countries that contain biodiversity hotspots, and with the majority experiencing repeated episodes of violence (Daskin & Pringle, 2018; Hanson *et al.,* 2009; McNeely, 2003). While the number of deaths in armed conflicts was declining in absolute terms until recent conflicts **(Figure 2.9A)**, the total number of armed conflicts within and between states keeps increasing **(Figure 2.9B)**.

Armed conflicts have a direct and devastating impact on all sectors of the nexus: health (death and injury of people, destruction of healthcare systems); food (damage to agriculture and fishery facilities); water (damage to water supply facilities); and biodiversity (direct damage to ecosystems, deaths of animals and plants).

Armed conflicts have intensified direct drivers of biodiversity loss **(Figure 2.10)**, with a substantial number of deliberately environmentally damaging acts undertaken during conflicts, such as the use of herbicides and defoliants in Indochina from 1962-1971 during the Vietnam War (1955-1975), deliberate burning of oil wells in Kuwait (1991) and draining the Mesopotamian wetlands in Iraq (1993-2008). After 1950, 80 per cent of armed conflicts have damaged ecosystems and killed animals in biodiversity hotspots (Hanson, 2018; Hanson *et al.,* 2009). In Africa, conflicts affected 71 per cent of protected areas and led to severe declines in large animal populations (Brito *et al.,* 2018; Daskin & Pringle, 2018).

Recent conflicts have impacted food supplies and risked environmental pollution (Fileccia *et al.,* 2014; Rawtani *et al.,* 2022), and impacted global and regional economies and

Box 2 6

policies (Alexander *et al.,* 2022; European Commission, 2022, 2023; Guénette *et al.,* 2022; Ruta, M. (ed.)., 2022; UNCTAD, 2022a, 2022b; UNEP, 2022).

While armed conflicts may sometimes also have inadvertent short-term positive impacts on biodiversity as economic and exploitative activities are reduced (e.g., biodiversity protection in demilitarized zones), in most cases countries then prioritize rapid economic development over sustainable development in the post-war period if effective policies for sustainable development are not introduced (McElwee, 2016).

Armed conflicts exact a toll on IPLC as well, with militarization efforts leading to a reduction in land and resources available to them, higher levels of poverty, spread of diseases and degradation of the role of biodiversity in local development. About 79 per cent (4.4 million km^2) of the Indigenous Peoples' lands within biodiversity hotspots had experienced armed conflict (Beattie *et al.,* 2023). However, even with conflicts, in some cases IPLC manage to deliver conservation successes. For example, the Democratic Republic of Congo has experienced significant biodiversity loss due to protracted regional conflicts and unchecked exploitation of natural resources (Beyers *et al.,* 2011; Draulans & Van Krunkelsven, 2002; Waller & White, 2016). Yet even after armed conflict, the environmental quality of Indigenous Peoples' lands in biodiversity hotspots surpasses that of non-Indigenous lands (Beattie *et al.,* 2023).

In addition to far-reaching transboundary effects, armed conflicts have impacted institutions and governance mechanisms. Armed conflicts can divert resources away from other investments necessary for transforming to sustainable development or can diminish social and political capital that is also necessary for this transition (McElwee, 2016). Additional erosion of political opportunities can be seen in a decline in the population-weighted liberal democracy index **(Figure 2.9C)**, indicating that liberal, democracy-based governance models are increasingly challenged. This makes it difficult for inclusive, integrated and cooperative policies to be developed and adopted, despite these approaches being more likely to be effective in addressing nexus interlinkages and challenges (see **Chapter 4**).

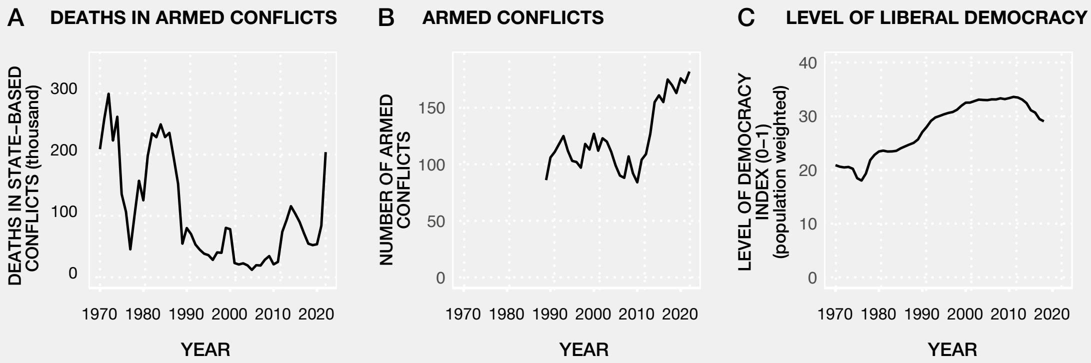


Figure 2 9 **Global values on conflict related indicators.**

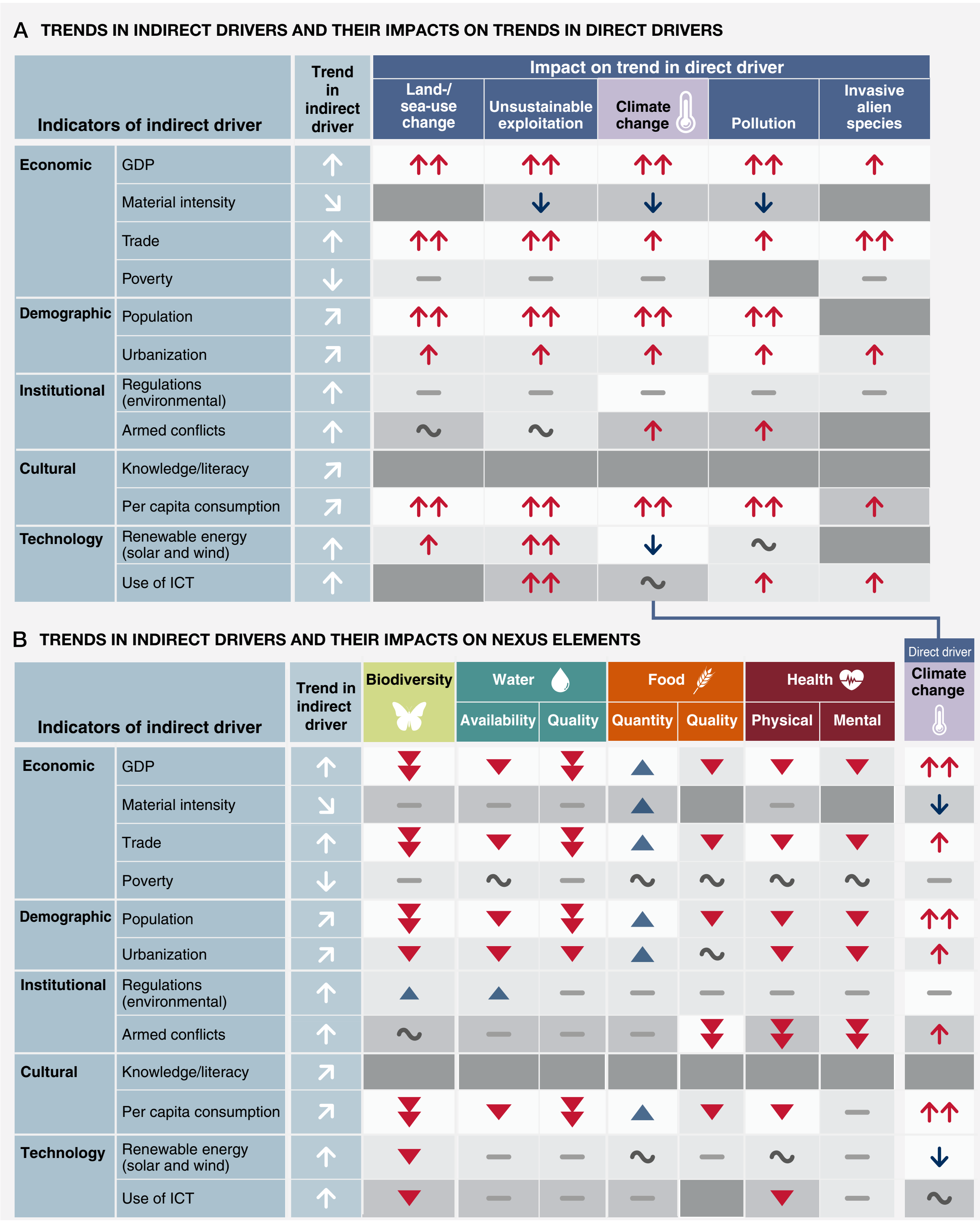
(A) Number of deaths in state-based armed conflicts (UCDP & PRIO, 2023 – processed by Our World in Data); **(B)** Number of armed conflicts (UDCP & PRIO, 2023a, 2023b, 2023b, 2023c, 2023d – processed by Our World in Data); **(C)** Population weighted average level of liberal democracy index (V-Dem, 2024; FAOSTAT, 2023a).

the military sector and war have contributed to past GHG emissions and pollution, such that geopolitical conditions that foster continued armament resonate to nexus elements via a range of different drivers – beyond the obvious direct negative impact of warfare on physical health, which occur independent from changes in direct drivers.

2.3.2.4 Cultural drivers

Per-capita consumption has been increasing rapidly in some societies over recent decades and has been among the most significant indirect drivers of trends in direct drivers **(Figure 2.6)**, with cascading effects on multiple nexus elements. Large increases in the consumption of animal protein (Afshin *et al.,* 2019), both marine and terrestrially sourced, is one example of this trend **(Figure 2.6)**, but this is also seen elsewhere, such as per-capita energy or housing area. Given the well-known correlation between income and consumption, impacts on the nexus elements are assessed to be similar in most cases to those from GDP. For example, access to more food is essential to reduce malnutrition, but can also lead to obesity (Mbow *et al.,* 2019). However, higher per-capita consumption can also reduce anxieties over undernourishment (Weinreb *et al.,* 2002).

Local culture and the level of environmental knowledge (either through formal education or as ILK) can be an important factor in the sustainable use of resources by providing knowledge to understand the consequences of over-use and to develop alternative use strategies (Bates *et al.*, 2022; Begum *et al.*, 2022; McKenzie, 2021; Molina *et al.*, 2023; Rad *et al.*, 2022). Literacy is an important indicator of education that has globally increased over recent decades. There is some evidence that education can support changes in people's attitudes towards addressing challenges and thus have impacts on direct drivers and nexus elements **(Figure 2.10, Figure 2.11)**. However, despite a positive relationship being demonstrated in several studies between increasing knowledge on environmental and health challenges and more sustainable behaviour by individuals (McKenzie, 2021, see also DMR[3]), the overall increasing levels of literacy appear to be insufficient to slow unsustainable per-capita consumption



Trend characterization, annual growth rate since 2001
- > +3%
- 0.3 to 3%
- -0.3 to 0.3%
- -0.3 to -3%
- < -3%

How trend in indirect driver impacted trend in direct driver
- Intensification
- Modest intensification
- Stable/little impact
- Small reduction
- Large reduction
- Variable

How trend in indirect driver impacted trend in nexus element
- High positive impact
- Moderate positive impact
- Stable/little impact
- Moderate negative impact
- High negative impact
- Variable

Level of evidence of impact
- Well established
- Established but incomplete
- Unresolved
- Inconclusive

Figure 2.10 **Trends in indirect drivers and their impacts on trends in direct drivers.**

The figure synthesizes established knowledge from a global perspective on how trends of important indirect drivers **(Figure 2.6)** affect trends in direct drivers. Recent trends (2001 to 2021, according to data availability) of indirect drivers **(Table 2.2)** are displayed as arrows in column 'Trend in indirect driver'. Impact of these trends on direct drivers are displayed as arrow icons in the respective direct driver column. Background shading in the direct driver columns refers to the level of evidence of the knowledge synthesis. See **Figure 2.6** for trends of important indirect drivers. Detailed information supporting the assessment can be found in the associated data management report[3] and **Box 2.1**.

(Figure 2.6). This may be a function of differences between general literacy and specific exposure to environmental education (which not everyone who is literate is getting).

The positive global trends among some indicators **(Figure 2.6, Figure 2.13)** should not distract from the large unequal distribution behind them. The fact that food produced globally could provide sufficient calories to everyone on the planet highlights that malnutrition and hunger are an issue of inequality and not insufficient production of food (Duro *et al.,* 2020). In 2021, globally the top 10 per cent of emitters were responsible for almost half of global energy-related CO_2 emissions. Furthermore, the richest 0.1 per cent of the world's population emitted 10 times more than all the rest of the richest 10 per cent combined, exceeding a total footprint of 200 tonnes of CO_2 per capita annually (IEA, 2023; Kartha *et al.,* 2020). This is mostly due to unequal access to energy. Inequality in the distribution of energy footprints varies across different goods and services. Energy-intensive goods tend to be more elastic, leading to higher energy footprints of high-income individuals, which results in large inequality in international energy footprints: the consumption share of the bottom half of the population is less than 20 per cent of final energy footprints, which in turn is less than what the top 5 per cent consume (Oswald *et al.,* 2020). Acting on consumption as an important indirect driver, therefore, means both reducing total consumption by those that consume the most, while simultaneously also allowing poor societies to enlarge their per-capita consumption to a comfortable level.

2.3.2.5 Technological drivers

Technology is an important indirect driver that supports economic development, including green growth and poverty reduction. Important indicators such as patent applications, access to information and communication technologies (ICT) and renewable energy capacity have strongly increased in recent years **(Figure 2.6)**.

Renewable energies, especially wind and solar power, are essential to counter climate change. While these have begun to reduce annual GHG emission growth, the impact on mitigating climate change has so far been too small to resonate to nexus elements. A particular challenge of technological development in view of solving sustainability challenges arises from its reliance on mined resources. The enhanced demand for minerals and their often destructive and polluting way of extraction contributes to already existing pressures on biodiversity, the freshwater system and health. However, literature on these nexus interactions remains scarce **(Section 2.5.1)**. Renewable energy, such as wind and solar power, has obvious benefits regarding reduction of air pollution **(Figure 2.11, Figure 2.12)**.

Increased land area use for renewable energy (until now mostly area demands for bioenergy crops) has begun to compete with food production by expanding into agricultural land **(Figure 2.11)**, although these conflicts could in principle be resolved (e.g., agri-voltaics; Hernandez *et al.,* 2019). Consequently, expansion of existing bioenergy crops continues to have direct and indirect land-use changes and increases in food prices with related negative impacts on all nexus elements (Arima *et al.,* 2011; Heck *et al.,* 2018; Persson, 2015; Verstegen *et al.,* 2016). Another energy-related but independent concept that aims to reduce atmospheric CO_2 is the large-scale application of bioenergy with carbon capture and storage (BECCS), which is considered in many future scenarios that are simulated in Integrated Assessment Models. However, this technology is not yet economically viable, nor is there a wider acceptance for investing in developing the technology further (Fridahl & Lehtveer, 2018).

Overall, technological drivers seem to have had limited importance when addressing challenges related to the nexus elements. In cases where impacts arising from technology have already been found, these have mostly been negative or

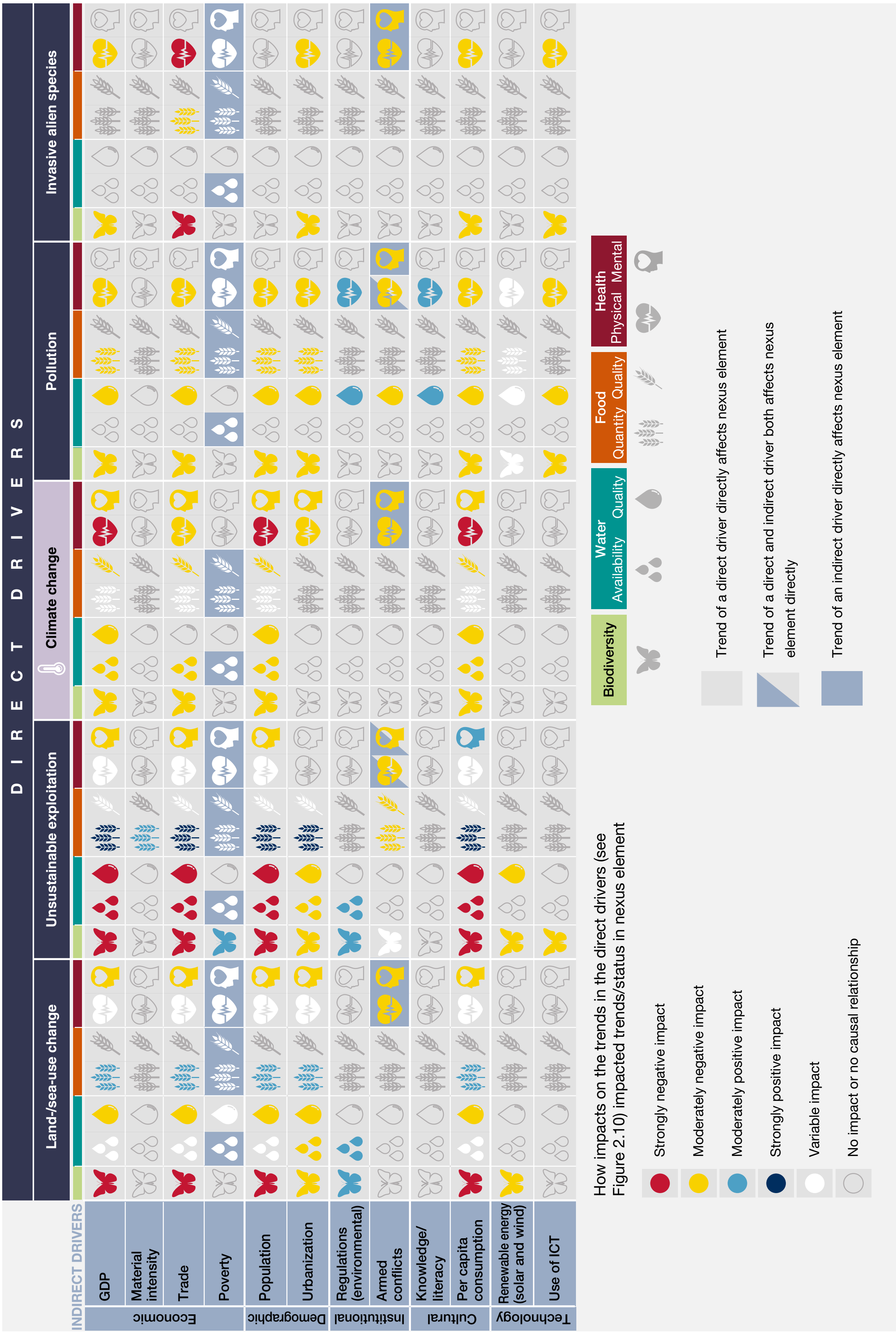

DIRECT DRIVERS
Land-/sea-use change
Unsustainable exploitation
Climate change
Pollution
Invasive alien species
INDIRECT DRIVERS
Economic
GDP
Material intensity
Trade
Poverty
Demographic
Population
Urbanization
Institutional
Regulations (environmental)
Armed conflicts
Cultural
Knowledge/ literacy
Per capita consumption
Technology
Renewable energy (solar and wind)
Use of ICT
How impacts on the trends in the direct drivers (see Figure 2.10) impacted trends/status in nexus element
Strongly negative impact
Moderately negative impact
Moderately positive impact
Strongly positive impact
Variable impact
No impact or no causal relationship
Biodiversity
Water
Availability
Quality
Food
Quantity
Quality
Health
Physical
Mental
Trend of a direct driver directly affects nexus element
Trend of a direct and indirect driver both affects nexus element directly
Trend of an indirect driver directly affects nexus element

Figure 2 11 Impact of trends in indirect drivers on the nexus elements.

Synthesis of established knowledge from a global perspective on how trends in indirect drivers (since 2001) affect the nexus elements (coloured icons) via the impact of indirect drivers on the trends in direct drivers (see **Figure 2.4** and **Figure 2.10**). In addition, some indicators of indirect drivers are also important direct drivers in the nexus (e.g., poverty or number of armed conflicts) (dark grey cell background). Climate change is included as a direct driver not a nexus element. Renewable energy refers mostly to solar and wind. See **Figure 2.6** and **Table 2.2** for long-term temporal trends of included indirect drivers. Detailed information supporting the assessment can be found in the associated data management report[3] and **Box 2.1**.

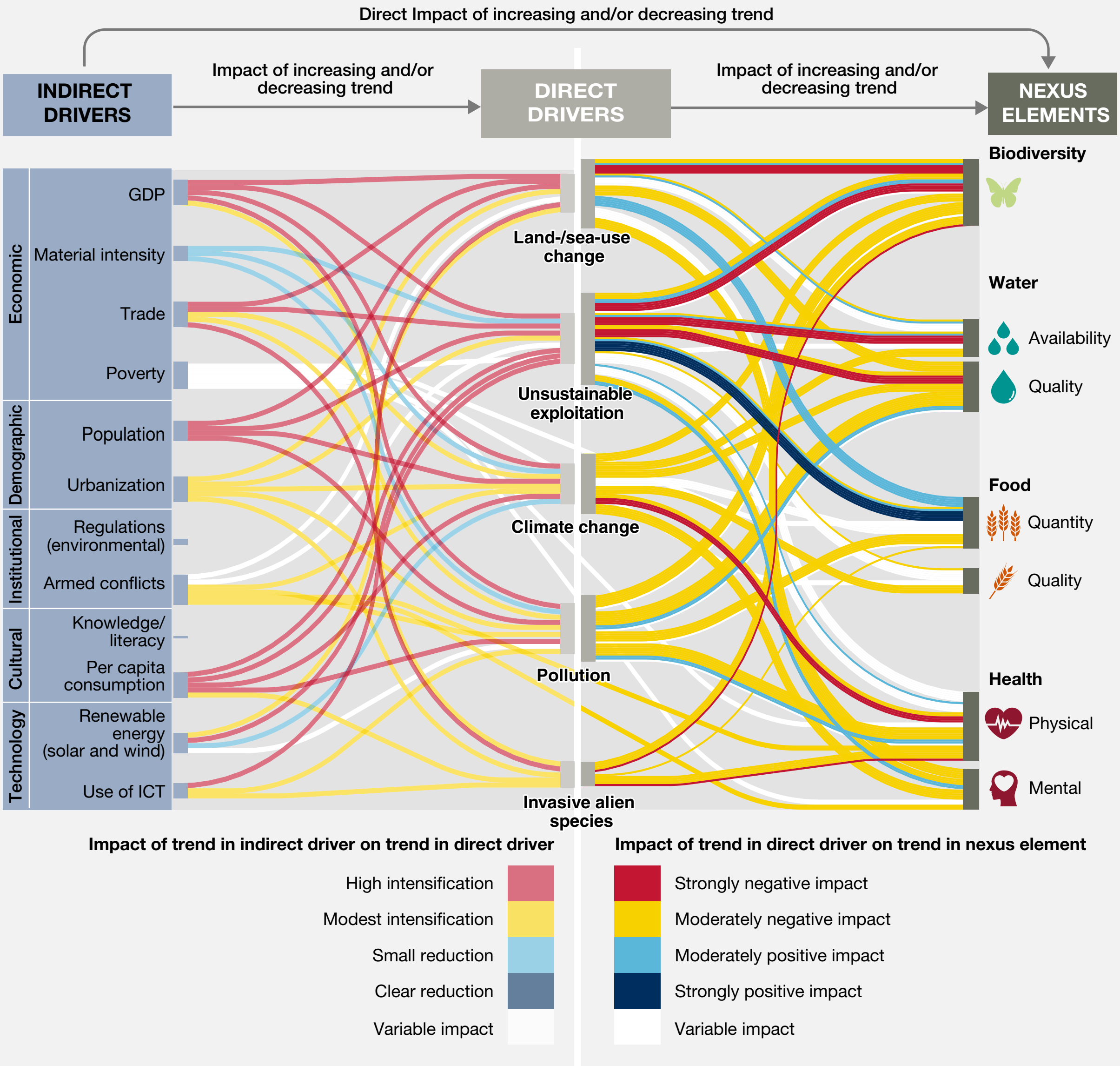


Figure 2 12 Impact of trends in indirect drivers on direct drivers and on the nexus elements.

Established knowledge from a global perspective (since 2001), from **Figure 2.10** (left) and **Figure 2.11** (right), are displayed in an aggregated version as a Sankey diagram (see **Table 2.2**, **Figure 2.4** and **Figure 2.10**). The impacts of trends in indirect drivers (nodes on left side) are shown as flows (lines), coloured according to the strength of impact (high intensification; modest intensification; small reduction; clear reduction or variable) on direct drivers (nodes in the middle). The respective changes in the impact of the trends of the direct drivers on the nexus elements (nodes on the right side: biodiversity, water quantity, water quality, food quantity, food quality, physical health and mental health) are displayed as flows coloured by the strength of impacts (strongly negative; moderately negative; moderately positive; strongly positive or variable impact). The width of each flow and node reflects the total number of possible impacts on the direct drivers and on the nexus elements. For example, available knowledge shows that mental health is

Figure 2 12

mostly impacted at a moderately negative level by climate change and direct exploitation (people working in industries such as mining). However, mental health is also moderately positively impacted through direct exploitation (allowing a reduction of malnutrition) as different indirect drivers moderate the effect (see **Figure 2.11**). Note that trends in indirect and direct drivers include both increasing or decreasing trends, which affects the resulting impact. For example, increasing or decreasing trends in some forms of pollution result in differing impacts on nexus elements such as health and water quality **(Figure 2.11)**. Note also that some indirect drivers have direct impacts on the nexus elements rather than via the direct drivers (notably poverty and armed conflicts). For example, current trends in declining poverty directly impact physical health, but variably. Where no flow is displayed, either the evidence is insufficient or the recent trends are unclear (e.g., see knowledge/literacy in **Figure 2.10**). Detailed information supporting the assessment can be found in the associated data management report[3] and **Box 2.1**.

variable **(Figure 2.11, Figure 2.12)**. Limitations in indicators precludes a more quantitative analysis in many cases and the literature on connecting trends in these indirect drivers is scant. Nevertheless, access to technology in principle could be an important aspect for solving sustainability challenges, e.g., by decarbonising the energy sector or adopting precision-farming.

2.3.3 Status and trends of nexus elements

Direct and indirect drivers affect the nexus elements of biodiversity, water, food, health and climate change in multiple ways (outlined in **Figure 2.1**). Consequently, indicators of global trends in nexus elements can only provide a broad overview of trends as such indicators aggregate information, including multiple feedbacks and non-linearities **(Section 2.5)**.

The different indicators characterise similar decadal trends for all nexus elements for the period 1961-2020 **(Figure 2.13)**. Trends in land expansion and intensification of land-use **(Section 2.3.1.1)** have resulted in biodiversity declines across all three indicators: Biodiversity Intactness Index (BII, see **Glossary** for definition), Living Planet index and Red List species index (-2 per cent, -6 per cent, -4 per cent per decade, respectively) **(Figure 2.13)**. Trends in biodiversity decline are more easily depicted from the decline in relative abundance of global wildlife populations (based on the Living Planet Index indicator). This indicator shows an average decline of 69 per cent from 1970 to 2018, with Latin America showing the greatest regional decline (94 per cent) and freshwater species populations the greatest overall global decline (83 per cent). Currently, only 16 per cent of terrestrial and inland aquatic ecosystems, 8 per cent of marine ecosystems (UNEP-WCMC & IUCN, 2021) and less than half of terrestrial and aquatic key biodiversity areas are covered by protected areas. In addition, despite consistent expansion over time, the number of new protected areas being created has slowed recently (UN, 2022).

The availability and quality of water is regionally variable and shows a very diverse pattern. However, increasing trends are shown for ocean acidification and water stress (+6 per cent per decade since 2000) **(Figure 2.13)**. A loss of 21 per cent (confidence interval 16–23 per cent) of global wetland area can be robustly estimated for the last 300 years (Fluet-Chouinard *et al.,* 2023). This net loss is lower than estimated previously, which suggests average values of 54-57 per cent or even more than 80 per cent loss of wetland area since 1700 AD (IPBES, 2019b) These estimates, however, are based on extrapolations of data disproportionately representing high-loss regions (Davidson, 2014; Fluet-Chouinard *et al.,* 2023). Globally, 59 per cent of large river systems are transformed by dams (Purvis *et al.,* 2019). In Europe, between 2008-2011, 30-50 per cent of water bodies were under pollution pressure and 40 per cent of rivers and 30 per cent of lakes were affected by habitat disturbance (European Environment Agency, 2012). Natural wetlands in Asia are declining more rapidly than elsewhere, and human-altered wetlands are increasing, mainly through the conversion of natural wetlands into paddy fields, land-use changes and IAS (Convention on Wetlands, 2021; Fluet-Chouinard *et al.,* 2023; Purvis *et al.,* 2019; Ramsar Convention on Wetlands, 2018; UNESCO, 2018).

Globally, 59 per cent of large river systems are transformed by dams (Purvis *et al.,* 2019). In Europe, between 2008–2011, 30-50 per cent of water bodies were under pollution pressure and 40 per cent of rivers and 30 per cent of lakes were affected by habitat disturbance (European Environment Agency, 2012). Natural wetlands in Asia are declining more rapidly than elsewhere, and human-altered wetlands are increasing, mainly through the conversion of natural wetlands into paddy fields, land-use changes and IAS (especially in Africa; Adeeyo *et al.,* 2022; Aitali *et al.,* 2022; Bhowmik, 2022; Davidson, 2014; Wasserman & Dalu, 2022).

Food production per capita has increased if measured by cereal (+8 per cent per decade) or livestock (+2 per cent per decade) production, while fish catch has slightly decreased (-0.4 per cent per decade, mainly due to a decrease since 1990) **(Figure 2.13)**. These increases in food production have improved human health through available calories, but have led to biodiversity loss (e.g., the Living Planet Index fell by 20 per cent per decade since 2001) and increases in emerging infectious diseases (arrow 16, **Figure 2.1**) (IPBES, 2020; Keesing *et al.,* 2010). Direct use of wildlife, including wildlife hunting, trade and farming has been the likely source of several emerging disease events (IPBES, 2020).

As a global average, life expectancy is increasing (+5 per cent per decade), and child mortality (-15 per cent per decade) and child malnutrition (-25 per cent) is declining **(Figure 2.13)**, although the data clearly shows how the COVID-19 pandemic has led to a global decline in life expectancy after 2020. Life expectancy at birth has increased drastically over recent centuries, with substantial improvements all over the world – from 51.1 years in 1950 to 73.5 years in 2019 (H. Wang *et al.,* 2020), mostly due to improvements in hygiene, healthcare, advancements in medicine and more diverse diets. Improvements to child mortality is leading to some populations having large numbers of young people, such as in sub-Saharan Africa, yet globally women are having fewer children and people are living longer. Due to this greater longevity and lifestyle and dietary changes, the prevalence of non-infectious chronic diseases has increased, accounting for a greater share of overall mortality (Barrett *et al.,* 1998; van Oostrom *et al.,* 2016). Diabetes and obesity have escalated in recent decades (FAO, IFAD, PAHO, *et al.,* 2023; J. Lawrence *et al.,* 2021; Melo *et al.,* 2023); between 1980 and 2020-2021, the number of adults with diabetes (90 per cent of which is type 2) increased from 108 million to 537 million, with corresponding increases in obesity from 100 million to 764 million adults (International Diabetes Federation., 2021). This phenomenon is global: no nation has experienced a decline in diabetes or obesity in the last 40 years (International Diabetes Federation., 2021), which can be linked with increases in suboptimal and less diverse diets (Golden *et al.,* 2011; Mozaffarian, 2016), and with economic costs of obesity reaching on average 2.19 per cent of GDP (Okunogbe *et al.,* 2021).

Mental health conditions have also significantly increased all over the globe (Patel *et al.,* 2018). In the United States between 2016 and 2019, anxiety increased by 27 per cent and depression by 24 per cent (Lebrun-Harris *et al.,* 2022), exacerbated by the COVID-19 pandemic (Yard, 2021). Emerging infectious disease events have risen significantly over time, including fungal diseases (Fisher *et al.,* 2018), those caused by pathogens originating in wildlife and by drug-resistant microbes (K. E. Jones *et al.,* 2008). Globally, infectious diseases account for approximately 16 per cent of all deaths and 44 per cent of deaths in low-resource countries (H. Wang *et al.,* 2016). In addition, the loss of traditional knowledge of biodiversity has resulted in declines in traditional medicine use by many IPLC **(Box 2.7)**.

For all indicators of the nexus elements, the trends are either most harmful to, or less beneficial for, low-income countries (LICs) **(Figure 2.13)**. Biodiversity decline (as measured by the Biodiversity Intactness Index) is also strongest in these countries, while gains in livestock and fish catch are greatest for high-income countries (HICs). Countries with a high share of agricultural production in their GDP also have the greatest deforestation, with a consequent substantial loss of ecosystem functioning (Václavík *et al.,* 2013). Total agricultural production continued to accelerate until approximately 2008 and since then has slowed (Seppelt *et al.,* 2014). This has benefitted mostly HICs with above average food supply, but also above average water stress **(Figure 2.13)**.

Health outcomes are also unequal – for example, in Sub-Saharan Africa the average life expectancy is 17 years less than in high-income countries (Singer *et al.,* 2001; H. Wang *et al.,* 2020). Child and maternal mortality have reduced, but with the same inequality patterns; the number of deaths under five years old decreased from almost 20 million to 5 million from 1950 to 2019, but LICs can have more than ten times higher rates of child mortality than HICs (H. Wang *et al.,* 2020). Trends in increases in agricultural production has not prevented more than 800 million people from suffering hunger (FAO *et al.,* 2022). Over 3 billion people (42 per cent of the global population) could not afford a healthy diet in 2021, with lower-middle-income countries (LMICs) having higher costs than HICs. Consequently, 86 per cent and 70 per cent of the population of LICs and LMICs cannot afford healthy diets (FAO, IFAD, UNICEF, *et al.,* 2023).

As populations experience transition towards diets high in processed foods and refined sugars, the number of overweight or obese people increases (Popkin *et al.,* 2012; Swinburn *et al.,* 2019). This leads to changes in the microbiome with observed impacts on human health in people with inflammatory bowel disease, psoriatic arthritis, types 1 and 2 diabetes, atopic eczema, coeliac disease, obesity and arterial stiffness more than in healthy controls (Valdes *et al.,* 2018). Poor diets and quality of food have therefore become one of the most important drivers of global mortality, accounting for nearly 11 million adult deaths in 2017 and 255 million disability-adjusted life years (DALYs) (15 per cent of all DALYs among adults) (arrow 5, **Figure 2.1**; Afshin *et al.,* 2019). In 2017, the global health risk from a diet low in whole grains was 3 million deaths and 82 million DALYs; from a diet low in fruits was 2 million deaths and 65 million DALYs; and from a diet low in nuts was 2 million deaths and 50 million DALYs (Afshin *et al.,* 2019). In addition, the global health risks in 2017 from a diet high in red meat include diabetes mellitus type 2 (934,010 DALYs; 8,954 deaths) and neoplasms (377,910 DALYs; 15,880 deaths) (Afshin *et al.,* 2019).

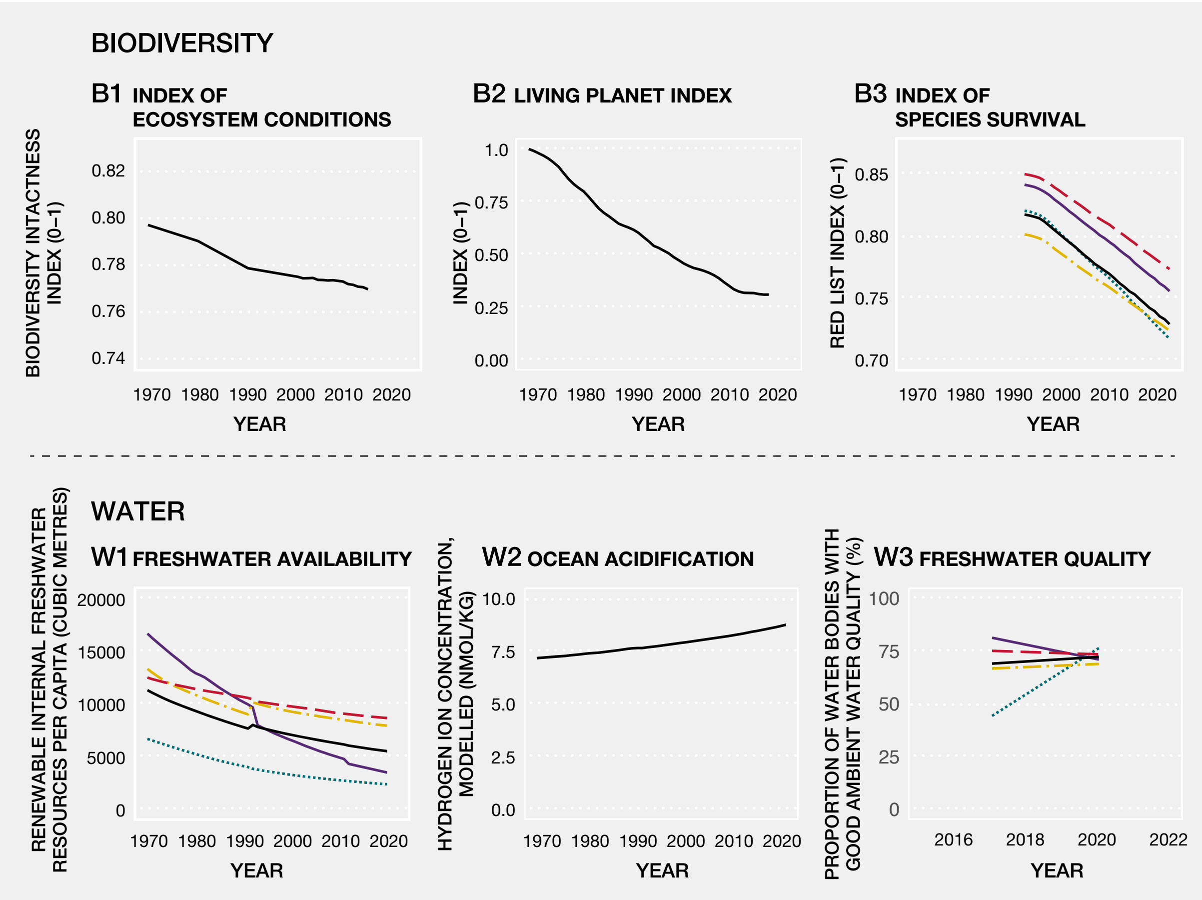
Undernutrition is the most common form of malnutrition in LICs (Kinyoki *et al.,* 2020) and can reduce the development and effectiveness of immune responses thereby increasing infections (Rohr *et al.,* 2019). Childhood undernutrition specifically is still a problem in LMICs (Vollmer *et al.,* 2017) due to low dietary diversity (Eshete Tadesse *et al.,* 2020; Kasimba, 2013), and despite decreases in global stunting prevalence, 149.2 million (or one in five) children under 5 were still stunted in 2020 (UNICEF *et al.,* 2021).

Box 2 7 **Decline of traditional medicine and the loss of traditional knowledge of biodiversity.**

The relationship between the decline of traditional medicine and loss of traditional knowledge of biodiversity is complex. Traditional medicine, as defined by the World Health Organisation, is the knowledge, skills and practices which are based on the theories, beliefs, and experiences of Indigenous Peoples and local communities from different cultures and used in the maintenance of health and the prevention, diagnosis and improvement or treatment of physical and mental health (WHO, 2023). Traditional knowledge of the use of wild species for medicine can be lost over time, particularly when transmission of this knowledge is discouraged or replaced by formal medical practices. Yet this traditional medicine has long been utilized to advance modern medicine itself. For example, willow bark is the basis of aspirin, while sweet wormwood (traditionally used to treat fever) is the source of an extract, called artemisinin, used to treat malaria. The process of vaccination in general was developed from traditional practices of inoculation.

Loss of knowledge regarding traditional medicine is a consequence of multiple socio-economic and environmental changes; this can include deforestation or loss of access to species which results in changes in how natural resources are used (Kodirekkala, 2017). Another trend regarding use and management of local wild species for medicine is urbanization and globalization. For example, in one study in Mexico, people in urban regions had a greater knowledge of introduced species, while those in rural regions had retained more knowledge of native and wild plants (Arjona-García *et al.,* 2021).

Information on the current challenges and status of traditional medicine in many countries is not available (Gakuya *et al.,* 2020). However, the high cost of modern medicines and increasing resistance to drugs such as antibiotics has led to some countries taking a different approach. For example, in Cameroon the Government has put in place a strategic platform for the practice and development of traditional medicine (Fokunang *et al.,* 2011). A WHO report in 2019 found that more than 170 states have some form of policy and programmes around traditional and complementary medicine, recognizing that traditional medicine has an important role in contributing to universal health coverage and the SDGs through primary health care (WHO, 2019) (see also **Section 5.4**). Thus, reversing the relationship between the decline of use of traditional medicine and traditional knowledge of wild species can help achieve the SDGs, particularly SDG 3 on good health and well-being.



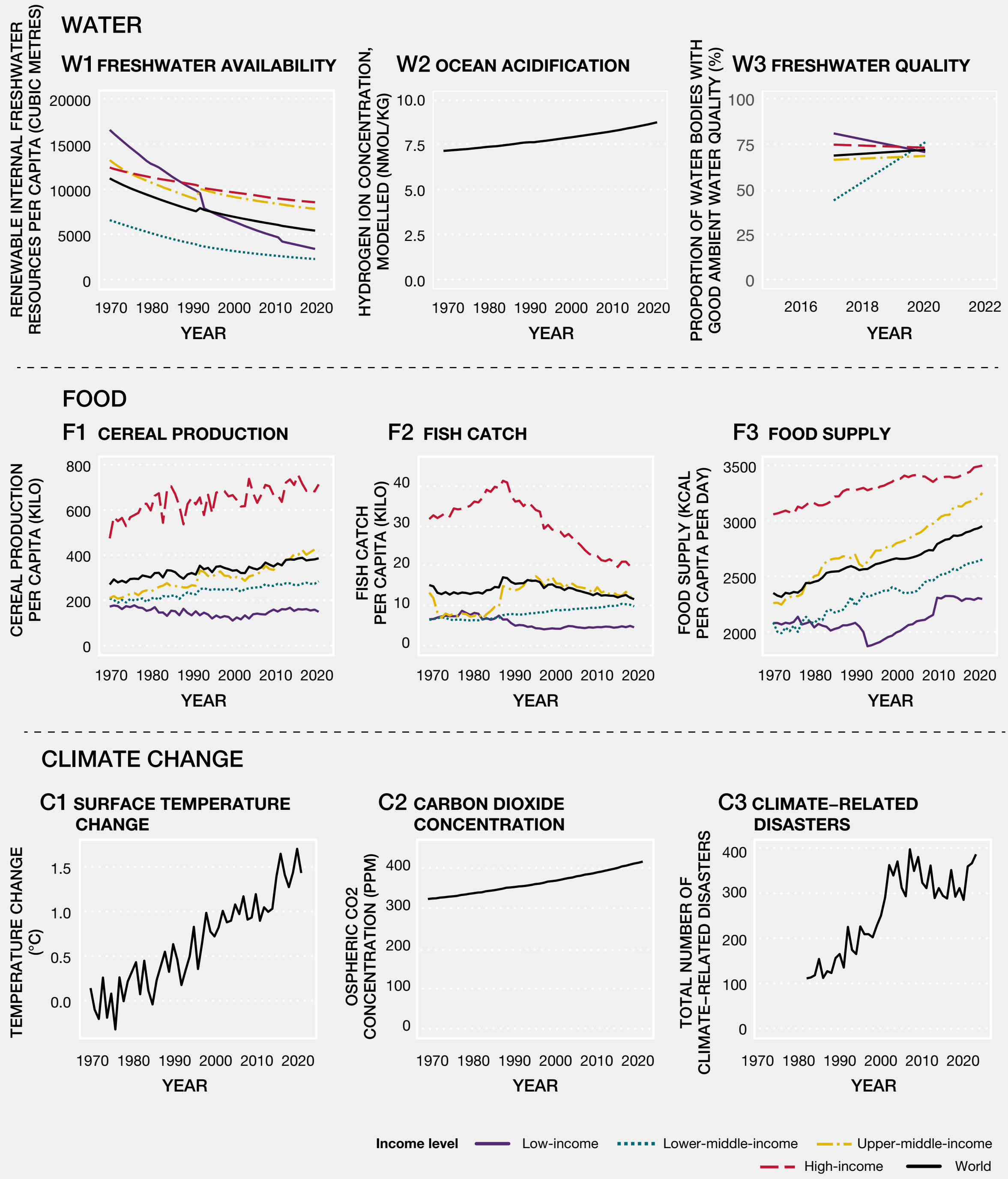


Figure 2 13 **Changes over time in indicators for the five nexus elements.**

Data cover the period 1970 to 2022. Time series shown are based either on global or country-level data that has been aggregated for four different income levels (World Bank, 2023m) and globally. Unless indicated otherwise, data shown are mean values. **Biodiversity**, represented by **(B1)** Biodiversity Intactness Index (see **Glossary**): Index (0-1) (Phillips *et al.,* 2021), **(B2)** Living Planet Index: Index (1970=1) (Zoological Society of London & WWF, 2022), and **(B3)**, Red List Index: Index (0-1) (BirdLife International & IUCN, 2023); **Water**, represented by **(W1)** Water stress: freshwater withdrawal as a proportion of available freshwater resources (per cent) (FAO AQUASTAT, 2021), **(W2)** Ocean acidification (mean hydrogen ion concentration; nmol/kg) (Ciais *et al.,* 2013), and **(W3)** Freshwater quality: proportion of bodies of water with good ambient water quality (UN, 2023b); **Food**, represented by **(F1)** Cereal production per capita (kilo) (World Bank, 2023c, 2023k), **(F2)** Fish catch: capture fisheries production per capita (kilo) (World Bank, 2023b, 2023k), and **(F3)** Livestock: number of live animals kept as livestock per capita (FAOSTAT, 2023b; World Bank, 2023k); **Health**, represented by **(H1)** Child mortality rate: mortality rate of children under 5 (deaths/1000 live births) (World Bank, 2023i), **(H2)** Child malnutrition: percentage of children under 5 years of age who are stunted (per cent) (UNICEF, 2023), and **(H3)** Life expectancy: life expectancy (in years) at age of 50 (Until, 2013);

Figure 2 13

Climate change, represented by **(C1)** Surface temperature change (°C) (FAOSTAT, 2023c), **(C2)** Carbon dioxide (CO_2 concentration: atmospheric CO_2 concentration (parts per million) (Keeling, 2022; NOAA, 2022), and **(C3)** Climate-related disaster frequency (disaster per year and country) (CRED, 2023b) (note: there are some data limitations – how effectively disasters are reported globally (CRED, 2023a); impacts (e.g., mortality) of the climate-related disasters are not shown which are generally greater in regions of high vulnerability, with low- and lower-middle-income countries being disproportionally affected (Birkmann *et al.,* 2023). For detailed information on used indicators and income levels, see the associated data management report[2] and **Box 2.1**.

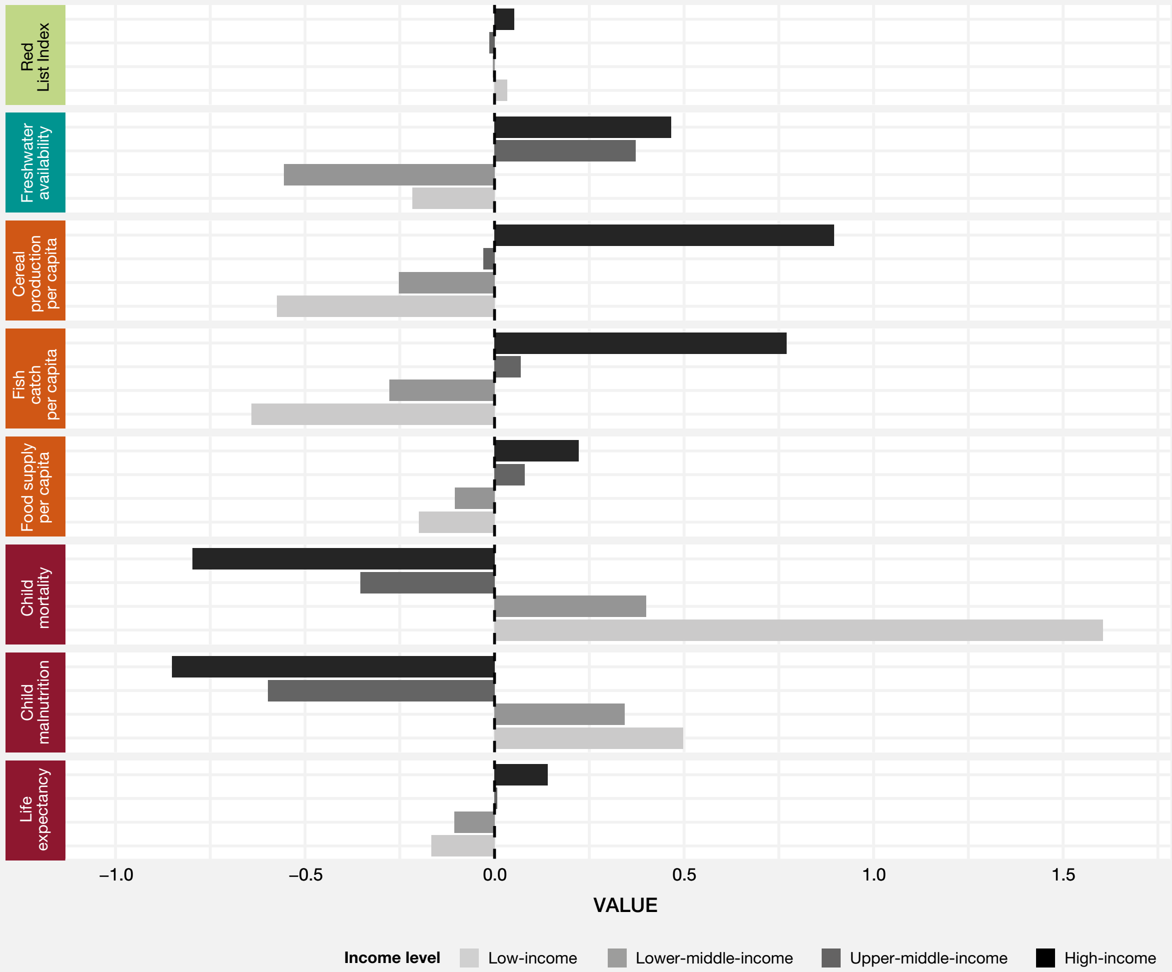


Figure 2 14 **Indicator mean values of income level groups relative to the global mean value.**

For the time period 2005-2014 indicator mean values were calculated for four income level groups (World Bank, 2023m) as well as a global mean value. Data was scaled such that the global mean value equals 0 (dashed line). Positive values signify that the respective income level mean is higher than the global mean while negative values signify that the respective income level mean is lower than the global mean. For detailed information on the used indicators and income levels, see the associated data management report[2] and **Box 2.1**. All indicators included in **Figure 2.13** for which country level data was available were considered: Biodiversity: Biodiversity Intactness Index (BII, see **Glossary**): Index (0-1) (Phillips *et al.,* 2021); Water: Water stress: freshwater withdrawal as a proportion of available freshwater resources (per cent) (FAO AQUASTAT, 2021); Food: Cereal production per capita (kilo) (World Bank, 2023c, 2023k); Fish catch: capture fisheries production per capita (kilo) (World Bank, 2023b, 2023k); Livestock: number of live animals kept as livestock per capita (FAOSTAT, 2023b; World Bank, 2023k); Health: Child mortality rate: mortality rate of children under 5 (deaths/1000 live births) (World Bank, 2023i); Child malnutrition: percentage of children under 5 years of age who are stunted (per cent) (UNICEF, 2023); Life expectancy: life expectancy (in years) at age of 50 (Until, 2013); and Climate change: Climate-related disaster frequency (disaster per year and country) (CRED, 2023b) (note: there are some data limitations – how effectively disasters are reported globally (CRED, 2023a); impacts (e.g., mortality) of the climate-related disasters are not shown which are generally greater in regions of high vulnerability, with low- and lower-middle-income countries being disproportionally affected (Birkmann *et al.,* 2023)).

2.4 INTERACTIONS BETWEEN BIODIVERSITY AND NEXUS ELEMENTS

Most knowledge on the interactions between the nexus elements comes from the well-studied two-way interactions between the different nexus elements. It is therefore necessary to summarize the most relevant evidence for the two-way interactions in a manner that highlights how these elements are directly linked with biodiversity before building the evidence base for the more complex (three-way and higher) interactions.

2.4.1 Biodiversity and water systems

As parts of the hydrological cycle, atmospheric water is the initial source of water on land, i.e., the blue water in rivers, wetlands and groundwater; green water in plants and soil; and grey water that has been used by people. Circulation of atmospheric moisture due to evaporation from inland ecosystems provides 20-50 per cent of precipitation over land globally and up to 70-80 per cent precipitation within vast inland regions (Creed & van Noordwijk, 2018; Ellison, 2018; Keys *et al.,* 2016; Tuinenburg *et al.,* 2020; van der Ent *et al.,* 2010; van Noordwijk *et al.,* 2014). For example, the forests of the Congo basin are the primary source of rainfall for the Sahel region, the Amazon forests account for 70 per cent of rainfall for the Rio de la Plata basin in Uruguay and Argentina, and Eurasian ecosystems are responsible for 80 per cent of China's water resources (van der Ent *et al.,* 2010).

Biodiversity supports vital nature's contributions to people by regulating all stages of the hydrological cycle (Creed & van Noordwijk, 2018; Ellison, 2018; van Noordwijk *et al.,* 2014), and healthy natural multi-species ecosystems do this more efficiently than human-made or disturbed simplified ecosystems (Creed & van Noordwijk, 2018; FAO, IUFRO & USDA, 2021; J. Jones *et al.,* 2020, 2022). Functional and species diversity of aquatic organisms ensures water purification in rivers, lakes and seas from chemical pollutants, nutrients and suspended solids (Cardinale *et al.,* 2012; Ostroumov, 2010; Vos *et al.,* 2014; Zhou *et al.,* 2023).

Mountains serve as "water towers", providing water for almost half of humanity and being the source of many rivers across the world, despite occupying only 27 per cent of the world's land surface (Immerzeel *et al.,* 2020; Romeo *et al.,* 2020). In humid regions, mountains provide 30-60 per cent of freshwater downstream, while in semi-arid and arid regions they contribute up to 70-95 per cent of freshwater (Kapos *et al.,* 2000; UNEP, 2002). The Hindu Kush Himalaya, with a total of 575 protected areas (S. Chaudhary *et al.,* 2022), is the origin of ten major rivers (Khanal *et al.,* 2021) and supports water provisioning to around 1.9 billion people (E. Sharma *et al.,* 2019). The region is also known as the "Third pole", since it has the largest reserves of cryosphere (snow, ice, glaciers and permafrost) outside the polar regions (Bolch *et al.,* 2019).

Forests are the most important terrestrial systems for water regulation, providing 75 per cent of accessible and clean freshwater and 85 per cent of the water for the largest cities (FAO, 2022a). Each 10 per cent of forest cover in a watershed can reduce water treatment costs by an average of 5 per cent (Vincent *et al.,* 2016; Warziniack *et al.,* 2017). In non-forest regions, grasslands also provide these functions (UNESCO, 2018; Y. Zhao *et al.,* 2020). Wetlands are the most efficient water regulators, but their global contribution is limited by their small area. Forests and wetlands also regulate the recharge of groundwater and springs (Acharya *et al.,* 2018; Creed & van Noordwijk, 2018; FAO, IUFRO & USDA, 2021; Ouyang *et al.,* 2019).

Nature's contribution to water quantity, quality and timing (i.e., flow and flood control) (Balasubramanian, 2019; Mengist *et al.,* 2020; Nedkov *et al.,* 2022; Vallecillo *et al.,* 2020) are highly unevenly distributed. They are severely lacking or overexploited in many of the most populated regions (Chaplin-Kramer *et al.,* 2019) and have been declining globally over the past 50 years (Brauman *et al.,* 2020). The value of water regulation is extremely high for humans. For example, in 2012, European ecosystems retained 20.2 million tons of nitrogen and water purification, worth €55.6 billion annually. This figure is equivalent to the cost of replacing water purification services for nitrogen removal with a comparable technological solution, as constructed wetlands for example (Vysna *et al.,* 2021).

Freshwater biodiversity is being lost faster than terrestrial (Albert *et al.,* 2021; Lynch *et al.,* 2023; Tickner *et al.,* 2020), with monitored populations declining 83 per cent since 1970, more than any other species group (WWF, 2022). Freshwater biodiversity has decreased in rivers, streams, lakes, ponds and wetlands. Freshwater and marine coastal ecosystems accumulate anthropogenic stressors from different sources (Reid *et al.,* 2019). Wetlands and inland water bodies covering only 2.6 per cent of global land area are most affected and vulnerable to human activities and climate change (UNESCO, 2018). Examples of some IPLC-managed wetland systems can provide best management options in providing essential goods, services or attributes; for example, in the Peruvian Amazon, presence of anthropomorphic wetland spirits respected by the Urarina people were key for helping preserve wetlands (Fabiano *et al.,* 2021).

Of the marine ecosystems, coral reefs are the most endangered and may disappear globally in the next 10-50 years (Purvis *et al.,* 2019), with a third of reef-building coral species at high risk of extinction (Carpenter *et al.,* 2008). This loss threatens ocean ecosystems and the lives of people who depend on the nature's contributions to people from coral reefs (Cinner, 2014; Kittinger *et al.,* 2012; Teh *et al.,* 2013). ILK can assist in combatting some of these negative trends; for example, local taboos or restrictions can help to reduce fishing mortality and conserve and restore fishing habitats such as coral reefs (Darkwa & Smardon, 2010). ILK can also provide unique information enabling monitoring of trends in aquatic and other ecosystems (Silvano *et al.,* 2022).

Coastal wetlands have been historically impacted by human activities (e.g., coastal development, agriculture, aquaculture ponds and pasture; Macreadie *et al.,* 2021). Global losses of 1-2 per cent per year are estimated for tidal marshes and seagrasses (Duarte *et al.,* 2008; Waycott *et al.,* 2009), while 3,363 km^2 (2.1 per cent) of global mangrove area was lost between 2000 and 2016 (Goldberg *et al.,* 2020). The global loss of mangroves has slowed but is still high in some regions such as Southeast Asia, particularly as a result of conversion to aquaculture (Goldberg *et al.,* 2020; Richards & Friess, 2016) **(Box 2.8)**.

Box 2 8 **Health and well-being benefits of mangrove conservation and restoration.**

Mangrove forests provide multi-functional benefits to people, including being useful sources of medicinal plants. The pharmaceutical industry has discovered several potentially useful substances (such as those with cytotoxicity that are potentially useful for anti-cancer drugs) among sponges, sea mosses, jellyfish and starfish. Cone shells of the molluscan family Conidae are highly prized for their conotoxins, with potential applications in many areas of medicine, including pain control, cancer treatment and microsurgery (UNEP, 2006). In contrast, aquaculture operations (e.g., shrimp, prawn, fish) that replace mangrove forests use antibiotics and other human-made drugs that can have negative health effects on humans, the ecosystem and other species (UNEP, 2006).

Mangrove protection and restoration can contribute to human well-being by providing nature's contributions to people related to protection from hydrometeorological hazards, aesthetical appreciation and food availability. Large economic benefits have also been shown related to shoreline stabilization, erosion control functions, flood prevention and disaster risk reduction functions of mangroves (A. Das *et al.,* 2023). Other recognized contributions to well-being include intangible benefits like aesthetic values of mangroves that can be attractive to tourists (Ewel *et al.,* 1998), cultural and historic values, and mental and social benefits (Friess *et al.,* 2022).

2.4.2 Biodiversity and the food system

Biodiversity plays a central role in all food systems: agriculture, pastoralism, forests, capture fisheries and aquaculture, improving food and nutrition security (**Figure 2.1**, arrows 1–5). Species, trait and genetic diversity in crops, their wild relatives and other harvested wild species maintain food diversity and its production, supporting human health (Sarkar *et al.,* 2012). The food system also impacts social (employment, health), economic (income, productivity) and political (governance) systems (FAO, 2018). Therefore, food systems interact tightly with biodiversity, impacting ecosystem functioning and services (Clapp, 2018; Rasul *et al.,* 2022) and connecting and influencing other nexus elements. It is well established that increased food demand and intensified food production account for a major part of water resource use (OECD & Food and Agriculture Organization of the United Nations, 2010) and contribute to climate change (P. R. Shukla *et al.,* 2022), all of which negatively impact biodiversity (Beckmann *et al.,* 2019; Emmerson *et al.,* 2016; Newbold *et al.,* 2015, 2016; Raven & Wagner, 2021). Cattle, sheep, goats, pigs, poultry and other livestock species now represent 70 per cent of avian biomass and 60 per cent of mammalian biomass (Bar-On *et al.,* 2018).

Factors such as climate change, trade, increased demand for food and the changing food habits of a growing population have increased dependence on a narrow range of crops, leading to intensification and a shift towards monoculture systems (Rasul *et al.,* 2022). Currently, global food production is heavily dependent on just 15 crop species (out of 300,000 edible plant species) that contribute to 90 per cent of the world's food supply (Gepts, 2006). This leads to negative impacts on biodiversity in local food systems (Rasul *et al.,* 2022), which has a major impact on IPLC in particular (see **Chapter 7**, online **Supplementary material 7.1**) (Rasul *et al.,* 2019, 2022). Notably, production of crop, dairy and meat products has outpaced population growth in previous decades, but production slowed from around 2008, likely due to factors such as a global decline in crop fertility due to biodiversity loss (IPBES, 2019a; Seppelt *et al.,* 2014), suggesting that food security cannot be achieved just by boosting production (FAO, IFAD, UNICEF, *et al.,* 2023).

Consequently, food security for all has not currently been achieved while global food demand is expected to increase (Global Agriculture towards 2050, 2009). To date, almost 80 per cent of the hungry live in developing countries; of these, 50 per cent are smallholder farmers (90 per cent of farmers worldwide are smallholders farming less than 2ha) who are the backbone of global food security (Lowder *et al.,* 2021; Tscharntke *et al.,* 2012). In addition, food production has mainly focused on quantity rather than nutritional quality to tackle hunger and support growing populations, but with health implications due to low diversity (Brinkman *et al.,* 2010; Oldewage-Theron & Kruger, 2008; Rah *et al.,* 2010) and consumption of highly processed foods (see Louzada *et al.,* 2015; Monteiro *et al.,* 2011). Although the number of malnourished people has decreased globally, nutritional imbalance is still a global problem.

Seventy-five percent of the world's leading food crops, representing 35 per cent of global food production, benefit from animal pollination for fruit, vegetable or seed production (Klein *et al.,* 2007), which is a key constituent of healthy food and nutrition (Chaplin-Kramer *et al.,* 2014). Worldwide, around 1 billion people, including many IPLC, depend to some extent on wild foods, such as wild meat, edible insects, edible plant products, mushrooms and fish, which often contain high levels of key micronutrients (see **Chapter 7**, online **Supplementary material 7.1**). For example, Indigenous communities in the Indian Vindhyan drylands (also called adivasi) have identified wild foods with excellent nutritional and medicinal values (Ernst, 2017; *FoodData Central*, n.d.; S. S. Kumar, Manoj, & Giridhar, 2015; S. S. Kumar, Manoj, Shetty, *et al.,* 2015) (see **Box 2.7**). The value of forest foods as a nutritional resource is not limited to LMICs; for example, more than 100 million people in the European Union regularly consume wild food (FAO & UNEP, 2020).

Conventional agricultural intensification increases pressure on agricultural habitats. It typically relies on chemical inputs, causing soil nutrient deficiency (Garibaldi *et al.,* 2017; Ramankutty *et al.,* 2018) and the consequent loss of insect diversity and biomass (Beckmann *et al.,* 2019; Duelli *et al.,* 1999; Norris *et al.,* 2016; Raven & Wagner, 2021). However, alternative approaches to conventional intensification and monocropping systems, including community-led agroecological approaches, can provide resilient food system transformations. These agroecological approaches can lead to improved long-term productivity of agriculture and rangelands (pastoral systems), and benefit conservation practices by reducing pressure from agro-chemical inputs on agricultural land and improving productivity through pollination services (P. K. Dubey *et al.,* 2020; IPBES, 2022; Kremen, 2020; Rasul *et al.,* 2022; J. Yang *et al.,* 2018) (see also **Section 5.3**) **(Box 2.9)**.

Some less intensive practices can reduce yields (e.g., by 5 per cent to 34 per cent) (Seufert *et al.,* 2012). However, diverse agricultural production systems have a positive influence on dietary diversity and nutritional balance and, hence, still minimize hunger (arrows 1-3 and 5, **Figure 2.1**) (Dwivedi *et al.,* 2017; Haselow *et al.,* 2016; Malapit *et al.,* 2015; Shively & Sununtnasuk, 2015). Polycultures and species diversity have positive impacts on the stability and productivity of agricultural systems and grassland systems used for livestock grazing (Egli *et al.,* 2020; Egli, Mehrabi, *et al.,* 2021; Egli, Schröter, *et al.,* 2021; J. B. Grace *et al.,* 2016; B. Liu *et al.,* 2018; Maestre *et al.,* 2016; Renard & Tilman, 2019; Y. Wang *et al.,* 2019). For example, mountain dwelling pastoralists often rotate pasture to manage pasture resources for livestock and help maintain relatively high species diversity compared to other livestock grazing practices.

Despite more focus on terrestrial food systems such as agriculture, blue food plays an important role as a component of a holistic and equitable food system that supports the health of people and the planet (Tigchelaar *et al.,* 2022), but receives less attention (Blue Food Assessment, 2022). The total production of fisheries and aquaculture reached a record high of 214 million tonnes in 2020 (FAO, 2022b), but it has not matched population growth, resulting in a per-capita decline of fish catch since 1990 **(Figure 2.13)**. Over 80 per cent of the 2019 landings of stocks was from biologically sustainable stocks, but the proportion of stocks within biologically sustainable levels decreased from 90 per cent in 1974 to 65 per cent in 2019 (FAO, 2022b). Polycultures and species diversity have similarly positive impacts on the stability and productivity on aquaculture productivity as on terrestrial systems (Brooks *et al.,* 2016; FAO, 2022b; Metian *et al.,* 2020; Thomas *et al.,* 2021).

Box 2 9 Food system transformations in Indian agriculture.

India began industrializing agriculture in the 1960s and became self-sufficient in food production as a result. Now, the country faces multiple pressures from resource extraction, soil health degradation, climate change and emanating social challenges amid its burgeoning human population. Estimates suggest 5.3 billion tons of Indian soil is being lost due to erosion and 37 per cent of Indian land is degraded with nutrient (N, Zn, Fe, Cu, Mn, B) deficient soil in need of rehabilitation (A. Shukla *et al.,* 2018). The excessive use of fertilizer and its imbalanced application has led to groundwater pollution, greenhouse gas emissions and soil infertility. Two-thirds of the Indian population is micronutrient deficient (Rao *et al.,* 2018), making growing diversified foods, such as fruit, leafy vegetables and legumes, on small land areas essential to fulfil calorie demand and address diet-related burdens of non-communicable diseases (Rao *et al.,* 2018; Sachdeva *et al.,* 2013). National and regional

Box 2 9

governments have championed a food system transformation through organic and natural farming initiatives. Both top-down and bottom-up approaches employing people and community participation, and embracing the principles of circular economy, are being used to provide more efficient and sustainable food production under changing environmental conditions (Fiksel *et al.,* 2021; Priyadarshini & Abhilash, 2023). Examples include:

Sikkim has adopted entirely organic farming practices that reinforce the concept of circular economies (Bhatt & John, 2023). Domestic top-down policy mandates favour Zero Budget natural farming (ZBNF) practices (The Times Of India, 2021; The Wire Staff, 2019), with efforts promoting the reintroduction of millets (*Shri anna*) through seed conservation along with initiatives that include women, farmers, local entrepreneurship in food processing and meal programmes for school children (G20-AWG, 2023).

Andhra Pradesh adopted organic 'community-managed sustainable agriculture' in 2004, later switching to ZBNF in 2016 (Saldanha, 2018; Veluguri *et al.,* 2021). ZBNF is essentially an agroecological approach without the use of credit and external inputs, with limited modern tool use, aiming to mimic nature (Governement of India, 2019). The approach aims to rejuvenate soil health, enhance yields and augment farmer incomes. ZBNF utilizes locally prepared bio-stimulants, bio-pesticides and bio-herbicides at community levels using mixtures of animal, food and plant waste. It also uses layered cropping models based on growing combinations of 15-20 diverse crops, with inter-, boundary-, or mixed cropping to utilize the land area across horizontal, vertical and temporal scales **(Table 2.3)**. Cultivation of legume-based crops in rotation with major cereals through inter- and cover-cropping may enhance crop yields by 10-25 per cent (Lalotra *et al.,* 2022), with wild edibles adding nutritional and medicinal value (Ernst, 2017; S. S. Kumar, Manoj, & Giridhar, 2015; S. S. Kumar, Manoj, Shetty, *et al.,* 2015; A. Singh *et al.,* 2018, 2019; A. Singh & Abhilash, 2019). ZBNF has been reported to reduce water use by 50 per cent, input costs by up to 18 per cent, improve biodiversity of earthworms (seven-fold), birds (55 per cent) and beneficial insects (60 per cent), while reducing pests by 66 per cent, GHG emissions by 30-91 per cent (depending on the crops), and enhancing farmer income by 56-80 per cent per year in comparison with chemically managed fields (FEF, 2023).

Andhra Pradesh community-managed natural farming (APCNF) is a rapidly growing initiative implemented by 850,000 primarily women farmers, expected to reach 1.3 million by 2025 (RySS, 2023) and supported by ten thousand farmer coaches. APCNF was a small scale, local market initiative applied to 100,000 ha land in 2021, but given its widespread adoption, 8,000,000 ha is targeted to be ZBNF by 2027 (Vijaykumar, 2021). APCNF have started the certification process for farmers who complete the transition to natural farming in 3 to 6 years, with financial support and training.

Sri Lanka, however, is in an agrarian crisis stemming from a complete ban on the import and use of agrochemicals and the adoption of nationwide organic farming. Hence, agricultural scientists and farmer organizations urge caution and ask for proper scientific validation of such approaches (S. Das *et al.,* 2024). For example, field trials of natural farming practices showed reduced yields for basmati rice (32 per cent) and wheat (59 per cent) crops in comparison with integrated crop management. Research estimated that if ZBNF is scaled up to 30 per cent, 50 per cent and 100 per cent cropped areas in India, this would cause declines in basmati rice by 10 per cent, 16 per cent and 32 per cent and wheat by 18 per cent, 30 per cent and 59 per cent (S. Das *et al.,* 2024). This gap is a concern given the country has rising food demands, showing the need for long-term assessments of natural farming approaches and adaptive farming policies.

Table 2 3 **Natural farming practices adopted by a local tribal community in Araku valley in A.S.R. District, Andhra Pradesh, India.**

Photo credits: Pradeep Kumar Dubey under license CC BY-NC-ND 4.0.

Field Photographs	Brief overview of the farming system
	Figure 2 15 **Crop diversification.** Clockwise from top left: cabbage fields with banana as a border crop, fields with mixed vegetables, including cabbage, maize and chilies, and mulching with banana leaves.

Box 2.9

Table 2.3

Field Photographs	Brief overview of the farming system
	Figure 2.16 **Cow urine collection.** Urine is collected via a pipeline from the cow shed, which has a sloping surface, for the preparation of bio-input. The storage tanks connect to a solar-powered production unit at the village level to prepare *Dhrava Jeevamrit* (a liquid soil microbial enhancer).
	Figure 2.17 **Traditional seed conservation.** For example, maize, cucurbits and millets.
	Figure 2.18 **Natural biopesticides.** For example, *Neemastra, Agnastra, Brahmastra* is made on farm by local farmers using cow urine and additional components, such as neem leaves, green chili, tobacco. The biopesticide is sprayed onsite.
	Figure 2.19 **Mixed poultry farming.** Local farmers practice mixed poultry farming with a five-layered fruit crop. For example, breeding farm is established to provide indigenous chicks to adjacent households. The chicks are housed in small poultry night shelters (15 m^2). The chicks and eggs provide household subsistence or are sold at premium prices in local weekly markets. Together with fruit-bearing trees such as sapota, guava, tapioca, bananas and others, the five-layered system also includes bushes, creepers, broom, vegetables and azolla plantation that provide the local tribe with subsidiary income.

2.4.3 Biodiversity and the health system

In 2012, almost 22 per cent of deaths and DALYs globally were linked to environmental factors (Prüss-Ustün *et al.,* 2017). Biodiversity can directly or indirectly affect human health via four main pathways (adapted from Marselle *et al.,* 2021) – through resources and resilience, physiological pathways, mental health and well-being, and infectious disease exposure and regulation – acknowledging that these themselves maybe be interlinked.

Resources and resilience: Biodiversity can have a direct impact on health (**Figure 2.1**, arrows 1-6) (Golden *et al.,* 2011) as it provides natural products and genetic resources, which form the basis of both traditional medicine and modern pharmaceuticals for use in both human and veterinary medicine (Marselle *et al.,* 2021) **(Box 2.7, Box 2.10)**. More than 28,000 plant species are currently recorded as being of medicinal use and many of them are found in forest ecosystems (Allkin, 2017). Moreover, 70-80 per cent of the global population depends on some form of traditional medicine for their primary health care (Chivian & Bernstein, 2008; Ekor, 2014; Newman & Cragg, 2012; Van Wyk & Wink, 2018). For example, the community forest in southern Meghalaya, India, is home to 85 medicinal plants, and almost every village has an herbal doctor (Tynsong *et al.,* 2011). However, loss of access to traditional medicines and discrimination by Western medical establishments are leading to the decline of traditional knowledge accumulated over thousands of years (see **Box 2.7** for more details; Alves & Rosa, 2007).

Physiological pathway: Biodiversity impacts physiological systems and, thus, health. For example, trees and other green areas can facilitate biofiltration (Meusel *et al.,* 1999), reducing concentrations of pollutants that negatively impact human health (Basner *et al.,* 2014; Churkina *et al.,* 2015; Freer-Smith *et al.,* 1997; Grote *et al.,* 2016; Lelieveld *et al.,* 2019). Air and water pollution are important drivers of biodiversity loss and ecosystem change (Groh *et al.,* 2022; IPBES, 2020) and among those environmental factors that have a significant impact on health, causing an estimated 9 million premature deaths in 2019 – 16 per cent of all deaths worldwide that year (Fuller *et al.,* 2022) (2.5.2.3).

Evapotranspiration by tropical forests provides cooling of up to 1°C for the entire globe (Baker & Spracklen, 2019; D. Lawrence *et al.,* 2022; Y. Li *et al.,* 2015), while green urban areas can cool up to 12°C in summer in European cities from tree shading and transpiration (Schwaab *et al.,*

Box 2 10 **Biodiversity-water-food-health-climate nexus among Indigenous Peoples: A case study of Tharu communities of Nepal.**

The Tharu community, an ethnic group Indigenous to the Terai region of Nepal, has been protecting, utilizing and sustainably managing ecosystems for millennia. Tharu communities are highly inter-connected with their land (*Jamin*), water (*Jaal*) and forest (*Jungle*) connected with their body, mind, soul and nature's well-being (M. Chaudhary, 2008; S. Sharma *et al.,* 2021). These inter-connections generate multiple benefits to both Tharu communities and their natural environment, reflecting an interconnected biodiversity-water-food-health-climate nexus.

The community is highly dependent on agriculture for their livelihoods and Tharu are adept gatherers and users of plants. Around 63 medicinal plants, 61 food plants, 14 fodder plants, 11 species for household utensils, 7 species for timber and 7 species for fuelwood are collected and used for food, rituals, household use and medicine (Müller-Böker, 1999; S. Sharma *et al.,* 2021). Collection and traditional use of the plants have not only shaped their nutrient needs but also contributed to their health, spirituality and overall well-being. Use of ritual plants are rooted in the Tharu tradition and practices, and some trees are believed to be favoured by the gods, with shady rest spots are often found to be planted in the vicinity of shrines. One shrine called *Baram* is under a mango tree (*Mangifera indica*), while another shrine is under a Kadum tree (*Anthocephalus chinensis*) – both have highly religious meaning and these trees are not felled by Tharu people. The *Flemingia strobilifera* is used in a ritual for small children for its calming effect, and *Elephantjhopus scaber* is used as a means of testing mutual attraction.

Living inside the forest before its declaration as a national park, Tharu have a harmonious relationship with wild animals and consider big animals like rhinoceros (*Rhinoceros unicornis*), tiger (*Panthera tigris tigris*), leopard (*Panthera pardus*) and sloth bear (*Melursus ursinus*) as the symbols of strength, with their indirect products being used for healing and soothing purposes. For example, a patch of wet sand where a rhino has urinated is rinsed out and the strained liquid is drunk in the belief that it cures bronchitis, ear and stomach aches (Müller-Böker, 1999). Tharus often collect freshwater snails, crabs and fishes, and consider lakes and rivers as an intricate part of their life system. Interactions with nature address varied social determinants of the Tharu people's health and well-being. In turn, the community manages and restores ecosystems through traditional knowledge, beliefs and practices.

The community worships ponds as sacred lakes and practices ethno-classification of climate including rainfall and its relation to the farming system; this ILK helps them to predict weather and therefore contributes to resilience (B. R. Chaudhary *et al.,* 2022). Furthermore, Tharu perform various rituals for food, health and biodiversity conservation, such as *hariyari* (a traditional worship by *gurau,* the local healer), which is performed for green and healthy crops as well as to drive out rice *gundhi* bug (*Lepocorisa sp*) from the fields (B. R. Chaudhary *et al.,* 2022). After harvesting, the first harvest is offered to the land god and goddess.

Tharu's interactions with their natural environment has not only contributed benefits to people but also enhanced socio-ecological resilience to shocks and climate change. During the COVID-19 lockdown, Tharu people collected fruits, vegetables and tubers from their nearby surroundings for their subsistence and health. However, Tharu's interactions with nature have been diminishing over time. Their interactions have been restricted due to the establishment of national parks, immigration of outside people to their areas resulting in competition for resource use, and gradual loss of traditional knowledge and practices (Agrawal & Ribot, 1999; S. Jones, 2007).

2021), affecting body heat stress and human health. Thus, increased deforestation and urbanization without concurrent development of green spaces will both result in increased negative impacts on human health from heat exposure (see **Box 2.14**). Human exposure to more diverse habitats is also likely to be critical for the development of human immune responses to allergens and other disease-causing factors (Haahtela *et al.,* 2013; Hanski *et al.,* 2012) (**Figure 2.1**, arrows 1, 2, 3-7). However, there is a racial and socio-economic disparity in access to public green spaces, which can affect health related benefits (Dai, 2011; Nesbitt *et al.,* 2019), especially for racial minorities (Nesbitt *et al.,* 2019).

Mental health and well-being: The global burden of mental disorders in 2019 was calculated to be 418 million in DALYs (16 per cent of global DALYs), with a cost of USD 5 trillion (Arias *et al.,* 2022). The quality of the natural environment is one of the structural protective factors that determine mental health (Arias *et al.,* 2022; WHO, 2022). Climate change, pollution and environmental degradation are risks that undermine mental health (WHO, 2022). Green and blue spaces play an important role in physical and mental well-being as more natural and biodiverse environments facilitate recovery from stress, depression and other related conditions, and have the ability to allow humans to rebuild adaptive capabilities that have been diminished through the demands of dealing with modern everyday life, increasing life satisfaction (**Figure 2.1**, arrows 2-7) (Cox *et al.,* 2017; Hartig, 2017; Houlden *et al.,* 2019; Johansson *et al.,* 2014; Lindemann-Matthies & Matthies, 2018).

Biodiversity is key for many cultures and traditions as a spiritual source and there is a growing volume of evidence showing positive links between natural environments and mental well-being and cultural ecosystem services, such as spirituality (Bratman *et al.,* 2019), sense of place (S. Chaudhary *et al.,* 2019), decreased mental distress (Orban *et al.,* 2017), positive social interactions and cohesion (Bratman, Daily, *et al.,* 2015; Bratman, Hamilton, *et al.,* 2015), positive social interactions, social cohesion and decreased loneliness (Astell-Burt *et al.,* 2022) **(Box 2.10)**.

Infectious disease exposure and regulation: Biodiversity also includes microbes and parasites that may cause harm and affect human health. Viruses, for example, are the most abundant organisms on Earth (Cobián Güemes *et al.,* 2016). Almost all human pathogens (75 per cent; K. E. Jones *et al.,* 2008) have their origins in other species and many have emerged since the Neolithic Agricultural Revolution as humans have modified landscapes and domesticated animals (N. D. Wolfe *et al.,* 2007). A range of zoonoses (human infections from pathogens transmitted by domestic, peri-domestic and wild animals) are together responsible for around 2.5 billion cases of human illness and 2.7 million human deaths a year (D. Grace *et al.,* 2012). Many now common human diseases likely emerged due to human contact with animals for food, including measles from cattle rinderpest in the sixth century BCE, perhaps with the concurrent rise in urbanization (Düx *et al.,* 2020; N. D. Wolfe *et al.,* 2007), through to the pandemic of HIV/AIDS from chimpanzees last century (Sharp & Hahn, 2011) and COVID-2019 most recently.

Evidence suggests that human activity, i.e., habitat and biodiversity loss, land-use change, and encroachment into biodiverse areas are the main drivers for zoonotic risk, exposing people, livestock and domestic animals to a high diversity of potential pathogens (IPBES, 2020; Loh *et al.,* 2015). Spillover events and the emergence of human disease or epidemics, therefore, tend to occur where land-use change is also leading to biodiversity loss (IPBES, 2020). Biodiversity loss itself may directly increase transmission of microbes from animals to people under certain circumstances. This may be because human adapted landscapes favour particular hosts (Gibb *et al.,* 2020) and in regions with high biodiversity a dilution effect may exist for some pathogens. This dilution effect is likely scale and system dependent but may reduce the transmission, and therefore the prevalence of particular pathogens, whereby more diverse systems control or limit high-quality pathogen hosts (with respect to the pathogen) in the community (Keesing & Ostfeld, 2021a). Therefore, reducing biodiversity may increase risk for some infections (**Figure 2.1**, arrows 2-7).

2.4.4 Biodiversity and climate change

Climate change impacts biodiversity at ecosystem, species and genetic levels, by altering composition of assemblages, habitat structure and function, and overall fitness in marine, freshwater and terrestrial ecosystems (**Figure 2.1**, arrow 9) (IPBES, 2019a; Weiskopf *et al.,* 2021). While some species benefit from warming, most plants and animals are negatively impacted by the changing climate (IPBES, 2019a; IPCC, 2018, 2022a).

Climate change has begun to cause observed range shifts of freshwater and terrestrial species poleward as well as upwards and marine species downward and poleward (IPCC, 2022a). The first species extinctions due to climate change have been identified with medium confidence in the latest IPCC report (IPCC, 2022a). Colonization of new areas by species has led to the composition of new communities, interactions between them and their abiotic environment (IPCC, 2022a; McDowell *et al.,* 2020). The observed woody encroachment in savannas and greening in boreal and temperate ecosystems are partially attributable to increasing levels of CO_2 in the atmosphere and releasing cold limitations of photosynthesis and growth (J. M. Chen *et al.,* 2019; Ruehr *et al.,* 2023; Stevens *et al.,* 2017). Climate change has led to the migration of invasive species (I.-C. Chen *et al.,* 2011) as increasing temperatures can positively affect invasive insects by influencing their movements, growth rates, phenology, dispersal and survival (Finch *et al.,* 2021). This trend is, however, highly variable across species and likely to depend on internal species traits and interactions with other drivers (I.-C. Chen *et al.,* 2011).

Land and ocean ecosystems remove nearly 50 per cent of anthropogenic CO_2 emissions from the atmosphere each year (Friedlingstein, Jones, *et al.,* 2022), with a substantial proportion of this carbon uptake taking place in natural ecosystems (Ahlström *et al.,* 2015; Dass *et al.,* 2018; Gao *et al.,* 2022; Pugh *et al.,* 2019). The frequently observed positive relationship between biodiversity and productivity also supports that ecosystems with greater species diversity are more resilient to the negative impacts of climate change (Hisano *et al.,* 2018; Mori *et al.,* 2021) **(Box 2.2)**. In tropical forests and dense savannahs – compared to agricultural ecosystems – biophysical exchange processes can in some regions contribute to additional cooling (IPCC, 2019c). Maintaining and restoring forests, savannas, grasslands, wetlands, mangroves or seagrass meadows hence provides co-benefits between climate change mitigation and biodiversity conservation, nature's contributions to people and options for climate change adaptation, such as regulation of runoff or providing refuge for pollinators (IPBES, 2019a; IPCC, 2018, 2022a) **(Box 2.8)**.

Biofuel production has been growing by 6.9 per cent on average annually between 2011 and 2021 (BP p.l.c., 2022). Although exact figures for global direct and indirect land-use change as well as biodiversity loss caused by biofuel production and other climate change mitigation measures are not available and estimates frequently rely on modelling outcomes, there is some evidence to suggest that an expansion of biomass-based energy (e.g., biofuels) could lead to the expansion of cropland area (e.g., Austin *et al.,* 2022). Measures exist to reduce these negative impacts, especially if implemented in context of sustainable ecosystem management, although the magnitude of their effects and costs remain unresolved (Fuss *et al.,* 2018; Nerini *et al.,* 2019; Pörtner *et al.,* 2021; P. Smith *et al.,* 2020).

Climate change mitigation and adaptation strategies, including both technological and nature-based solutions, are also related to land-use rights and tenure situations of IPLC, given the role of IPLC lands in conserving carbon stocks at higher rates than surrounding lands (Molua *et al.,* 2023; W. S. Walker *et al.,* 2020). IPLC are however often on the frontlines of experiencing climate change impacts (Schlingmann *et al.,* 2021) with limited financial capacities to adapt to the uncertainties and speed of climate change (Ford *et al.,* 2020). There is evidence that the use of ILK can also help communities to mitigate and adapt to climate change through their close connections to place which have shaping their beliefs, knowledge and identities and allowed them to experience, understand, resist and respond to environmental changes (see **Box 2.10**) (Ford *et al.,* 2020; ILO, 2017).

2.5 INTERACTIONS BETWEEN MULTIPLE NEXUS ELEMENTS

2.5.1 Status of the knowledge on the different nexus interactions

To comprehensively synthesize knowledge on multiple interactions between nexus elements, a systematic review resulted in 84 relevant publications between 1997 and 2022 (see data management report[4]). Water, food and climate change were the most studied nexus elements, occurring in 78 (92 per cent), 76 (89 per cent) and 73 (86 per cent) papers found in the systematic review respectively. Health systems were the most neglected in analyses of the nexus and included in only 36 (42 per cent) multi-element papers. Biodiversity was one of the systematic search inclusion criteria, thus by default was included in all papers. Direct drivers are mentioned in 29 (35 per cent) studies, with only a few addressing multiple drivers; indirect drivers were mentioned 36 times (42 per cent). Land-/sea-use change (35 per cent, N=29) and pollutants (31 per cent, N=26) were the most prevalent of the identified direct drivers and demographic changes were the most prominent indirect driver (44 per cent, N=38).

Due to lack of quantitative data in the papers included, it was difficult to assign a weighting to the strength of the interactions, however, for many of the interactions it was possible to record whether the interaction had resulted in a positive change in multiple elements concurrently (synergies) or a negative change in a nexus element resulting from an increase in another element (trade-off). A total of 256 trade-offs and 223 synergies were recorded, of which 447 (either trade-offs or synergies) involve only two elements of the nexus and 32 involve three elements of the nexus. There are only three interactions which consistently record a much more significant number of synergies than trade-offs: biodiversity-food (61of 97 or 61 per cent of records), biodiversity-water (36 of 45 or 80 per cent of records), and biodiversity-health (100 per cent – all 18 cases recorded of this interaction were synergies; **Figure 2.20**). A study conducted in Europe that assessed interlinkages between biodiversity, climate change, water, food, health, energy and transport identified 194 papers evidencing 354 interlinkages

4. The data management report on a systematic literature review (https://doi.org/10.5281/zenodo.13913053).

between three nexus elements and analysis of these records showed that 53 per cent of the interlinkages involving biodiversity were negative while 29 per cent were positive (H. Kim *et al.,* 2024). Examples of synergies between biodiversity and health include the presence and number of green spaces (which includes biodiversity) positively influencing mental and physical health (Firbank *et al.,* 2013; Heywood, 2011; A. Jenkins *et al.,* 2018); wetland biodiversity positively impacting clean air and subsequently human health (A. Jenkins *et al.,* 2018); and increased freshwater biodiversity leading decreases in waterborne disease (A. Jenkins *et al.,* 2018).

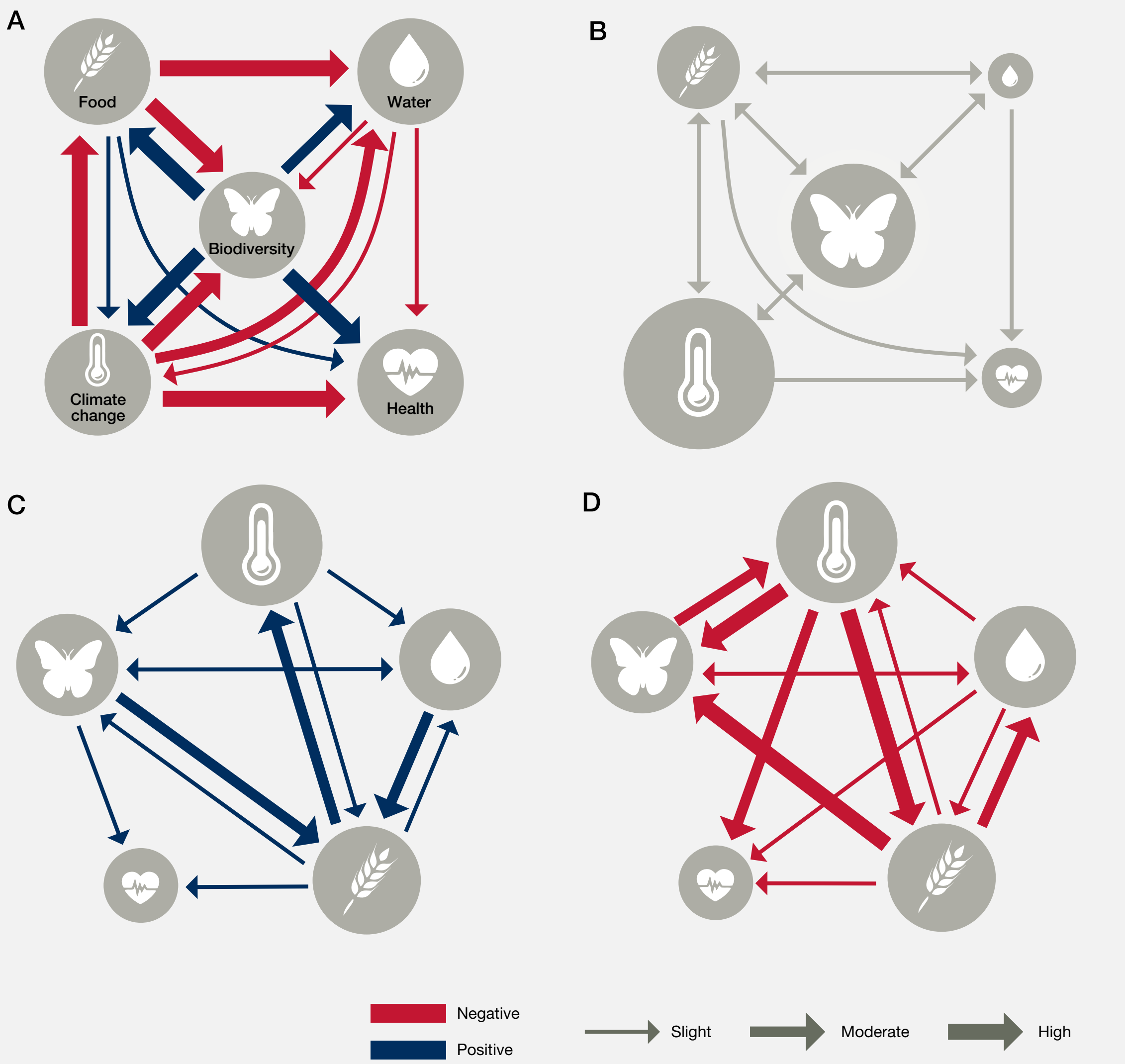


Figure 2 20 **Number of studies found in the literature review addressing multiple interlinkages between biodiversity, water, food, health and climate change, and interactions among them.**

(A) Overall interconnections found between the nexus elements. The direction of the arrows indicates the direction of the effect, the width of each arrow depicts the number of studies and the colour of the arrow indicates whether the interaction is positive/beneficial (blue), e.g., an improvement in the status of a nexus element, or negative (red), e.g., a decline in the status of a nexus element. **(B)** Overall impact of a nexus element on the rest of the nexus. The size of the circle indicates the number of studies reporting an effect of an element on the nexus. The arrows show the direction of the relationship between different nexus elements. **(C)** Synergies interactions, e.g., interactions that have the same effect between the nexus elements (i.e., increases in biodiversity leading to increases in food production). **(D)** Trade-offs interactions, i.e., interactions that lead to different effects of the nexus elements (i.e., increases in biodiversity leading to decreases in water quantity). For **(C)** and **(D)** the size of the dots represents the number of studies incorporating each element, while the size of the arrows indicates the number of positive or negative effects found in the studies. For detailed information on the systematic review see the associated data management report.[4]

It is worth noting the systematic review looked for 4 or 5-way interactions between elements of the nexus and thus does not provide a complete overview of the relationship between the nexus elements. Thus, not all biodiversity-health interactions may be synergistic and it is established that, in some cases, biodiversity can have a negative impact on human health, for example, if human activities lead to greater exposure to novel infections increasing the risk of infectious diseases (Lafferty & Wood, 2013; Randolph & Dobson, 2012; Rohr *et al.,* 2020; Wood & Lafferty, 2013).

Although many examples are two-way interactions, the evidence highlights the fundamental role of biodiversity in driving different nexus interactions and its importance in providing scaffolding for robust and healthy support systems for people and the planet **(Figure 2.20A)**. All two- and three-way interactions involving climate change resulted in significantly more trade-offs, indicating the strength of climate change as a driver in breaking down the environmental support systems provided by biodiversity **(Figure 2.20D)**.

Over 50 per cent of interactions involving biodiversity and food were impacted by land- and sea-use change. This is unsurprising, as land-/sea-use change is a key driver related to agriculture **(Section 2.3.1.1)**. Interestingly, considering climate change was involved in significantly more trade-off interactions than other elements, only 20 per cent of the papers that contain climate change as a nexus element stated climate change to be a direct driver, indicating that studies using the nexus approach to understand the influence of climate change on biodiversity and how this cascades to other nexus elements is not yet widely undertaken.

Looking at indirect driver relationships, 46 per cent of interactions are influenced by demographic changes and 59 per cent by technological changes. Food was the most frequently included nexus element in these studies. These results indicate that demographic changes are driving pressure for increased global food requirements, which is being (at least partly) satisfied through technological changes influencing food production (i.e., improvements to agricultural methodologies, such as pesticide use or disease-resistant crop species) (Notenbaert *et al.,* 2021). However, some technological improvements have made crops and livestock more vulnerable to external pressures arising from climate change or land-use change. For example, intensively cultivated monoculture crop species lack the adaptability necessary to survive extreme climate events (M. A. Altieri *et al.,* 2015).

In contrast, governance drivers were only reported to influence 4 per cent of the recorded interactions. This influence was either through the context of formal discussions with various governing bodies, research institutions addressing various nexus elements, IPLC governance of nexus elements or evaluation of institutional policies on specific nexus elements. Where economics was a noted key indirect driver, 30 per cent of the interactions involved health, highlighting that as society alters the nexus, health impacts are likely to become more dominant, and these will interact with the economic system, potentially increasing costs associated with delivering health benefits traditionally provided by the environment.

2.5.2 Direct drivers impacting multiple nexus interactions

It can be anticipated from the synthesis of the two-way interlinkages between biodiversity and the other nexus elements **(Section 2.4)** that more complex interrelationships emerge if multiple interactions between those elements are analysed. This is important because there is a lack of understanding about how and when these interactions will lead to critical thresholds beyond which significant, irreversible changes occur, i.e., tipping points **(Box 2.11)**. This section unpacks these more complex interactions with respect to direct drivers.

2.5.2.1 Land- and sea-use change and direct exploitation

The ongoing expansion of agriculture, including to produce feed rather than food, continues to compete with nature conservation efforts and contributes to climate change. In 2018, GHG emissions from agriculture and land-use associated with food production totalled 12 billion tonnes of CO_2 equivalent (Gt CO_2eq), making up 21 per cent of global emissions (Nabuurs *et al.,* 2022). Methane emissions from enteric fermentation, mainly from cattle and sheep digestion, accounted for 25 per cent of total sector emissions, while managed soil and pasture (11 per cent), rice cultivation (9 per cent), and manure management, biomass burning and synthetic fertilizer application collectively made up the remaining emissions (Lamb *et al.,* 2021). The conversion of natural ecosystems for use in agriculture (including bioenergy crops) continues currently, mostly in the tropical region **(Section 2.3.1.1)**, while these transformations took place in most temperate regions centuries ago (Ellis *et al.,* 2013). Land-use changes in both regions lead to significant impacts on the nexus elements. The impact of land-use change on boreal forests is also important, especially in relation to water and climate regulating functions (Keys *et al.,* 2016; D. Lawrence *et al.,* 2022; Wei *et al.,* 2018).

Cropland and grasslands have lower evapotranspiration compared with forest and dense savannahs. Land-use changes that reduce evaporation, such as deforestation and wetland drainage, generally lead to increased runoff in watersheds locally and decreased precipitation downwind. Changes that increase evaporation, such as reforestation

Box 2 11 **Tipping points and elements in the Earth system: Major largely irreversible events affecting all nexus elements.**

Tipping points are "*critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible*" (Lenton *et al.,* 2019) (see also **Chapter 1**, **Box 1.3**). A system is "tipped" from one stable state into a profoundly different state, often without the possibility to "tip" back in human time scales. There are many "negative" tipping points in the Earth system that could harm both nature and people.

A tipping element is an Earth system component that is susceptible to a tipping point. Key tipping elements as the result of climate change and other human activities include the dieback of the Amazon rainforest, the collapse of the Atlantic Meridional Overturning Circulation (AMOC) or the collapse of the West Antarctic and Greenland ice sheets. For some elements, there are signs of approaching a tipping point, although uncertainty is high about when exactly this could occur (Lenton *et al.,* 2019). Many interactions between tipping elements exist, with proof of reinforcing or cascading effects (Armstrong McKay *et al.,* 2022).

The Amazon rainforest produces a large part of its own rainfall by recycling moisture and provides rainfall to locations downwind, such as in Argentina, Bolivia and Colombia (Rockström *et al.,* 2023). However, when forest is lost due to deforestation and climate change (droughts and fires), eventually, large parts of the rainforest may die off and transform into a dry savanna landscape, mostly in the southern and eastern Amazon. When this tipping point will arrive is uncertain (Amigo, 2020). Studies indicate that the Amazon may have two tipping points, namely, deforestation exceeding 40 per cent of the forest area or temperature increase of 4°C (Nobre *et al.,* 2016). The region has warmed about 1°C over the last 60 years and total deforestation is reaching 20 per cent of the forested area (Nobre *et al.,* 2016). Research has shown that the Amazon has been losing resilience since the early 2000s (Boulton *et al.,* 2022), which increases the risk of reaching a tipping point.

The AMOC is a current in the Atlantic Ocean that carries heat from the tropics to the Arctic circle. The Gulf Stream, which brings warm water from the Gulf of Mexico and is responsible for the mild climate of northwestern Europe, is part of the AMOC. The system has been weakening over the last century due to greater inflow of freshwater from melting ice. With increasing ice melt due to climate change, the AMOC is predicted to reach a tipping point, with large effects on its strength and direction. The timing of the tipping point is, again, uncertain (Boers, 2021; Latif *et al.,* 2022). Recently, Ditlevsen & Ditlevsen (2023) predicted a collapse of the AMOC to occur around mid-century under a business-as-usual scenario of future emissions and climate change. While still debated in the scientific community these tipping points could have radical implications for biodiversity, water and food systems, and human health and well-being.

and irrigation, lead to a decrease in surface runoff and an increase in downwind precipitation (Creed & van Noordwijk, 2018; Ellison, 2018; J. Jones *et al.,* 2022; Keys *et al.,* 2016; UNESCO, 2018; M. Zhang *et al.,* 2017). This was confirmed by large-scale reforestation programmes in China (Y. Li *et al.,* 2018; Pan *et al.,* 2022; Peng *et al.,* 2019; C. Ran *et al.,* 2020). Thus, the loss of surface runoff due to forest growth can be compensated on a larger-scale by the recirculation of precipitation (Ellison, 2018; Hoek Van Dijke *et al.,* 2022; Wang-Erlandsson *et al.,* 2018). Local declines in runoff increase pressure on already limited water supplies, particularly important in hot and dry regions where competition between water as a resource for drinking and for irrigation is already high. This situation can lead to a feedback loop, as new crop areas may have less water available for irrigation and hence lower yields than expected. Furthermore, reduced evapotranspiration in croplands and pastures, compared to natural vegetation, generates a feedback to climate change as it results in local warming and regional decreases in rainfall (Alkama & Cescatti, 2016; IPCC, 2019a, Chapter 2). This in turn amplifies warming, droughts and forest dieback (see 2.4) (IPCC, 2019a, 2021, 2022b), as seen in tropical forests (Boulton *et al.,* 2022; Falkenmark *et al.,* 2019; D. Lawrence & Vandecar, 2015; Lovejoy & Nobre, 2018).

Large monocultures in any region of the world impact health, providing seasonal food or resource sources for wildlife hosts of zoonotic pathogens, such as rodents and mosquitoes, and/or by incorporating and benefiting species amplifiers of infection (Kuiken & Cromie, 2022; Loh *et al.,* 2015; Mills, 2006; Prist *et al.,* 2017). For example, land-use change and forest fragmentation from livestock farming may increase the risk of coronavirus emergence in Asia (Rulli *et al.,* 2021), while deforestation caused by oil palm production is linked with zoonotic malaria emergence (Fornace *et al.,* 2019) and increased potential for mosquitoes to transmit dengue virus locally (Gregory *et al.,* 2022). Forest fragmentation also increases the risk of Ebola virus disease outbreaks in Africa (Olivero *et al.,* 2017; Rulli *et al.,* 2021; Wilkinson *et al.,* 2018) and yellow fever outbreaks in Latin America (Prist *et al.,* 2023). Therefore, food production can cause the emergence of infectious diseases mainly through three ways: (a) through biodiversity loss, community simplification and the proliferation of host populations; (b) through the proliferation of vector populations feeding on these hosts; and (c) by increasing the likelihood of encounters between wildlife and domestic animals or humans (IPBES, 2020; Keesing *et al.,* 2010; Keesing & Ostfeld, 2021b; Richter *et al.,* 2015).

Moisture and energy exchange between ecosystems and the atmosphere affects atmospheric currents, including the so-called atmospheric rivers (Paltan *et al.,* 2017). The flying rivers (i.e., seasonal winds) carry water vapour to other regions, affecting climate and biodiversity status far away from their location (Ferrante *et al.,* 2023). Moreover, the "biotic pump" hypothesis suggests that forests can cause moisture movement from the oceans deep into the continents (Makarieva *et al.,* 2013; Makarieva & Gorshkov, 2010). The influence of ecosystems on the climate affects other countries and even distant continents (see **Box 2.11**). In Asia and Africa, many countries (e.g. Pakistan, Nepal, Mongolia, Mali, Niger, Chad, Sudan) receive most of their precipitation from the territory of other countries (Keys *et al.,* 2016); in some of the world's largest basins, precipitation was influenced more strongly by land-use change occurring outside than inside the basin (Wang-Erlandsson *et al.,* 2018). Deforestation in Amazonia and Central Africa affect precipitation in Europe, North America and Asia (D. Lawrence & Vandecar, 2015). Feedback between agriculture, biodiversity and climate can, therefore, reduce agro-productivity. Through teleconnections, negative impacts of tropical deforestation on climate (i.e., increase in average temperature and decrease in precipitation, as well as increase in the fluctuations of both), extend well beyond the tropics and limit food production in other regions, including in the USA, India and China (D. Lawrence & Vandecar, 2015).

Globally human activities withdraw 25 per cent of terrestrial primary production, leading to accelerated turnover of terrestrial plant biomass. Current anthropogenic land-use accelerates biomass turnover by 1.9 times. Land conversion, for example from forests to agricultural fields, is responsible for 59 per cent of this acceleration and the use of forests and natural grazing land accounts for 26 per cent and 15 per cent, respectively (Erb *et al.,* 2016; Krausmann *et al.,* 2013). Biomass reduction and acceleration of biomass turnover contributes to fundamental trade-offs between carbon turnover and carbon stocks, affecting both water and climate regulating nature's contributions to people **(Section 2.5.2.2)** (Erb *et al.,* 2016; Krausmann *et al.,* 2013).

Increased resource appropriation through conventional intensification of agriculture based on high-yielding seeds, expanding irrigation, fertilizers, pesticides, hormones and antibiotics (Matson *et al.,* 1997) shows positive and negative effects on human health (Rekarsem, 2005). For example, irrigation agriculture contributes to 40 per cent of global food production on 20 per cent of the total cultivated land (Puy *et al.,* 2021). However, irrigation structures link biodiversity, food production and health through the proliferation of disease vectors such as mosquitoes inhabiting irrigated areas (arrow 15, **Figure 2.1**) (Patz *et al.,* 2000; Richter *et al.,* 2015). This and other risks to human health, such as the negative effects of polluting chemicals that have been associated with neurological disorders, immune suppression and reduced fertility, are also amplified by climate change (Bhidayasiri *et al.,* 2011; Crisp *et al.,* 1998; Straube *et al.,* 1999).

Inappropriate fertilizer use leads to increases in short-term yields, but decreases in biodiversity (Beckmann *et al.,* 2019; Mozumder & Berrens, 2007) **(Section 2.4.2)**. The related loss of ecosystem function is already causing decreases in yields as soil biodiversity has a key role in filtering water and pollutants, modulating both the yield and nutrient content of crops, reducing crop pests and disease, and conferring protection against foodborne, waterborne and soilborne illnesses (Mattei *et al.,* 2015; Wall *et al.,* 2015; G.-J. Yang *et al.,* 2015). Biodiversity is in fact a central link between nutrition and environmental health (WHO, 2020), being the source of variety in essential foods, nutrients, vitamins and minerals, as well as medicines (Romanelli *et al.,* 2015).

IPLC often face multiple environmental, socio-economic and policy challenges, including biodiversity loss due to illegal activities (such as mining **(Box 2.12)**, poverty, limited access to healthcare and marginalization (P. Wolfe, 2006)). These factors, coupled with a transition to industrialized, highly processed diets contribute to a higher prevalence of obesity, type 2 diabetes and other related chronic diseases (Kuhnlein, 2015). This is despite undernutrition among many Indigenous Peoples compared to the general population due to inadequate dietary intake, limited access to clean water, biodiversity loss and inadequate healthcare systems. In South America, IPLC suffer health problems and food access challenges due to deforestation and pollution releases in the exploitation of natural resources. This is well documented for the Yanomami people in the remote areas of Brazilian Amazon and Venezuela **(Box 2.12)**.

Water consumption (both blue and green water) for food production, including crops and terrestrial livestock products (combined 7,113 km^3/year) as well as aquaculture (99 km^3/year), constitutes 80 per cent of humanity's total water demand, amounting to 7,212 km^3/year out of 9,008 km^3/year (Gerbens-Leenes *et al.,* 2012; B. F. Kim *et al.,* 2020; Mekonnen *et al.,* 2015; Mekonnen & Hoekstra, 2012; Schyns *et al.,* 2019; Vanham, 2016). Water consumption for meat production may be even higher than for non-livestock food production, as it includes water in livestock feed **(Figure 2.22)**. Meanwhile, water consumption for non-food production, encompassing the manufacturing industry and non-edible agricultural products such as cotton, rubber, oils and wood (excluding firewood), makes up 14 per cent of the total, with 1,273 km^3/year, of which 740 km^3/year is allocated for wood (Gerbens-Leenes *et al.,* 2012; B. F. Kim *et al.,* 2020; Mekonnen *et al.,* 2015; Mekonnen & Hoekstra, 2012; Schyns *et al.,* 2019; Vanham, 2016).

About 1.4 billion people live in river basins where either surface water use surpasses safe limits or where a decrease

Box 2 12 Impact of resource extraction on IPLC: A case of mining activities in Latin America.

Resource extraction and pollutants emitted from activities like mining, agriculture and fossil fuel extraction, if not controlled and properly managed, can cause negative impacts on the environment, such as loss of biodiversity and water quality, which in turn affects food production systems and the health of the local people. The impact of resource extraction and consequently pollution on the biodiversity-water-food-health nexus in Indigenous communities in Latin America is significant, with alarming levels of mercury (Hg) found in land, sediments, fishes and water column in the areas with Indigenous communities in the Colombian and Brazilian Amazon (Alcala-Orozco *et al.,* 2019; Olivero-Verbel *et al.,* 2021). For example, in the Madre de Dios River of Peru, artisanal-scale gold mining is leading to increased mercury concentration in suspended-sediment (i.e., a well-documented impact of mining activities) and decreases in fish diversity (Dethier *et al.,* 2019). This is negatively affecting the provisioning of protein sources (Roach *et al.,* 2013) and the health of local communities (Langeland *et al.,* 2017), even those located hundreds of kilometres downstream of the mining activity (Diringer *et al.,* 2015).

In the Brazilian Amazon, the Indigenous Yanomami are suffering from serious health problems due to deforestation and contamination from illegal mining activities, especially mercury (Da Luz Scherf & Viana Da Silva, 2023). This exposure to mercury-contaminated water leads to foetal abnormalities, neurological and motor (movement) problems. Chronic exposure to mercury compounds from different sources (e.g., water, food, soil and air) may also cause other serious illness, with toxic effects on skin, cardiovascular, pulmonary, urinary and gastrointestinal systems (Birn *et al.,* 2018; K.-H. Kim *et al.,* 2016). In addition, the health of the Yanonami is at risk due to food insecurity caused by biodiversity loss (i.e., the loss of fish stocks), increased diarrhoea and malaria from ecological changes due to deforestation, and a rise in child mortality (Da Luz Scherf & Viana Da Silva, 2023). When people in the communities get sick, they lose strength and are unable to go hunting, further exacerbating food insecurity. Considering these interlinkages among the nexus elements could inform the diverse governmental efforts underway to counter mining activities inside these areas.

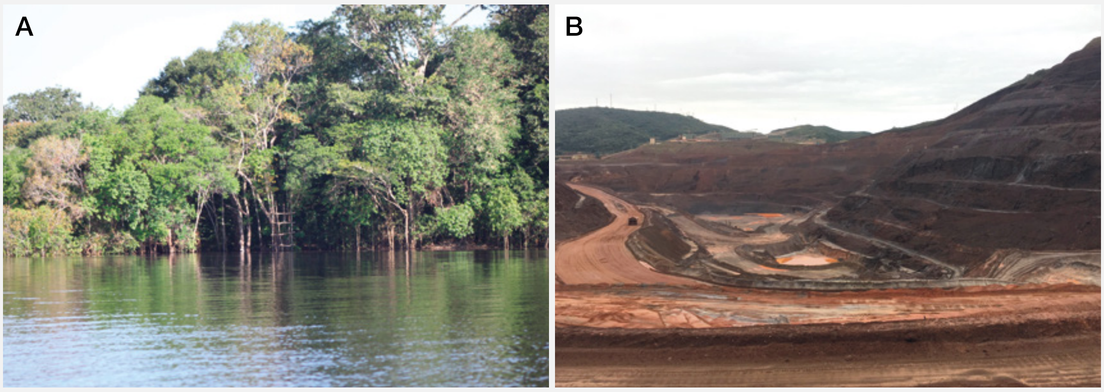


Figure 2 21 **Contrasting landscapes.**

(A) Conserved environment. **(B)** Area threatened by mining activities.

Photo credit: Paula R. Prist under license CC BY-NC-ND 4.0.

Mining activities can also exacerbate emission of other contaminants that occur naturally in the environment, thus affecting human health. In Lake Poopó, Bolivia Altiplano, surface and groundwaters contain arsenic concentrations 25 and 14 times, respectively, exceeding the WHO limit for drinking water (0.01 mg/L). As a consequence, a wide range of urinary concentrations of arsenic (12–407 µg/L) are detected in IPLC women living there (Quaghebeur *et al.,* 2019), due to dependence on this lake for water and fishing. In the Huanuni river, that runs through the community of Alantañita, the pH is low due to acid drainage from the Huanuni mine much higher in the watershed, demonstrating the extent of influence from mining and the severe risk of persistent pollutant contamination (Quaghebeur *et al.,* 2019).

In addition, regions with mining activities also have soil and air contamination with heavy metals, exposing people to vaporized mercury and airborne dust. Water and soil contamination, or water shortages due to water depletion from mining processes, can negatively affect food production and harm animal health (Birn *et al.,* 2018). Therefore, deforestation, resource extraction and uncontrolled mining pollution can have a negative impact on biodiversity, water, food and health in the local communities. However, these nexus effects are poorly documented, especially when considering IPLC.

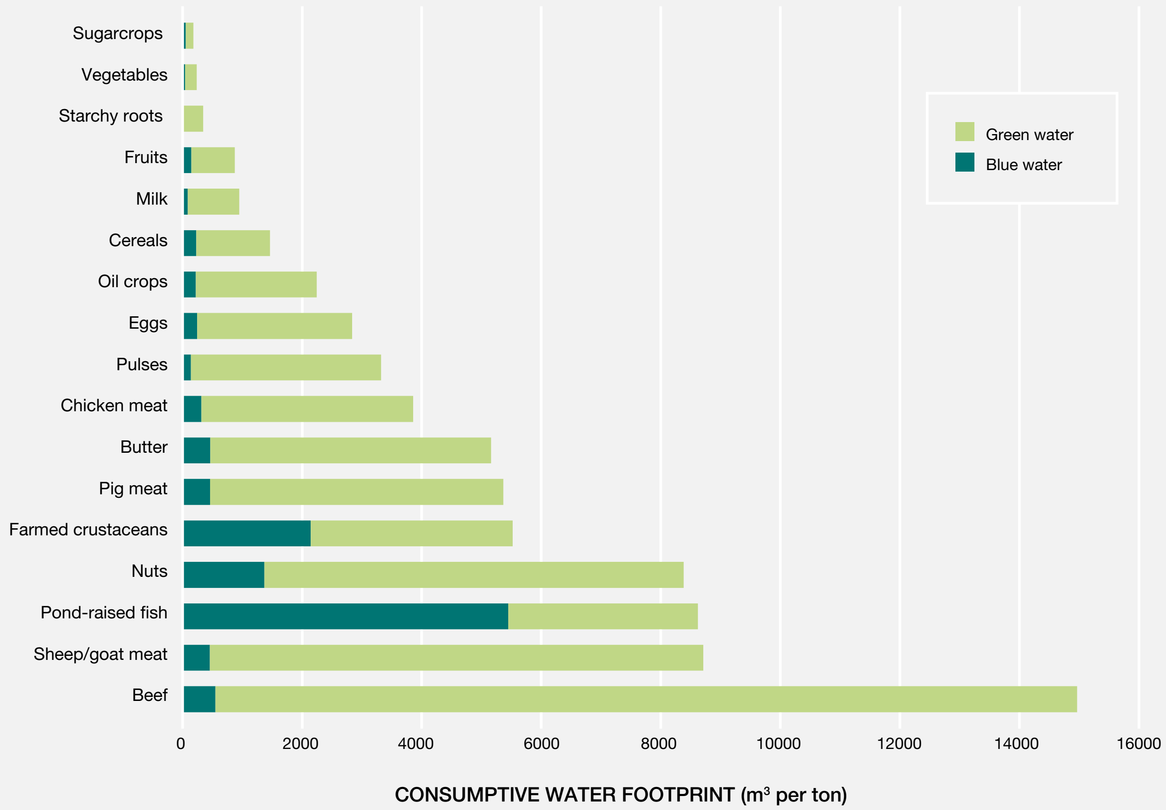


Figure 2 22 **The consumptive water footprint of selected food products.**

Units are m^3 per ton (or litres per kg). The blue water (i.e., lakes, rivers and reservoirs) footprint refers to the volume of surface water and groundwater consumed (evaporated after withdrawal) as a result of production; the green water (i.e., water available in the soil for plants and soil microorganisms, being released into the atmosphere through evapotranspiration) footprint refers to rainwater consumed. Figure adapted from B. F. Kim *et al.* (2020) under license CC BY-NC-ND- 4.0 Deed.

in groundwater recharge is encountered. An additional 1.5 billion people live in river basins lacking sufficient surface water to meet basic needs (Stewart-Koster *et al.,* 2023). This results in approximately 2 to 3 billion individuals experiencing water stress for at least one month annually (Vanham *et al.,* 2021). Roughly 80 per cent of those live in Asia, notably in India, Pakistan and northeast China. Globally, 1.0 to 1.9 billion people experience water stress for at least six months each year, with 149 to 496 million individuals enduring these conditions year-round (UNESCO, 2023; Vanham *et al.,* 2021).

The water footprint of food products varies widely, with animal products requiring much higher water per unit produced as compared to vegetal products **(Figure 2.22)** (B. F. Kim *et al.,* 2020; Mekonnen & Hoekstra, 2011, 2012). The nutrition transition during the last decades implies that in many countries, a shift from traditional diets (plant-based, high in cereal and fibre) towards diets with low fruits and vegetables, and high in fat and sodium has occurred. This diet, rich in animal products and processed food, has a typical high dietary water footprint (Lares-Michel *et al.,* 2021; Vanham *et al.,* 2013). Countries still characterised by more traditional diets show much lower average dietary water footprints (Tuninetti *et al.,* 2022; Vanham *et al.,* 2013).

Addressing food demand, such as reducing per-capita meat consumption in overconsuming societies, coupled with more equitable food distribution, has been proposed as an effective strategy to save water, mitigate climate change and conserve biodiversity (IPCC, 2019a, Chapter 6; P. Smith *et al.,* 2020, 2022; Stoll-Kleemann & Schmidt, 2017). Biotechnological advances aim to reduce chemical use, yet usage currently remains high (Jørgensen *et al.,* 2018). Healthy and sustainable diets provide adequate levels of micronutrients (Moursi *et al.,* 2008; W. Zhao *et al.,* 2017), which protect children against infectious diseases. Diverse diets in Europe are associated with lower rates of total and cause-specific mortality (Hanley-Cook *et al.,* 2022).

Marine environments face overexploitation due to fishing practices driven by consumer demand for seafood. Recent consumption trends of specific products like farmed species such as salmon indicate the intensification of industrial activities in salmon farming. Salmon farms often allow faeces, antibiotics and food waste to be discharged directly into the ocean. The accumulation of excess nutrients, such as nitrogen and phosphorus, from fish waste and uneaten feed in surrounding waters can lead to water pollution and impact organisms that live on the seafloor. Marine resources (i.e., blue foods) play a central role in food and nutrition security for billions of people and are important as they support the health of people and the planet (Leape *et al.,* 2021). Animal protein from the seas provides about 17 per cent of all animal protein consumed by humans and 50 per cent or more in many small island states (FAO, 2020d). It also supports about 12 per cent of human livelihoods (United Nations Environment Programme, 2021). Despite contributing to healthy diets for billions of people, blue foods are often undervalued as a nutritional solution because their diversity is often reduced to the protein and energy value of a single food type as "sea food" or "fish" (Golden *et al.,* 2021).

In recent decades, the pressure on the marine environment has significantly increased due to resource exploitation including fishing, climate change and other human activities such as seabed mining, maritime transport, land-based activities and coastal development (European Environment Agency, 2019; Halpern *et al.,* 2019; United Nations Environment Programme, 2021). These intensifying pressures cause significant negative impacts on marine ecosystems, which in turn affect human well-being (Borja *et al.,* 2024) (see **Box 2.13**).

Box 2 13 **Intensifying pressures on marine environments and consequences for the nexus elements.**

The impacts of human activities on the oceans (e.g., climate change, fishing, coastal development; **Sections 2.3** and **2.5**) are expanding and intensifying, leading to negative effects on the marine environment (Halpern *et al.,* 2019) and the nexus elements. Pressures, such as fishing activities, which have been increasing in recent years, contribute disproportionately to carbon emissions, due to operations on the high seas and the consumption of fuel oil to access remote areas. In addition, this activity reduces the potential for carbon sequestration and stocks by removing large marine animals that are responsible for sequestering carbon from the surface to the deep ocean (Bianchi *et al.,* 2021; Mariani *et al.,* 2020). One example is the capture of mesopelagic fish (living at depths of 200 to 1,000 m) for fishmeal for aquaculture. These animals contribute to the biological pump and sequester carbon to the depths due to their diurnal vertical migration that transfers the carbon obtained by feeding in surface waters at night to deeper waters during the day (Davison *et al.,* 2013).

Bottom trawling or trawling heavy nets along the seabed to catch fish and shellfish also has detrimental effects on marine ecosystems, disturbing marine sediments and leading to the release of carbon from the seabed. This leads to a consequent increase in ocean acidification, as well as negatively affecting the productivity and biodiversity of ecosystems (Epstein *et al.,* 2022). Therefore, regulating the exploitation of the high seas and deeper marine environments would offer an immediate opportunity to significantly reduce carbon emissions and associated negative impacts on marine ecosystems through overfishing, while enhancing blue carbon sequestration. Harmful fisheries subsidies, i.e., those that encourage fishing capacity to develop and exploit fish stocks beyond the maximum sustainable yield, are particularly detrimental. These are also associated with increasing inequalities among nations since 40 per cent of harmful subsidies that support fishing in the waters of nations with very low human development index (HDI) originate from high-HDI and very-high HDI nations. Furthermore, high seas fisheries, which are mainly operated by large-scale (industrial) fleets, play a negligible role in global food security (~3 per cent; see Schiller *et al.,* 2018). Hence, eliminating harmful subsidies would enable greater economic viability of small-scale fisheries (Schuhbauer *et al.,* 2017) that support people livelihoods and health (Cisneros-Montemayor *et al.,* 2016; Skerritt *et al.,* 2023; Sumaila *et al.,* 2021).

Concurrently, increasing demand for valuable minerals, such as cobalt, copper and lithium, required to produce technologies and support the green transition, heavily relies on mining activities, with some happening on the seabed in shallow waters or in the deep sea. Deep sea mining, over 200 meters underwater, has been proposed as a potential solution for meeting increased mineral demand (Levin *et al.,* 2020) because it may result in lower impacts on human societies compared to shallow-water mining (Kaikkonen & Virtanen, 2022). Deep sea environments potentially host rare and unique species and habitats that are largely undiscovered and, by living in such extreme environments, some species could offer new biomedical applications (Jin *et al.,* 2019). Beyond the negative impacts on marine biodiversity and environments, seabed mining activities may also release sediment clouds and toxic chemicals in the water column, produce noise and vibration that disrupt marine life, affect connectivity between deeps oceans and surroundings oceans and hinder the flow of ocean nutrients. These potential damages are most likely long-term and the scientific community and global groups, such as the Deep-Ocean Stewardship Initiative, emphasize increasing concern and point to the need to better quantify and monitor these deep environments before further exploitation (Levin *et al.,* 2020; Mengerink *et al.,* 2014).

2.5.2.2 Climate change

The increasing pressure of climate change on biodiversity is well established **(Section 2.4.4)**. Climate change impacts on marine systems include ocean acidification, which massively impacts coral reefs and threatens the ecosystems they create and the species and people's livelihoods that depend on them (**Table 2.1**, **Sections 2.3.1.2** and **2.4.1**). More frequent and more severe heats and droughts (IPCC, 2022a) reduce the carbon sink in natural ecosystems, dampening their climate change mitigation potential (2.4.4; Anderegg *et al.,* 2020). In forests and savannahs, for example, tree mortality and increased frequency and severity of wildfires in response to heat and drought have already resulted in ecosystems turning from a sink to a source, as seen in parts of Europe in 2003 and 2022, or some tropical forests in South America in 2015/16 (Bennett *et al.,* 2023; Ciais *et al.,* 2005; Van Der Woude *et al.,* 2023). Even though many ecosystems are well adapted to – and in fact need – regular fires, recovery from them may become impeded if these become too frequent in response to climate change as seedlings cannot grow tall enough to escape the flame height (Seidl & Turner, 2022; Stevens-Rumann *et al.,* 2018; M. G. Turner & Seidl, 2023). Wildfires are not only returning large amounts of carbon into the atmosphere (for example the 2019/20 Australian wildfires released ca. 715 Tg CO_2, exceeding Australia's 2018 anthropogenic CO_2 emissions (Van Der Velde *et al.,* 2021)), but are also the cause of significant number of health problems. This occurs through associated air pollution which causes hundreds of thousands of premature deaths globally (Johnston *et al.,* 2012) and destruction of people's livelihoods, which also leads to increases in mental health problems (Adu *et al.,* 2023), such as depression and generalized anxiety (To *et al.,* 2021).

The climate change feedback from reduced ecosystem carbon uptake and/or ecosystems becoming a carbon source are well established (IPCC, 2022a). In addition, ecosystems that are species-poor tend to be more vulnerable to the negative impacts of climate change (Mori *et al.,* 2021; Oliver *et al.,* 2015). This gives rise to a further feedback, such that a climate change-induced biodiversity decline further enhances the loss of ecosystem resilience, which in turn amplifies climate change-induced disturbances (such as if climate stresses and biotic agents interact to enhance tree mortality), which in turn strengthens the carbon-climate feedback (Anderegg *et al.,* 2020; Mahecha *et al.,* 2022). Climate change impacts on ecosystems – and associated feedbacks – also affect many other NCPs provided by the nexus, for example, flood regulation. Analyses of flood frequency in LICs have found that the reduction in the amount of natural forest cover (which can be either due to deforestation or climate change-related mortality) explains 65 per cent of the variation in flood frequency (Belongia *et al.,* 2023; Bradshaw *et al.,* 2007) and can be further linked to the number of people displaced and killed by such events.

Climate change – even at small spatial scales – can alter plant physiology and reproductive behaviours in ways that will likely affect human health. For example, urban effects on the climate have been found to alter the general characteristics of the ragweed pollen season leading to a greater atmospheric pollen amount resulting in increased cases of allergic rhinitis (Ziska *et al.,* 2003). Furthermore, a meta-analysis documented that about 277 pathogens, representing 58 per cent of known human infectious diseases, are favoured as a result of climate change (warming, drought, flooding or land cover change) (Mora *et al.,* 2022). Higher temperatures are associated with faster development rates in insects (Arrese & Soulages, 2010), affecting both the abundance of the vector, e.g., mosquitos (Delatte *et al.,* 2009), and the incubation period of pathogens within the vector (Afrane *et al.,* 2008), thus affecting disease risk (Carlson *et al.,* 2022). Increases in temperature are leading to mosquito-borne dengue and malaria spreading into higher altitudes and latitudes, which exposes many immunologically naïve populations (Caminade *et al.,* 2019), with impacts more pronounced in urban areas more strongly effected by climate change than other habitats (Misslin *et al.,* 2016).

Currently, more than 55 per cent of humanity live in urban areas, and by 2050 this may rise to 68 per cent of the human population (UN, 2019b). Urban areas affect local climate through increasing surface albedo, reducing evapotranspiration, increasing aerosols and anthropogenic heat sources, resulting in locally elevated temperatures and possible changes in precipitation patterns (Arnfield, 2003). CO_2 concentration and air temperatures within urban environments can be 30 per cent and 2°C higher, respectively, than those in rural environments (Ziska *et al.,* 2003). Urban heat islands cause drastic changes in local climate, with enhanced heat stress during heat waves being a well-established cause of increased mortality, especially in elderly populations (Guo *et al.,* 2017, 2018; Van Steen *et al.,* 2019). There were 74 temperature-related excess deaths per 100,000 inhabitants globally between 2000 and 2019 (Q. Zhao *et al.,* 2021), 5,600 deaths annually in the United States between 1997 and 2006, and about 61,672 in Europe during the hot summer between 30 May and 4 September 2022 (Ballester *et al.,* 2023). In addition, in Africa nearly 12,000-19,000 child deaths were estimated to be linked to climate change between 2011-2020 (Chapman *et al.,* 2022) **(Box 2.14)**. In the past 50 years, extreme weather, climate and water-related events have caused nearly 12,000 disasters, with 2 million human deaths (90 per cent in low-and-middle-income countries) and $4.3 trillion in total costs globally (WMO, 2023b).

Climate change has already led to significant impacts on the high glaciated mountain regions in the world, nearly 30 per cent of which is in Hindu Kush Himalaya. These areas

Box 2 14 Urbanization as a melting pot of nexus elements and people.

Urbanization, the movement of populations from rural to urban areas, and urban expansion as a form of land-use change cause alterations in the interactions among nexus elements. It is predicted that by 2050 about 64 per cent of low- and lower-middle-income country populations and 86 per cent of the highest income country populations will be urbanized. Urban dwelling provides technological, social and economic advantages to people, yet cities – no matter how protected, wealthy and powerful they seem – may be particularly vulnerable to various negative effects among the nexus elements. The continuous transition of populations from rural to urban environments has resulted in changing global patterns of disease and mortality (Harpham, 1997). Analyses of a 48-year long dataset of haemorrhagic fever with renal syndrome incidence caused by hantaviruses in China from 1963-2010 indicated that epidemics coincide with urbanization, geographic expansion and migrant movement. Cities with a higher economic growth rate experienced more rapid urbanization and prolonged epidemics. The process of urbanization and associated economic growth may delay zoonotic disease decline, possibly due to a higher volume and the specific living conditions of recent immigrants (Harpham, 1997; Tian *et al.,* 2018). In addition, more urbanized members of Indigenous groups in Brazil have higher rates of obesity and hypertension, suggesting that living in towns and cities has a negative impact on cardiovascular health (Armstrong *et al.,* 2023). Furthermore, urban areas are major sources of airborne pollutants and carbon emissions, causing respiratory and other diseases and adding to GHG emissions, negatively impacting health and contributing to climate change (Liang & Gong, 2020).

Urban heat islands, exacerbated by climate change, provide high-risk habitats for mosquito vectors of dengue virus in tropical regions and have driven cycles of significant outbreaks (Akhtar *et al.,* 2016; IPBES, 2020). In Nepal, dengue virus outbreaks began to occur in the last two decades. The rapidly growing capital city of Kathmandu, 1400 meters above mean sea level, had the largest outbreak in 2019 which claimed six lives and infected 14,000 people (Adhikari & Subedi, 2020). Known wildlife hosts of human pathogens may occur at higher levels of species richness and abundance in areas with secondary forest and in agricultural and urban ecosystems compared to undisturbed areas (Gibb *et al.,* 2020; Johnson *et al.,* 2020), including in city parks and gardens (Földvári *et al.,* 2011; Himsworth *et al.,* 2013; Rizzoli *et al.,* 2014; Rothenburger *et al.,* 2017; Szekeres *et al.,* 2016, 2019). In Dutch cities the hazard from most rat-borne pathogens increased in greener urban areas **(Figure 2.23)**. This was mainly caused by the increase in rat abundance rather than pathogen prevalence, which did not significantly change with greenness (De Cock *et al.,* 2023).

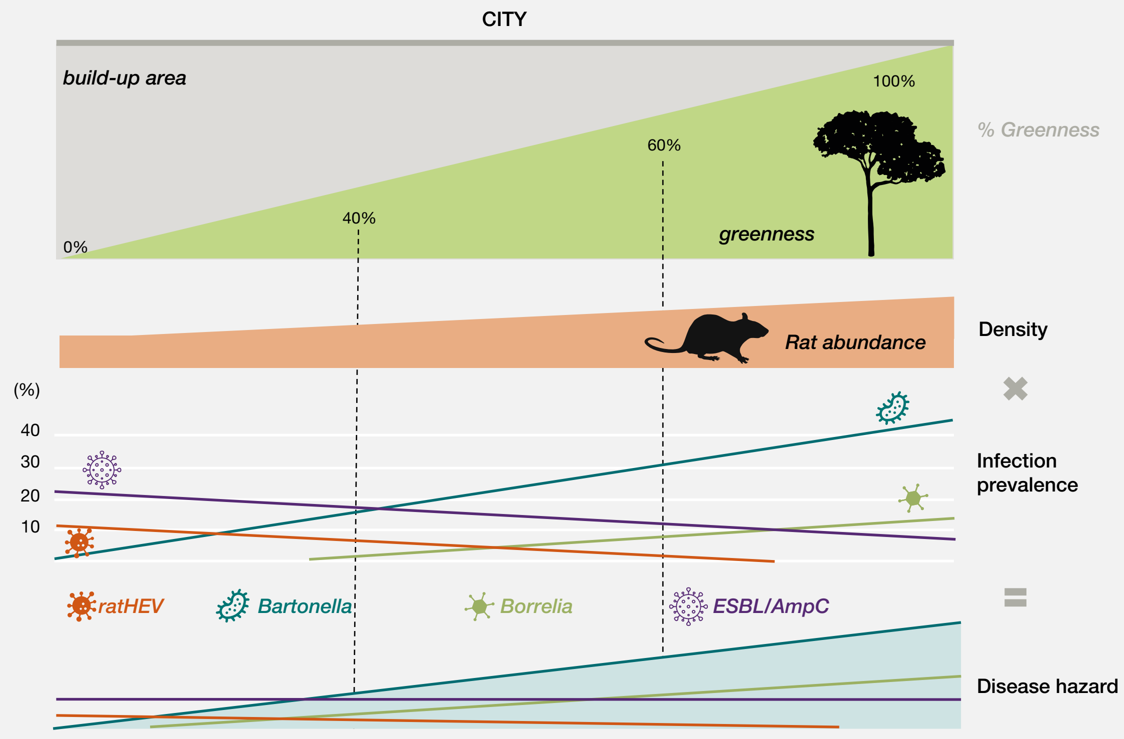


Figure 2 23 Changes in rat-borne disease hazard with urban greenness.

Data is based on rat density and pathogen prevalence (*Bartonella* spp., *Borrelia* spp., ESBL/AmpC-producing *E. coli* and ratHEV) by screening of wild brown rats (*Rattus norvegicus*) and black rats (*Rattus rattus*) from three urban areas in the Netherlands (Kingdom of the) for a total of 18 zoonotic pathogens. From: De Cock *et al.* (2023) under license CC BY-NC-ND- 4.0 Deed.

Box 2 14

Urbanization alters biodiversity, including at the molecular level, with possible health implications; bacterial genes have been shown to be shared among wild animals, livestock, and humans across Nairobi, Kenya – one of the world's most rapidly developing cities (Hassell *et al.,* 2019). In South America urban areas represent a high risk for canine and human visceral leishmaniasis due to the presence of both the sand fly vectors and large feral dog populations (Thomaz-Soccol *et al.,* 2018). While the overlapping distribution of urban and forest mosquitoes at park edges increase arbovirus exchange in Brazilian urban forest parks (Hendy *et al.,* 2020), perhaps explaining the local expansion (De Melo Ximenes *et al.,* 2020). These risks are often countered by enhanced disease control systems to protect, treat and help urban residents to recover from infectious diseases in urban regions, but these often rely on methods that negatively impact biodiversity, such as insecticide use.

The further expansion of emerging infectious diseases does not require animal reservoirs but occurs due to community spread through rapidly urbanizing landscapes, megacities and travel and trade networks; itself a driver for moving other invasive alien species. City apartments and hotels in south China (including Hong Kong) became super spreading centres during SARS (R. M. Anderson *et al.,* 2004). Urban centres became a focus of rapid amplification of Ebola virus infection in West Africa (Coltart *et al.,* 2017) and cities emerged as the central focus of outbreaks and impacts of COVID-19. In the long term, urbanization may significantly impact the quality of life in negative ways. As urban habitats often show climate and health effects in an enhanced way, they can also serve as harbingers (models) for understanding and predicting future scenarios of complex nexus interactions globally.

encompass around 54,000 glaciers covering 60,000 km^2 (Bajracharya & Shrestha, 2011). However, high altitude environments are experiencing profound impacts, including increased frequency of hazards such as snow avalanches and landslides (Ballesteros-Cánovas *et al.,* 2018). These hazards have contributed to 21 per cent (4,115 of 18,956) of the major disaster events in between 1980 and 2015, and 36 per cent in Asia (Vaidya *et al.,* 2019). Mountain areas overall cover about 25 per cent of the land area but harbour more than 85 per cent of the Earth's species of birds, mammals and amphibians (in high altitude regions as well as in foothills and mountain valleys (Rahbek *et al.,* 2019)).

Climate change has resulted in impacts on biodiversity, for example as habitats move to higher altitudes and/or are reduced, such as observed for the snow leopard habitat due to snowline shifts (S. Chaudhary *et al.,* 2023; J. Li *et al.,* 2016) or the golden snub-nosed monkey population in the Tibetan Plateau (Luo *et al.,* 2012). There have also been increases in plant richness observed in response to global warming (Steinbauer *et al.,* 2018). Altered hydrological cycles in mountain catchments due to climate change (coupled with anthropogenic activities such as land degradation and infrastructure development), have reduced water discharge, affecting millions of people in large catchments, even far away from mountain areas (Ghimire *et al.,* 2019; Palomo, 2017; Panwar, 2020; Prakash & Molden, 2020; Tambe *et al.,* 2012). In the past two decades, this caused severe water crises for 60–70 per cent of the Himalayan population that directly rely on springs for drinking water and irrigation (Tiwari & Joshi, 2012; Verma & Jamwal, 2022). Jointly with warmer temperatures, the altered runoff also has a negative impact on food production (e.g. due to less water being available for irrigation, although warmer temperatures can also result in longer growing seasons and new crops being grown; Palomo, 2017).

2.5.2.3 Pollution

Pollution, the introduction of harmful substances into the environment, adversely affects ecosystems, biodiversity and human health. Pollutants include a wide range of substances and energy forms, from chemicals and particulate matter to noise and light. Pollution impacts various environmental mediums, including the atmosphere (air), hydrosphere (water), lithosphere (soil) and all living organisms (see **Box 2.5**, **Figure 2.20**).

Indoor and outdoor air pollution is one of the world's leading driving factors for sickness and death (Landrigan *et al.,* 2018; Thurston *et al.,* 2017), increasing the risk for ischaemic heart disease, chronic obstructive pulmonary disease, lung cancer, stroke and childhood respiratory infections (Burnett *et al.,* 2014; Landrigan *et al.,* 2018; Lim *et al.,* 2012). Air pollution caused an estimated 9 million premature deaths in 2015 – 16 per cent of all deaths worldwide that year, and also in 2019 (Fuller *et al.,* 2022; Landrigan *et al.,* 2018). A major source of air pollution originates from burning fossil fuels and firewood as well as forest fires, also driving climate change.

In severely affected countries, such as China and Indonesia, pollution is responsible for over 25 per cent of deaths, with nearly 92 per cent of pollution-related deaths occurring in LMIC. All forms of pollution combined contribute to major non-communicable diseases, including ischaemic heart disease (26 per cent) and strokes (23 per cent), chronic obstructive pulmonary disease (51 per cent) and lung cancer (43 per cent, Landrigan *et al.,* 2018). Water pollution, soil pollution and occupational pollutants (e.g., carcinogens) from various sources, including chemicals such as lead, mercury, chromium, arsenic, asbestos and benzene, all kill hundreds of thousands of people annually (Landrigan *et al.,* 2018). Children are also at high risk of pollution-related disease through exposure to pollutants in the uterus and in early infancy, which can lead to death but may also result in chronic disease and disabilities (Landrigan *et al.,* 2018).

Water and soil are polluted by many different sources, including heavy metals, (micro)plastics, chemicals, antibiotics and excess nutrients **(Box 2.4, 2.3)**. Agriculture contributes to water and soil pollution through the intensive use of agricultural inputs (i.e., fertilizer, pesticides) and to air pollution through burning of organic matter (e.g., slash and burn techniques, burning of peatlands etc.). Excessive nutrient loads in food production have contributed to freshwater and marine biodiversity loss. Many river estuaries and coastal zones are characterized by dead zones, the result of eutrophication by predominately excess of nitrogen and phosphorus nutrient inflow from agriculture and are often transboundary problems. More than 400 so-called dead zones in coastal waters around the world have been identified, affecting a total area of more than 245,000 km^2 (about the size of the United Kingdom), where excess nutrients lead to areas of low to no oxygen that can kill fish and other marine life (A. H. Altieri & Gedan, 2015; Diaz & Rosenberg, 2008).

Large rivers which drain agricultural lands transport excess nutrients to such dead zones, such as the Yangtze and Pearl River estuaries on the Chinese coast, the Po in the Mediterranean (Grizzetti *et al.,* 2012; Malagó *et al.,* 2019) or the Mississippi in the Gulf of Mexico, where during years with low river flow, the area of hypoxia shrinks to <5000 km^2, only to increase to $>15,000$ km^2 when river flow is high (Rabalais *et al.,* 2007). The Baltic Sea has suffered eutrophication over the past century, with recurring algal blooms resulting from increased nutrient loading from 1965 onwards. This has remained high despite policy measures in the late 1970s to reduce incoming nutrient loads (Andersen *et al.,* 2017). Algal blooms due to eutrophication produce natural toxins that can cause sickness and death in humans and other animals (McCabe *et al.,* 2016).

Biological or synthetic pesticides applied to crops are a threat to biodiversity (Beckmann *et al.,* 2019) as well as human health directly through human exposure or indirectly through ecosystem degradation (Jørgensen *et al.,* 2018; Richter *et al.,* 2015; Romanelli *et al.,* 2015). Some pesticides penetrate through the food chain, causing impacts in the environment and in human and animal health if chronic exposure happens in the long-term (Bai & Ogbourne, 2016). The repeated use of the herbicide glyphosate, for example, in crop systems promoted the relative abundance of gram-negative bacteria in soils, such as *Burkholderia* spp., which can be linked to the emergence of human melioidosis (Lancaster *et al.,* 2010; Limmathurotsakul *et al.,* 2010). Pesticide contamination affects the health of consumers of regional drinking water, produce and aquatic organisms (Richter *et al.,* 2015). Accordingly, regional populations relying on surface water as a source of drinking water may already be at considerable risk of developing symptoms associated with the long-term consumption of local pesticide residues (Richter *et al.,* 2015). Contamination of aquatic organisms with pesticide residues can be found in concentrations that are harmful based on daily consumption rates of local diets (Pham *et al.,* 2011).

Industrial livestock production commonly employs anabolic steroids and antibiotics as growth promoters, leading to contamination of surface waters and meat (Al-Amri *et al.,* 2021; Dungan *et al.,* 2017) and contributing to antibiotic resistance in food-borne bacteria (Croft *et al.,* 2007). Livestock can serve as intermediate hosts, facilitating pathogen evolution and transmission to humans (Childs *et al.,* 2007; D. Grace *et al.,* 2012; Kuiken & Cromie, 2022; Woolhouse & Gowtage-Sequeria, 2005). High-density confinement of animals in commercial operations, supported by automated feeding systems, increases contact rates and induces immunosuppressive stress, promoting intra- and interspecies pathogen transmission (Greger, 2007; King & Lively, 2012). These conditions have been linked to the emergence of highly pathogenic avian influenza viruses in poultry, originating from low pathogenic viruses in wild bird reservoirs, with subsequent reinfection of wild species, causing high mortality (Global Consortium for H5N8 and Related Influenza Viruses, 2016; Kuiken & Cromie, 2022; Lebarbenchon *et al.,* 2010).

Pollution of freshwater and marine waters with other pollutants have multiple impacts on biodiversity and human health. Seafood contaminated with methylmercury and polychlorinated biphenyls, for example, can cause cardiovascular diseases in humans as well as severe impacts to infants in the uterus during pregnancy (Landrigan *et al.,* 2020). However, well-functioning wetlands with their inherent biodiversity contribute to maintaining water quality through filtration and sedimentation, removing pollutants and excess nutrients, and helping to protect people and other species from waterborne chemical and biological risks (Cardinale *et al.,* 2012).

Soil pollution leads to the degradation of soil quality, primarily caused by the accumulation of hazardous chemicals, heavy metals and other pollutants, disrupting the delicate balance of soil ecosystems (Feckler *et al.,* 2023). Such pollutants originate from a variety of sources, including industrial discharge, agricultural practices involving the excessive use of pesticides and fertilizers, and improper waste disposal (Gan *et al.,* 2023). The presence of these contaminants in soil not only reduces its fertility and alters its physical and chemical properties but also has a cascading effect on the biodiversity it supports. Plants and soil microorganisms, which form the foundation of terrestrial food webs for humans and animals, are particularly vulnerable. Their impairment or loss due to soil pollution can lead to a reduction in species diversity and abundance, affecting higher trophic levels and ultimately human health through the disruption of food chains (Okoye *et al.,* 2021). Moreover, soil pollutants can leach into water bodies, extending their detrimental effects to aquatic ecosystems (Mao *et al.,* 2023).

Clean air, water and soil are essential assets for human well-being, but their pollution by human activities has led to biodiversity loss, decreases in food sources (i.e., fisheries) and contributed to increases in global animal and human disease burdens. Y. Ran *et al.* (2024) estimated that in 2019, global total air pollution accounted for 6.67 million deaths, water pollution for 1.36 million deaths and total occupational pollution (carcinogens and particulates) for 0.87 million deaths (Fuller *et al.,* 2022).

More than 80 per cent of industrial and municipal sewage from human activities discharged into rivers, estuaries and oceans are untreated (Y. Liu *et al.,* 2021), and consequently more than 50 diseases are caused by poor water supply, water quality and sanitation (L. Lin *et al.,* 2022). Excessive sewage from areas of high population density, like Mumbai and Karachi, are driving coastal water oxygen deficiency in the Arabian Sea. Poor water quality and related activities (including drinking water, sanitation and hygiene) has been conservatively estimated to result annually in 1.4 million deaths and 74 million DALYs, with a high burden in the poorest countries (Fuller *et al.,* 2022; Wolf *et al.,* 2023) **(Figure 2.24)**. Global and regional disparities in access to clean water persist, with coverage varying widely from 96 per cent in Europe and Northern America to just 30 per cent in sub-Saharan Africa. In sub-Saharan Africa, inequalities are particularly stark, with national estimates ranging from 94 per cent in Reunion to only 6 per cent in Chad (UNICEF & WHO, 2023).

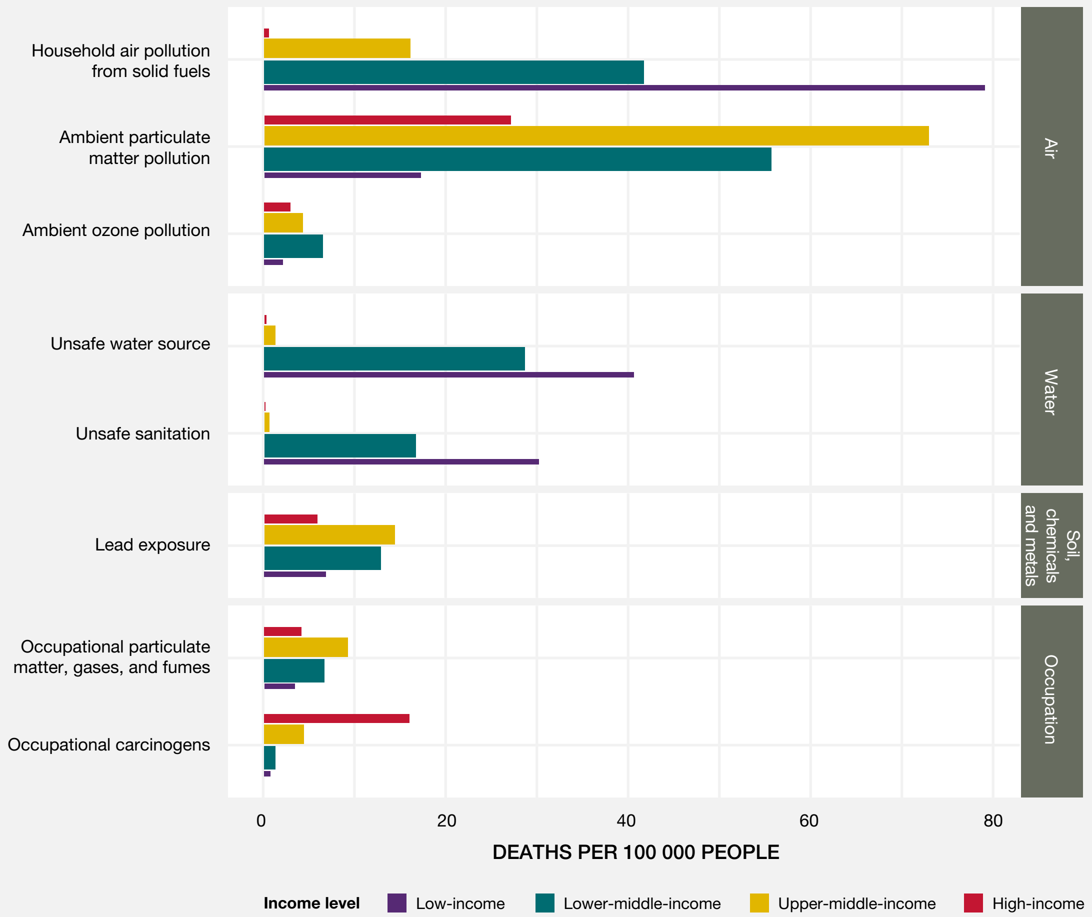


Figure 2 24 **Number of deaths attributable to all forms of pollution per 100,000 people in 2019 by income level.**

The width of the bars is proportional to the total population of the respective income level group (World Bank, 2023m). Pollution risk factors considered according to Landrigan *et al.* (2018): (1) air pollution, (2) water pollution, (3) soil, chemical and heavy metal pollution, (4) occupational pollution. Data source: IHME (2023b), see data management report.[5]

5. The data management report on number of deaths attributable to pollution (https://doi.org/10.5281/zenodo.13913196).

2.5.2.4 Invasive alien species

Over 37,000 IAS due to human activities have been reported worldwide, with approximately 200 new IAS documented each year, of which over 3,500 are proven to be harmful and 85 per cent detrimental to native species and capable of transforming ecosystems (IPBES, 2023) **(Box 2.16)**.

Notably, the most severe damage caused by IAS occurs on islands, where more than 25 per cent of all islands now have a greater number of alien plants compared to native plants. However, documented impacts have been reported from biological invasions in the Americas (34 per cent), Europe and Central Asia (31 per cent), Asia and the Pacific (25 per cent) and Africa (7 per cent) (IPBES, 2023). The majority (75 per cent) of these negative impacts are concentrated on land, particularly affecting forests, woodlands and cultivated areas, with smaller proportions of impacts reported in freshwater ecosystems (14 per cent) and marine environments (10 per cent, see **Box 2.8**) (IPBES, 2023).

Most IAS move due to trade and travel, some initially introduced due to perceived benefits, such as for hunting or food sources (e.g., European rabbits (*Oryctolagus cuniculus*) to Australia and New Zealand). Nearly 80 per cent of IAS documented impacts on nature's contributions to people are unfavourable and IAS have been the primary driver behind 16 per cent of documented global animal and plant extinctions. Individuals and communities most directly reliant on nature, including IPLC, are particularly vulnerable to IAS impacts. More than 2,300 IAS are found on lands managed by Indigenous Peoples (IPBES, 2023), sometimes threatening their quality of life and cultural identities (Australian Government, n.d.). Many IAS are agricultural pests and damage food supplies, with their global spread being further facilitated climate change (Schneider *et al.,* 2022). Examples include the tomato leafminer (*Tuta absoluta*), which damages a range of nightshade plants (e.g. tomato, potato or pepper; Biber-Freudenberger *et al.,* 2016), the European shore crab (*Carcinus maenas*), which affects commercial shellfish beds in New England, and the Caribbean false mussel (*Mytilopsis sallei*), which has caused considerable harm to locally significant fishery resources in India (IPBES, 2023).

Conversely, the food industry is an IAS source, with more than 35 per cent of alien freshwater fish in the Mediterranean basin originating from aquaculture (IPBES, 2023). Aquatic IAS, such as water hyacinth (*Pontederia crassipes*), zebra mussels (*Dreissena polymorpha*) or Invasive carp (multiple genera), can disrupt food webs, impacting fish populations of significance for human consumption and disrupt natural water flow, obstruct waterways and alter water quality, harming aquatic life (IPBES, 2023). The Great Lakes ecosystem in North America has had repeated invasions, with species such as the zebra, and more recently quagga, mussel outcompeting native mussels and reducing available food and spawning grounds for other fish, likely costing billions (Escobar *et al.,* 2018; Haubrock *et al.,* 2022). In Lake Victoria, fisheries have declined due to the depletion of native tilapia following the introduction of Nile perch (*Lates niloticus*) and more recently Nile tilapia (*Oreochromis niloticus*) for food, and because of the proliferation of water hyacinth (*Pontederia crassipes*), recognized as the world's most widespread terrestrial IAS (Outa *et al.,* 2020; IPBES, 2023). Lantana (*Lantana camara*), a flowering shrub, and the black rat (*Rattus rattus*) are the second and third most

Box 2 15 **Nexus approach in small-scale fisheries: A success story from Türkiye.**

Fishing in the Mediterranean region has been carried out for millennia with the involvement of IPLC. The small-scale fisheries sector coexists alongside industrial and semi-industrial fisheries and contributes to food security and nutrition, economic growth, rural development and cultural wealth, while providing valuable employment opportunities. However, according to the report on the "State of Mediterranean and Black Sea Fisheries" of the General Fisheries Commission for the Mediterranean, fisheries in the region are subjected to many stressors and are unsustainable due to high levels of overfishing that affects about 75 per cent of the assessed stocks (FAO, 2020c).

In Türkiye, an ecosystem-based fisheries management system has been implemented with small-scale fishers in Gökova Bay since 2010, with support from two non-governmental organisations: Ecological Research Society (Ekolojik Araştırmalar Derneği) and Mediterranean Conservation Society (Akdeniz Koruma Derneği). Gökova Bay is one of the largest bays on the Mediterranean coast of the Anatolian Peninsula and has rich biodiversity. Local fishers use traditional and small-scale fishing gears such as longlines and gillnets (Ünal & Kizilkaya, 2019). The Gökova marine protected area **(Figure 2.25)** covers an area of 82,700 ha, including 20 no-fishing zones (NFZs), where any type of commercial fishing activity is forbidden (Bann & Başak, 2013; UNESCO/IOC, 2021). The establishment of the first group of NFZs in 2010 did not immediately have the desired result due to a lack of effective control and illegal fishing. In 2012, a system was developed for training and employing local fishers as marine rangers and equipping them with faster boats to work together with the coast guard to monitor activities and stop illegal fishers from other regions (Ünal & Kizilkaya, 2019). These actions, among others, have led to a significant recovery of fish stocks and increases in the apex predator biomass **(Figure 2.27)** (Vasconcellos & Ünal, 2022) with a concurrent increase in local communities' incomes **(Figure 2.26)**.

Box 2 15

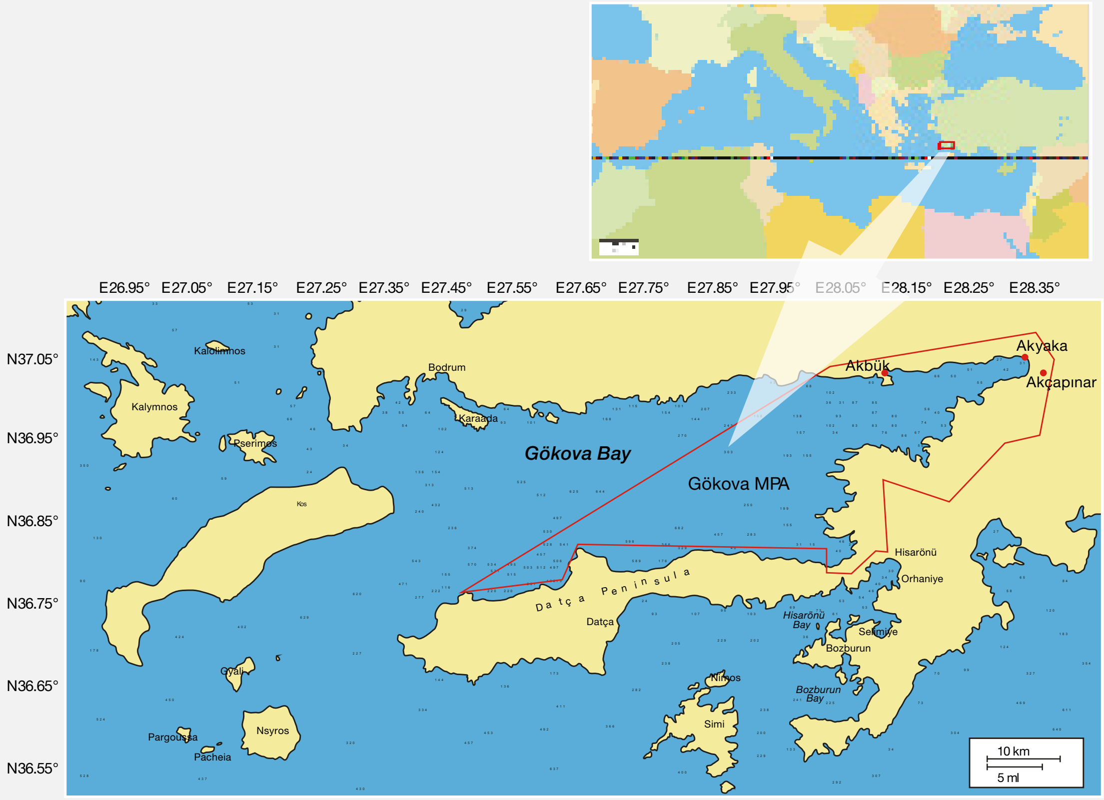


Figure 2 25 **Location of Gökova marine protected area.**

From Vasconcellos & Ünal (2022) under licence CC BY-NC-SA 3.0.

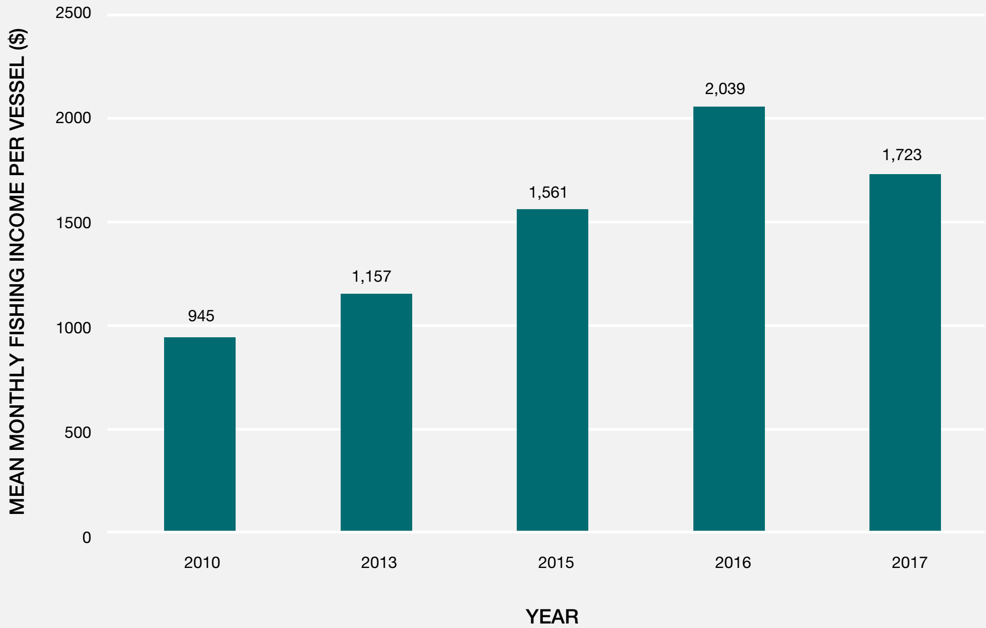


Figure 2 26 **Improvements of fishing income of local fishers by years in USD.**

From Ünal & Kizilkaya (2019); copyright American Fisheries Society, one-time use of figure permission granted.

Box 2 15

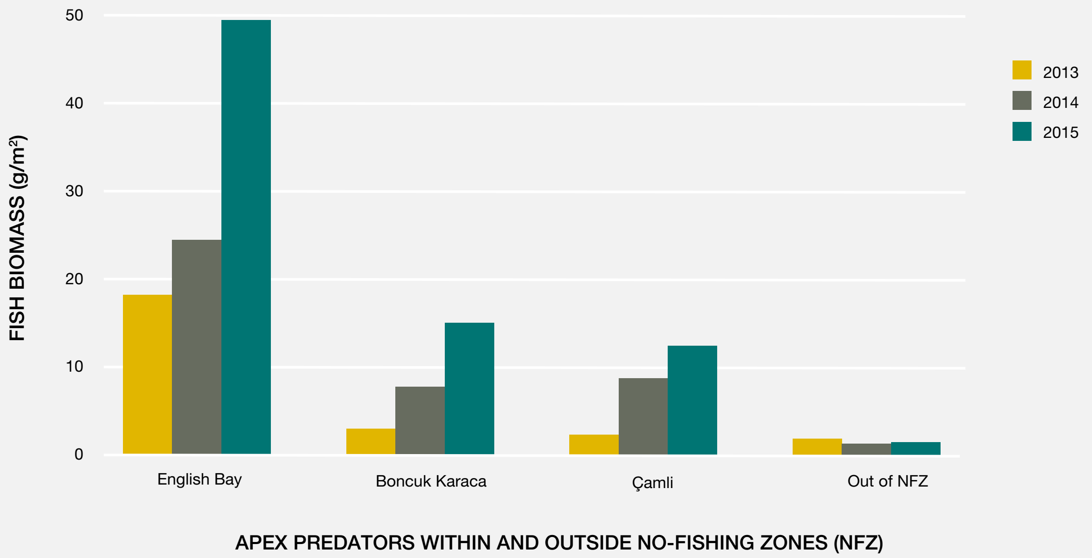


Figure 2 27 **Increase in apex predator biomass of three no-fishing zones (NFZs) compared to non-NFZs.**

From Ünal & Kizilkaya (2019); copyright American Fisheries Society, one-time use of figure permission granted.

Recovered populations of local apex predator species and improved habitat quality have helped control the numbers and spread of invasive species (IPBES, 2023). In addition, the project is promoting consumption of the invasive fish, as the Mediterranean Conservation Society collaborates with restaurants, culinary-gastronomy institutions and TV shows such as MasterChef Türkiye on national television to promote to a wider audience the importance of edible invasive species consumption to help restore marine ecosystems.

This example shows how conservation and improvement of small-scale fisheries for the benefit of local communities' traditional and artisanal fishing practices can be achieved, while at the same time providing effective solutions for the restoration of marine ecosystems and the control of invasive species (Ayaz *et al.,* 2010; Ünal *et al.,* 2009). The success of this project highlights that when management authorities, resource users and other stakeholders are willing to work together to achieve common objectives, good management outcomes are possible (see **Chapter 4**). The process was supported by appropriate communication strategies and well-designed awareness activities involving an inclusive contribution from local communities. The case study also shows how the establishment of marine protected areas can profit IPLC through adopting a nexus approach. This is likely to become more important as the world moves towards protecting 30 per cent of the oceans in line with the United Nations High Seas Treaty (UN, 2023d) and the Kunming-Montreal Global Biodiversity Framework (Secretariat of the Convention on Biological Diversity, 2020).

widely distributed IAS globally, with far-reaching impacts on both people and nature (IPBES, 2023), with the black rat the source of many zoonotic infections that cause serious human diseases, such as *Leptospira* bacteria. Leptospirosis is principally hosted by rodents, though also by many other domesticated and wild mammals, and causes many billions of costs (Agampodi *et al.,* 2023). Leptospirosis cases particularly increase during flooding events, especially after storms or hurricanes in tropical countries, including islands, typically impacting the most financially poor.

Eighty five per cent of documented IAS impacts have detrimental effects on people's quality of life (IPBES, 2023). Certain invasive plants, like poison ivy or giant hogweed, can trigger skin irritations and allergies, while invasive animals, including specific mosquito and tick species, can transmit diseases to humans. Water-dependent, anthropophilic *Aedes* mosquitoes like *Aedes albopictus* and *Aedes aegyptii* have spread through human population growth, movement and urbanization to transmit dengue fever, chikungunya, Zika fever and yellow fever-causing viruses around the tropics (Kraemer *et al.,* 2015).

Interactions between IAS and deforestation, habitat degradation and breakdown of ecological connectivity and other drivers of change can amplify their impacts. For example, invasive alien plants can interact with climate change leading to more frequent and intense wildfires (IPBES, 2023). These wildfires release additional carbon dioxide into the atmosphere, exacerbating climate change.

Eighty percent of countries (156 out of 196) have established targets to manage IAS, though these measures are frequently under-resourced. However, successful eradication has proven effective and cost-efficient for certain IAS, usually when their spread is slow, populations small and in isolated ecosystems, such as islands like in French Polynesia where black rat (*Rattus rattus*) and rabbit (*Oryctolagus cuniculus*) elimination has been possible, with recorded success rates of 88 per cent on 998 islands (Spatz *et al.,* 2022). Biological control programmes targeting invasive alien plants and invertebrates have also shown notable success rates, exceeding 60 per cent (IPBES, 2023). However, the eradication of invasive plants poses a greater challenge due to the prolonged dormancy period of seeds in the soil. Preparedness, early detection and swift response have proven effective in reducing the establishment rates of alien species, especially in marine and connected water systems.

Box 2 16 Domestic cats and toxoplasmosis: Impacts on the biodiversity, water, food and health nexus.

Domestic cats (*Felis catus*) are common pets, peri-domestic and feral animals throughout the world, likely exceeding 500 million (Maggi *et al.,* 2022). Cats are skilled hunters and obligate carnivores and have been used for centuries to control rodents, notably around food stores and on ocean-going ships. This relationship, however, has led to devastating impacts on biodiversity as they are now globally distributed (Hess *et al.,* 2009). Cats also host several infectious diseases, for example, *Toxoplasma gondii* is a protozoan parasite that sexually reproduces only in felids and is now one of the world's most common parasites, infecting most genera of warm-blooded animals with impacts on biodiversity, water, food and health.

Direct biodiversity impacts through predation: Cats are one of the most common causes of anthropogenic mortality for birds, reptiles and mammals, having contributed to the extinction of species globally and currently threatening 430 species worldwide (Doherty *et al.,* 2016; Loss *et al.,* 2013; Rebolo-Ifrán *et al.,* 2021; Stobo-Wilson *et al.,* 2022). Cats are a leading cause of passerine bird mortality in urbanized areas, reducing urban biodiversity (Loss *et al.,* 2015; Rebolo-Ifrán *et al.,* 2021). They are estimated to kill 1.3-4.0 billion birds and 6.3-22.3 billion mammals annually in the USA, and 100 million birds and 350 million mammals annually in Canada (Loss *et al.,* 2013; Medina *et al.,* 2011; Woinarski *et al.,* 2017). Along with foxes, another invasive species, cats are also estimated to kill 697 million reptiles, 1,435 million mammals and 377 million birds annually in Australia (Stobo-Wilson *et al.,* 2022).

Toxoplasmosis and human health impacts: Definitive hosts of *T. gondii* include wild cats, such as bobcats (*Felis rufus*), and mountain lions (*Puma concolor*), yet domestic cats have spread toxoplasma globally as people have taken cats around the world (J. P. Dubey, 2016). *Toxoplasma gondii* is spread by oocysts in cat faeces, and these can persist in the environment for long periods and spread to soil and water, and environmental contamination is ubiquitous (Maleki *et al.,* 2021). People can be infected, with a pooled worldwide prevalence of *T. gondii* infection of 35.8 per cent (95 per cent CI 30·8–40·7) (Z.-D. Wang *et al.,* 2017). Infection is frequently asymptomatic but can cause abortion or stillbirth in pregnant women, congenital toxoplasmosis with major ocular and neurological consequences, and life-threatening cerebral toxoplasmosis in the immunosuppressed. The estimated disease burden of congenital toxoplasmosis in the Netherlands (Kingdom of the) is 620 (range, 220-1900) DALYs per year, similar to salmonellosis and largely due to foetal deaths and eye infections (chorioretinitis) (Havelaar *et al.,* 2007). Higher burdens are reported in South America, some Middle Eastern and low-income countries (Gómez-Marin *et al.,* 2011; Torgerson & Mastroiacovo, 2013). For example, 5-23 children are born infected per 10,000 live births in Brazil, with the burden of 1.20 million DALYs (95 per cent CI: 0.76–1.90) (Strang *et al.,* 2020; Torgerson & Mastroiacovo, 2013).

Toxoplasmosis and food systems: Cats are related to food systems, not least through pet cat food consumption, which has environmental impacts (Pedrinelli *et al.,* 2022). In addition, cats and toxoplasma are related to food systems through rodents that predate domesticated food crops and through food-borne transmission, as infection can be via raw or undercooked meat with tissue cysts and oocyst contaminated raw fruits and vegetables. Toxoplasmosis also has a significant economic impact on livestock farmers, as well as welfare and health issues (Stelzer *et al.,* 2019), because domesticated ruminants, such as goats and sheep, are commonly infected with *T. gondii*, and toxoplasmosis may cause early embryonic death and resorption, foetal death and mummification, abortion, stillbirth and neonatal death (Stelzer *et al.,* 2019).

Toxoplasmosis and terrestrial biodiversity: Toxoplasma can infect wild birds (J. P. Dubey, 2002), fatally infecting a range of endangered species, including the Hawaiian Goose (Nēnē; *Branta sandvicensis*) and Hawaiian Crow (ʻAlalā; *Corvus hawaiiensis,* the world's most endangered Corvid) (Chalkowski *et al.,* 2020; Work *et al.,* 2000) in Hawaiʻi and kākā (*Nestor meridionalis*), red-crowned kākāriki (*Cyanoramphus novaezelandiae*), kererū (*Hemiphaga novaeseelandiae*) and several kiwi species (*Apteryx* spp.) in New Zealand (Roberts *et al.,* 2020), all of which evolved in locations with no native felids. These species, in addition to some aquatic and marine species, are *taonga* (treasured, socially and culturally valuable to the identity and well-being) among Māori.

Box 2 16

Toxoplasmosis and water systems: T. gondii oocysts can be transported by runoff into waterways, contaminating bivalve molluscs (Shapiro, Bahia-Oliveira, *et al.,* 2019) and marine systems. This water pollution has led to *Toxoplasma* infection among marine mammals, with high prevalences among mustelids (otters; 55 per cent, 95 per cent CI 34-75) and cetaceans (whales, dolphin and porpoises; 31 per cent, 95 per cent CI 18-46) (Ahmadpour *et al.,* 2022). Eurasian otters and North American sea otters have died (Miller *et al.,* 2023; Shapiro, VanWormer, *et al.,* 2019; Viscardi *et al.,* 2022), while Amazon river dolphins (*Inia geoffrensis*) in Brazil have been infected (Santos *et al.,* 2011), along with estuarine and coastal dwelling dolphins, such as Guiana dolphins (*Sotalia guianensis*) in Brazil (Costa-Silva *et al.,* 2019; Groch *et al.,* 2020), and Hector's and Māui dolphins (*Cephalorhynchus hectori hectori* and *Cephalorhynchus hectori maui*, respectively) in New Zealand. Fatal infection has been reported in the endangered Hawaiian Monk Seal (Ilio holo I ka uaua; *Monachus schauinslandi*) (Chalkowski *et al.,* 2020; Honnold *et al.,* 2005), including after rain events in Hawai'i (Robinson *et al.,* 2023), along with spinner dolphins (*Stenella longirostris)* (Landrau-Giovannetti *et al.,* 2022). This is similarly reflected in the Mediterranean, where the Mediterranean monk seal (*Monachus monachus*) (Petrella *et al.,* 2021), striped dolphin (*Stenella coeruleoalba*), common bottlenose dolphin (*Tursiops truncates*) (Fernandez-Escobar, 2022) and Mediterranean fin whale *(Balaenoptera physalus)* have all been fatally infected (Mazzariol *et al.,* 2012), with both striped and bottlenose dolphins infected in the Americas (Costa Rica and United States)) (J. P. Dubey *et al.,* 2007, 2008). Infection in the Indo-Pacific humpbacked dolphins (*Sousa chinensis*) have been reported in Australia (Bowater *et al.,* 2003). Further evidence of toxoplasma's ubiquitousness and possible dispersal by ocean currents or migratory intermediate hosts like birds is evidenced by a study in Antarctica that found 13 per cent of seals had *T. gondii* antibodies (Rengifo-Herrera *et al.,* 2012).

2.5.3 Hotspots of nexus elements and their degradation

2.5.3.1 Geographical distribution and area of nexus hotspots

Section 2.5.2 showed that nexus interactions are manifold, and a comprehensive representation of the nexus is complex even conceptually (see **Figure 2.1**). A spatially explicit representation of all processes involved is not yet possible due to its complexity and data gaps. In this section, the results of a spatially explicit analysis of the state of the five nexus elements are presented. This includes the identification of marine and terrestrial areas (including areas inhabited by Indigenous Peoples) where beneficial or degraded conditions of biodiversity, water, food, health or climate change (co-)occur. The beneficial hotspots are areas where the indicators of species richness, accessible groundwater volume, food production or life expectancy have the highest values. Likewise, the degradation hotspots are areas where the indicators of threatened species richness, blue water scarcity, malnutrition, DALYs or ecological impact of climate change have the highest values (see **Box 2.17** and data management report[6] for detailed information on used data and methods).

In total approximately 41 per cent of the terrestrial and 20 per cent of the marine area are covered by at least one beneficial hotspot of the selected indicators of biodiversity, water, food or health **(Figure 2.30C, D)**. Hotspots in which there is only one beneficial nexus element indicator cover around 34 per cent of the terrestrial and 16 per cent of the marine area. Co-occurring hotspots of two nexus elements cover around 4 per cent of both terrestrial and marine area, while co-occurring hotspots of three elements cover 3 per cent of the terrestrial area. In the terrestrial realm food hotspots (high food production) evenly co-occur with biodiversity, water or health hotspots (high species richness, volume of accessible groundwater or life expectancy, respectively), whereas biodiversity hotspots and health hotspots co-occur only to a negligible extent (**Figure 2.31**, inner circle).

In contrast, approximately 41 per cent of the terrestrial and 21 per cent of the marine area are covered by at least one degradation hotspot of the selected indicators of biodiversity, water, food, health or climate change **(Figure 2.30C, D)**. Hotspots in which there was only one degradation indicator of nexus elements were identified for 32 per cent of the terrestrial and 20 per cent of the marine area. Multiple degradation hotspots occur less frequently, comprising 8 per cent of the terrestrial and 1 per cent of the marine area for co-occurrence of two nexus elements and less than 1.5 per cent of the terrestrial area for co-occurrence of three nexus elements. In the terrestrial realm degradation hotspots of biodiversity (high threatened species richness) co-occur mostly with health degradation hotspots (high health burdens (DALYs)) but co-occur also with food degradation hotspots (high malnutrition) (**Figure 2.31**, inner circle). Food degradation hotspots mostly co-occur with water and climate change (high water scarcity; high ecological impact of climate change) but also with health degradation hotspots (high DALYs).

6. The data management report for the overlay analysis is available at https://doi.org/10.5281/zenodo.13913127.

Box 2 17 Methodology: Hotspot analyses.

Indicators needed to have global coverage, a spatial resolution of at least 5 arcmin (~10km), stem from a scientific peer- review process and be publicly available (data management report[6] for details). The exception was for health data, for which useful indicators were only available at the national level. The selected datasets cover the period from 2000 to 2010 (but see **Section 2.7.3**).

The hotspot analyses are based on two sets of indicators (**Table 2.4** and **Table 2.5**). Indicators to identify hotspots representing beneficial conditions for nexus elements are shown in **Table 2.4**, which when mapped provide indications of a positive outcome for people or the environment at that location. Note that climate change is not included as part of the analysis of beneficial hotspots due to lack of positive outcomes of climate change. **Table 2.5** shows indicators used to identify hotspots where there has been degradation of nexus elements, which when mapped indicates a negative outcome for people or the environment at that location.

Table 2 4 Indicators used to identify beneficial nexus element conditions.

For the marine realm the nexus elements water (freshwater) and health (human health) are not applicable and were excluded from the benefit hotspot analysis. Furthermore, climate change was excluded from the analysis due to a lack of positive outcome of climate change on people or the environment.

Realm	Nexus element	Indicator	Reference
Terrestrial	Biodiversity	Species richness	IUCN (2022)
	Water	Volume of accessible groundwater	Gleeson *et al.* (2016)
	Food	Food production (livestock & crop production)	Herrero *et al.* (2013); Monfreda *et al.* (2008)
	Health	Life expectancy	Global Data Lab (2023)
	Climate change	Not applicable	
Marine	Biodiversity	Marine species richness	Jenkins & Van Houtan (2016)
	Water	Not applicable	
	Food	Food production (fisheries production)	Watson, 2017
	Health	Not applicable	
	Climate change	Not applicable	

Table 2 5 Indicators used to identify degrading nexus element conditions.

For the marine realm the nexus elements water (freshwater) and health (human health) are not applicable and were excluded from the degradation hotspot analysis.

Degradation			
Realm	**Nexus element**	**Indicator**	**Reference**
Terrestrial	Biodiversity	Threatened species richness	IUCN, 2022
	Water	Blue water scarcity	Mekonnen & Hoekstra, 2016
	Food	Malnutrition (Wasting or overweight prevalence for children under 5 years)	IHME (2020a, 2020b)

Box 2.17

Table 2.5

Degradation			
Realm	**Nexus element**	**Indicator**	**Reference**
Terrestrial	Health	Disability-adjusted life years (DALYs)	IHME (2023a)
	Climate change	Velocity of climate change (ecological impact of climate change) calculated based on temperature and precipitation anomalies.	Loarie *et al.* (2009)
Marine	Biodiversity	Threatened marine species richness	Jenkins & Van Houtan (2016)
	Water	Not applicable	
	Food	No data/indicator available	
	Health	Not applicable	
	Climate change	Velocity of climate change (ecological impact of climate change) calculated based on temperature anomalies.	Loarie *et al.* (2009)

Mapping hotspots: An overlay analysis of the upper 10 per cent quantile of the data (hotspot) on a given indicator was conducted based on multiple indicators for the five nexus elements biodiversity, water, food, health and climate change (see **Figure 2.28** as example). Resulting focal areas of (co-)occurrence of nexus element hotspots of benefits or degradation were identified separately for the marine and terrestrial realms.

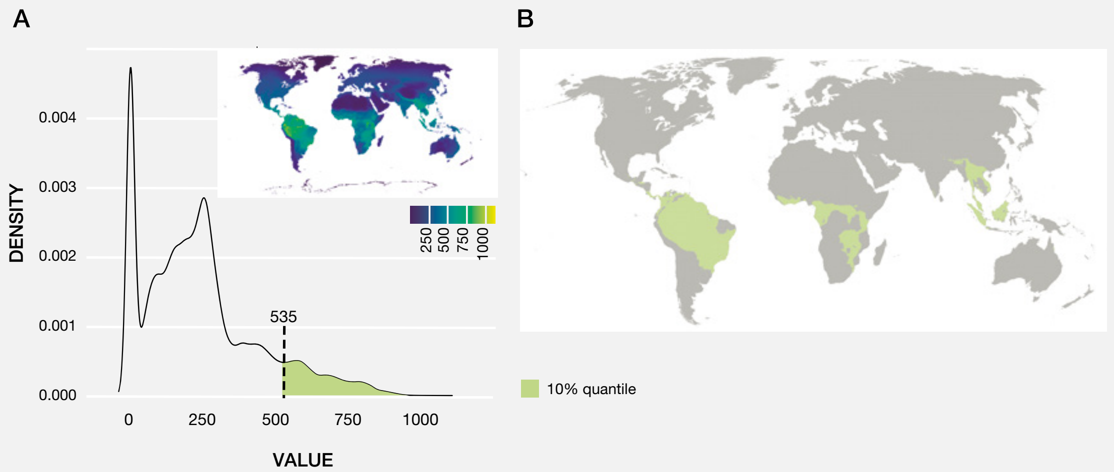


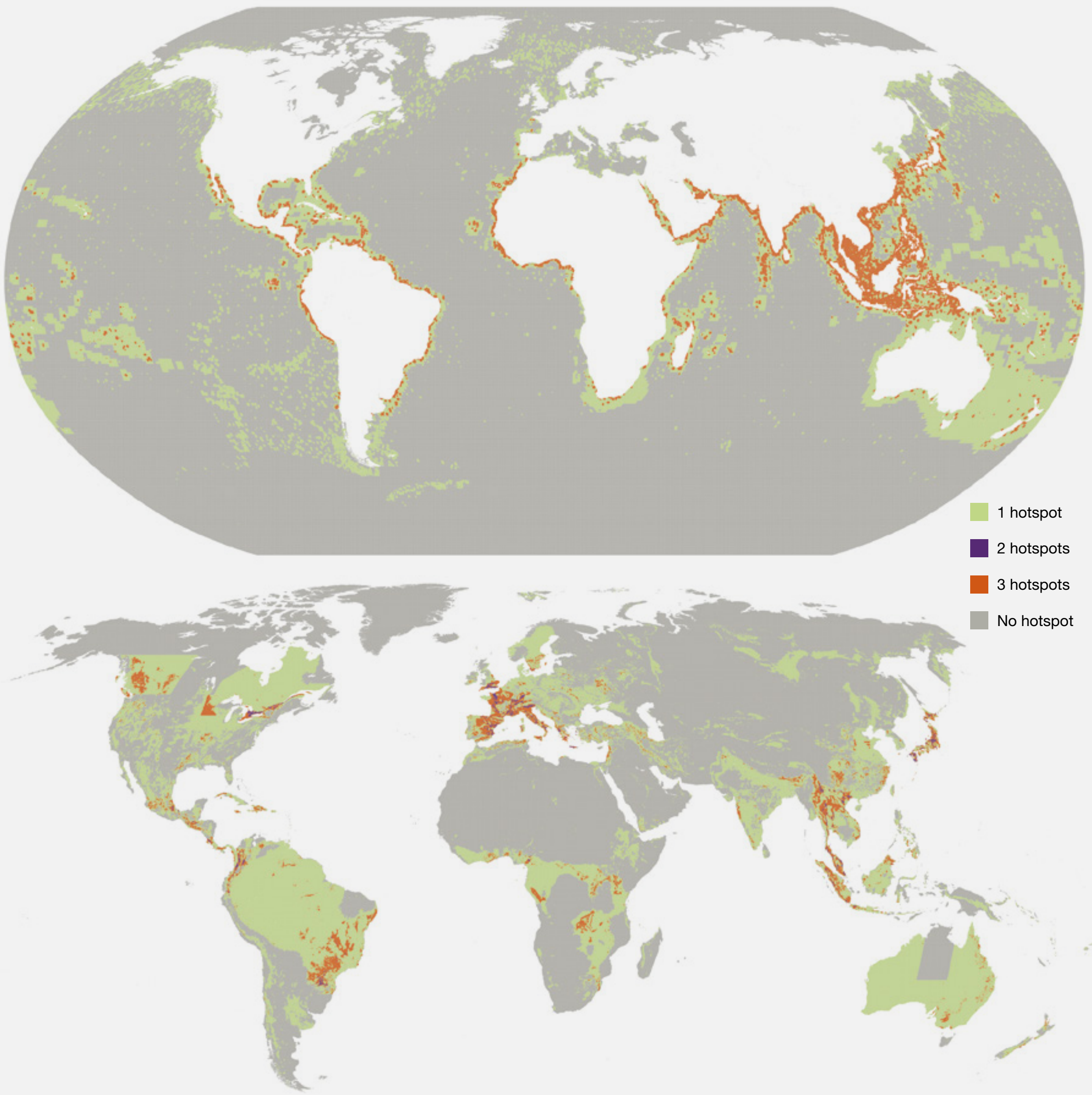
Figure 2.28 **Identification of hotspots of species richness.**

(A) The 10 percent quantiles (10 per cent of the cells with the highest species richness values). **(B)** Hotpots (green-coloured regions) based on the 10 per cent quantiles in panel **(A)**." Please use this version and present the panels in the order they appear.

Mapping impacts: Population numbers (Sims *et al.,* 2023) and income level data (World Bank, 2023m) were used to calculate how many people with which income level live within the hotspot areas. Income levels are not purchasing power parity corrected (World Bank, 2023n). Summary statistics were calculated to identify the percentage of total terrestrial and marine area covered by the hotspot areas and the percentage of Indigenous Peoples' managed area covered by the hotspot areas (see **Figure 2.30**). Areas managed by Indigenous Peoples were identified using data from Garnett *et al.* (2018). See the data management report[6] for detailed information on used data, methods and results.

Compared to the total terrestrial land cover, the area managed by Indigenous Peoples is covered to a smaller percentage by at least one beneficial nexus element hotspot (32 per cent compared to 41 per cent) but is covered to a higher percentage by at least one degradation hotspot (49 per cent compared to 41 per cent) **(Figure 2.30D).** The smaller share of beneficial hotspots compared to total terrestrial land cover mainly results from a smaller share of food hotspots, i.e., Indigenous Peoples managed lands are less likely to be in the top 10 per cent of food production areas based on quantity, but this is in line with what is known about the relatively low-intensity land-uses of Indigenous Peoples' on their managed lands and the comparably high proportion of natural lands and protected areas they manage (Garnett *et al.,* 2018; WWF *et al.,* 2021). Thus, this food hotspot indicator does not represent many of the values that Indigenous Peoples hold with regard to food production, such as around diversity, quality, availability or access, or cultural and spiritual dimensions (see **Chapter 7**, online **Supplementary material 7.**1). The comparatively higher share of degradation hotspots associated with Indigenous Peoples' managed lands results primarily from a higher coverage with climate change hotspots, i.e., compared to the total terrestrial area a higher share of their lands face high ecological impacts of climate change. To a smaller extent, Indigenous Peoples' managed lands also show a higher relative coverage with two co-occurring degradation hotspots of biodiversity and health, and of food and health, as well as water and health. Note that these results do not imply that Indigenous Peoples' lands are less well managed (see **Section 2.5.4**). Known successes from Indigenous Peoples and local communities' management include Indigenous food systems that deliver sustainable outcomes across the nexus elements (**Chapter**

A HOTSPOTS OF BENEFITS



B HOTSPOTS OF DEGRADATION

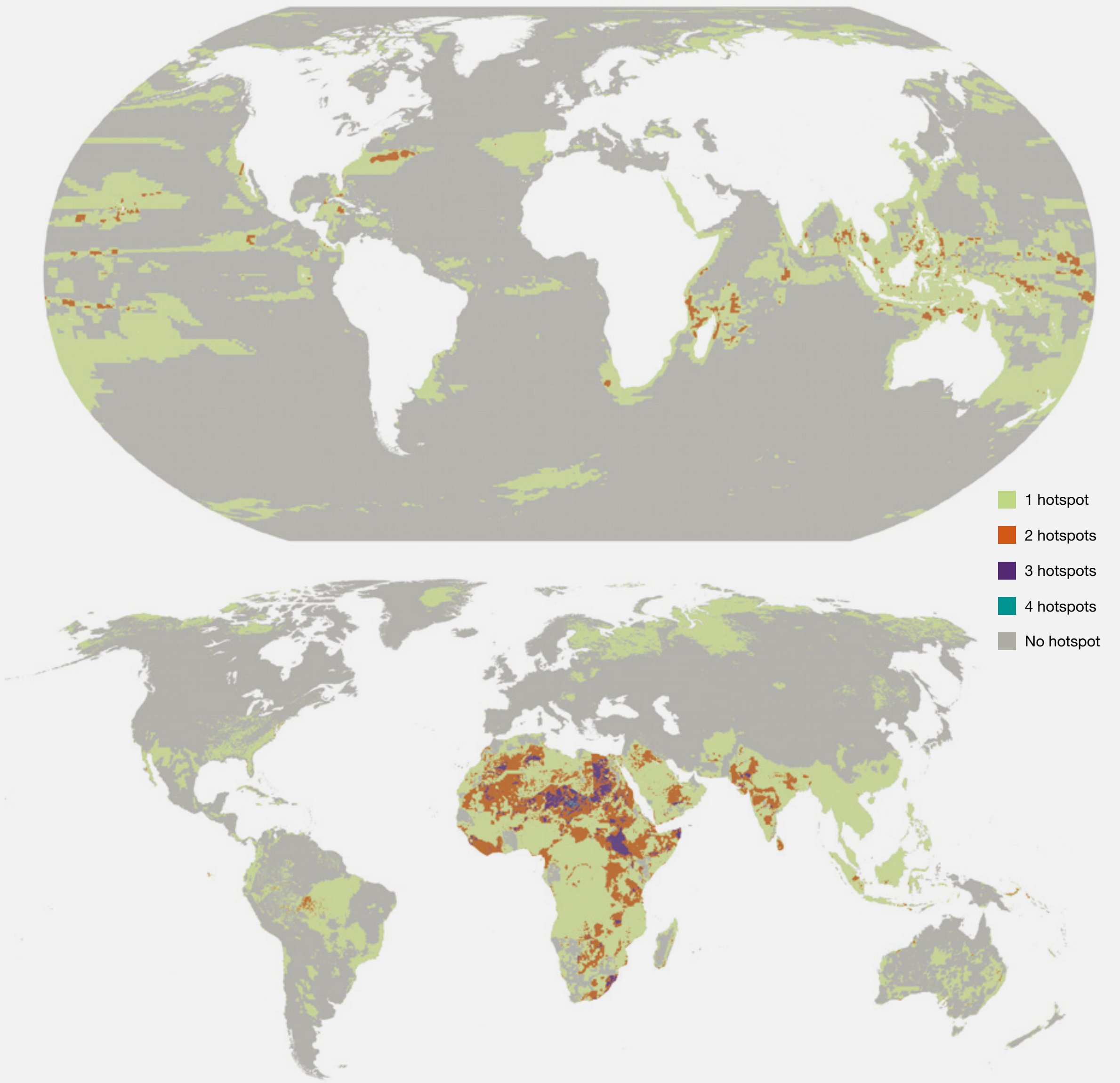


Figure 2 29 **Geographic distribution of global beneficial hotspots and degradation hotspots of the five nexus elements.**

Panel **(A)** displays beneficial hotspots; panel **(B)** displays degradation hotspots. Analyses were conducted separately for the marine (top map) and terrestrial (bottom map) realms show in each panel. See data management report[6] for detailed information on data and methods. Beneficial hotspots are areas with high species richness, food production, life expectancy and groundwater volume, whereas degradation hotspots are areas with high threatened species richness, ecological impacts of climate change (climate velocity), malnutrition, DALYs and blue water scarcity.

5, **Chapter 7**, online **Supplementary material**) and effective conservation measures (Alves-Pinto *et al.,* 2021; Arjjumend & Beaulieu-Boon, 2018; Corrigan & Graziera, 2010; Gurney *et al.,* 2021; WWF *et al.,* 2021). For example, Indigenous Peoples' often are more successful in preventing deforestation and forest degradation on their territories in comparison with non-Indigenous managed lands (Fa *et al.,* 2020; Schleicher *et al.,* 2017; Sze, Carrasco, *et al.,* 2022) **(Section 4.2.5.1, Box 5.1.3)**.

2.5.3.2 People affected by nexus hotspots

The spatially explicit mapping of beneficial and degradation hotspots of nexus elements and their co-occurrence allows the number of people living within the area of the respective hotspots to be estimated **(Figure 2.29A, B)**. Accordingly, 65 per cent of the world's population live in areas covered by a beneficial hotspot of at least one of the nexus elements of biodiversity, water, food or health. Half (50 per cent) of the world's population live in areas with the highest food

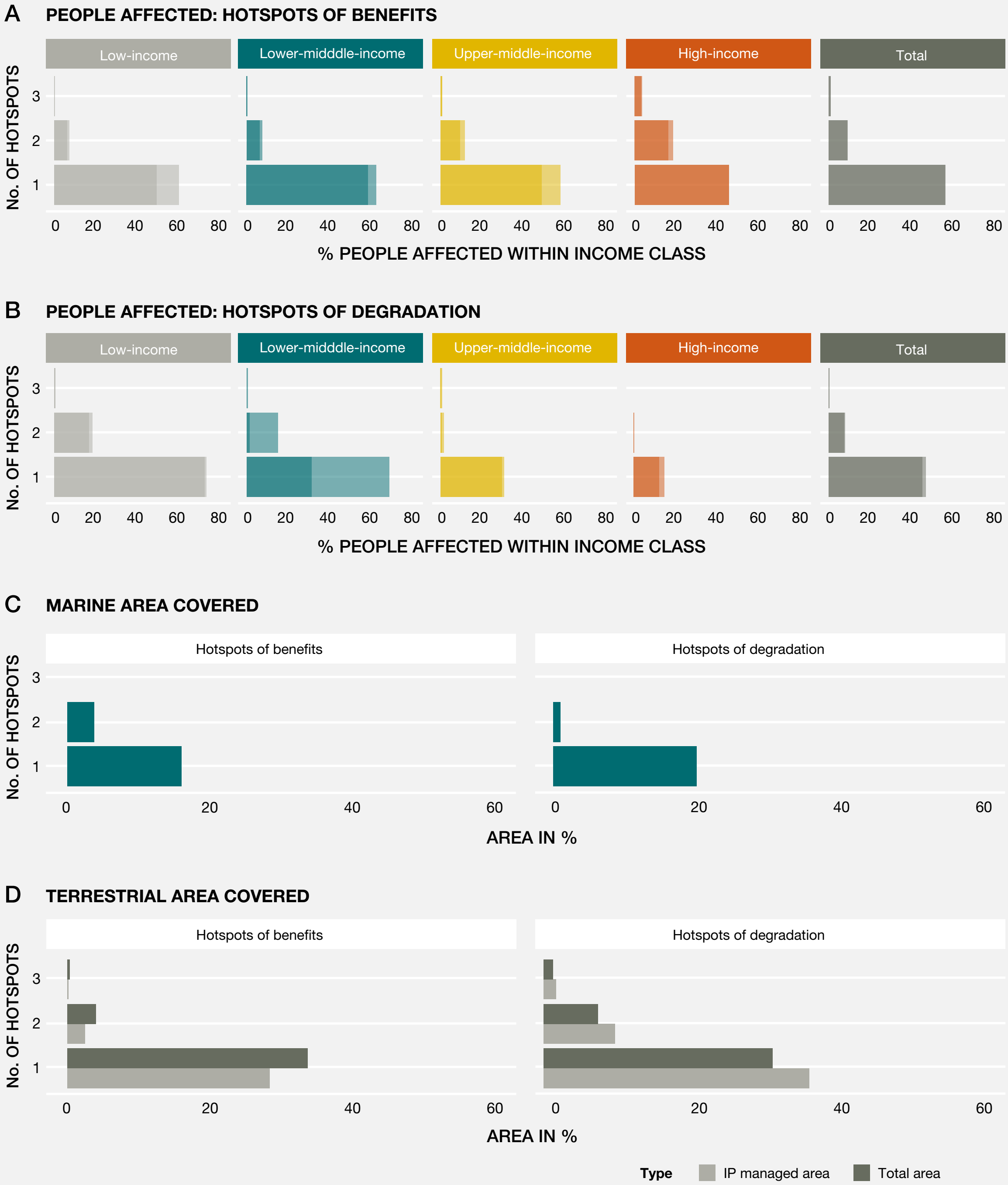


Figure 2 30 **Area covered and people affected by beneficial or degradation hotspots.**

Beneficial hotspots are areas with high species richness, food production, life expectancy, and groundwater volume, whereas degradation hotspots are areas with high threatened species richness, climate change velocity (ecological impact of climate change), malnutrition, DALYs and blue water scarcity. Panels **(A)** and **(B)**: percentage of people within income class groups that live in areas covered by beneficial hotspots **(A)** or degradation hotspots **(B)** of the nexus elements. Panels display the percentage of affected people within different income classes (World Bank, 2023m). Shading, i.e., range of people affected, differs through the synthesis of population and income level data from the years 2000 and 2010 and illustrates that population growth as well as economic growth, i.e., wealth, lead to a reclassification of large numbers of people from one income level category to another (e.g., reclassification of China from low-income to lower-middle-income between 2000 and 2010). Panel **(C)** displays marine area: percentage of total marine area covered by nexus element hotspots. Panel **(D)** displays terrestrial area: percentage of total terrestrial area (dark grey) and percentage of Indigenous Peoples' managed area (light grey) covered by nexus element hotspots. Panels display beneficial hotspots (left) or degradation hotspots (right). Areas managed by Indigenous Peoples were identified using data from Garnett *et al.* (2018). See the data management report[6] for detailed information on used data, methods and results.

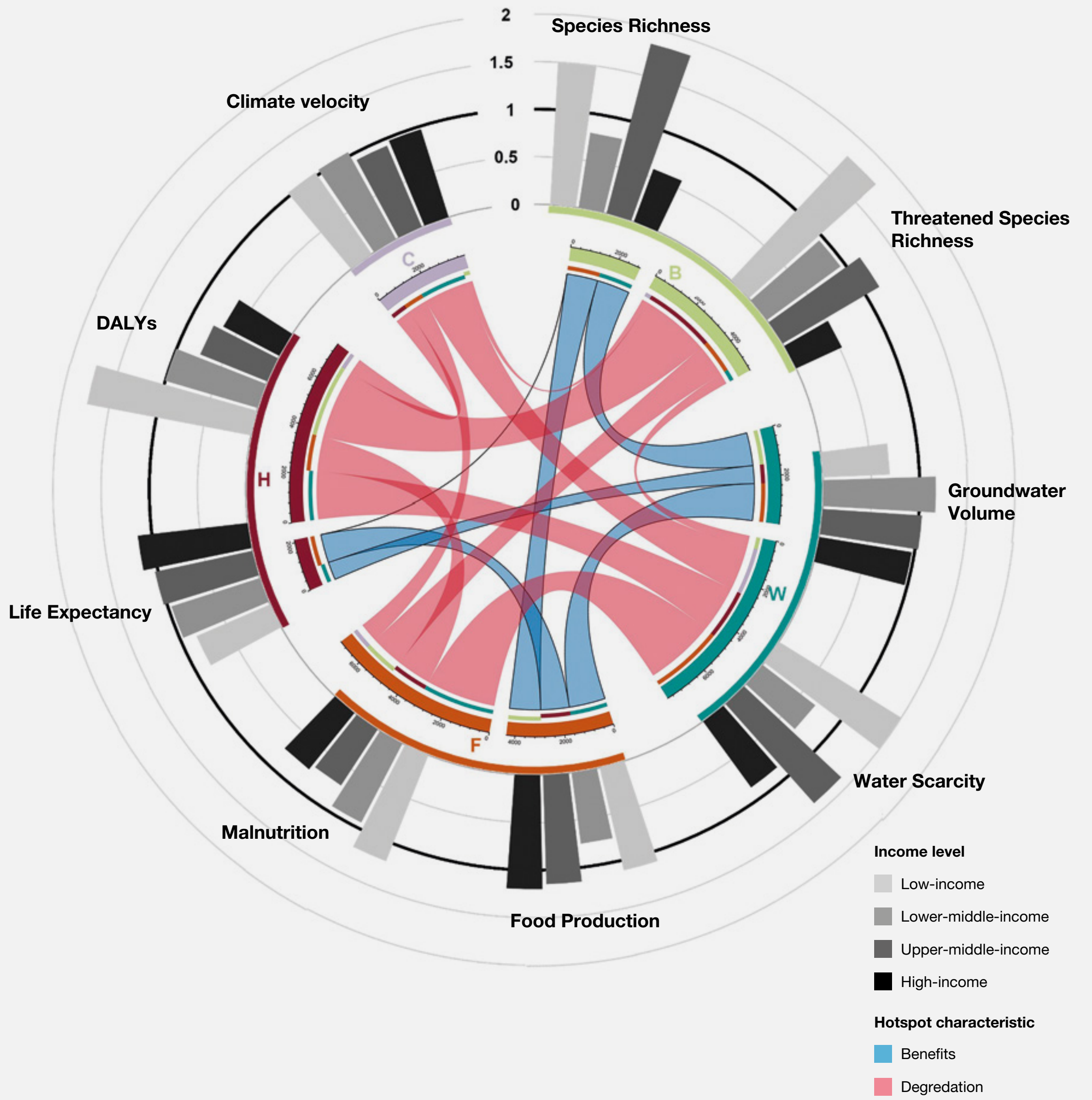


Figure 2 31 **Synthesis of income level characteristics and spatial co-occurrence of benefits and degradation of the nexus element indicators.**

The bar plots in the outer ring of the figure shows how indicator values on benefits and degradation of each nexus element differ by income level category and compared to a global average (scaled to 1, black circle line). Note that the bar plots are based on the indicator distribution of the total terrestrial area, which goes beyond the hotspot analysis (see **Box 2.17**). The inner circle shows the spatial co-occurrence of two beneficial or degradation hotspots (top 10 per cent of the values). The width of linkages relates to the area extent in which hotspots co-occur. Blue linkages (including edges) depict co-occurrence of beneficial and red linkages (without edges) depict co-occurrence of degradation hotspots. Indicators for beneficial hotspots: Beneficial hotspots: B = species richness, F = food production, H = life expectancy, W = groundwater volume; Indicators for degradation hotspots: B = threatened species richness, C = climate change velocity (ecological impact of climate change), F = malnutrition, H = DALYs, W = blue water scarcity. See **Box 2.17** and data management report[6] for detailed information.

production, 6 per cent live in areas with exceptionally good health conditions (e.g., longer life expectancy), 10 per cent with exceptionally high biodiversity (e.g., higher species richness), and 10 per cent live in areas with exceptionally high volume of accessible groundwater.

A comparable proportion of people (52 per cent) live in areas covered by a degradation hotspot of at least one of the nexus elements of biodiversity, water, food, health or climate change. Two fifths (41 per cent) of the world's population live in areas with an extremely strong decline in biodiversity (high threatened species richness), 9 per cent in areas with the highest health burdens (high DALYs), 5 per cent in areas with the highest malnutrition, and 2.5 per cent and 3 per cent in areas with the highest ecological impact of climate change (velocity of climate change) and blue water scarcity, respectively.

When differentiated by income level the data shows that people living in LMICs share the burden of single or multiple co-occurring degradation hotspots. Nearly three quarters (72 per cent) of the population of LICs experience at least one, while 17-18 per cent experience two or more comparably degraded conditions of any nexus element. LMICs have the lowest values for food production and volumes of accessible groundwater **(Figure 2.30)**. Similarly, 31 per cent to 68 per cent of the global population of LMICs experience at least one, and between 1-15 per cent experience two degraded conditions of any nexus element. This relatively large range of affected population originates from the synthesis of population and income level data for 2000 and 2010. Between these years both population growth as well as economic growth led to a reclassification of large numbers of people from one income level category to another. With respect to health and water, LICs show a higher value of DALYs (a greater disease burden) than the global average and lower volumes of accessible groundwater while at the same time facing comparably high values of blue water scarcity.

By contrast, only 12-15 per cent of the global population in HICs experience comparably degraded conditions of any nexus element, while 64-67 per cent of the same income class live in beneficial hotspots of at least one nexus element. The highest values of species richness are found in LMICs and UMICs. However, LICs are, more than all other countries, faced with a higher number of threatened species.

2.5.4 Specific nexus challenges for Indigenous peoples and local communities

IPLC are responsible for the management of a considerable amount of land, natural resources and range of ecosystems globally (Neil M. Dawson *et al.,* 2021; Sangha *et al.,* 2019). Indigenous Peoples alone manage 38 million km^2 of land worldwide, or around a quarter of global land surface; this area overlaps with 40 per cent of global terrestrial protected areas (Garnett *et al.,* 2018). Indigenous-managed lands have lower rates of deforestation and forest degradation globally as compared to non-Indigenous lands (Simkins *et al.,* n.d.; Sze, Carrasco, *et al.,* 2022), with protective value equivalent with formal protected areas in terms of forest landscape integrity (Sze, Childs, *et al.,* 2022) and vertebrate diversity (Schuster *et al.,* 2019; Sze *et al.,* 2024).

The contribution of IPLC in global biodiversity conservation has gained recognition since the 2003 World Parks Congress in Durban, South Africa (Brosius, 2004) culminating in their important recognition by the Kunming-Montreal Global Biodiversity Framework. The diverse ecosystems managed by IPLC provide a range of nature's contributions to people that are beneficial for both local communities and regional and global populations, leading to positive economic and health impacts (Prist *et al.,* 2023; Sangha *et al.,* 2019). For instance, the Baka community in the Congo Basin (Fungo *et al.,* 2023; Gallois & Henry, 2021; Reyes García *et al.,* 2017) rely on biodiversity as a means of ensuring food, water and health security, as well as adapting to climate change (Molua *et al.,* 2023; Nkem *et al.,* 2013; Tumusiime & Vedeld, 2015) **(Box 2.19)**.

Since IPLC often rely largely or solely on natural resources for their subsistence, they can be particularly vulnerable to drivers of biodiversity loss (Scheidel *et al.,* 2023), water and food insecurity (Leonard *et al.,* 2023; Torres-Vitolas *et al.,* 2019; Webb *et al.,* 2016), poor health (I. Anderson *et al.,* 2016; Brubacher *et al.,* 2024) and climate change (Petzold *et al.,* 2020; Reyes-García *et al.,* 2024). Thus, the findings from the hotspot analysis **(Section 2.5.3)** that Indigenous Peoples' managed lands are disproportionately represented by more degradation hotspots is concerning. However, these globally aggregated trends across the nexus elements and drivers of change may miss important issues for IPLC as such communities often have their own perceptions, understandings, approaches and ILK that result in them perceiving drivers and impacts distinctly from global trends (Junqueira *et al.,* 2021). Thus, to understand these specific dynamics for IPLC, a systematic review was undertaken to assess regional trends across nexus elements and direct and indirect drivers of change across the elements as perceived or experienced by IPLCs, and the types of place-based or locally derived indicators IPLC use to identify these trends and drivers (see data management report[7]).

2.5.4.1 Trends in nexus elements and local indicators as observed by IPLC

There is growing research on the interactions and relationships of IPLC with the nexus elements across local, regional and global scales, with most studies in Asia, followed by North America and Africa **(Figure 2.32)**. Assessed studies focused on nexus interactions (e.g., two to five order interactions across elements), with smaller numbers of studies addressing more complex interactions (four to five order interactions) affecting IPLC **(Figure 2.32B)**. The literature focusing on Asia showed more attention to higher order interactions, while other regions mostly reflect three to four order nexus interactions

7. The data management report for indicators of drivers of change for Indigenous Peoples and local communities (https://doi.org/10.5281/zenodo.13913182).

(Figure 2.32B) (e.g., most IPLC studies on Oceania only noted two-order interactions while for Africa three order nexus interactions were most common).

Overall, this literature indicates that IPLC are experiencing change in ways that vary from global-level trends. There are more cases of negative than positive trends for all nexus elements and all regions **(Figure 2.32A)** with some exceptions in Oceania which report equal numbers of positive and negative trends. Studies indicating negative biodiversity trends were most prominent in the literature review across all the continents, with particularly negative impacts in Asia and North America. Negative trends for food, water, health and climate were also noted, with negative trends for food in Africa more reported than negative biodiversity trends, whereas biodiversity was the strongest negative trend elsewhere. Some comparable positive trends for nexus elements are also reported (blue bars in **Figure 2.32A**), though the negative trends across all global regions still dominate.

IPLC often use local indicators to identify changes in nexus elements (e.g., indicators of snow volume to identify trends in climate change). The systematic review shows that most local IPLC-identified indicators in the literature relate to biodiversity and climate change, followed by food **(Figure 2.32C)**, while the Local Indicators of Climate Change Impact (LICCI) database (Reyes-García *et al.,*

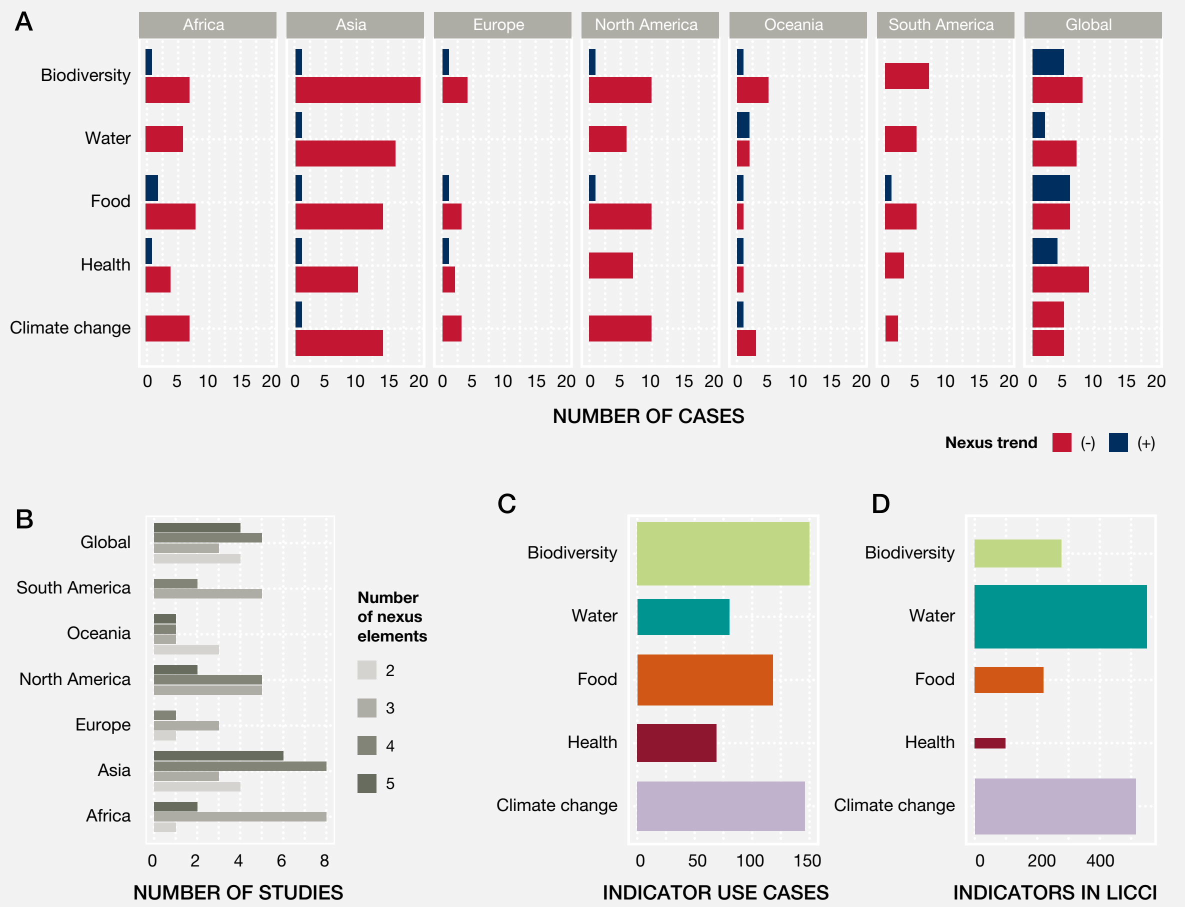


Figure 2 32 **Number of cases from studies relevant to Indigenous Peoples and local communities and Indigenous and local knowledge focusing on regional trends in the nexus elements and their interactions.**

Data are based on a systematic review of 87 studies relevant to Indigenous Peoples and local communities and Indigenous and local knowledge related studies from all global regions (see data management report).[7] Local indicators for trends in nexus elements in panel **(C)** are documented from the systematic review, while panel **(D)** shows local indicators from the Local Indicators of Climate Change Impact database reported by García *et al.* (2024), which primarily focuses on indicators of climate change but also covers other nexus elements. The length of bar in panels **(C)** and **(D)** represents the number of indicators recorded per nexus element. The width of the bar in panel **(C)** represents the number of studies and in panel **(D)** represents the number of local interviewees recorded as per the LICCI database protocol.

2024) has most indicators related to water and climate change followed by biodiversity **(Figure 2.32D)**. Across both data sets, health indicators were the least reported **(Figure 2.32C and D)**.

IPLC biodiversity indicators: Many indicators for change in biodiversity are recorded by IPLC, for example, forest fires and extirpation of tree species (Anjum *et al.,* 2023; Astutik *et al.,* 2019; Nkomwa *et al.,* 2014; N. J. Turner & Clifton, 2009). Other important biodiversity loss indicators include changes in terrestrial wildlife (e.g., due to increased human-wildlife conflict, illegal hunting and poaching (Everard *et al.,* 2017; Yua *et al.,* 2022)) and changes in marine ecosystems and fisheries (e.g., incidents of fish kills or changes in fish migration) (Magcale-Macandog *et al.,* 2014). Some communities, like the Saami, have a range of indicators of change, with particular focus on safeguarding culturally important species, such as reindeer, and the ecosystems they depend on, such as mountain birch forests (Markkula *et al.,* 2019) (see **Box 2.20**). However, some IPLC, like Māori communities in New Zealand, have been facing intergenerational shifts in perceiving these locally important environmental indicators (Lyver *et al.,* 2021); this loss of knowledge over time can lead to what has been termed 'shifting baseline syndrome' (see **Glossary**) whereby there are shifting norms and perceptions about the state of change in the environment (e.g., degradation becomes the 'normal state' as knowledge about an original state is lost).

IPLC water indicators: The majority of indicators on trends in water include those related to depletion of groundwater, changes in water supply and increases in water scarcity, particularly for use in agriculture, drinking, cooking and sanitation (Black & McBean, 2017; B. R. Chaudhary *et al.,* 2021; Constant & Taylor, 2020). Indicators around flood occurrence and/or the absence of rain and presence of drought are also frequently mentioned (Nkomwa *et al.,* 2014).

IPLC food indicators: The majority of food indicators in the literature relate to changes in dietary preferences and consumption patterns (Jandreau & Berkes, 2016), such as changes in access to meat or how it can be prepared (e.g., if preferred tree species used for smoking meat are no longer available) (Krarup Hansen *et al.,* 2022). Other food indicators include attention to declining germination, changes in growth and yield of crops, and cases of altered food security, sovereignty, safety, nutrition and agrobiodiversity which affect the health of IPLC (Kuhnlein *et al.,* 2006; Levkoe *et al.,* 2019; Shafiee *et al.,* 2022).

IPLC health indicators: Health indicators encompass both altered physical and mental health, with examples relating to the decline of preferred traditional foods and increases in consumption of processed foods and sugary beverages (Balasooriya *et al.,* 2023). Changes in mental health and well-being, including declining self-esteem (Löw, 2020), have also been noted. IPLC also include ecosystem health in some of their health indicators, such as changes in forest health (Lyver *et al.,* 2021), increases in the incidence of zoonoses, pathogens, pests and the prevalence of diseases in human, animals and crops (Klement & Pazienza, 2019; Kongnso *et al.,* 2021; Miclotte & Van de Wiele, 2020; Safari *et al.,* 2021).

IPLC climate change indicators: IPLC-relevant and ILK-derived indicators for climate change are discussed in **Section 2.5.4.2** and mostly relate to variation in rainfall frequency/pattern/intensity, warming temperatures, snow melting, drought, floods and storm cycles. Other indicators cited less frequently include ocean acidification, algal blooms, forced migration from rural to urban areas, abandonment of nomadic pastoralism, and delays in fruit ripening.

Box 2 18 **Trends in Indigenous food systems in relation to the biodiversity-water-food-health nexus.**[8]

There is a demonstrated synergy between biodiversity, water, food and health in Indigenous Peoples' and local communities' (IPLC) food systems where food is associated with cultural, medicinal, nutritional, healing, spiritual, relational, social and emotional values. These food systems are an expression of the interlinkages between the biotic and abiotic components of the ecosystem (i.e., between lands, waters, biodiversity and the spiritual world), which are deeply rooted in the knowledge, practices, strategies, techniques, value-sharing and relationships of IPLC with their natural environments (Swiderska *et al.,* 2022). They utilize Indigenous and local knowledge (ILK) to achieve a delicate balance between sustaining communities and preserving their cultural traditions, while promoting environmental sustainability, biodiversity, water quality and human health through nutritional well-being.

IPLC diets have traditionally incorporated a wide variety of plants, animals and aquatic species which provide high nutritive and health values. For example, the Maasai in East Africa traditionally consumed a mix of milk, meat and blood from their cattle, providing essential nutrients and hydration (Oiye *et al.,* 2009), while the Hadza people relied on foraging for wild berries, tubers, honey and bee larvae that contain a substantial nutritive level of protein, fibre, macronutrient and carbohydrate, but are low in fat (Murray *et al.,* 2001). However, the shift away from traditional diets towards processed foods has had adverse health

Box 2 18

effects on Indigenous populations, such as high rates of obesity, diabetes and other diet-related diseases (Kuhnlein, 2015).

IPLC food systems across the globe have also shaped the conservation of land and wild plant diversity (Brondízio *et al.,* 2021), including through domestication of crops, cultivars and varieties through centuries of experimentation, seed selection and diversification, transportation and upkeep of plants by ILK knowledge holders (van Andel *et al.,* 2023). Similar management practices of marine resources that have ensured healthy fisheries and access to rich foods have also been documented (Ban *et al.,* 2019). IPLC food systems often conserve culturally important or medicinal wild plants to ensure a diversity of uses, considering species characteristics and seasonality across landscapes (Monroy-Sais *et al.,* 2022; Riechers *et al.,* 2021). Other IPLC have developed traditional irrigation systems, which conserve water and minimize erosion in farmed lands (Joshi *et al.,* 2022; Temam & Abebe, 2022; Utami & Oue, 2022), often using sophisticated knowledge of weather patterns, local hydrology or the water cycle and crop types to maintain their food systems. For example, in the North-West Himalayan foothills of India, communities are using ILK to sustain their food systems in the erosion-prone fragile ecosystems with limited water resources through techniques such as bunding of fields, ploughing before the monsoon, filter strips, mulching, compression of soil in sugarcane farms to restore soil fertility, reducing erosion losses, improving land productivity, and ultimately improving food security in the region (Arora *et al.,* 2023). These practices demonstrate how IPLC have long understood the importance of sustainable water management for maintaining food systems under pressure from climate change in order to sustain good health and well-being among their communities.

ILK-based systems of ecosystem management and community/local seed banks have been useful in conserving plant genetic resources and often focus on weather-adaptive local varieties of crops (IPBES, 2019a). For example, the Quechua, an Indigenous population of Peru, protect a huge variety of potatoes through their knowledge integrated with science to mitigate and adapt to the impacts of climate change (Sayre *et al.,* 2017). Another example in India, Nepal, Bangladesh and Myanmar shows how double rice transplanting practices lead to greater crop resilience in extreme rainfall events, and lower costs and improve soil health by increasing biodiversity, microbial biomass carbon, water retention capacity and moisture content (A. Das *et al.,* 2023; P. K. Dubey *et al.,* 2022, 2023; Goswami *et al.,* 2006; Khatun *et al.,* 2010; D. T. Kumar *et al.,* 2017; Rai & Mishra, 2022; Roxy *et al.,* 2017) **(Box 2.9)**.

In recent years, Indigenous food systems have faced threats from the globalization of food production, pressures from climate change and other emerging challenges (Domingo *et al.,* 2021). As traditional knowledge erodes and market pressures increase, many IPLC have shifted towards monoculture farming and the consumption of non-locally produced and increasingly more processed foods (Kuhnlein *et al.,* 2006; Levkoe *et al.,* 2019). This trend has led to a loss of agricultural biodiversity, endangering heirloom varieties and species. Other threats include lack of access to traditional lands and seas for collecting and cultivation, contamination of soils and waters from development and infrastructure projects, lack of financing for sustaining these food systems and increases in health problems (Blanco *et al.,* 2023; N. J. Turner *et al.,* 2013) (see **Chapter 7**, online **Supplementary material 7.11**).

2.5.4.2 Direct and indirect drivers of trends in nexus elements as perceived by IPLC

IPLC perceive direct and indirect drivers of change across multiple nexus elements, with several studies noting interactions among three to five nexus elements **(Figure 2.33 A and B)**. These were more frequently reported from Asia, followed by global studies and those relating to North America and Africa. Climate change, land- and sea-use change, and direct exploitation/utilization are perceived as the most important direct drivers to IPLCs **(Figure 2.33 C)**, which is in contrast to global trends that usually point to land and sea-use changes as the primary driver of biodiversity loss. Pollution and invasive alien species drivers were less reported as direct drivers from the IPLC studies. The most important indirect drivers influencing nexus elements as perceived by IPLCs were those related to cultural, economic, and institutional or governance drivers **(Figure 2.33 D)**. Again, most reports came from Asia, followed by North America and Africa. Across all regions, technological drivers were the least commonly mentioned indirect drivers. In terms of regional differences, demographic drivers are reported to be more important for Asia relative to other global regions.

2.5.4.2.1 Indicators related to direct drivers

Indicators of climate change: The largest number of direct driver indicators used by IPLC related to climate change **(Figure 2.33 C)**. Examples include attention to species moving directions and locations, or identification of signs to predict rain (e.g., appearance of fog around mountains or better fruiting and flowering in trees) (Everard *et al.,* 2017; Liwenga, 2008). Other climate change indicators noted by IPLC included physical changes such as

8. Common case study highlighting Indigenous Peoples' and local communities' (IPLC) food systems. See **Chapters 1**, **3**, **4**, **5.1** to **5.5** and **6** for additional IPLC food system case studies. Lessons learned from the common case studies are presented in **Chapter 7**, online **Supplementary material 7.1**.

Figure 2 33 **Indigenous Peoples' and local communities' perceived indicators of direct and indirect drivers of change in nexus elements.**

Direct (panel **(A)**) and indirect (panel **(B)**) drivers of change in nexus elements in studies that focus on two to five order nexus interactions (only for Asia were there 3-, 4- and 5-way interactions reported). Panel **(C)** presents summaries of perceived indicators of direct drivers and panel **(D)** shows indicators of indirect drivers as noted in the systematic review of 87 ILK/IPLC related studies from all global regions (see DMR[8]). The length of the bar in panels **(C)** and **(D)** represents the number of indicators and the width represents the number of studies indicating direct and indirect drivers.

warming temperature, drought, erosion and unpredictable winds/storms, with the LICCI database recording over 1600 different indicators used by IPLC in the researched sites spread across physical climate indicators and other nexus elements (e.g., changes in food supply as indicators of climate change impacts).

Indicators of land- and sea-use and direct exploitation: Direct exploitation of natural resources and land-/sea-use change were the next most frequently cited direct drivers of change. IPLC depend on natural resources from a variety of ecosystems, such as timber, non-timber forest products, wild foods and wild medicines and herbs for health benefits (e.g., for treating hypertension, diabetes, digestive and respiratory disorders) **(Box 2.7, Box 2.10, Box 2.19)**. However, resources used by IPLC are experiencing increasing harvesting pressure in terms of overfishing and hunting (Berkes, 2012; Díaz *et al.,* 2018; Lyver *et al.,* 2021; Shah, 2008), alongside other resource pressures such as unsustainable groundwater use, urbanization and other conflicts over development (e.g., mining activities, which often take place in remote or sensitive habitats like the Arctic (Tolvanen *et al.,* 2019) or the Amazon **(Box 2.12)** and which may conflict with Indigenous land claims and negatively impact their livelihoods). Indicators cited frequently in IPLC studies to document land- and-sea-use change include changes in quality and quantity of grassland, pastures, forests and other native habitats (e.g., Islas, 2019; Jandreau & Berkes, 2016; Oba & Kaitira, 2006). In addition, changes in or prohibitions to IPLC practices, such as bans or abandonment of the use of fire, was a frequently mentioned driver that greatly alters local habitats and ecosystems (e.g., Angassa & Oba, 2008; Knapp & Fernandez-Gimenez, 2009). Indicators of sea-use change were less frequently recorded than land-use change.

Indicators of pollution and invasive alien species: Pollution and invasive species were the direct drivers with the fewest indicators. The most commonly recorded indicators of pollution were around contaminated food (either due to heavy metals or polycyclic aromatic hydrocarbons) and contaminated water (e.g., due to mercury pollution, noted by changes in water colour and disappearance of fish species, or chemical and microbial contamination noted in terms of eutrophication and algal blooms) (Fernández-Llamazares *et al.,* 2020). IPLC often have complicated relationships to invasive alien species (IPBES, 2023), e.g., dependence on hunting of invasives like feral pigs (Periago *et al.,* 2017). Thus, the biocultural importance for certain IAS to IPLC can influence their perceptions and support for removal and eradication (Constant & Taylor, 2020).

2.5.4.2.1 Indicators of indirect drivers

Indicators used in IPLC studies for indirect drivers are location-specific and defined according to cultural background, traditional ecological knowledge, subsistence-oriented activities and experience in the sustainable management of nature's contributions to people (Lyver *et al.,* 2021; Moller *et al.,* 2004; Whyte, 2018). For example, language, age, experience and gender influence various factors such as dietary behaviours and connection with the landscape, e.g., IPLC women have extensive ethnobotanical knowledge relating to medicinal plants that helps with treating illness and is transferred by elders within families (Zank *et al.,* 2022).

Indicators of cultural indirect drivers: Most indicators of indirect drivers of change used by IPLC relate to cultural change **(Figure 2.33 D)**. Examples of cultural change indicators included loss of ILK, loss of language and community conflicts. Indicators for cultural drivers often refer to oral or written knowledge in the form of beliefs, awareness, understanding, perception and leadership. Other examples of indicators related to knowledge for alternate foods, hunting, leisure time experiences, materials, virtual activities, prediction of rain, seasonality, soil fertility and ethnobotanical knowledge transferred through generations. Declines in ILK driven by greater integration of the market economy and related landscape and socio-cultural changes were particularly noted **(Box 2.7)**. In Latin America, Asia and Africa the social and cultural disruption to IPLC caused by limited access to quality housing, healthy food, clean water and health services, and to nature in urbanized cities were noted, as these contributed to high levels of poverty, mental health problems and poor emotional well-being (Kshatriya & Acharya, 2016; Levkoe *et al.,* 2019). Cultural indicators also include spiritual connections with species such as totems, sacred values linked to culture, freedom or independence, identity and sense of place (Novera & Kark, 2023), alongside culturally relevant indicators related to specific uses of natural resources (e.g., medicinal plants) (van de Water *et al.,* 2022) (see **Section 1.2.2**).

Indicators of economic indirect drivers: Economic and institutional indicators were the next most frequently cited indirect drivers on biodiversity and other nexus elements. Indicators of economic drivers mostly related to market and commercial approaches of selling and trading products derived from nature, remittances, credit borrowing, changes in income and employment opportunities, and saving money for difficult times (Garai *et al.,* 2022; Kanwal *et al.,* 2021). Variation in socio-economic status, hunger, cyclical and endemic poverty within IPLC were also relevant economic indicators (Addaney *et al.,* 2022; Vogliano *et al.,* 2021). Some economic drivers related to changes in access to resources, for example, whether or not IPLC benefited from protection of nature (Tumusiime & Vedeld, 2015; Yousefpour *et al.,* 2022). For example, in protected forest areas in countries like Uganda, households accrue an average net annual loss of 12.5 per cent of total income when forests are protected, while the sharing of tourism revenues, integrated conservation and development projects and park-related employment only provides benefits constituting 3.5 per cent of the total annual income (Tumusiime & Vedeld, 2015). In other words, while benefits of nature protection accrue nationally, local areas can see protection of nature as an economic driver of decline in access to resources.

Indicators of institutional indirect drivers: Institutional and governance drivers cover local, provincial or national government policies, with indicators including language policies aimed at either supporting maintenance of minority languages or discouraging them; gender policies involving the important role of women and girls; and climate change mitigation policies. However, often local Indigenous values are ignored and not integrated in policies, resulting in negative impacts on traditional IPLC practices (S. Chaudhary *et al.,* 2019). Other important institutional indicators include the role of non-governmental organizations, as well as indicators related to lack of institutional capacity. Lack of enforcement in regulations, legislation and decisions of courts, as well as lack of support for capacity building, benefit and knowledge sharing and collective action among IPLC were also mentioned in some studies.

Indicators of demographic and technology indirect drivers: Demographic and technological indirect drivers had the fewest indicators mentioned. Major demographic indictors include disease occurrence and population declines, e.g., IPLC populations living at higher altitudes such as in the Himalayas are susceptible to the impacts of glacier melting on agriculture and are moving accordingly (Anjum *et al.* 2023); nomadic populations are becoming semi-nomadic or sedentary farmers and being excluded from their traditional land (Tugjamba *et al.,* 2023); and there is weakening of sociolinguistic resilience of minority languages by small population sizes (Addaney *et al.,* 2022). Demographic indicators also relate to urbanization, globalization, colonization or decolonization, affecting migration or displacement of IPLC from their traditional land, undermining their cultural identity and disrupting traditional food systems

Box 2 19 **Biodiversity, water, food and health among Indigenous Peoples and local communities: A case of the Baka community in the Congo Basin.**

The Baka Indigenous People, an ethnic group inhabiting the southeastern rainforests of Cameroon, northern Republic of the Congo, northern Gabon and southwestern Central African Republic, remain stewards of biodiversity in the Congo Basin (Pemunta, 2019). The interaction of the Baka and their environment demonstrates harmony and interconnectedness with nature that is based on balance, accessing food, water and health (FAO, 2021; Reyes García *et al.,* 2017). The main activities and livelihoods in the food system include hunting, gathering, fishing, cultivation and exchange of non-timber forest products (Fongnzossie *et al.,* 2023).

Honey remains an important commodity that is exploited by the Baka. The Congo Basin forest hosts the economically important honeybee (*Apis mellifera*) species, essential for human and ecosystem health. Honey and other products have medicinal properties, and the role of bees as pollinators makes them vital for food supplies. "When gathering honey from beehives high up in trees, Cameroon's Baka people sprinkle seeds of fruit trees along the way to mark the path to the hive. This helps to regenerate the area and spread biodiversity, offsetting the disturbance to vegetation during the honey harvest" (FAO, 2021). Keeping honeybees promotes pollination of naturally occurring (non-crop) plants in the Basin. The Baka further exploit honey for food, direct income and health benefits. The by-products from honey farming (e.g., ashes of burnt combs) are used as compost-manure or fertilizer for farmlands. Beeswax is used in waterproofing, fuel and skincare. For medicine, the Baka use honey when treating a wide variety of conditions, including eye diseases, bronchial asthma, throat infections, fatigue, dizziness, constipation, eczema and wounds. Other bee products that may benefit human health include propolis, bee pollen, royal jelly, and beeswax and bee venom. The natural water systems connecting rivers and streams in the Basin provide water for bees, are used for drinking and regulate the temperature of the hive, feed young bees and dilute stored honey. The protection of the ecosystem in turn provides conducive habitat for honeybees. The Baka community in southeastern Cameroon have established the economic, social and ecological importance of honeybee in their forest-based livelihood (FAO, 2021).

However, drivers of biodiversity loss such as climate change, exploitation and trade, population expansion and other factors have influenced the interactions between the Baka and their environment. Trade in timber and non-timber forest products has caused the community to suffer from the rapid expansion of logging activities since the 1960s, which reduced their forest resources and degraded their reliance on biodiversity and ecosystems. Climate change also affects the livelihood of the Baka community, limiting access to adequate food (via deforestation, degradation, damage to seedlings and crops), negatively affecting water availability and their health (increases in vector-borne and water-borne diseases) (Batumike *et al.,* 2022; Leal Filho *et al.,* 2022; Molua *et al.,* 2023; Nkem *et al.,* 2013). This disconnection with nature has been reinforced by poor design and implementation of climate change mitigation via Reducing Emissions from Deforestation and forest Degradation (REDD+) measures, such as establishment of parks and reserves that have affected local communities, accompanied with expropriation of lands for biofuel plantations and renewable energy projects (Carson *et al.,* 2018).

(Kuhnlein, 2015). Technology as a driver can be indicated by attention to indicators such as access to information and media, means of communication (such as radio, television and social media) and machine-based technical advancements (such as dredging machines, efficient fishing techniques using inexpensive monofilament gill nets, scuba equipment and GPS). In addition, indicators of native species or habitats at risk can reveal the impacts of technological advancements (e.g., noise and pollution from ships or oil spills from the oil and gas industry drilling activities).

Box 2 20 Climate change impacts on Indigenous Peoples in the Arctic: A Saami case study.

Indigenous Peoples living in the Arctic have been observing climatic changes over recent decades, and knowledge of their surroundings is a vital resource for their well-being. Indigenous observations and perspectives offer great insights into the nature and extent of environmental change and the significance of such changes for people whose cultures are built on intimate connections with the Arctic landscape **(Figure 2.34)**. Indigenous Peoples of the Arctic have adapted to great environmental variability: cold, extended winter darkness and fluctuations in animal populations, among many other challenges posed by geography and climate. Although people plan around expectations built on experience of the climate of their area, their daily activities are affected by weather that is becoming more variable and less predictable by traditional means. Most Arctic residents are aware of climate change, have experienced these changes and are concerned about the implications for themselves, their communities and the future. In describing the significance of climate change for Indigenous Peoples, it is however also important to remember that there are many forms of environmental change in the Arctic, as well as extensive social changes related to modernization and globalization. For example, mining activities in Arctic regions have also disturbed habitat of reindeer and altered migration routes, with impacts on Saami livelihoods (Herrmann *et al.,* 2014), that are then further compounded by climate change.

This can be seen in a case study from the SnowChange programme, organized by the Environmental Engineering Department at Tampere Polytechnic in Finland, that includes multiple statements from Sapmi, the Saami communities of Purnumukka, Ochejohka and Nuorgam. Sapmi is the Saami (also spelled Sami or Sámi) homeland that extends across northern Norway, Sweden, Finland and the Russia Federation. These perspectives are based on communications and interviews with elders, who have the most extensive knowledge, with additions from younger generations of Saami living in the region to show insights into what the changes mean for people in the area. Examples include:

Arkady Khodzinsky, a reindeer herder from Lovozero: "*The weather has changed to worse and to us it is a bad thing. It affects mobility at work. In the olden days, the 1960s and 1970s, the permanent ice cover came in October and even people as old as myself remember how on 7 of November we would go home to celebrate the anniversary of the Great Socialist Revolution. These days you can venture to the ice only beginning in December*".

Larisa Avdeyeva, director of the Saami Culture Center in Lovozero: "*I have conversed with reindeer herders and they have told me of these kinds of observations. They have seen as well that in areas where it was possible to collect a lot of cloudberries (Rubus chamaemorus) before, now the berries are not ripe because of climatic warming and melting of glaciers. Changes are very visible. Nowadays snows melts earlier in the springtime. Lakes, rivers and bogs freeze much later in the autumn. Reindeer herding becomes more difficult as the ice is weak and may give away. The rhythm of the yearly cycle of herding and slaughtering of reindeer is disrupted and the migration patterns of the reindeer change as well."*

Reindeer, a key species for the Saami communities in cultural, social, economic and ecological terms, are acting differently and herders spend less time with the herds on the tundra. Mixing wild or feral reindeer herds is another concern. Maria Zakharova, a Lovozero Elder: "*On the tundra the reindeers used to run towards people, but now they run away. The reindeers are our children. In the olden times when we used to have just the reindeers the air was clean. How should I explain? Now they drive around in skidoos and you can smell the gasoline, yuck! What did they herd with? The reindeer! Now they have started to herd with skidoos. Why on earth? They should rather train the reindeers like our fathers and forefathers did. Now everything is in ruins. There used to be many young reindeers. Yes, at the time the herds were bigger as well*."

Vladimir Lifov: "*Our income diminishes because of climate change, of course, and in a very drastic way. Even my wife has said that it would be time to forget the reindeer. But I tell her always: "Tamara, we depend on these reindeer. If there are no reindeer, we have nothing to do here either*".

Summarized from Huntington *et al.* (2005).

Box 2 20

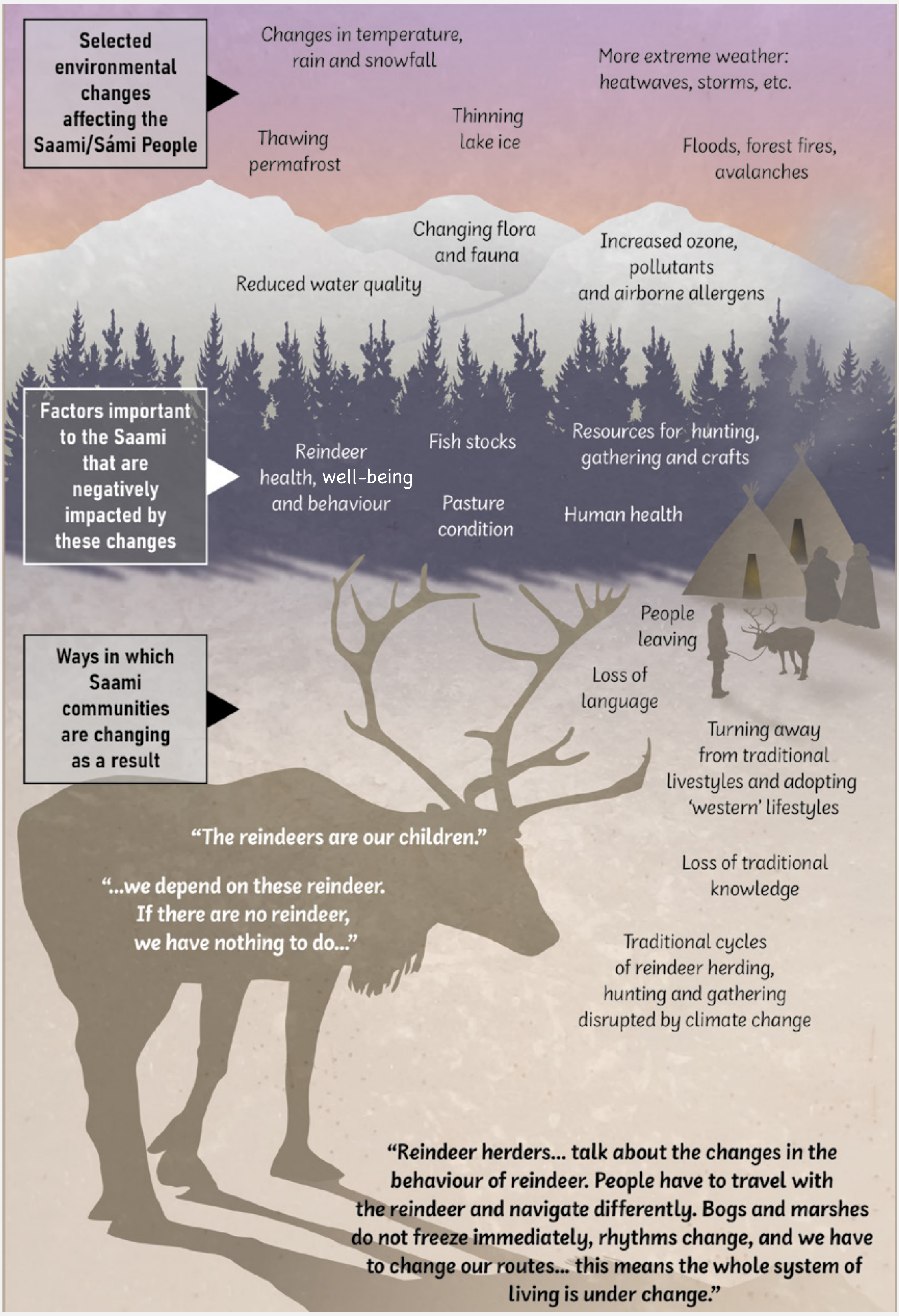


Figure 2 34 **Impacts of environmental change on Saami communities.**

2.6 SYNTHESIS

2.6.1 Main findings of status and trends of the nexus

Most past and current trends in the nexus elements have been negative trends in recent years **(Figure 2.13)**, having been affected by a range of indirect and direct drivers **(Figure 2.4, Figure 2.6)**. Among the drivers, resource extraction is the strongest direct driver of negative trends among the nexus elements, specifically strongly affecting the decrease in biodiversity, water quality and quantity and with moderate negative (mental) or variable (physical) impacts on health **(Figure 2.11)**. Historically, climate change has shown comparatively less evidence of strong negative effects relative to resource extraction (except for physical health), but climate change has had moderate negative impacts on all the nexus elements **(Figure 2.11)**, and climate change is perceived as the most significant driver of negative environmental changes by IPLCs **(Figure 2.29)**. Land- and sea-use change has strongly negatively affected biodiversity with moderate negative effects on water (especially quality) and like resource extraction, moderate negative (mental) or variable (physical) impacts on health **(Figure 2.11)**. Pollution has moderate negative effects on all elements – biodiversity, food quantity, water quality and mental health. Among the indirect drivers, per capita consumption, population growth, trade and GDP are the most important, affecting the direct drivers and consequently the different nexus elements **(Figure 2.11, Figure 2.12)**.

There is well established evidence on the interactions between two and three nexus elements to show that biodiversity has a significant and positive impact on all the other elements, being imperative for maintaining water, food, health and climate systems. At the same time, the analysis of multiple nexus interlinkages shows that the current state of knowledge about the complex interactions involving more than three elements of the nexus is still poorly studied. Nevertheless, the analyses of the interlinkages between all nexus elements still indicates that biodiversity improves water, food and health outcomes whilst also mitigating for the negative impacts of climate change **(Figure 2.35)**.

INTERACTIONS AMONG NEXUS ELEMENTS

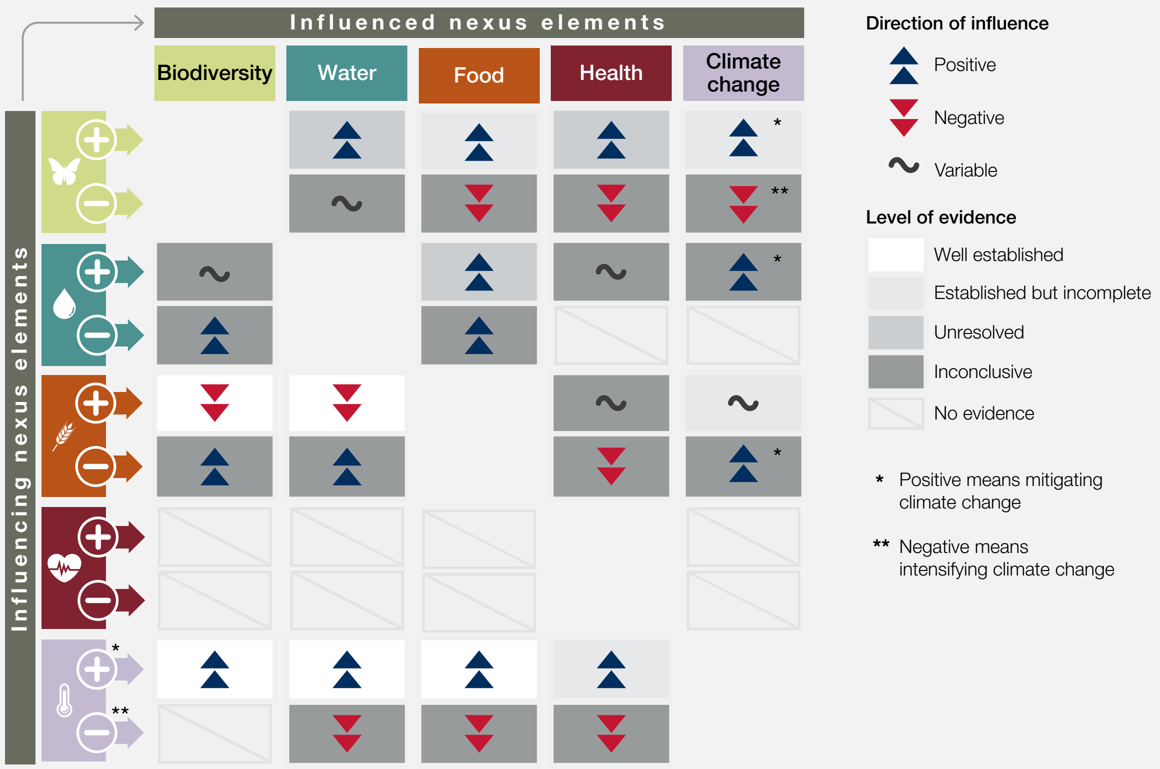


Figure 2 35 **Matrix showing the evidence and directionality of interactions between the nexus elements.**

The matrix displays evidence from the systematic literature review of studies including four and five nexus elements. The overall effect of either positive/improving (+) or negative/declining trends in a nexus element, denoted by the (+) or (-) sign in the left column, on other nexus elements are displayed, with the number of studies finding each effect being shown by the level of confidence (see data management report[4] for details).

There is also evidence of negative impacts from biodiversity, e.g., from communicable disease risk, which must also be accounted for, but these are driven by changes in biodiversity-human interfaces, including by expansion and intensification of food systems.

While biodiversity leads to more positive interactions, food and climate change lead to a greater number of negative effects on the other nexus elements. Specifically, climate change has a significant and predominantly negative impact on all nexus elements, leading to biodiversity loss, water and food insecurity and an increased risk of negative health outcomes, including emerging infectious disease risk and mental health, among others.

Although the quantity and quality of food has a positive impact on many aspects of health, its production is also linked to significant negative impacts on other elements of the nexus, especially on the quantity and quality of water and on biodiversity, with consequent negative impacts on other aspects of health (in addition to those linked to poor diets). Within the context of the nexus, human health was always studied as an endpoint, having been assessed through physiological and measurable aspects, such as an increase in mental illnesses, infectious diseases, etc., yet health is the most neglected element among multi-element assessments and food production and water use is mostly to support health **(Figure 2.35)**.

In summary, policies that act to conserve biodiversity and mitigate climate change can have secondary positive effects on all the other elements of the nexus, given these interconnections.

2.6.2 The nexus and global policy frameworks

The results summarized in this chapter are relevant for global policy frameworks, such as the SDGs, the Kunming-Montreal Global Biodiversity Framework and the Paris Agreement **(Section 1.3.2)**. Despite these frameworks having been developed in different and often siloed policy domains, they increasingly acknowledge synergies and trade-offs between different policy goals and nexus elements and the need for coordinated action, given that the negative trends outlined in this chapter are often transboundary problems in a highly interconnected world (Kroll *et al.,* 2019; Renaud *et al.,* 2022; Z. Zhao *et al.,* 2021). To unpack these challenges, the results of this chapter are mapped to the SDGs and discussed in the context of other global policy frameworks, namely the Kunming-Montreal Global Biodiversity Framework and the Paris Agreement, for opportunities and barriers in terms of more integrated and effective policy approaches.

2.6.2.1 Interactions and interlinkages among global policy frameworks

The SDGs are a comprehensive set of global goals that aspire to be "integrated and indivisible" (United Nations, 2015), while the Kunming-Montreal Global Biodiversity Framework has a similar focus on integrated "whole-of-government" and "whole-of-society" approaches (CBD, 2022). Particularly for the SDGs, there are numerous potential interactions among goals in the sense that achieving one may either advance or hinder the attainment of others (e.g., the presence of trade-offs and synergies among both goals and outcomes) (Blicharska *et al.,* 2019; Pradhan *et al.,* 2017; Scherer *et al.,* 2018; Weitz *et al.,* 2018). A promising finding from several studies is that synergies among the goals are numerous and can outweigh trade-offs (Alcamo *et al.,* 2020; Bennich *et al.,* 2023). However, a recent systematic analysis of this literature concluded that SDG14 and SDG15 on life on land and under water are most at risk as a result of negative impacts from progress on other goals (Bennich *et al.,* 2023) (see also **Section 3.7.2**).

These conclusions are supported by evidence from this chapter that direct and indirect drivers affecting nexus elements can feedback within the SDGs **(Figure 2.36)**. For example, expanding infrastructure to provide rural communities with access to services and markets (SDG9) is driving land-use change with negative implications on biodiversity (SDG15), which is in turn likely to affect other dimensions of sustainable development (Ibisch *et al.,* 2016). Thus, all SDGs are affected by interlinkages between different nexus elements, but some of them also act as drivers of worsening trends (Spangenberg, 2017). This argues for the need to locate synergies between SDG goals and identify response options that can help enforce and multiply synergies and better manage for trade-offs that may occur **(Section 5.6)**.

The focus of the Kunming-Montreal Global Biodiversity Framework on economic, social and financial systems for reversing biodiversity loss is synergistic with a nexus approach (Obura, 2023; Obura *et al.,* 2023). In addition, this chapter's conclusions regarding the fundamental importance of biodiversity in achieving positive outcomes for the other four nexus elements support this framing. The Kunming-Montreal Global Biodiversity Framework targets on implementation and mainstreaming (14 – 23) also address problems that map onto identified nexus challenges **(Section 1.1.2)**. Thus, successful implementation of the Kunming-Montreal Global Biodiversity Framework to 2030 will require understanding and leveraging direct and indirect interlinkages across multiple nexus elements **(Section 2.6.1)**. The challenge remains, however, as to whether conventional approaches (such as establishing 30 per cent protected areas by 2030) or more transformative action

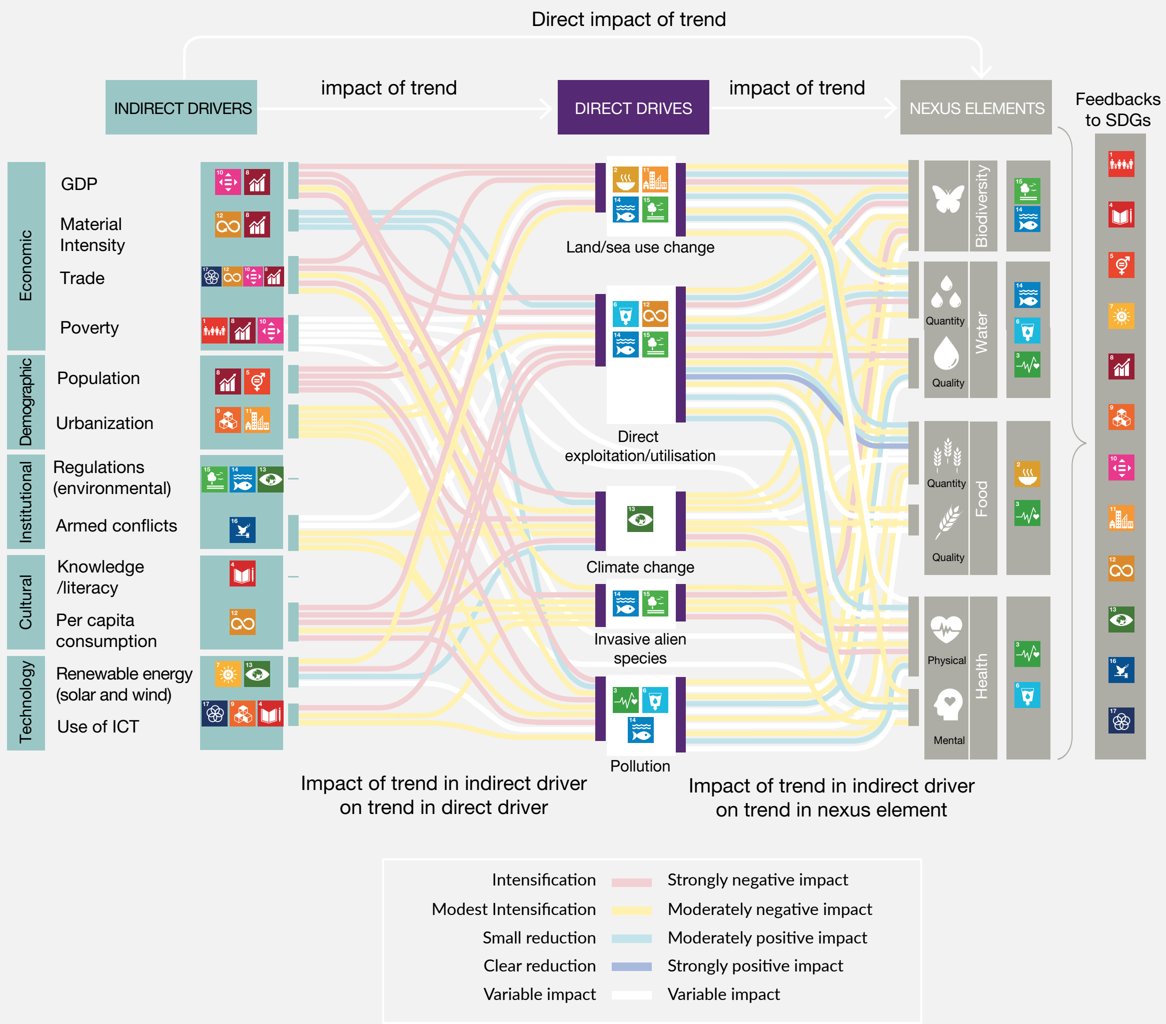


Figure 2 36 **Overview of the complex systemic links between Sustainable Development Goals acting as indirect and direct drivers as well as nexus elements.**

The Sustainable Development Goals (SDGs) and their feedbacks are mapped and overlaid onto the Sankey diagram shown in **Figure 2.12**, with the connections in opaque colours to bring the SDGs into focus.

within the Kunming-Montreal Global Biodiversity Framework will guide national strategies and decisions (Obura, 2023).

With regards to the Paris Agreement, the interlinkages between climate change and the other elements highlights the importance of a nexus approach. This chapter clearly shows that failing to act on climate change leads to negative outcomes across biodiversity, water, food and health. The functional separation between biodiversity and climate change in many decisions taken by governments to meet the Paris Agreement goals may lead to actions that inadvertently trade-off one or the other, or both, issues (Pörtner *et al.,* 2023). This is in large part due to the fact that existing governance systems often lack effective mechanisms to improve integration between biodiversity and climate change at national to subnational scales (Pascual *et al.,* 2022). However, nature-based solutions or ecosystem-based approaches are increasingly recognized as promising approaches for utilizing synergies between biodiversity conservation and climate action, as indicated by the significant and increasing reference to them in the Nationally Determined Contributions (NDCs) (Seddon *et al.,* 2020).

Calls for cohesion among implementation of the Kunming-Montreal Global Biodiversity Framework, Paris Agreement and the SDGs are aimed at helping avoid these unintended consequences and trade-offs (Gomez-Echeverri, 2018; Janetschek *et al.,* 2020). Levering complementarities can ensure that synergies help strengthen outcomes, such as grounding nature-based solutions for climate change that are encouraged under the Paris Agreement with the strong biodiversity safeguards of the Kunming-Montreal Global Biodiversity Framework (Streck, 2023). In practice, however, integrated approaches within the SDGs and coordination across the three policy frameworks is still relatively uncommon at the national level; this is attributed in part to difficulties in managing multiple goals covering many disparate sectors (Biermann *et al.,* 2022; Bogers *et al.,* 2022).

2.6.2.2 Measuring status and progress of global policy frameworks

Overall, only about 18-20 per cent of the SDGs targets are projected to be achieved by 2030 (Sachs *et al.,* 2023; UN, 2023c). About half are significantly off track and over 30 per cent have seen no progress or regression since 2015 (UN, 2023c). Targets considered as on track primarily concern health (SDG3) and access to infrastructure and services (Sachs *et al.,* 2023). Major challenges remain for the targets associated with all other nexus elements, with stagnating or regressing trends – biodiversity (SDG15 and 14), food (SDG2), climate change (SDG13) and water (SDG6).

Overall, there are similar trends for many indicators, especially for those SDGs related to the biosphere. Interestingly there are partly diverging trends for targets related to food (SDG2) and health (SDG3). Agricultural production has, for example, increased **(Section 2.3.3)**, yet this did not seem to benefit SDG2, as access to food is getting worse (UN, 2023c). Similarly, while life expectancy has been increasing and child mortality decreasing **(Section 2.3.3)**, major challenges in the field of health remain (e.g., in terms of maternal mortality (UN, 2023c), indicating that improvements did not benefit all dimensions of human well-being nor all global regions equally (UN, 2023c).

Likewise, progress towards fulfilling the Paris Agreement is not on track. Although a coherent implementation of NDCs would lead to a significant reduction of GHG emissions and might even be sufficient to limit global warming below 2°C (Meinshausen *et al.,* 2022), countries are either lacking adequate implementation to meet ambitious targets or did not establish ambitious targets in the first place (Roelfsema *et al.,* 2020). Many of the NDCs also do not take integrated nexus approaches to mitigation and adaptation action (Paim *et al.,* 2020).

While the SDGs and Paris Agreement have been in place for about a decade and allow for an evaluation of progress in reaching the goals, the Kunming-Montreal Global Biodiversity Framework has only recently been established and thus stocktaking is not yet in place. However, based on past achievements of previously set biodiversity targets, efforts to achieve the Kunming-Montreal Global Biodiversity Framework goals need to increase substantially, including around financing **(Section 6.2)**.

2.6.2.3 Critical reflections on the implementation of monitoring of global policy frameworks

All nexus elements are directly related to one or more SDGs as well as targets of the Kunming-Montreal Global Biodiversity Framework and the Paris Agreement. This indicates the increasing recognition of the significant complex relationships among, and cascading effects between, different nexus elements among decision-makers. While global policy frameworks are important instruments for international governance, they have also been criticized and previously set targets have repeatedly been missed (Mace *et al.,* 2018). Since progress towards the SDGs and other policy frameworks is measured via a suite of different indicators, informative yet efficient summarization of progress remains a challenge, prone to simplified conclusions and usually assessed within national boundaries **(Section 7.3.8)**. Considering various indirect drivers (e.g., global trade) regularly affect direct drivers (e.g., land-use change), such an assessment is neither meaningful nor fair as environmental costs of resource consumption are often externalized. Such externalization can be measured by means of environmental footprints (Hoekstra & Wiedmann, 2014; Vanham *et al.,* 2019), including the ecological footprint, carbon footprint, water footprint and others. The ecological footprint, for example, indicates that human demand for resources and ecological services increased from 7.0 billion global hectares (gha) in 1961 to 20.6 billion gha in 2014, reaching a point where the planet's bio-productive area is not sufficient to support the competing demands (D. Lin *et al.,* 2018).

The SDGs recognize that international trade may act as an engine for inclusive economic growth and poverty reduction (Blicharska *et al.,* 2019), but also that trade can have negative impacts on sustainable development. Yet the existing indicator framework to assess sustainability of consumption and production fails to consider this sufficiently because it lacks some indicators of interest across both the domestic and foreign footprint. For example, although the SDGs consider material footprint as indicators for SDG12 (responsible consumption and production) and SDG8 (decent work and economic growth), other well-established footprints, such as the carbon, ecological or water footprint are not included. In general, there is a bias in the SDG monitoring towards indicators that focus on efficiency gains rather than total resource consumption (Wackernagel *et al.,* 2017). As per capita footprints across and within countries differ substantially, not including them puts countries or socio-economic groups with low overall consumption rates at a disadvantage. As an example, countries may decrease their domestic footprints by outsourcing carbon intensive industries. In the meantime, they can increase their consumption related footprints (Brizga *et al.,* 2017). As a result, composite indices (e.g., the SDG index) are positively correlated with high per capita ecological footprints (Wackernagel *et al.,* 2017) and high import rates of biomass (Freudenberger *et al.,* 2010).

Furthermore, there are significant consumption footprint differences within and between countries. Globally, the wealthiest 10 per cent of people are responsible for nearly half the world's CO_2 emissions, against 12 per cent of emissions by the poorest half of the world's population (Chancel, 2022). Moreover, the Kunming-Montreal Global Biodiversity Framework has been criticized as the costs of conservation are likely to have disproportionate negative impacts on LMICs, while benefits are distributed globally (Waldron *et al.,* 2022). This is despite the fact that biodiversity loss and climate change have been mainly driven by consumptions demands in HICs. Expanding protected areas in ways that are not equitable and inclusive, especially in the most biodiverse parts of the world, is likely to affect rural communities in the poorest countries of the world, raising concerns of so-called green colonialism and land-grabbing for conservation (Collins *et al.,* 2021; Henry *et al.,* 2022).

Issues of global justice when it comes to the costs and benefits of action as well as responsibilities are aspects that are not sufficiently considered in the global conservation agenda nor easily monitored. For example, the implementation of climate adaptation actions (SDG13), particularly in ocean and coastal and mountain ecosystems, is having negative impacts on gender equality (SDG5) (Roy *et al.,* 2022). As another example, additional protected areas might be ineffective if poorly implemented and managed (Meng *et al.,* 2023). These findings suggest that the current monitoring frameworks lack a consistent consideration of complex interactions between different sustainability dimensions and fall short in considering global justice aspects. This includes goals both within and between frameworks (e.g., between different SDGs or between the SDGs, the Kunming-Montreal Global Biodiversity Framework and Paris Agreement) as well as other policy silos (e.g., international trade and economic development). Although there is mixed evidence regarding the potential of increased policy coherence by itself for achieving sustainable development **(Chapter 4)**, based on evidence in this chapter, effective implementation of policy frameworks clearly requires a more careful consideration of trade-offs and synergies between different goals. This is in alignment with the need for improved 'nexus governance' which is further outlined in **Chapter 4**. As part of this move towards nexus governance, a stronger consideration of justice issues within indicator frameworks, including the rights of IPLC, is crucial given this chapter's findings about the unequal burdens that negative declines in nexus elements are having on them, and would support a more substantial and equitable realization of the global policy frameworks.

2.7 KNOWLEDGE GAPS AND RESEARCH NEEDS

2.7.1 Scientific evidence

Utilizing the nexus approach to understand today's environmental challenges supports understanding of the complexity of the interacting nexus elements of biodiversity, water, food, health and climate change. As the nexus concept has only emerged recently, it is inevitable that previous research does not directly address nexus questions but had to be interpreted according to the framing of this assessment. Although interdisciplinary research is accumulating, most of the scientific literature focuses on issues with one specific focus (such as water management and nature protection), and lacks the interdisciplinary evidence needed to provide innovative and systemic solutions.

This can be evidenced in **Section 2.5.1** **(Figure 2.37)**, where on close analysis, of 84 of the articles investigating four and five interactions (43 per cent four; and 25 per cent five interactions), most were found to be evaluating the different elements of the nexus through simple cause-and-effect relationships between two (in 93.6 per cent) or, at most, three elements (in 6.2 per cent) **(Figure 2.37)**. This means that despite the large pool of data accumulated on the importance of biodiversity for ecosystem functioning and the provision of nature's contributions to people, this knowledge is rarely exploited for exploring higher order nexus interactions.

2.7.2 Scientific foci and siloed approaches in science and research

Although the systematic review **(Section, 2.5.1; Figure 2.20)** did not consider other sources of scientific knowledge, such as grey literature, there is a lack of scientific publications that quantitatively access interactions between more than three nexus elements. This might be due to the complexity and the lack of incentives to collaborate in an interdisciplinary way. Today's science system acknowledges and supports specialization rather than holistic, interdisciplinary thinking (Seppelt *et al.,* 2018). Consequently, scientists who leave academia to work in consultancy, policy, decision-making or management are also not trained to work in an interdisciplinary, nexus-informed way. Furthermore, interdisciplinary science is complex and requires specific incentives and training for its realization, as well as a high level of collaboration between the different disciplines (Adisasmito *et al.,* 2022). The systematic review also only considered studies published in English (i.e., the common language of science), leaving out a possible variety of studies published locally in different languages. Although in 2021 the United Nations Educational, Scientific and

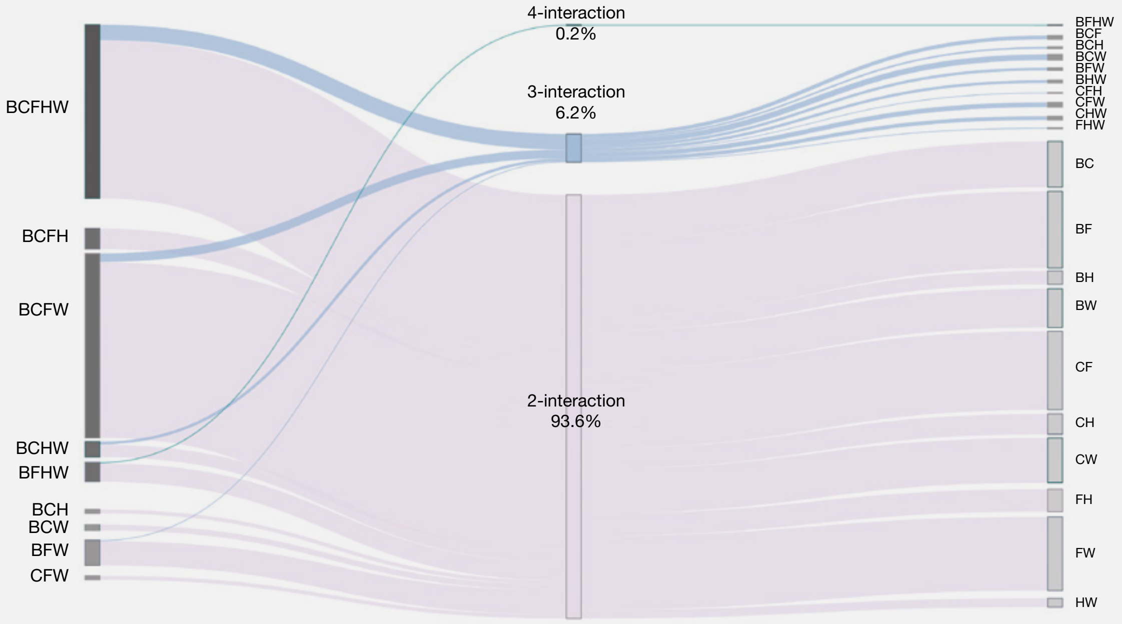


Figure 2 37 **Differences in nexus element interactions based on a review of multi-element interaction studies.**

The nexus elements mentioned (left column) *versus* addressed (right column) in publications from the literature review of multi-element interaction studies (see data management report[4] for details) are presented. Most interactions studied in the 84 articles selected evaluated relationships between two elements of the nexus only (in 93.6 per cent of the cases), with a few considering three (6.2 per cent) and only 1 study (0.2 per cent) considering interactions among four elements of the nexus (middle column). Capital letters represent the five nexus elements: B: biodiversity, W: water, F: food, H: health and C: climate change.

Cultural Organization (UNESCO) highlighted the need to overcome language barriers in order to achieve the values and guiding principles of open science, there is still little effort to reduce these barriers (Amano *et al.,* 2023).

2.7.3 Data availability

The temporal and spatial scale differs significantly across drivers and nexus elements. Data on indirect drivers relating to institutional, cultural and technological indicators are less comprehensive than for demography or economics. The analyses in **Sections 2.3.1**, **2.3.2**, **2.3.3** and **2.5.3** focused on those indicators for which there were clear trends that could be synthesized. Other indicators are relevant, especially for a more comprehensive overview of possible levers and to reveal unexploited potentials. Furthermore, the analysis focused on time periods for which data were available, but recent trends of indirect drivers are often too short to show a strong effect on direct drivers and the nexus elements, resulting in data gaps **(Figure 2.13)**. Much important health-related data is only available at coarse levels, such as annually by country. In addition, impacts of trends in direct drivers on nexus elements are most likely non-linear, such that both a strong and medium continuation of trends in direct drivers could result in strongly negative impacts on the nexus elements **(Box 2.11)**. Indirect drivers are the levers for reducing negative impacts of direct drivers on the nexus elements **(Figure 2.11, Figure 2.12)**, although trade-offs will in some cases be difficult to avoid. Given the fact that most of the analysed trends (be it nexus elements or drivers) cannot look further back using a nexus perspective than recent history (i.e., 1970 onwards), the results of this chapter are prone to a biased assessment (e.g., because of shifting baselines) (Mehrabi & Naidoo, 2022; Papworth *et al.,* 2009). Lastly, many data sources are aggregated to national levels limiting fine-scale analyses, which in turn limits important information from different scales, including both local differences and transboundary assessments.

2.7.4 Overcoming limitations

1) The general lack of spatially explicit data regarding the nexus elements in recent years should be addressed by high-resolution data and information on environmental and socio-economic conditions, as well as governance and legal settings from the global to the small-scale community level, which requires a continuous, comprehensive monitoring of the nexus elements and their interactions **(Section 7.3.8)**.

2) Despite the large amount of data on the importance of biodiversity (diversity of genes, species and ecosystems) for ecosystem functioning and the provision of nature's contributions to people **(Figure 2.1)**, this knowledge hardly penetrates the literature on the complex nexus interactions, with most papers considering biodiversity as ecosystems or certain useful species (primarily important for food production). Consequently, studies lack good indicators for biodiversity, with this being often considered in its most general sense (e.g., the presence of green areas, land cover types or ecosystems, which do not accurately reflect biodiversity).

3) All elements of the nexus are seen as equally important to assess possible response options and pave the way ahead towards just and sustainable futures. This, however, requires comprehensive and balanced investigations of the nexus elements and their interactions. Most research focuses on food-energy-climate change or water-energy-food relationships, with health being the most understudied element when considering its interactions with the other elements. To overcome these limitations, it is suggested to (i) foster longitudinal studies, such as those based on birth cohorts between human health and biodiversity; (ii) promote standardization for health databases, always considering places of infection (rather than residence) and more refined spatial scales; and (iii) increase the understanding of the complex ecological and socio-economic factors that link biodiversity and different aspects of human health, especially when considering the nexus elements and their potential non-linearities and feedbacks.

4) Interactions among multiple nexus elements, and their attribution to drivers, are complex and often context and place dependent. To allow for an assessment of possible success or failure of implemented management activities or response options, research needs to focus on a quantitative understanding of the relationship between indirect drivers, direct drivers and nexus elements. Systematic reviews, meta-analysis and within and cross-country comparison of policies would allow the assessment of programme implementation practices, but these would benefit from enhanced scientific and technical cooperation and investments in research to strengthen international, national and regional capabilities for monitoring nexus elements' status and trends.

5) The application of the nexus approach quickly reveals that most if not all environmental problems have amplified and matured into 'wicked problems', that defy easy solutions and need cooperation across knowledge (and policy) domains (Adisasmito *et al.,* 2022; Hayman *et al.,* 2023; Rayne *et al.,* 2023). For example, knowledge gained from local studies with respect to solving nexus challenges does not necessarily include (unintended) implications of possible side-effects elsewhere, or so-called telecoupling effects (J. Liu *et al.,* 2015) (2.6.2). Frameworks such as One Health now aim to facilitate collaboration, communication, capacity building and coordination across sectors to tackle these problems **(Box 1.4)**.

6) There is little evidence on the potential of greater policy coherence to achieve sustainable development **(Section 2.6.2.1)**. Furthermore, there is little interaction between different frameworks and policies and they often do not consider the multitude of connections that exist between the different elements. For example, climate change and biodiversity policies often do not consider the interconnected effects of these elements and their feedback on other elements in the nexus. Likewise, health policies do not consider that this is an outcome that can often result from biodiversity, food, water and climate change policies.

7) While there is a growing recognition of the importance of ILK in sustainable resource management, there is limited empirical research that systematically examines the specific trends and current status of ILK within the context of the interconnections between biodiversity, water, food and health. Most ILK-focused studies engaged with lower-level interactions (2 and 3-way across nexus elements), mirroring the challenges of other data sources, despite the fact that IPLC have strong traditions of holism that guide their management of nature **(Section 1.2.2)**.

2.8 CONCLUSION

This chapter provides evidence that direct and indirect drivers that impact the nexus elements are increasing over the last five decades and negatively affecting biodiversity, water, food and health and leading to climate change. This chapter also shows that there is a complex interrelationship between the nexus elements, with decreases in biodiversity negatively impacting water, food, health and climate systems, which in turn affect human well-being and environmental sustainability. Changes in biodiversity, water, food, health and climate significantly impact people worldwide, albeit unequally. About 65 per cent of the global population lives in areas with beneficial hotspots of at least one nexus element, yet 52 per cent live in degradation hotspots, particularly affecting people in low- and lower middle-income countries who are experiencing the greatest impacts of this degradation. Indigenous Peoples and local communities perceive more negative trends than positive ones in local biodiversity, water, food, health and climate change, with negative biodiversity trends being most prominent.

Economic growth, population dynamics, urbanization and institutional policies impact biodiversity, water, food, health and climate change. Economic expansion drives land and resource use changes, intensifying exploitation and pollution. Population growth and urbanization increase demand for housing, food and energy, leading to land- and sea-use changes and resource extraction. Effective governance and regulations reduce pollution but often fall short globally. Cultural drivers, such as increasing consumption, intensify resource exploitation. Armed conflicts divert political capacity from addressing climate change and biodiversity decline. These indirect drivers influence direct drivers of biodiversity loss, i.e., land- and sea-use changes, exploitation of species, climate change, pollution and invasive alien species, which in turn impact food security, clean water and health. Deforestation and agricultural expansion are major contributors to biodiversity decline, especially in tropical regions. Urban expansion exacerbates health issues due to pollution and reduced green spaces. Overfishing and resource extraction degrade ecosystems and increase greenhouse gas emissions. Agricultural pollution contaminates water and soil, posing risks to ecosystems and human health. Invasive alien species disrupt ecosystems, leading to biodiversity loss and affecting food supplies.

As a consequence of these changes, the global wildlife population, for example, has declined by 69 per cent in nearly 50 years, with the greatest declines being observed in Latin America and freshwater species. Ecosystems play a central role in regulating water cycles, which are crucial for human consumption and food production, but their loss and degradation compromises not only water quantity, but also quality, with feedbacks to the other nexus elements. Biodiversity supports agriculture and food production through pollination, pest control and soil health. However, modern agricultural practices and climate change drive biodiversity loss, reducing food security and nutritional diversity, especially for smallholder farmers. Monocultures and dependence on a few crops affect ecosystem stability and resilience, contributing to diet-related diseases and other aspects of human health. Biodiversity influences human health as a source of medicines, by regulating air and water quality and by improving mental health. Biodiversity loss increases the risk of zoonotic and some vector-borne diseases as human activities encroach on natural habitats. Climate change stresses biodiversity, altering species distributions and ecosystem functions, which cascades to other nexus elements. Water quantity and quality as well as food security can be directly impacted by climate change, while direct and indirect effects on human health are also observed. The failure to recognize the interconnectedness of the nexus elements and of these direct and indirect drivers is a key reason why only 18-20 per cent of SDG targets are on track for 2030, and why challenges in meeting the Kunming-Montreal Global Biodiversity Framework and Paris Agreement targets are also likely to occur.

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