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Enriching the European Shared Socio-economic Pathways with considerations of biodiversity and nature using a nexus approach

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A R T I C L E I N F O

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A B S T R A C T

The global climate and biodiversity crises are deeply interconnected, yet current research and policy frameworks often treat them in isolation. The widely used Shared Socio-economic Pathways (SSPs), which underpin climate change assessments and guide policy, exemplify this gap: they neglect biodiversity and nature, overlooking critical feedbacks between socio-economic and environmental systems. This omission constrains options for addressing both crises simultaneously and obscures cascading risks. We address this gap through a co-creation process at the European scale, enriching the European-SSPs with considerations of biodiversity and nature using a nexus approach (spanning biodiversity, energy, food, health, water, and transport). We compare the original and enriched narratives through a systems analysis, revealing a substantial increase in system complexity that shifts the relative significance of indirect drivers across SSPs due to novel feedbacks with biodiversity and other sectors. For example, across several scenarios economic and technological development reinforce unsustainable resource extraction, even if partially oriented toward sustainability. In contrast, governance, environmental respect and social cohesion prove critical to enabling positive outcomes for biodiversity but can also perpetuate biodiversity loss if not fully aligned with environmental goals. These findings highlight the need for adaptive approaches that respond to emergent socio-economic conditions and systemic policymaking that accompanies technical interventions with improvements in governance. They also demonstrate how 'biodiversity-centric' scenarios can strengthen the IPCC scenario framework by capturing critical feedbacks between biodiversity and socio-economic drivers of climate change, enabling more integrated research and policy.

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1. Introduction

Climate change and biodiversity loss are deeply entangled crises (Pörtner et al., 2021; IPBES, 2024). Human activities such as land use change, overexploitation of natural resources, and pollution are driving the degradation, fragmentation, and loss of habitats, which is accelerating species extinction (Jaureguiberry et al., 2023; McCallum, 2015; Turvey and Crees, 2019). Climate change is mainly caused by greenhouse gas emissions, which are driven by similar direct and indirect drivers to those driving biodiversity loss (e.g., land use and pollution, in addition to social preferences, technological change, economic growth). The impacts of climate change, such as sea level rise, frequency and severity of extreme weather events, and shifts to the overall climatic regime (IPCC, 2021), further disrupt ecosystem structures and processes, thereby disrupting carbon sequestration further and perpetuating biodiversity loss (Carey, 2009; IPCC, 2022; Lawrence and Soame, 2004).

These dual crises have significant impacts on people. The loss of biodiversity and nature's contributions to people threatens many aspects of human wellbeing (Díaz et al., 2018), such as a greater risk of infectious pathogen emergence (Schmeller et al., 2020) and threats to food security and nutritional diversity (Sunderland, 2011; Wahlqvist and Specht, 1998). Climate change amplifies these impacts and introduces new threats, such as direct risks to human life and infrastructure during extreme weather events (IPCC, 2022) and forced migrations as sea level rise renders coastal areas uninhabitable (Lincke and Hinkel, 2021; Storlazzi et al., 2023). Further, the potential crossing of biodiversity and climatic tipping points increases the possibility for nonlinear impacts and cascading risks, with uncertain yet potentially severe consequences for both nature and people (Lenton et al., 2023). These impacts are distributed unequally, disproportionally affecting the most vulnerable populations (Chaplin-Kramer et al., 2023; IPCC, 2022). Moreover, solutions for halting and reversing biodiversity loss and climate change often interact in complex ways. For example, monoculture afforestation or bioenergy production can mitigate climate change through carbon sequestration but may reduce biodiversity (Calvin et al., 2021; Stephens and Wagner, 2007). Conversely, maintaining or enhancing biodiversity in these ecosystems can strengthen their resilience to disturbances, including climate change (Seddon et al., 2020; Thompson et al., 2009).

The intertwined nature of these crises highlights the importance of a nexus approach to science and policy (IPBES, 2024). In a nexus approach, interlinkages between biodiversity and climate, in addition to a range of other sectors such as energy, food, health, water, and transport, can be addressed in a systemic and integrated way (Müller et al., 2015; Pascual et al., 2022). The aim of such approaches is to understand and mitigate trade-offs while identifying opportunities for synergistic action. The Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) play an important role in synthesizing evidence on their respective issues and have recently taken steps toward a nexus approach. For example, the IPBES Nexus Assessment, which went to plenary in December 2024, considers interlinkages between biodiversity and the climate system, in addition to a range of other sectors and systems (IPBES, 2024, 2019). The IPCC Working Group II (Impacts, Adaptation, and Vulnerability) characterized the impact of climate change on ecosystems and their services in the Sixth Assessment Report (IPCC, 2023a, 2023b). Most notably, the IPCC and IPBES hosted a joint workshop in December of 2020, which resulted in a co-sponsored workshop report on biodiversity and climate change (Pörtner et al., 2021). Yet, synergistic action remains limited, and the failure to address both climate change and biodiversity loss can be at least partially attributed to challenges dealing with the systemic nature of these crises, which requires mainstreaming solutions across socio-economic drivers and sectors that may be resistant to change (IPBES, 2018; Rounsevell et al., 2020).

Scenarios are increasingly popular tools for exploring complex futures (Börjeson et al., 2006; Oteros-Rozas et al., 2015; Pereira et al., 2021). Both the IPCC and IPBES have adopted scenario frameworks that explore futures deemed relevant to their flagship issues. The IPCC community scenario framework includes Shared Socioeconomic Pathways (SSPs) that describe five possible global socio-economic trajectories, which are combined with Representative Concentration Pathways (RCPs) and Shared Policy Assumptions (SPAs) to explore complex futures under climate change and climate policy (van Vuuren et al. 2011; Kriegler et al. 2014; O'Neill et al. 2014; Riahi et al. 2017). The SSPs have been taken up as useful narratives of a global future for many different applications across sectors and scales (O'Neill et al., 2020), including to underpin recent global biodiversity projections (Pereira et al., 2024).

These existing scenario frameworks offer useful contributions to understanding the future of both climate change and biodiversity loss. However, every scenario framework can only offer a limited view of the diverse domains, scales, or perspectives implicated in the future of these challenges (Lazurko et al., 2023; Swart et al., 2004; Verburg et al., 2016). For example, Kok et al., (2019) state the need for "further extension" of the downscaled European SSPs (Eur-SSPs) to address the necessary scope of drivers, factors, sectors and actors that may be relevant for different applications of the SSPs. An important identified gap in the SSPs is the lack of explicit consideration of environmental change, including biodiversity and nature, as intertwined with socio-economic futures driving climate change (O'Neill et al., 2020; Pereira et al., 2021). This gap applies broadly as representations of biodiversity are often oversimplified in global models, where it is usually considered as an outcome or impact rather than as a driver of change (IPBES, 2016). Yet, a nexus approach requires efforts to consider interactions between indirect drivers underpinning these dual crises and their implications and feedbacks, including with biodiversity and across sectors. This gap points to the potential for limits to the plausibility and comprehensiveness of the SSP narratives, particularly when applied at sub-global scales and for a wide range of topics beyond climate change (O'Neill et al., 2020). As a result, the scenarios may fail to serve their desired outcomes, such as to motivate transformative actions to reverse climate change and biodiversity loss simultaneously or to build resilience to multiple interconnected risks.

In this paper, we aim to enrich the SSPs with considerations of biodiversity and nature using a nexus approach. We use the term 'biodiversity nexus' to refer to a nexus approach that considers interlinkages and feedbacks between biodiversity, energy, food, health, water, and transport. We focus on the European SSPs (Eur-SSPs) as a demonstrative case, which were downscaled and extended from the global SSPs (Kok et al. 2019). Our objectives were to 1) enrich the original Eur-SSPs narratives by detailing them with interlinkages and feedbacks between biodiversity and nature and the other elements of the biodiversity nexus using a co-creative, systems approach and 2) compare the dominant interactions and biodiversity implications across the scenarios and in relation to the original Eur-SSPs through a systems analysis. These insights inform reflections on future scenario work for the IPCC and IPBES.

2. Methods

2.1. The IPCC scenario framework

The SSPs are a key part of the scenario framework used by the IPCC community. The SSPs describe five possible global socio-economic future trajectories located on two axes: socio-economic challenges for adaptation and socio-economic challenges for mitigation (O'Neill et al., 2017). The SSPs have been taken up as useful narratives of a global future for diverse applications across scales and sectors (O'Neill et al., 2020). The global SSPs have been extended to produce European SSPs (Eur-SSPs), resulting in four distinct scenarios that mirror the global SSPs, excluding SSP2 which is often considered a more business-as-usual trajectory as depicted in Fig. 1 (Kok et al., 2019). These narratives are located on two axes: inequality (low to high) and carbon intensity per GDP (low to high). The narratives include a sustainable future with global cooperation and less intensive lifestyles (We are the World; Eur-SSP1); a future in which countries struggle to maintain living standards in a high-carbon intensive Europe (Icarus; Eur-SSP3); a future in which power becomes concentrated in a small elite and Europe becomes an important player (Riders on the Storm; Eur-SSP4); and a future in which a lack of environmental concern leads to the over-exploitation of fossil fuel resources addressed by technological solutions (Fossil-fuelled Development; Eur-SSP5).

The enriched Eur-SSPs presented in this paper are situated within the larger IPCC community scenario framework (O'Neill et al. 2020). We visualise this conceptually in Fig. 2, which shows how enrichment of the Eur-SSPs introduces novel consideration of biodiversity and sectoral change as *drivers* of the societal pathways underpinning integrated scenarios and analysis, rather than only as *impacts*. The figure highlights how this begins to address key gaps in the representation of biodiversity in scenarios and models (IPBES, 2016), as the enriched societal pathways for the European scale developed in this paper can be combined with downscaled climate model simulations and policy assumptions for more nuanced regional integrated scenarios and analyses. Because the enriched Eur-SSPs are regional, they cannot directly influence global climate scenarios: globally enriched SSPs and significant adaptations to global integrated assessment models (IAMs), or other modelling methods, would be required for this approach to be applied and simulated for impacts within global scenarios and analyses.

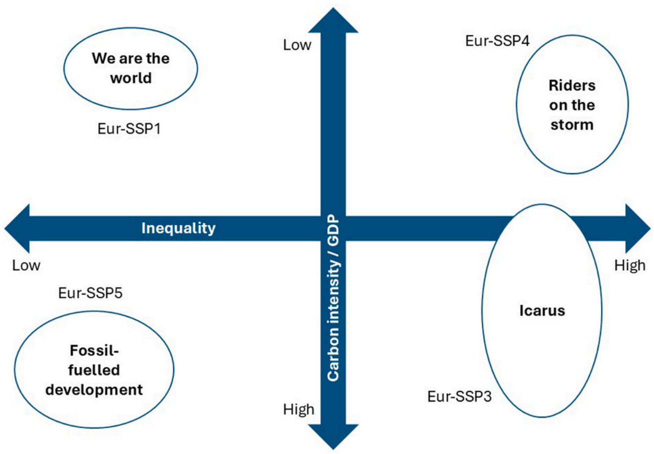

Fig. 1. European SSPs for climate change research, used as a starting point for enriching with biodiversity and nature using a nexus approach (adapted from Kok et al. 2019).

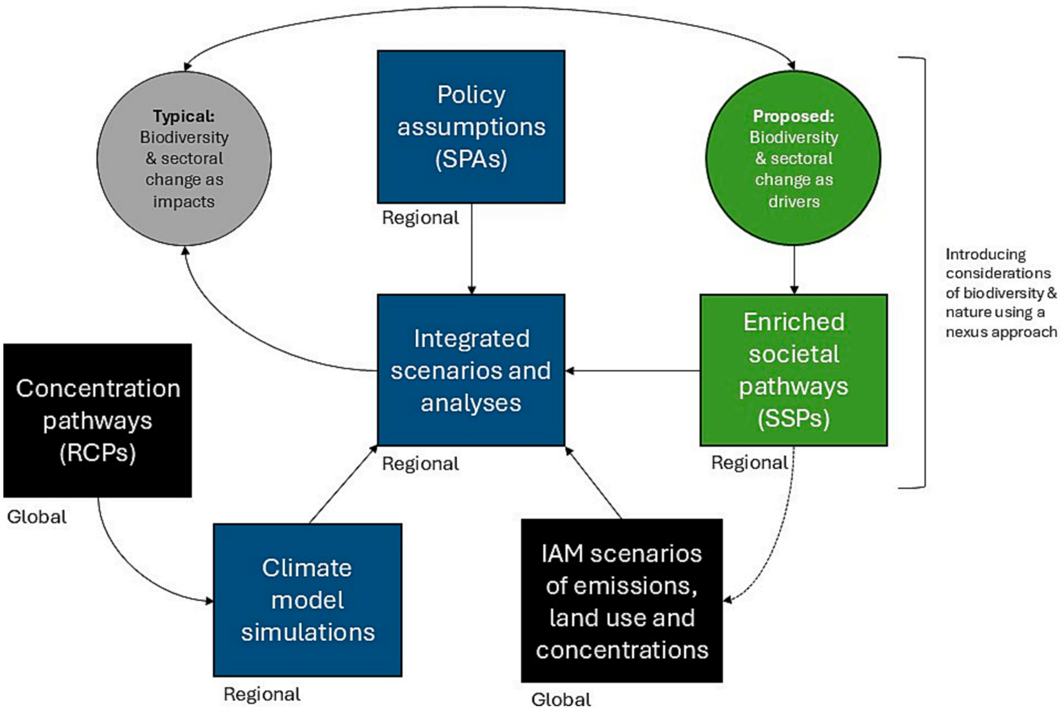

Fig. 2. Adapted version of the scenario framework used in climate research (O'Neill et al. 2020) highlighting the contribution of this paper. The boxes are the original framework, with those in green most relevant for clarifying the contribution of the enriched Eur-SSPs. Blue boxes apply at regional and global scale whereas black boxes apply at global scale only. The green circle highlights how this study proposes consideration of biodiversity and sectoral change as drivers, in contrast to the grey circle, which describes how typical approaches view biodiversity and sectoral change as impacts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. *Enriching the Eur-SSPs with considerations of the biodiversity nexus*

The initial data for enriching the Eur-SSPs were collected during the first stakeholder co-creation workshop of the BIONEXT project (bionext-project.eu) held on 4–5 May 2023 in Santorini, Greece. The workshop was attended by 26 participants, who were selected to ensure diverse representation of regions of Europe (northern, central and eastern, western, and southern Europe), organisational types (government, business, civil society or non-governmental organisation, and advocacy for minority groups), and expertise related to

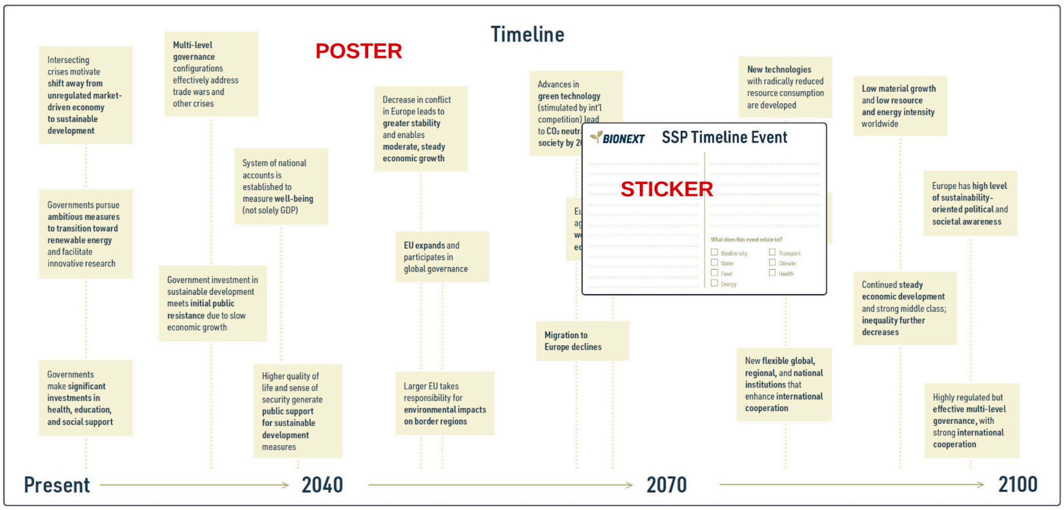

Fig. 3. Example of poster and stickers used to enrich the original European SSPs with considerations of biodiversity and nature, using SSP4 as an example.

seven nexus elements (biodiversity, water, food, health, energy, transport and climate change). During the workshop, BIONEXT researchers served as facilitators and notetakers to capture the data emerging from verbal discussion and visual materials (e.g., in notetaker templates, audio recordings and photos of visual materials).

During the SSP exercise of the workshop, workshop participants were familiarized with the four Eur-SSP scenario narratives (Eur-SSPs 1, 3, 4 and 5) through a presentation. Participants were then randomly assigned into four groups where a facilitator for each Eur-SSP asked them to add additional events or impacts that may occur within the Eur-SSP narratives at different time points to the year 2100 related to the elements of the biodiversity nexus (by putting stickers on posters, e.g., Fig. 3). These 'events' or 'impacts' were meant to be additional drivers or implications of existing events in the narratives to ensure they enriched the narrative yet were still coherent with the existing Eur-SSP. If not already explicit in the 'event' or 'impact', participants were then asked to indicate whether the events had positive or negative implications for biodiversity and nature. Participants repeated this exercise across the four Eur-SSPs until the posters were filled with additional events and implications for biodiversity and nature.

The data collected during the workshop exercise were synthesised and analysed to enrich the original Eur-SSP narratives by integrating the events/impacts and implications for biodiversity at appropriate sections of the SSP narratives across different time scales. To do so, contributions were clustered across time periods and common themes. Summary statements were then integrated into the original Eur-SSP narratives in ways that maintain internal consistency and thus the plausibility of the scenarios (Schweizer & Kriegler, 2012). These were then verified by a reviewer against the workshop notes and to bring coherence to the events and implications across time scales. A final quality assurance review was conducted by an independent researcher. The detailed procedure can be found in the Supplementary Material Text S1. The full dataset used to enrich the Eur-SSPs can be found in Table S1.

2.3. *Validating the enriched Eur-SSPs*

The draft enriched Eur-SSPs were then further elaborated with a subgroup of stakeholders during an online webinar on 21 November 2023, which aimed to validate the enriched Eur-SSP narratives from the workshop and to further enrich them with more explicit consideration of the elements of the biodiversity nexus (i.e., biodiversity, energy, food, health, water, and transport). Climate change was excluded as a nexus element in this exercise, since the intention was to enrich the socio-economic drivers of the SSPs, which would then be paired with RCPs to consider climate change impacts. The 26 participants from the workshop were invited and 10 attended. During the webinar, participants gave general feedback on the enriched Eur-SSPs before moving into breakout groups where they drew a collaborative system diagram for each Eur-SSP. This allowed them to map elements of, and interlinkages within, the biodiversity nexus in the existing narrative and enrich them further with additional interactions. During this process, a facilitator helped discussion to reach consensus about each interaction before adding it to the diagram, with all points captured on a virtual diagramming board and in notes. The captured data were synthesised into a final version of the enriched Eur-SSP narratives by collating comments and making in-text changes, keeping record of when contributions from participants were rejected or moved to different time periods for internal consistency. The new narratives were subject to the same quality assurance review as the draft narratives and then circulated to the participants for final validation. A detailed procedure can be found in Text S1.

2.4. *Systems analysis of the enriched Eur-SSPs*

A systems analysis was conducted to further describe and evaluate the implications of enriching the original Eur-SSPs with considerations of biodiversity and nature. To do so, the full enriched Eur-SSP narratives were analysed to find interlinkages between a standardized set of nodes. These nodes were (a) elements of the biodiversity nexus (Kim et al., 2024) and (b) indirect drivers of change used to describe the original Eur-SSPs (Kok et al., 2019) as defined in Table 1. Broad definitions allowed the systems analysis to capture a comprehensive picture of the narratives.

Four researchers qualitatively coded the enriched Eur-SSP narratives for statements that implicitly or explicitly state a relationship or interlinkage between two nodes in Table 1. These were entered into a database, which characterised each interlinkage in a standardized format (i.e., 'from' and 'to' nodes, text summary of the nature of the interlinkage, original or enriched Eur-SSP, implicit vs explicit reference to the interlinkage, direct or indirect relations between nodes, corresponding time period, descriptive positive, negative or mixed/neutral sign of node–node relationship (see Fig. 4 caption), and implications for biodiversity if relevant). We designated descriptive signs as directional, wherein a change in the originating node causes an increase (positive), decrease (negative) or mixed/neutral change in the receiving node, except for the energy node due to the origins of the SSPs in the climate community. For interlinkages to energy, an increase in renewable energy production, lower energy demand or increased energy efficiency were coded as positive while an increase in fossil fuel production, higher energy demand or decreased efficiency were negative. A detailed procedure for how the database was created including quality assurance procedures can be found in Text S1.

The first analysis of the database assessed changes to the relative importance of different nexus elements or indirect drivers in the enriched versus original Eur-SSPs. This was done by producing a summary table detailing a count of the interlinkages from and to all nexus elements and indirect drivers across the original versus enriched Eur-SSPs, in addition to two systems maps for each Eur-SSP, one representing interlinkages in the original narrative from Kok et al. (2019) and the other representing interlinkages in the enriched narratives. These system maps were produced to show the nodes (Table 1) and the edges as interlinkages between these nodes. The diagrams allow for interpretation of the relative prevalence of interlinkages in the scenario narrative, as inferred by the number of database entries for that interlinkage (i.e., thickness of the arrows), the relative importance of that node in the scenario narrative, as inferred by the number of database entries implicating that node (i.e., the size of the nodes), and the positive, negative or neutral/mixed direction of the interlinkage (i.e., the colour of the edges).

Table 1
Scenario nodes and definitions used in the systems analysis.

Category	Nodes	Description
Elements of the biodiversity nexus	Biodiversity	Directly related to the state of terrestrial, inland water, and marine biodiversity and nature broadly defined, including the state of ecosystems, the land area of nature, outcomes for individual species, etc.
	Water	Directly related to the state of water resources, including infrastructure development for water supply and water/wastewater treatment, in addition to the state of freshwater and marine resources.
	Food	Directly related to the state of food systems across supply chains, including agricultural inputs and agricultural systems, fisheries, food culture, diets, etc.
	Health	Directly related to the state of human health, including both the state of the health sector and connections between human health and nature.
	Energy	Directly related to the state of the energy transition, including energy supply and mixes (i.e., renewables vs fossil fuels), change in energy demand and infrastructure/technology development.
	Transport	Directly related to the state of transport systems, including active transport (walking, cycling) and public and private modes.
Indirect drivers of change	Geopolitical stability	Degree of geopolitical stability or lack of conflict, i.e., high/low.
	International cooperation	Degree of international cooperation, e.g., strong EU, weak/strong trade.
	Globalisation	Pace of businesses/policies/etc gaining international influence and/or coordination.
	Net migration	Balance of immigration and emigration, with a focus on demographic change as influenced from outside of Europe.
	Mobility across borders	Degree of openness for mobility across borders, with a focus on border control and economic opportunity primarily within Europe.
	Economic development	Pace of economic growth, i.e., high/low, gradual, and/or type of economic development taking place.
	Technology development	Pace, reach and nature of technology development.
	Decision- making level	Dominant level of decision-making, i.e., international, EU, national, local, fragmented, with a focus on who has power.
	Quality of governance	Quality of structures and processes related to governance, including relative priority on environment vs economy or short-term vs long-term orientation.
	Choice	Degree/freedom of choice related to land and resource use, usually related to policies.
	Social cohesion	Extent of connectedness among groups in society, with a focus on public attitudes, perception and culture.
	Social respect	Degree of respect between countries or between societies, with a focus on respect and explicit participation across groups in society.
	Environmental respect	Degree and distribution of appreciation for the environment in the population.
	Education investments	Relative quantity and distribution of investment in education, i.e., high/low and equitable or elites, in addition to other aspects such as the type or quality of education.

The second analysis assessed the role of biodiversity and the biodiversity nexus in each enriched Eur-SSP. A synthesized version of the database was created that summarised the multiple database entries relevant for each interlinkage. This database was used to create two sets of sub-system maps that detail 1) the impact of the biodiversity nexus on indirect drivers and 2) the impact of indirect drivers on the biodiversity nexus. An interpretation of the relative prevalence of interlinkages in the scenario narrative, relative importance of nodes, and positive, negative or mixed directions were made possible using the same procedures as for the first analysis.

3. Results

3.1. Description of enriched Eur-SSP narratives

This section summarises the enriched Eur-SSP narratives, focusing on changes to the original Eur-SSPs when introducing the state of the biodiversity nexus (Kok et al., 2019). The full enriched Eur-SSP narratives are included in Text S2, which highlights any text that has been adapted or added to the original narratives in blue text.

3.1.1. Enriched Eur-SSP1

The world shifts away from a market-driven economy towards moderate but steady economic growth for sustainable development. There is overall higher political stability and lower inequality with strongly regulated multi-level governance. The European Union (EU) is expanding with strong international cooperation towards renewables and green technology and reduced consumption. From the present to 2040, the governments pursue ambitious measures for the energy transition and social support with an emphasis on plural knowledge and cultural and biological diversity. There are initial trade-offs between renewable energy and pressures on land and biodiversity with public resistance to spending due to slow economic growth. Protected areas are expanded with more green space and green infrastructure. From 2040 to 2070, the European political agenda focuses on well-being over economic growth as the EU expands and participates in global governance, empowering local authorities and communities to implement solutions with co-benefits for climate, biodiversity and wellbeing. Agricultural reform leads to more positive impacts on biodiversity and AI-assisted policy planning mainstreams biodiversity policy across sectors. People lead more sustainable lives in smaller rural towns. From 2070 to 2100, Europe has a high level of sustainability-oriented awareness with continuing economic development, decreasing inequality and improving health. The state of biodiversity is among the core societal indicators.

3.1.2. Enriched Eur-SSP3

Economic woes in major economies and regional conflict fragments the EU, leading to high inequality within and between countries. Increasing border controls and barriers to trade result in rising energy and food prices and increasing demand for natural resources, causing severe ecosystem failures. From the present to 2040, populist movements fuel rising international tension and persistent conflicts, resulting in the reprioritization of environmental policies in favour of defence. Rising food insecurity and poorer environmental quality impact human health. Travel is reduced between countries due to border controls, reducing pressure on nature, but lower environmental protection allows for continued use of pesticides, herbicides and antibiotics. The economy in Europe stagnates and the EU breaks apart. From 2040 to 2070, the gap between poorer and richer countries in the EU widens. Legislation for protected areas is abandoned and water wars arise with the collapse of some fisheries. The social fabric disintegrates and increases migration away from poor countries in Europe. From 2070 to 2100, the EU loses its leading position and deindustrialises. Criminal organizations and corruption take hold, and well-educated people migrate outside of Europe. These factors eventually reduce demand for energy and materials, alleviating environmental pressure and allowing rewilding in certain areas. Food production becomes extensive, with many people leading a subsistence lifestyle. The majority accepts political instability and social injustice and learns to live with less.

3.1.3. Enriched Eur-SSP4

The world shifts strongly towards innovation leading to a high-tech green Europe with strong partnerships between business and European governments. Power is concentrated in a small political and economic elite with growing inequality within and between the European countries. From the present to 2040, new innovations improve biodiversity in economically important ecosystems. Business and political elites gain control over land, which in some cases benefits ecosystems and biodiversity at the expense of a large population. As public trust grows, industrial greenwashing expands, and businesses exploit nature for profit. Tipping points are crossed affecting countries outside of Europe initially, as green innovation enables adaptation within Europe. From 2040 to 2070, technological development becomes the backbone of the economically strong EU but increases demands for resources outside of Europe, exploiting ecosystems on a global scale. Inequalities rise due to skill-based technological development, unequal education and political power. Access to quality resources (e.g., food, healthcare, water) is unequal. Sub-cultures and counter-movements begin to move to rural areas to adopt land-based sustainable practices, while slums in cities put pressure on nature. Overseas territories begin to adopt localized policies for biodiversity protection. From 2070 to 2100, the EU has become a market leader in green technologies, but the need for strategic autonomy and international pressure leads the EU to endogenize mining and production, reducing pressure on ecosystems abroad but degrading local ecosystems. The small, connected elite benefits and becomes increasingly disconnected from other classes. Social cohesion is low and stratified, so people begin to turn back to the land to adopt sustainable lifestyles.

3.1.4. Enriched Eur-SSP5

The push for economic, technological and social development is coupled with the exploitation of cheap and readily available fossil fuel resources. Significant investments are made in health, education and social support with people embracing high consumption lifestyles. From the present to 2040, market deregulation leads to a strong labour market and prosperity-driven technology development. Technological and scientific innovation enables the creation of new food systems, and higher purchasing power reduces meat consumption. However, increased imports and fossil-fuel-based transport systems impact biodiversity and deep-sea fossil fuel extraction is allowed in Marine Protected Areas. The resulting ecological degradation motivates governments to close or limit access to valuable ecosystems. From 2040 to 2070, public trust in political decision-making increases. There is a strong faith in technological solutions to environmental problems, including geo-engineering, but the environment continues to degrade as people remain unaware. Despite the lower meat consumption, overconsumption and agricultural efficiency reduce dietary diversity and everyone adopts a very energy-intensive lifestyle. People in cities become used to living in an artificial and 'closed' society divorced from nature. Near 2070, biodiversity tipping points are reached, ecosystems collapse and food insecurity grows. From 2070 to 2100, the EU continues its focus on technological solutions fuelled by the exploitation of fossil fuels. New carbon markets and available investments in biodiversity protection are accompanied by a growing risk of corruption. The environment degrades seriously, and human innovation cannot keep pace in masking its impact. Human health suffers with increasing diseases and the health system breaks down. There is a slow re-emergence of renewables as fossil fuel prices rise.

3.1.5. State of the biodiversity nexus in enriched Eur-SSP narratives

Table 2 describes the state of biodiversity and the other elements of the biodiversity nexus in the four enriched Eur-SSPs, which are the key additions to the original Eur-SSP narratives. The findings highlight how the state of biodiversity varies across Eur-SSPs, with enriched Eur-SSP1 having the most positive and Eur-SSP5 having the most negative impacts. How these impacts change over time are included in a more comprehensive table in Table S2.

Table 2
Description of the state of the elements of the biodiversity nexus in each of four enriched Eur-SSPs.

Element	SSP1	SSP3	SSP4	SSP5
Biodiversity	+ Biodiversity improves due to nature restoration, mainstreaming into policy, and enhancing human-nature relations	+ / − Biodiversity has mixed impacts from geopolitical fragmentation, initially increasing natural resource use but later reducing pressure in late century due to governance failure	+ / − Biodiversity has mixed impacts from technology development, until inequality worsens biodiversity and counter movements return to nature	− Biodiversity declines and collapses due to uncontrolled economic development and resource extraction and use
Water	Water resources in good condition due to more sustainable practices	Water resources degraded and a source of conflict, with unequal access	Water resources improve from technology, but inequality puts pressure on infrastructure and availability of resources	Water resources improve from technology, but uncontrolled development eventually degrades water resources
Food	More sustainable and integrative food production	Food insecurity from governance fragmentation, leading to intensification and eventually more extensive land use from deindustrialisation	High-tech food system caters to economic and political elite, resulting in food crisis for poorer majority	High-tech food system eventually degrades the environment, ultimately causing Europe to rely on food imports
Health	Healthcare and wellbeing improve due to government investment and more sustainable ways of living	Healthcare and wellbeing declining and unequal, with healthcare only for richer countries and regions	Healthcare privatised and technology driven, with wellbeing declining and healthcare only for societal elite	Healthcare and wellbeing decline as focus on economic development and treatment rather than prevention neglects other aspects of wellbeing
Energy	Sustainable, renewable and cooperative energy systems across Europe	Governance fragmentation and economic development affect energy demand and access and perpetuates reliance on fossil fuels	Technology innovation, renewable transition, and elite control of energy supply	Continued fossil fuel exploitation eventually resulting in peak fossil fuel and beginnings of switch to renewables at the end of the century
Transport	Transition toward sustainable transport systems across Europe	Decreased innovation and priority in transport sector due to fragmentation and militarisation	High-tech clean and active transport systems implemented in Europe	Increased demand for fossil-fuelled transport to enable economic growth

Table 3
Summary of the count of the number of statements describing interlinkages from (Fr) or to (To) the node (nexus element or indirect driver) in each row for the original versus enriched Eur-SSPs. The sum (+) is the total count of from and to for that original or enriched Eur-SSP. The change (Δ) is the sum (+) of the enriched minus the sum (+) of the original, to show how the relative importance of that node increased when the Eur-SSPs were enriched with considerations of the biodiversity nexus. The cell colours show a linear gradient from least significant (i.e., lowest count) in the narrative (red) to most significant (i.e., highest count) in the narrative (green).

	Eur-SSP1							Eur-SSP3							Eur-SSP4							Eur-SSP5						
	Original			Enriched				Original			Enriched				Original			Enriched				Original			Enriched			
	Fr	To	+	Fr	To	+	Δ	Fr	To	+	Fr	To	+	Δ	Fr	To	+	Fr	To	+	Δ	Fr	To	+	Fr	To	+	Δ
Biodiversity	1	0	1	9	16	25	24	0	2	2	3	13	16	14	0	2	2	5	24	29	27	0	6	6	8	23	31	25
Health	0	2	2	2	11	13	11	1	5	6	1	9	10	4	0	1	1	2	7	9	8	2	1	3	3	8	11	8
Water	0	0	0	0	3	3	3	0	1	1	3	3	6	5	0	0	0	2	3	5	5	0	0	0	2	1	3	3
Food	0	0	0	3	3	6	6	1	0	1	7	10	17	16	0	0	0	8	5	13	13	0	0	0	6	10	16	16
Energy	0	2	2	5	5	10	8	0	8	8	5	11	16	8	2	1	3	6	2	8	5	3	6	9	6	10	16	7
Transport	0	0	0	4	2	6	6	5	1	6	5	2	7	1	0	0	0	1	3	4	4	0	2	2	4	4	8	6
Geopolitical stability	3	1	4	3	1	4	0	2	0	2	6	2	8	6	1	1	2	1	3	4	2	0	1	1	0	2	2	1
International cooperation	2	1	3	3	2	5	2	2	0	2	3	0	3	1	0	0	0	0	0	0	0	1	1	2	1	2	3	1
Globalisation	0	1	1	1	2	3	2	1	0	1	2	1	3	2	1	0	1	1	0	1	0	4	0	4	4	0	4	0
Net migration	0	0	0	0	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0
Mobility	0	0	0	0	0	0	0	0	1	1	2	3	5	4	0	1	1	2	2	4	3	0	1	1	2	1	3	2
Economic development	4	3	7	5	3	8	1	7	0	7	12	3	15	8	1	3	4	6	4	10	6	14	5	19	23	9	32	13
Technology development	2	0	2	6	2	8	6	0	2	2	1	2	3	1	5	4	9	20	6	26	17	3	0	3	12	3	15	12
Decision-making level	3	0	3	6	0	6	3	0	0	0	3	0	3	3	8	1	9	10	1	11	2	2	0	2	2	0	2	0
Quality of governance	8	0	8	24	2	26	18	5	2	7	8	3	11	4	3	0	3	3	0	3	0	3	3	6	10	3	13	7
Choice	0	1	1	0	4	4	3	1	1	2	4	1	5	3	1	3	4	5	4	9	5	1	0	1	4	2	6	5
Social cohesion	1	1	2	4	3	7	5	2	1	3	3	2	5	2	2	1	3	9	6	15	12	0	2	2	0	4	4	2
Social respect	0	9	9	2	12	14	5	3	4	7	3	6	9	2	1	6	7	4	11	15	8	1	5	6	2	5	7	1
Environmental respect	2	5	7	8	12	20	13	0	0	0	4	3	7	7	0	0	0	2	6	8	8	0	1	1	1	4	5	4
Education investments	1	1	2	1	2	3	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	2	1	3	4	1	5	2

3.2. Comparison of the original and enriched Eur-SSPs

This section examines differences between the original and enriched Eur-SSP narratives by analysing shifts in the relative significance of indirect drivers and their interlinkages to the elements of the biodiversity nexus. Table 3 presents a high-level summary of the relative prevalence of nexus elements and indirect drivers in the original and enriched Eur-SSP narratives. Overall, the comparison between the original and enriched Eur-SSPs reveals how consideration of implications for biodiversity and nature, and subsequently of the biodiversity nexus, enriched the complexity of interlinkages within the narratives significantly. Biodiversity itself showed the greatest change in prevalence across the enriched Eur-SSPs, compared to the original narrative. SSP3 exhibited the fewest new interlinkages (n = 14), while all other SSPs added between 24 and 27, indicating substantial expansion.

Across all enriched SSPs, biodiversity emerged as both a foundation for other nexus elements and a recipient of indirect drivers, though the relative importance of these relationships varied by scenario. In Eur-SSPs 3, 4 and 5, food was the next most significant nexus element after biodiversity, whereas in SSP1, health was the next most significant. Food is shown as particularly important in Eur-SSPs 3, 4 and 5 as concerns related to food supply and the intensive use of agricultural land is central to these scenarios. In Eur-SSP3 food insecurity is a widespread issue, whereas in Eur-SSPs 4 and 5 technological and economic development have strong influences on agriculture and its role in the nexus, with inequality also playing a significant role in SSP4 as the poorer masses experience food crises and return to the countryside to grow their own food. Health is shown to be particularly important in Eur-SSP1 due to the move to a well-being economy where quality of life and connections to nature are central.

Table 3 also highlights how including the biodiversity nexus in the narratives had indirect effects, which appear as marked increases in the significance of different indirect drivers in the original narratives. A comparison between the original and enriched Eur-SSPs details the complex interactions behind these higher-level findings, particularly focusing on interactions between indirect drivers and nexus elements. Eur-SSPs 1 and 4 are visualised in Fig. 4 and Fig. 5 as examples, and Eur-SSPs 3 and 5 can be found in Fig. S1 and S2. A full table summarising the interlinkages, including from node, to node, direction (positive, negative, or mixed/neutral), and the various time periods in which any interlinkage was present is included in Table S3.

A comparison of the size of the nodes in enriched versus original Eur-SSP1 (Fig. 4) shows that environmental respect and quality of governance increased in importance significantly. This change was due to the important role of environmentally friendly lifestyles and strong governance in enabling and reinforcing positive outcomes across the biodiversity nexus, both directly and indirectly through their influence on economic development and education. In contrast, a comparison of the size of the nodes in enriched versus original Eur-SSP4 (Fig. 5) shows that technological development gained influence due to mixed interactions with the biodiversity nexus, as innovation leads to intensive extraction of natural resources that have negative impacts on biodiversity, while green technological developments in food production ease some pressure on land and ecosystems. Environmental and social respect also gained importance

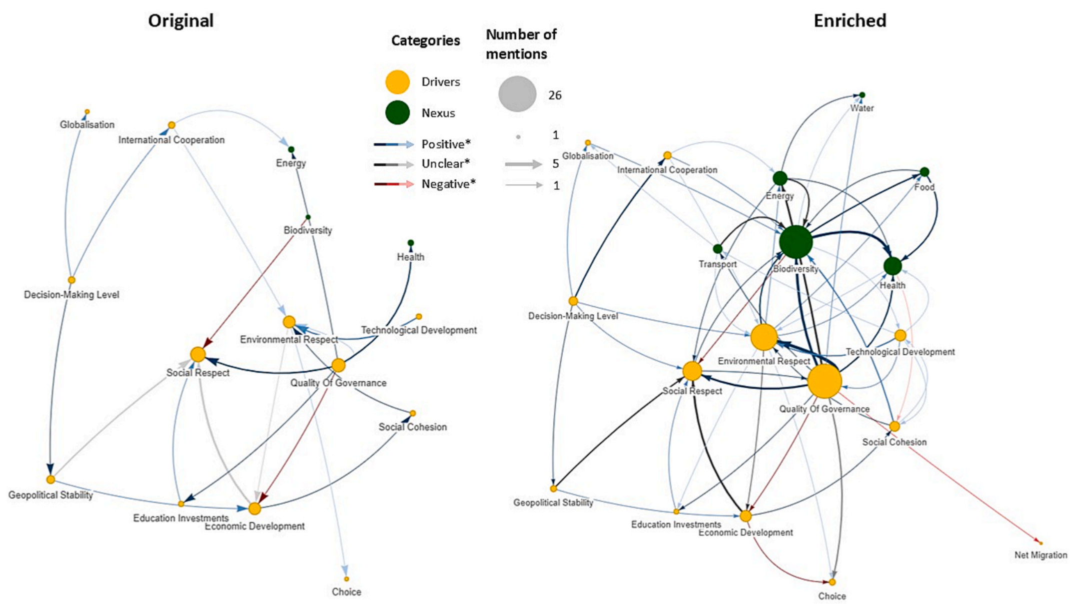

Fig. 4. Original (left) versus enriched (right) system map of the narratives for Eur-SSP1. The nodes include the biodiversity nexus elements in green and indirect drivers in yellow. The size of the nodes corresponds to the number of times the element is mentioned in the interlinkages to and from that node. The position of the nodes was selected for clarity and ease of comprehension. The thickness of the edge corresponds to the number of mentions underlying that interlinkage. The colour of the edge corresponds to the sign of the node-to-node relationship, where the change in the originating node causes an increase (positive, blue), decrease (negative, red), or mixed/neutral (grey) change in the receiving node. Edges between nodes are shaded according to the time span in which they are introduced, from darkest to lightest moving further in time (present to 2040; 2040 to 2070; 2070 to 2100). 'Number of mentions' refers to the number of times the node was mentioned in the scenario narrative. *. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

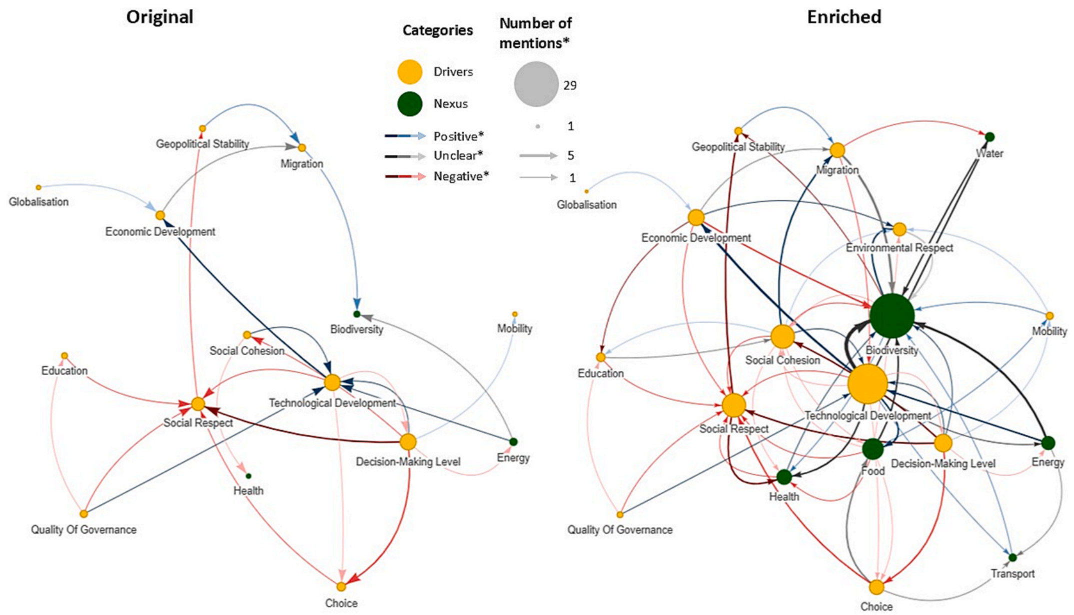

Fig. 5. Original (left) versus enriched (right) narratives for Eur-SSP4. See Fig. 4 caption for a detailed explanation of the figure.

in both SSPs, as improved ecosystems allow people to enjoy nature for recreation in Europe while high-tech solutions in some sectors (e.g., food) disconnect people from nature, drive inequality and perpetuate biodiversity loss.

In the enriched Eur-SSP3 (Fig. S1), economic development becomes more influential through its role in increasing demand for natural resources within the biodiversity nexus, eventually leading to economic crisis that creates stress within various aspects of the system. Geopolitical stability also gains influence as escalating regional rivalry causes wealthy countries within Europe to reduce their living standards and invest in the military, limiting Europe's overseas environmental footprint and reducing mobility between countries. In enriched Eur-SSP5 (Fig. S2), economic development increases in significance, as fossil-fuelled development is enabled by technological enhancements that increase the efficiency and pace of natural resource extraction.

3.3. Detailed interlinkages between the biodiversity nexus and indirect drivers in the enriched Eur-SSPs

Enriching the Eur-SSPs with considerations of biodiversity using a nexus approach increased the relative significance of indirect drivers in the narratives (Section 3.2). These results examine how interlinkages within the biodiversity nexus and interactions between biodiversity nexus elements and indirect drivers in the wider socio-economic system manifest within the different scenarios. These dynamics are visualised and discussed for enriched Eur-SSPs 3 and 5 as examples, with annotated figures available for all Eur-SSPs (showing labelled interlinkages) in Figs. S3, S4, S5 and S6.

The sub-system maps for enriched Eur-SSP3 in Fig. 6 show how nexus elements influence one another and indirect drivers directly. Regarding interlinkages between nexus elements, biodiversity, food and energy are most strongly interconnected. A decline in pollinators reduces food production while increasing energy prices affect food prices. Agricultural expansion leads to biodiversity loss and increased demand for energy leads to environmental degradation, both of which motivate a turn later in the scenario toward localized food production and in turn reduce energy demand in ways that positively impact biodiversity. Direct influences of the biodiversity nexus on indirect drivers are numerous and diverse. For example, depleted biodiversity causes societal and economic shocks while unequal distribution of energy resources leads to a decline in social respect. Privatization of healthcare and water scarcity further influence unequal access to services and frequent large-scale desertification drives water wars.

In enriched Eur-SSP3, the feedbacks from indirect drivers back toward the biodiversity nexus (right, Fig. 6) show how quality of governance has the most negative influence on the biodiversity nexus, as the deterioration of governance systems across regions and scales gradually makes it impossible to coordinate the maintenance of transport and healthcare infrastructures and ensure food security. Importantly, the quality of governance contributes to ceasing regulations related to biodiversity and the environment. However, food security is still enabled by other drivers, such as decision-making level and choice. Geopolitical instability has detrimental impacts on multiple aspects of the biodiversity nexus, for example as increasing incidence of political and social conflicts requires resources to be shifted from investments in transport and health to military spending. Still, the collapse of value chains forces societies across Europe to use less clean energy and cope with worsening healthcare. Energy is influenced by multiple indirect drivers, with poor countries lowering energy demand by learning to live with less and international cooperation attempting to mitigate the lack of energy resources by establishing alliances for energy supply. At the same time, Europe's instability decreases its involvement in global value chains and thus decreases its pressure on ecosystem outside Europe.

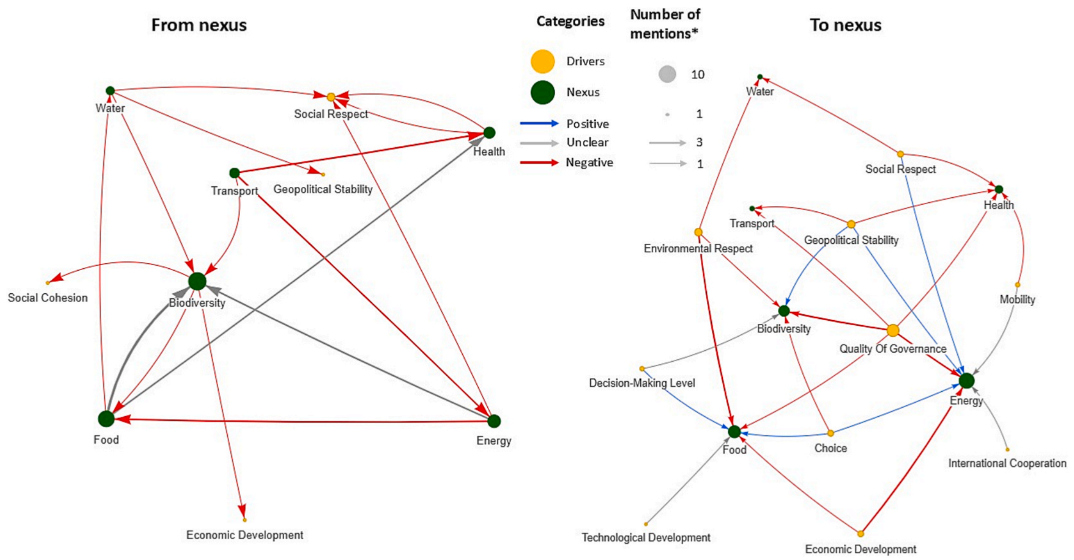

Fig. 6. Sub-system maps of enriched Eur-SSP3 highlighting (a) interlinkages within the biodiversity nexus and first-degree interlinkages from it to indirect drivers (left); and (b) first-degree interlinkages from indirect drivers directly on the biodiversity nexus (right). The nodes include the biodiversity nexus elements in green and indirect drivers in yellow. The size of the nodes corresponds to the number of times the element is mentioned in the interlinkages to and from that node. The position of the nodes was selected for clarity and ease of comprehension. The thickness of the edge corresponds to the number of mentions underlying that interlinkage. The colour of the edge corresponds to the sign of the node-to-node relationship, where the change in the originating node causes an increase (positive, blue), decrease (negative, red), or mixed/neutral (grey) change in the receiving node. If different instances of the interlinkage had different signs in the scenario narrative (i.e., positive and negative), the summarised interlinkage in the figure was designated at mixed/neutral. *'Number of mentions' refers to the number of times the node was mentioned in the scenario narrative. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The sub-system maps for enriched Eur-SSP5 in Fig. 7 show how biodiversity nexus elements influence one another and indirect drivers directly. Biodiversity is strongly but negatively connected with health, energy and food within the nexus. This is due to the role of environmental degradation, biodiversity loss, and limited access to nature negatively affecting wellbeing and public health, and the role of fossil fuel exploitation, which is exacerbated by energy policy and strategies, in damaging natural resources and marine biodiversity. Environmental degradation also has negative impacts on food production to the point of causing food insecurity. Health

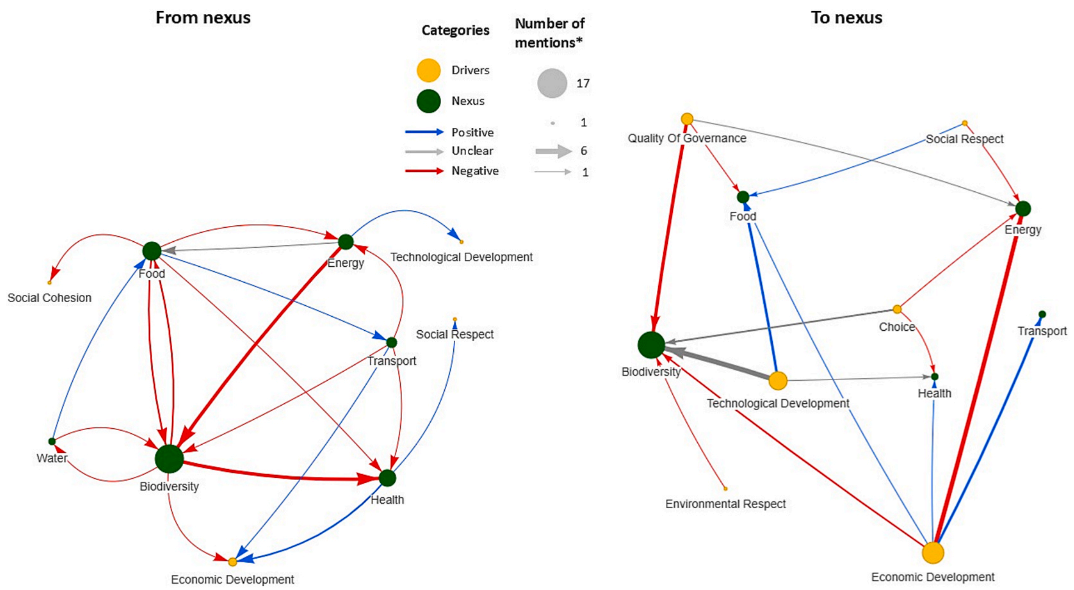

Fig. 7. Sub-system maps of enriched Eur-SSP5 highlighting (a) interlinkages within the biodiversity nexus and first-degree interlinkages from it to indirect drivers (left); and (b) first-degree interlinkages from indirect drivers directly on the biodiversity nexus (right). See Fig. 6 caption for a detailed explanation of the figure.

has a positive influence on indirect drivers, as the rebound from the economic and health crises in Europe allows long-term investments in health that lead to economic and social sustainability. Economic development is strongly influenced by the nexus elements. For example, increased demand for transport and investments in health boost economic development, but people relying on the fish sector transition to other livelihoods due to the negative consequences on marine biodiversity caused by fossil fuel extraction.

The indirect drivers also influence the biodiversity nexus (right, Fig. 7). Economic development based on fossil fuel exploitation and natural resource use negatively impacts biodiversity but has a range of mixed outcomes for other sectors. For example, near-term economic prosperity allows for increases in health investments, accompanied by a rise in transportation demand. Technological development has mixed impacts on biodiversity as technological solutions initially reduce dependency on ecosystem services, yet over time technology developments motivates increasing resource use that severely degrades the environment. Quality of government also feeds back onto biodiversity and the nexus including energy and food, as governments limit environmental protection to prioritise economic interests, contributing to a reliance on energy and food imports.

4. Discussion

These findings suggest important implications for biodiversity governance and scenario development in the IPCC and IPBES research communities.

4.1. Implications for biodiversity governance

Enriching the Eur-SSPs with considerations of biodiversity and nature offers important insight into the underlying socio-economic dynamics that drive changes to the state of biodiversity. The analysis of the enriched Eur-SSPs shows that all indirect drivers interact with biodiversity directly or indirectly through other elements of the biodiversity nexus, with widely varying outcomes for the state of biodiversity and other nexus elements (Table 2). Which indirect drivers are most important for the overall system dynamics depends on the scenario storyline (Table 3). For example, quality of governance is a highly influential driver in Eur-SSP1 as society transitions toward sustainability, whereas geopolitical stability is highly influential in Eur-SSP3 which is characterised by fragmented governance and conflict. Together, these findings suggest that the state of biodiversity (i.e., positive, neutral, or negative over time) across Eur-SSPs is highly influenced by the evolution of deeply uncertain indirect drivers (Pereira et al., 2024) whose relative priority will change depending on the future trajectory in different regions across Europe (IPBES, 2024).

The findings suggest interactions between indirect drivers that hold more leverage for halting and reversing biodiversity loss. For example, under multiple Eur-SSPs, interactions between economic development and technological development perpetuate unsustainable extraction or use of natural resources, even when oriented toward sustainability (e.g., green business and its externalities outside of Europe in Eur-SSP4). A similar finding occurred when downscaling the global SSPs to the United Kingdom (Harmáčková et al., 2022). This finding reinforces the importance of policy interventions that break the feedback loop between natural resource use and development: for example, by accounting for social needs and environmental limits and externalities within and beyond Europe (Chava, 2014; Raworth, 2017; Sala et al., 2020). In contrast, quality of governance and to a lesser extent environmental respect and social cohesion play a cornerstone role in the transition toward more nature-positive and sustainable futures in enriched Eur-SSP1. However, if these governance and societal drivers orient away from biodiversity, as they do in other scenarios, these drivers also play a significant role in perpetuating biodiversity loss (e.g., fragmented governance deprioritising environmental policies in Eur-SSP3). This finding reinforces the importance of a systemic policy approach that situates interventions to support biodiversity within an enabling and even transformative governance context (Huang et al., 2018; Smith et al., 2003; Visseren-Hamakers et al., 2021). Further, it aligns with recent findings in IPBES (2024), which highlights how future scenarios with positive outcomes for biodiversity and other sectors are characterized by sustainable lifestyles, more equitable distribution of benefits, and pro-sustainability policies and regulations, in addition to shifts to a range of indirect drivers related to governance and power relations. Importantly, our findings also highlight how each Eur-SSP is not wholly 'good' or 'bad' for biodiversity: even the scenarios that result in negative biodiversity outcomes overall include the crossing of ecological tipping points later in the century, after which society recognises and begins orienting toward sustainability (see also Harmáčková et al., 2022). Such findings reveal the importance of embedding nature-positive actions across policy portfolios in anticipation of these windows of opportunity, even amid more challenging socio-economic conditions (Bennett et al., 2016; Westley et al., 2011).

The findings also reinforce the need for a nexus approach in biodiversity governance, which embeds biodiversity objectives and goals across sectors and nexus elements (IPBES, 2024). Across the enriched Eur-SSPs, positive or negative outcomes for biodiversity are not always felt directly from indirect drivers themselves (e.g., quality of governance or economic development), but rather through their influence on other nexus elements (e.g., food, energy, health, water, transport) and their interactions with biodiversity (IPBES, 2024; Kim et al., 2024). For example, in Eur-SSP1, improved governance and environmental respect enable mainstreaming of agro-ecological practices that can benefit biodiversity (e.g., Chappell and LaValle, 2011). In turn, biodiversity positively impacts health through access to green space and indirectly through its contribution to organic and nutritious food (e.g., Crinnion, 2010). In contrast, in Eur-SSP3, a decrease in environmental respect and related increased use of pesticides in high-yield unsustainable agricultural intensification leads to biodiversity loss in land and water systems, negatively impacting human health. Similarly, in Eur-SSP5, fossil fuel-based energy and transport sectors cause cascading effects in various sectors including health and food, which have both direct and indirect impacts on biodiversity. In such cases, biodiversity 'bites back', for example through its influence on food prices or food quality, or as ecological tipping points are crossed that affect human health directly (e.g., Hough, 2014). Importantly, the implications of unsustainable practices and overconsumption of resources across sectors, and the resulting state of biodiversity, is intimately tied to societal outcomes, as under multiple scenarios a lack of access to resources is linked to deep and widening inequalities and conflict (Carmignani, 2013; Mildner et al., 2011). Thus, a nexus approach that considers these cross-sectoral interactions and feedbacks is needed if governance is to address the risks of social injustice accompanied by environmental collapse (IPBES, 2024), as overlooking them may underestimate the scope and scale of plausible socio-economic and environmental change.

4.2. Implications for IPBES and the IPCC

The findings have important implications for the biodiversity and climate change research communities developing and applying the scenario frameworks, including IPBES and the IPCC. The SSPs were originally developed as exploratory socio-economic scenarios for climate change research and have now been downscaled to regional and local contexts and operationalised for scenario analyses in sectors beyond climate change. These processes include quantitative, data-driven approaches drawing from databases and literature (Absar and Preston, 2015; Rohat et al., 2018) and co-creation processes drawing from stakeholder knowledge (Chen et al., 2020; Frame et al., 2018; Harmáčková et al., 2022; Zandersen et al., 2019). This uptake and extension of the SSPs is a testament to the appetite for scenario frameworks that address socio-economic uncertainty. Yet, the original SSPs were not necessarily designed with all of these applications in mind, affirming the need to be transparent about their strengths and limitations for applications in different sectors and scales (O'Neill et al., 2020).

This paper speaks directly to the discussion on gaps and future applications of the original Eur-SSPs. Kok et al. (2019) state the need for "further extension" of the Eur-SSPs to address a wider set of drivers, factors, sectors and actors, highlighting that the SSPs have been developed for different purposes than they may be applied and thus may result in mismatching drivers, sectors, and content. We affirm that these challenges exist and offer a methodology for enriching existing narratives in ways that begin to address these gaps for applications of the Eur-SSPs in biodiversity and climate research. For example, we have shown that introducing consideration of biodiversity and nature to the original Eur-SSPs had significant implications on the overall system dynamics. This manifested differently across each of the Eur-SSPs, including by magnifying the importance of particular indirect drivers and introducing feedbacks from biodiversity back onto direct and indirect drivers of biodiversity loss. Additionally, we have shown that considering nexus interactions in scenario development (i.e., across biodiversity, food, energy, transport, water and health) reveals a much richer picture of the cause-and-effect mechanisms within the scenario and the relative importance of certain indirect drivers and nexus elements within the interactions that lead to or mitigate environmental challenges. Kok et al. (2019) also point to methodological choices that simplified the original Eur-SSP narratives (i.e., to develop 'equivalent scenarios' that directly translate outcomes from global to European scale), and thus resulted in narratives that may have excluded European-specific uncertainties. We confirm the existence of this challenge, as the incorporation of biodiversity and the biodiversity nexus introduced European-specific considerations that were masked in the original scenarios (e.g., green, technology-led development in Eur-SSP4 creating environmental externalities in other countries).

We have also gone beyond the gaps stated by Kok et al. (2019) to show that the original Eur-SSPs may underestimate the complexity and scale of change that may only be revealed when the biodiversity nexus is introduced as intertwined with socio-economic futures. For example, the crossing of biodiversity tipping points has significant socio-economic consequences in the latter part of the century in Eur-SSPs 4 and 5. Additionally, we reflect how the SSPs can help explore a wide range of outcomes for biodiversity, though few are truly nature-positive, which affirms the finding of Alexander et al. (2023). More specifically, we show that the original Eur-SSPs can benefit from being enriched by details that could help mediate the relationships between climate- and biodiversity-related interventions. For example, renewable energy initiatives have mixed impacts on biodiversity in multiple Eur-SSPs, drawing attention to the need for mechanisms for decarbonisation (e.g. hydro, solar, wind powered energy, decarbonised transportation) to be carefully weighed against broader consequences such as resource exploitation, metal waste generation and species habitat losses and collision (e.g., Gasparatos et al., 2017; Santangeli et al., 2016). A nexus perspective highlights the need for evidence on response options with multiple benefits across sectors including and beyond biodiversity and climate (IPBES, 2024).

Enriching the Eur-SSPs demonstrates opportunities to better represent complex system dynamics within the IPCC community scenario framework by incorporating interactions and feedbacks between socio-economic change and biodiversity. At the regional or finer scale, these enriched SSPs can be parameterised and modelled to assess quantitative outcomes, for example by pairing them with downscaled climate simulations to generate more nuanced integrated scenarios and analyses at the European scale. They can also be used by the IPBES community to inform regional, national or local biodiversity projections and demonstrate how existing scenario frameworks from other research communities – such as the SSPs – might be enriched to better represent the diverse contributions of biodiversity and nature to societal wellbeing. While the enriched Eur-SSPs are at a regional scale and thus can only feed into regional IAMs, this study points to possible implications for global-scale SSPs. Enriching global-scale SSPs in a similar way may prove challenging due to the context-dependent and heterogenous nature of biodiversity, yet efforts to do so could fundamentally alter understanding of the nature and severity of climate impacts in its complexity. Such an effort may require aggregation of local and regional efforts to characterise interactions of biodiversity and societal conditions globally. In addition, significant innovation in modelling approaches such as global IAMs would be required as they currently rely on simplified assumptions with structural limitations to represent biodiversity and ecological dynamics. Nevertheless, this study provides a strong rationale for future research – for both IPBES and the IPCC assessments – that more thoroughly evaluates and potentially quantifies how scenarios that lack consideration of biodiversity and nature may underestimate the scope, scale and speed of change expected to the end of the century, motivating stronger integration of biodiversity and ecological processes in model development. Advancing this agenda could have far-reaching implications, including more accurate and realistic estimates of material and non-material costs of biodiversity loss and a clearer understanding of how environmental degradation will affect people across the globe.

4.3. Methodological considerations

This study offers numerous methodological reflections. We aimed to demonstrate an iterative, participatory, and complexity-oriented process for enriching the Eur-SSPs with considerations of biodiversity and nature using a nexus approach. This process prioritised co-creation, wherein the researchers structured an accessible process that relied heavily on a carefully selected group of stakeholders and experts to identify key interactions and drivers that addressed the range of sectors in the biodiversity nexus. We embarked on one iteration to fill gaps (i.e., the webinar), which offered the level of detail and rigour required to meet the aims of this study. However, more iterations in the participatory process may have enabled more interactions to be identified and added, which may have allowed for bolder conclusions about exactly which indirect drivers, nexus elements and interactions are most critical for the future. Further, stakeholders' ability to enrich the Eur-SSPs depended on existing knowledge about these nexus interactions, many of which are still uncertain or under researched (Kim et al., 2024; IPBES, 2024). This gap points to open questions about our findings, such as whether the indirect drivers with few interlinkages can be assumed as less important or perhaps represent gaps in knowledge. Further, rigorous evidence is required to better quantify the impacts across interlinkages in the systems analysis.

5. Conclusion

In this paper, we showed how considering interlinkages and feedbacks between indirect drivers and the biodiversity nexus in the Eur-SSPs enriched the complexity of narratives, highlighting the importance of biodiversity in underpinning other nexus elements and in reciprocal relationship with indirect drivers. By looking at sub-system maps of the influences from – and to – the biodiversity nexus, we were able to paint a clearer picture of the feedbacks between the biodiversity nexus and the wider system of indirect drivers. These findings have various implications for biodiversity governance. For example, our findings show the diverse outcomes for biodiversity across socio-economic futures, highlighting the need for an adaptive and context-relevant policy approach that can respond to emerging socio-economic trajectories of change. We also reveal interactions between indirect drivers that may hold more leverage for halting and reversing biodiversity loss amid diverse other priorities (including climate change), reinforcing the need for a systemic policy approach that situates technological interventions to support biodiversity within an enabling societal and governance context and a wider economic system.

For the scenario communities, we reinforce previous calls for extension of the Eur-SSPs to address a wider set of drivers, factors, sectors and actors. We demonstrate a methodology for doing so in ways that explore the nature of the entangled biodiversity and climate crises, thereby offering more 'biodiversity-centric' scenarios to the climate research community – and in turn, climate-relevant scenarios to the biodiversity community. However, this is only a first step. A deeper analysis of the entangled biodiversity-climate crisis may also introduce the implications of various RCPs to detail how climate change impacts on biodiversity interact with these already-complex interactions between biodiversity and socio-economic change. Further, climate projections themselves do not sufficiently account for feedbacks between climate and biodiversity nor interactions between interventions (climate mitigation and adaptation, biodiversity conservation, habitat restoration, and nature-based solutions), highlighting an opportunity for deeper integration between these two domains. Moreover, a nexus perspective highlights the need for further evidence regarding how multiple sustainability targets across temporal and spatial scales could be achieved, as evaluated within scenarios and models. Beyond these areas, interactions and feedbacks between the indirect drivers themselves and their effects on the nexus elements are reflected to some extent in the narratives, but require further exploration. Finally, our analysis focused on the scenario narratives as a whole and further iterations would detail how the systemic interactions evolve over time. We hope this contribution demonstrates and inspires more intentional application of scenario frameworks that reflect the complexity of interacting environmental challenges.

CRediT authorship contribution statement

Anita Lazurko: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **HyeJin Kim:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **George Linney:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation. **Elizabeth Díaz-General:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Simeon Vaňo:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Zuzana V. Harmáčková:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization. **Mark Rounsevell:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization. **Paula A. Harrison:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2025.100741.

Data availability

No additional data beyond the workshop data (Table S1) and the final enriched European SSPs (Text S1) were produced during this study. All data used for this paper has been anonymized and published in accordance with the research ethics protocols for confidentiality and informed participant consent.

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