Towards a better future for biodiversity and people: modelling Nature Futures

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Highlights

- **Nature Futures Framework** is a tool for creating positive futures for nature and people
- **Nature Futures scenarios** explore a mix of policies that help progress towards positive futures
- Reflecting diverse **values** and **worldviews** helps identify context-relevant **interventions**
- Mutually reinforcing **social-ecological feedbacks** can accelerate **transformation pathways**
- **Indicators** representing diverse values of nature build comprehensive **evidence base for policy**

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Towards a better future for biodiversity and people: modelling Nature Futures

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Contributions

HMP coordinated this work as co-chair of the IPBES Expert Group. HJK, HMP, WWLC, SF and GP developed the idea for the manuscript and led discussions and post-workshop synthesis. All authors participated in workshops and contributed to co-developing concepts and approaches presented. HJK led writing and revision with the guidance of HMP. All authors improved the manuscript with comments and corrections. HJK developed figures based on input from all authors and graphical support from Sandy van Tol at PBL. All authors gave final approval for publication.

Towards a better future for biodiversity and people: modelling Nature Futures

Abstract

The Nature Futures Framework (NFF) is a heuristic tool for co-creating positive futures for nature and people. It seeks to open up a diversity of futures through mainly three value perspectives on nature – Nature for Nature, Nature for Society, and Nature as Culture. This paper describes how the NFF can be applied in modelling to support decision-making. First, we describe key considerations for the NFF in developing qualitative and quantitative scenarios: i) multiple value perspectives on nature as a state space where pathways improving nature toward a trade-off frontier can be represented, ii) incorporating mutually reinforcing key feedbacks of social-ecological systems, iii) indicators describing the evolution of complex social-ecological systems. We then present three approaches to modelling Nature Futures scenarios in the review, screening, and design phases of policy processes. This paper seeks to facilitate the integration of relational values of nature in models and strengthen modelled linkages across biodiversity, nature's contributions to people, and quality of life.

Keywords: scenario analysis, biodiversity, conservation, sustainability, values, futures

1. The need for positive scenarios in transformative change

The Global Assessment of Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) found that existing scenarios developed by the broader climate community (e.g., shared socio-economic pathways [SSPs], representative concentration pathways [RCPs]), even in their most sustainable combinations (i.e., SSP1 and RCP2.6), would fail to halt biodiversity loss and continue to deteriorate regulating ecosystem services into the future in many parts of the world (H. M. Pereira *et al.*, 2020). This comes with potentially large socio-economic consequences (Johnson *et al.*, 2020) and inequitable impacts borne by poorer countries (Chaplin-Kramer *et al.*, 2019).

The drivers of biodiversity loss and other environmental degradation are rooted in population growth and inequality (Hamann *et al.*, 2018), unsustainable production and consumption patterns (Hoekstra and Wiedmann, 2014), provision of environmentally harmful subsidies (Dempsey, Martin and Sumaila, 2020), poor governance regimes and limited recognition of the importance of biodiversity conservation (Smith *et al.*, 2003), the strong reliance on fossil fuels (Arneth *et al.*, 2019) and the combined impact of multiple anthropogenic stressors in complex social-ecological systems (Alava *et al.*, 2022), among others. To effectively address these and to increase the willingness to enhance biodiversity conservation policies, we need societal transformations across sectors at all levels concurrently and synergistically (Chan *et al.*, 2020). Furthermore, revitalizing the relationship between people and nature is fundamental in increasing priority for sustainability issues, in particular, but not exclusively, in developed countries (Amel *et al.*, 2017), that have a growing share of responsibility for remote biodiversity and habitat loss from natural resource exploitation (Swartz *et al.*, 2010), international trade (Chaudhary and Kastner, 2016) or degraded ecosystem capacity (Marques *et al.*, 2019). We need changes in norms and beliefs that result in the behavioural change (Kinzig *et al.*, 2013), aided by effective governance (Amano *et al.*, 2018), financial instruments (Waldron *et al.*, 2017), as well as individual champions who inspire collective action (Amel *et al.*, 2017). Most importantly, optimism and empathy can contribute to responsible actions if actors see that they can make a difference (Brown *et al.*, 2019; Knowlton, 2019; Blythe *et al.*, 2021) and when the process engages the imagination of transformative futures (Pereira *et al.*, 2019).

Scenarios that incorporate societal transformation can contribute to reversing negative biodiversity trends and moving towards positive futures (Fischer and Riechers, 2019; Leclère *et al.*, 2020). Drawing on a rich plurality of people's values and preferences on nature is key to an improved decision-making (Pascual *et al.*, 2021; IPBES, 2022b), ensuring equitable sharing of benefits and responsibilities. Since 2017, a new scenarios and modelling framework is being developed under IPBES to reposition biodiversity and nature at the centre of policy and governance at all levels, recognizing their essential role in supporting human well-being and sustainability (Rosa *et al.*, 2017). A series of visioning consultations took place with stakeholders and experts from diverse backgrounds. As a result, the Nature Futures Framework (NFF) emerged to inspire the development of nature and people positive, diverse values-integrated, and multiscale scenarios (L. M. Pereira *et al.*, 2020).

This paper reflects on how the NFF can be applied in modelling Nature Futures scenarios to inform policy, based on results of stakeholder visioning and expert elicitation workshops (see Supplementary Materials for more details). First, we present three key principles of the NFF for developing qualitative and quantitative scenarios and models. We then describe three types of applications for integrating Nature Futures scenarios in policy processes. This paper aims to help enhance the utility of scenarios and modelling in the implementation of multiscale policy frameworks such as the Kunming-Montreal Global Biodiversity Framework (GBF) of the United Nations (UN) Convention on Biological Diversity

(CBD), Paris Agreement of the UN Framework Convention on Climate Change (UNFCCC) and the UN Sustainable Development Goals (SDG) agenda with critical challenges to be overcome (Leadley *et al.*, 2022; Perino *et al.*, 2022).

2. Key considerations for Nature Futures scenarios

This section presents three key considerations that are important in developing qualitative and quantitative scenarios of Nature Futures. These were conceptualized through expert elicitation (PBL, 2019a, 2019b), building on limitations and gaps identified in the IPBES Methodological Assessment on Scenarios and Models (IPBES, 2016) and stakeholder visions on positive futures for nature and people (Lundquist *et al.*, 2017; L. M. Pereira *et al.*, 2020) (see Supplementary Materials, SM hereafter).

2.1 Nature Futures value perspectives and the frontier

Individuals and societies value nature in diverse ways. The NFF attempts to capture these in three main perspectives. The Nature for Nature (NN) perspective appreciates and preserves nature for what it is and does and maps to intrinsic and existence values of biodiversity (e.g., maintaining natural processes and function such as evolution and migration) (Chan *et al.*, 2016). The Nature for Society (NS) perspective focuses on instrumental values as in benefits that nature provides to people (e.g. supporting crop production and climate regulation) (Pascual *et al.*, 2017). Finally, the Nature as Culture (NC) perspective values the relationships that nature and people co-create, not as separate entities but as an indivisible whole (e.g., preserving emblematic species, sacred landscapes, and traditional knowledge) (Himes, 2018). These value perspectives of the Nature Futures Framework are envisaged to broaden and diversify stakeholders' visions for nature and people through exploring, mapping and combining different futures and interventions that can help achieve those visions on gradients such as autonomy of nature, instrumental values and the importance of culture in shaping and being shaped by nature (Figure 1). It is important to note that these three value perspectives are a simplification of a hyperdimensional space representing the multiple and varied perspectives of individuals and communities about nature. One way of thinking about the three perspectives is as a principal component analysis of the hyperdimensional space of nature preferences that captures three main complementary axes.

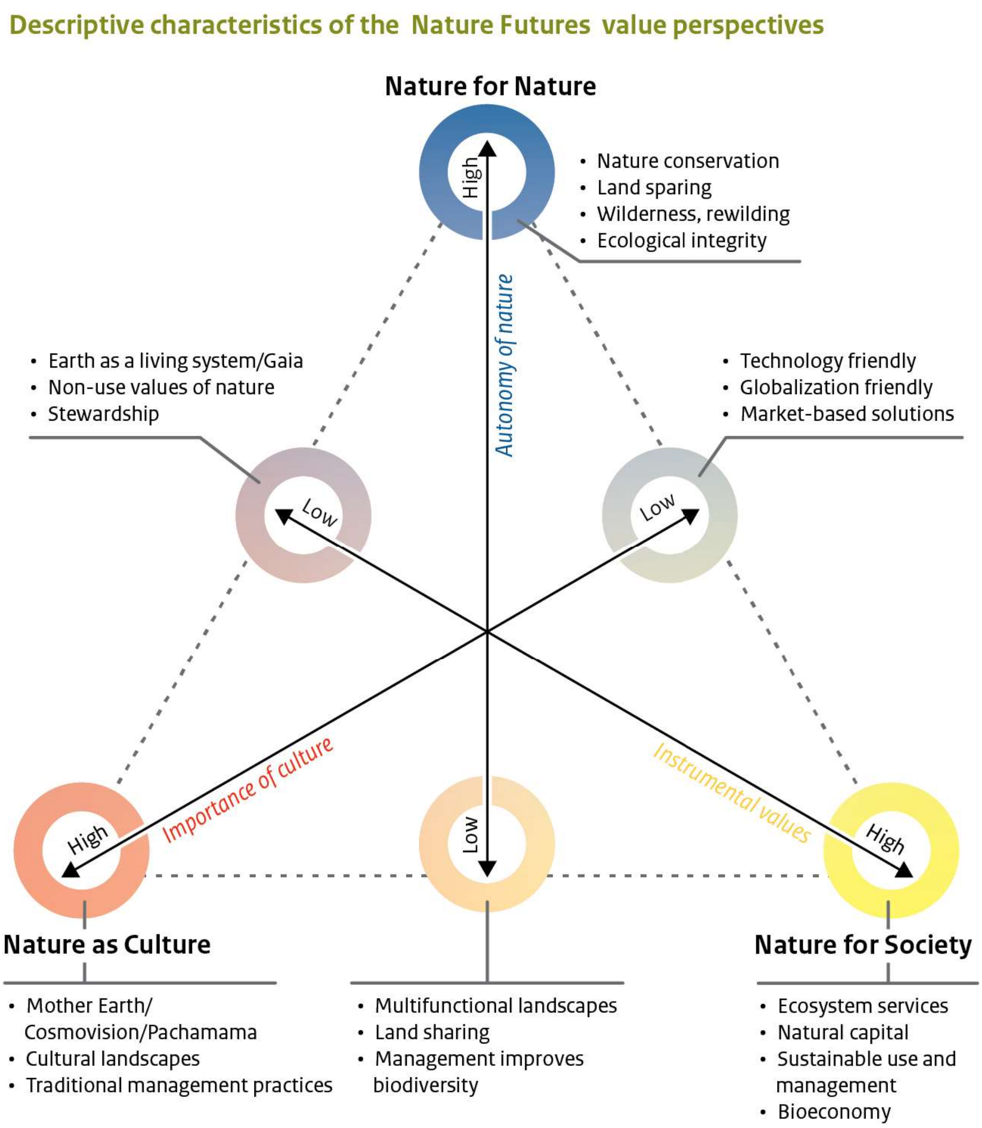

Figure 1. Descriptive characteristics of the Nature Future value perspectives and the space between these perspectives where the values converge. A wide range of interventions can be identified using the Nature Futures Framework, reflecting the local context where the framework is being applied. Most systems and places in the world have a mix of these values and map somewhere inside the triangle of the Nature Futures Framework.

However, the three value perspectives on nature are not mutually exclusive of each other – in fact, they are intricately connected and can reinforce each other (Martín-López, 2021). Keystone species are such an example with their functional role benefiting both nature and people (e.g., top predators play an important function by controlling herbivore populations but incidentally this also reduces damage to crops) (Schmitz *et al.*, 2018; Martin, Chamaillé- Jammes and Waller, 2020). Thus, although we represent the Nature Futures state space of social-ecological systems with three axes as orthogonal for simplicity (Figure 2a), a more precise representation would have these axes as partially overlapping (see SM F Glossary for the definition of 'state space'). This means an increase in the values along one axis can correspond to an increase along another axis. In some parts of the state space, there may be trade-offs between improvements in different axes, corresponding effectively to a frontier in the state space (Figure 2a) (See SM F Glossary for the definition of 'frontier') (Polasky *et al.*, 2008). When the value of a given axis is already very high, further improvements along that axis may only be achievable by decreasing the value along another axis. We do not know the shape of this frontier, but we represent it as a convex surface because the trade-offs in most instances may not be as strong, and for most of the state space, increases are possible across the three value perspectives.

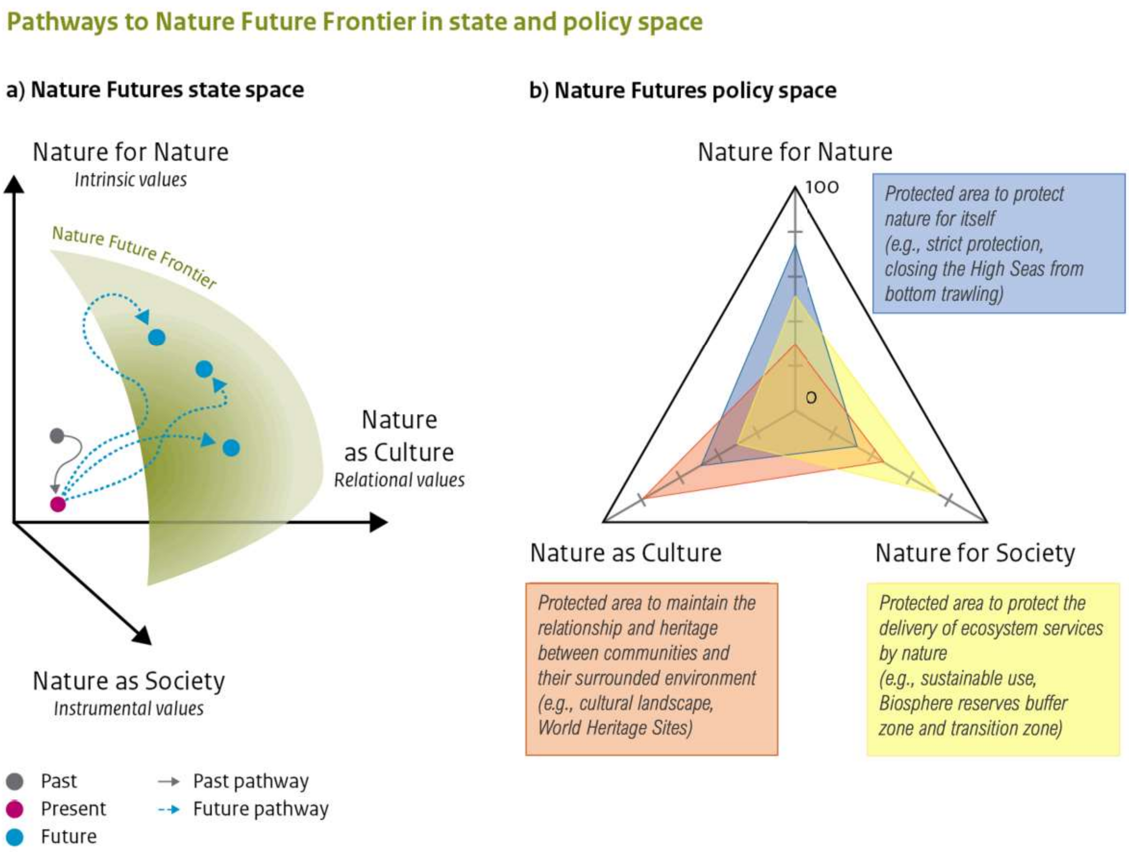

Figure 2. (a) Nature Futures state space with multiple pathways (blue dotted non-linear paths) to the Frontier (green convex with blue dots) where all three value perspectives improve relative to the present. (b) Nature Futures policy space with example policies for the three nature value perspectives and the overlapping presence of these values illustrated by blue, yellow and orange triangles.

The state of systems can be plotted into a multidimensional state space by evaluating the system on each dimension of the value perspectives (Figure 2a). Conceptually speaking, these perspectives can then be seen as projections representing both the historical pathway of a system to date and future pathways towards desirable endpoints (so-called ‘Nature Futures Frontier’) in this state space (Figure 2a). Typically, desirable Nature Futures correspond to points in the state space where there is an improvement in all three value perspectives into the future relative to the present. We can assess particular actions or policies to see how the system moves towards different points of the state space. To do this, we can score the relative contribution of a given action or policy on the axes representing different value perspectives and map them in a policy space of Nature Futures (Figure 2b) (see SM F Glossary for the definition of ‘policy space’).

An important feature of the NFF is that many interventions can be appropriate and are necessary under more than one perspective. In this sense, many individual interventions and even scenarios (i.e., sets of multiple interventions) representing Nature Futures would map somewhere inside the NFF triangle with positive impacts across the three perspectives. As an illustrative example, there are different categories of protection in protected areas – they can strictly protect nature with limited human use (predominantly representing Nature for Nature), allow active management for sustainable use (Nature for Society), or protect cultural landscapes to maintain the relationship and heritage between communities and their surrounding environment (Nature as Culture). These land protection and management regimes have the greatest impacts in one of the perspectives but also have positive impacts in the condition of nature in the other perspectives. For instance, strictly protected areas benefit society in the longer-term future by improving regulating services such as improved air and water quality. Similarly, protecting cultural landscapes and ensuring sustainable use of natural resources contribute to conserving many species that are associated with human management of landscapes and seascapes while improving social cohesion and inter-generational equity that can contribute to quality of life (Figure 2b, Figure 4).

Furthermore, one can envision a world where different places of the world are managed exclusively for one of the value perspectives at the more local scale, but at the regional and certainly, at the global scale, all three value perspectives must coexist given the diversity of values and human-nature relationships across the globe. One can also envision futures where all perspectives co-exist in all locations or where there is some spatial segregation of the perspectives, corresponding either to a cloud of points towards the centre of the frontier or dispersing them across all corners of the frontier in the Nature Futures state space (Figure 2a).

2.2 Social-ecological systems with feedbacks

Feedbacks between people and nature are central to the IPBES conceptual framework (Díaz, 2015). Understanding interactions and feedbacks is key to understanding the types of non-linear dynamics that move the system or place towards or away from nature and people positive futures (Rocha *et al.*, 2020). However, only limited social-ecological feedbacks are captured in existing environmental models (Akçakaya *et al.*, 2016; Elsawah *et al.*, 2020; Pereira *et al.*, 2021).

In Nature Futures scenarios, we want to find interventions that lead to improvements in one or more nature value perspectives or even trigger synergies in interventions across the perspectives in social-ecological systems. For instance, securing land ownership and management by indigenous peoples and local communities can maintain habitats to conserve biodiversity (NN), whilst preserving long-standing traditional knowledge and cultural heritage (NC) and ensuring societal benefits from sustainable livelihoods (NS) (Dinerstein *et al.*, 2020). Thus, identifying interventions with a single or multiple nature value perspectives is particularly important for understanding where multiple values are present (O'Connor *et al.*, 2021; Sala *et al.*, 2021) and can reinforce each other.

Each Nature Future value perspective has different feedback dynamics, but feedbacks between conservation interventions and social-ecological systems are not well studied (Miller, Caplow and Leslie, 2012), let alone well represented in existing models. To date, most modelling approaches have adopted Nature for Nature and Nature for Society perspectives (Robinson *et al.*, 2018), but only partially (e.g., the role of pollination in food provision but not the soil). First, the link between biodiversity and ecological functions and ecosystem service provision is not well modelled, though attempts are being made (Weiskopf *et al.*, 2022). Furthermore, many models represent agricultural land conversion in which crop production interacts with demand for it to drive land-use change (Lambin and Meyfroidt, 2011; Stehfest *et al.*, 2019) and, in some cases, changes in production feedback to impact human wellbeing (Chaplin-Kramer *et al.*, 2019). But we lack models representing how some interventions such as land-use change that optimize values of nature in different combinations (e.g., extending protected areas in indigenous land, increasing multifunctional agroforestry) result in changes in ecosystem services and good quality of life, and this may, in turn, affect societal decisions on the processes of future land-use. The Nature for Nature perspective is represented in ecological models, some of which capture ecological feedback processes such as fire dynamics (McLauchlan *et al.*, 2020), but for instance, multiple roles and benefits of keystone species, such as beavers creating wetlands and landscape heterogeneity by felling trees and blocking water flows, is still missing in estimating their eventual contributions to human wellbeing (Wohl, 2013; Lazar *et al.*, 2015; Stout, Majerova and Neilson, 2017; Willby *et al.*, 2018) (Figure 3).

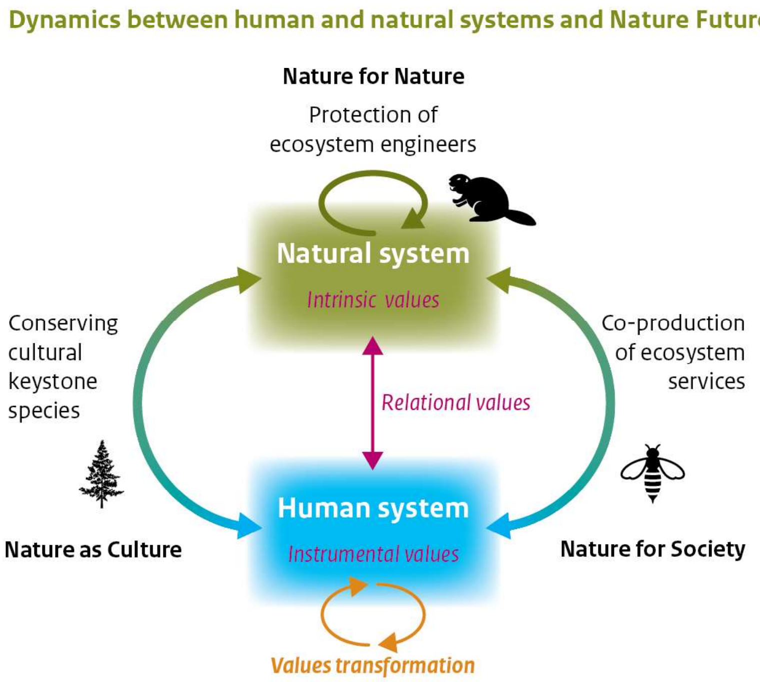

Figure 3. A simple diagram with feedback loops represents the dynamics between human and natural systems within and between the systems that reflect Nature Futures' value perspectives.

Feedbacks that are important for Nature as Culture perspective are the least understood and modelled. For example, cultural keystone species, such as Western Red Cedar in Coastal British Columbia, connect a web of social-ecological feedbacks in which cultural practices are linked to spiritual traditions and a long-term outlook of the community's livelihood and heritage (Garibaldi and Turner, 2004). However, we do not have models that incorporate social-ecological feedbacks around cultural keystone species. There are initiatives that enhance a structured understanding of the social-ecological feedbacks (Lauerburg *et al.*, 2020; Rocha *et al.*, 2020) with participatory scenarios applied at one system's scale (Sitas *et al.*, 2019). In general, however, coupled social-ecological modelling is still in its infancy and requires further development, particularly in representing consequential cross-scale interactions (Leadley *et al.*, 2014; Cheung *et al.*, 2016; Keys *et al.*, 2019; Elsawah *et al.*, 2020)

2.3 Indicators of knowledge and data as multiple evidence bases

Going from the visions and narratives of Nature Futures scenarios to policy support, indicators derived from models, data, and other knowledge systems become an integral part of the evidence bases for decision-making (Tengo *et al.*, 2014). Indicators can describe and measure the state, trends, and magnitudes of relationships between different components of key social-ecological systems, and help identify models, variables and data required to generate evidence (Gutzler *et al.*, 2015; Guerra, 2019). Methods such as mental mapping, decision tree and multi-criteria analyses can be used to select or derive key indicators. To be inclusive of and to explicit diverse value perspectives on nature, indicators are ideally co-determined and co-developed with stakeholders and users of the information (van Oudenhoven *et al.*, 2018; Miola, 2019).

Using the IPBES conceptual framework and the Nature Futures Framework, interventions can be explored and selected on a range of direct (anthropogenic, natural) and indirect (institution, governance, anthropogenic assets) drivers for the assessment of their potential impact on goals set on nature, nature's contributions to people and quality of life. As illustrated in Table 3 and Figure 4, interventions and goals can be cross-cutting, (e.g., supporting community learning facilities that enhance public awareness on conservation and sustainability issues, preventing species extinction and ecosystems degradation for intergenerational equity) or they can have a "home" in one of the value perspectives, as demonstrated in the policy space of Figure 2b (e.g., different types of land and ocean protection and management). For life satisfaction as an illustrative example goal on quality of life, NN can be measured by the enjoyment of experiencing nature and knowing that other species are protected, NS from using quality goods from nature and knowing that they are equitably shared or NC from preserving nature-based cultural heritage and thereby maintaining people's relationship with nature and social cohesion (Table 1).

As illustrated, indicators representing diverse values, roles and benefits of nature can provide richer insights and evidence for assessing and introducing changes in social-ecological systems that can lead to more integrated and comprehensive analyses, optimization, and prioritization of conservation and sustainability strategies for multiscale policy frameworks such as the CBD GBF, Paris Agreement, and UN SDGs (O'Connor *et al.*, 2021; Sala *et al.*, 2021; Soto-Navarro *et al.*, 2021; CBD Secretariat, 2022).

Table 1. Illustrative features of the Nature Future scenarios perspectives with example indicators associated with those features. The components of the IPBES conceptual framework are used to identify the interventions and goals (rows) across the three Nature Futures value perspectives and those that can be cross-cutting (columns). Existing indicators are identified from the CBD Global Biodiversity Framework (CBD Secretariat, 2022), UN SDGs (UNDESA, 2021; UNSTATS, 2022), and Indigenous Navigator (Indigenous Navigator, 2023) and the remaining indicators are aspirational (gaps) without the global coverage in data.

Framework components	**Cross-cutting**	**Nature for Nature**	**Nature for Society**	**Nature as Culture**
Interventions on indirect drivers - Institutions and governance	Promoting national and international systems and cooperation on biodiversity issues *(e.g., CBD Goal D. Funding on conservation and sustainable use of biodiversity and ecosystems by international and domestic public and private sources)*	Giving legal rights to nature and adequate management capacity to protect nature *(e.g., % of countries or municipalities that have assigned rights to nature in their constitutions)*	Developing environmentally friendly infrastructure for human settlement *(e.g., SDG 7.b.1 Installed renewable energy-generating capacity in developing countries (in watts per capita))*	Including indigenous and local knowledge of nature in education curriculum *(e.g., % education facilities that have curriculum on indigenous and local knowledge of nature)*
	Implementing agro-environmental measures not perverse to nature conservation and human wellbeing *(e.g., CBD Target 18. indicator/index measuring the overall impact of agro-environmental measures on nature and people)*	Implementing agro-environmental measures targeting high production on most fertile lands, avoiding biodiverse areas, to spare space for nature *(e.g., % agro-environmental measures allocated to fertile lands and their productivity level)*	Implementing agro-environmental measures targeting maximum co-production of ecosystem services *(e.g., % agro-environmental measures allocated to maximize co-production of ecosystem services)*	Implementing agro-environmental measures targeting environmentally friendly smallholder production in cultural landscapes for local consumption *(e.g., % agro-environmental measures allocated to smallholder production in the cultural landscape for local consumption)*
- Anthropogenic assets	Community learning facilities that enhance public awareness and activities on conservation and sustainability issues (*e.g., Number of public events on conservation and sustainability topics)*	Creating protection, management and education facilities for wildlife watching *(e.g., Number of wildlife-watching facilities by protection level, management type, and educational programs)*	Engaging the private sector to deploy nature-based solutions that benefit both nature and people *(e.g., Amount of investment by private firms in deploying nature-based solutions)*	Establishing community associations for supporting local production and consumption and fair trade *(e.g., INI Art 20. Trends in consumption of diverse locally-produced food)*
Interventions on direct drivers - Anthropogenic and natural	Designating different types of protected areas *(e.g., CBD Target 3. % area covered by protected areas by type – marine, coastal, terrestrial, inland water)*	Strict protection areas and rewilding of abandoned and degraded land to improve biodiversity, e.g., introduction of large herbivores *(e.g.,* strict protection areas,	Sustainable use protected areas and nature-based solutions to mitigate climate impact, e.g., afforestation, urban parks, renewable energy like solar and wind power	Cultural landscape protection and traditional management of natural resources, e.g., other effective area-based conservation measures (OECMs) where wild crop relatives grow

Framework components	**Cross-cutting**	**Nature for Nature**	**Nature for Society**	**Nature as Culture**
		% of total land being rewilded, reforested and restored)	*(e.g., % contribution of NBS to climate change mitigation by type)*	*(e.g., % of the total land with wild crop relatives by management type)*
Goals on nature - Biodiversity and ecosystems	Preventing species from extinction *(e.g., CBD Goal A. Species Habitat Index, number of species prevented from extinction, extent of natural ecosystems)*	Protecting species important for biodiversity, ecological processes and ecosystem functions (*e.g., Protection status of species important for ecosystems)*	Protecting species and ecosystems important for material and regulating services (*e.g., Protection status of species important for providing ecosystem services)*	Protecting species and landscape important for local communities and cultural heritage *(e.g., Protection status of species important for cultural reasons)*
Goals on nature's contributions to people - Ecosystem services	Preventing degradation of ecosystem functions and services *(e.g., CBD Goal B. water regulation)* Equitable sharing of benefits from nature *(e.g., Distribution, stocks and flows of ecosystem services by type across regions)*	Advancing remote and longer-term benefits from conserving nature *(e.g., % change in carbon capture and sequestration from nature by type – forest, oceans, etc.)*	Provision of immediate material and regulating services from nature *(e.g., % population who benefited from pollination-based crop consumption, % population who benefited from water regulation/nitrogen retention)*	Provision of benefits from nature that communities appreciate for their relational connections (*e.g., # of cultural keystone species, % population that preserved intergenerational cultural heritage from nature)*
Goals on quality of life	Life satisfaction from basic needs met (e.g., food, water, security) *(e.g., SDG 2.1.1 Prevalence of undernourishment, SDG 6.1.1 % of population using safely managed drinking water services, % population that were protected from nature-based coastal risk reduction)*	Life satisfaction from the enjoyment of experiencing nature and knowing that other species are being protected *(e.g., % population with life satisfaction from experiencing nature, % population with access to green space within X miles of their residence, % population donating their time or money to environmental causes)*	Life satisfaction from various types of quality goods and services from nature and knowing that they are equitably shared *(e.g., % population with life satisfaction from goods and services from nature, % population that believe nature's benefits should be equally distributed)*	Life satisfaction from preserving nature-based cultural heritage and intergenerational social cohesion *(e.g., INI Art 26(2). Possibility to perform traditional occupations (such as pastoralism, hunting/gathering, shifting cultivation, fishing) without restriction as a proxy)*

*Sources (for existing indicators): CBD: Convention on Biological Diversity, SDG: Sustainable Development Goals, INI: Indigenous Navigator Indicator

*Note that the assignment of specific interventions to specific value perspectives does not mean that they cannot be used under other value perspectives. It only indicates that they are particularly relevant from that value perspective. The indicators in this table are provided only as examples to illustrate a selection of indicators for Nature Future scenarios.

3. Modelling Nature Futures scenarios to inform policy

This section presents three application approaches to modelling Nature Futures scenarios to inform policy processes: policy review, policy screening and policy design or agenda-setting, as laid out in the IPBES methodological assessment on scenarios and models (Table 1) (IPBES, 2016).

Table 2. Modelling application of Nature Futures scenarios in policy processes

	Application 1. Policy review *(ex-post)*	**Application 2. Policy screening** *(ex-ante)*	**Application 3. Policy design or agenda setting** *(ex-ante)*
Objectives	Evaluates the effects of implemented policies retrospectively in time	Assesses particular policy and management options, often for the short term	Identifies broader goals for policy-making over longer time scales
Policy question (examples)	What were the trends of biodiversity and ecosystem services in the past? What happened in places where particular policies were implemented (e.g., different types of protected areas and their impact)?	What will be the consequences for biodiversity, ecosystem services and quality of life of different policy interventions affecting, particularly, direct drivers (e.g., location and types of protected areas)?	What societal transformations need to occur to achieve long-term visions for people and nature? How do changes in nature's contributions to people affect societal decisions (e.g., how do benefits of protected areas inform societal decisions on land/sea spatial planning)?
Policy tool (examples)	CBD National Reports	CBD Local and National Biodiversity Strategy and Action Plans	CBD Post-2020 Global Biodiversity Framework
Modelling approaches (examples)	Emphasizes past observations. Counterfactuals can be examined with techniques such as statistical matching or before-after control impact	Models of impacts of direct drivers on biodiversity and ecosystem services models	Integrated assessment models at large scales, dynamic social-ecological models at smaller scales
Key modelling challenges	Integrating time series monitoring in biodiversity and ecosystem services, impact models of diverse drivers	Connecting biodiversity, ecosystem functions and services, and quality of life, incorporating a broader set of drivers in impact models	Long-term social-ecological feedbacks at large scales, and incorporation of tipping points/regime shift

3.1 Objectives and methods for modelling application

The Nature Futures Framework can be used in exploring a much broader array of interventions, compared to previous environmental scenarios, integrating diverse values, roles and benefits of nature. Thus, it can be used to inform multiscale policy frameworks at local, national and global scales (e.g., CBD National Biodiversity Strategy and Action Plans, CBD National Reports, CBD Post-2020 Global Biodiversity Framework), helping to identify interventions, set targets, and monitor progress towards the goals (Baylis *et al.*, 2016; Strassburg *et al.*, 2020). The NFF can be applied retrospectively to evaluate the performance of implemented policies (policy review) (Kim, HyeJin, 2022), assess potential consequences of a particular policy (policy screening) (O'Connor *et al.*, 2021) or identify broader goals for policy agenda (policy design and agenda-setting) (Sala *et al.*, 2021) (Table 2).

In policy review, evidence synthesis can use methods such as systematic review (Pullin and Stewart, 2006; Bowler *et al.*, 2010) and meta-analyses (Konno and Pullin, 2020) or impact assessment employing econometric and statistical techniques such as matching (Schleicher *et al.*, 2020; Ribas, Pressey and Bini, 2021) and before-after control impact (Smokorowski and Randall, 2017; Ferraro, Sanchirico and Smith, 2019). Counterfactual analysis of the impact of direct drivers on biodiversity and nature's contributions to people can inform where and how biodiversity has been changing due to implemented policies (e.g., protected areas with different priorities on nature, people and culture) compared to those areas where such measures did not take place (Jellesmark *et al.*, 2021; Sze *et al.*, 2021). Furthermore, impact models of direct drivers on biodiversity (Balvanera, Patricia *et al.*, 2019) can fill spatial and temporal gaps in historical data that are then key to assessing impacts on ecosystem services (Fernández *et al.*, 2020).

In policy screening, models can predict the consequences of different policy interventions, particularly direct drivers (e.g., changes in land use or direct exploitation, such as fishing, or location and types of protected areas), reflecting different nature value perspectives on biodiversity, ecosystem services, and quality of life (Fulton *et al.*, 2015; O'Connor *et al.*, 2021; Sala *et al.*, 2021). For these relatively short-term analyses (e.g., one decade), modelling a broader range of direct drivers (e.g., control of invasive species, pollution, resource exploitation) (Kettenring and Adams, 2011; Ning *et al.*, 2021) is more important than incorporating full dynamics of indirect drivers (e.g., demographic change, GDP, institutional effectiveness), which may not be necessary or feasible (Akçakaya *et al.*, 2016; Brotons *et al.*, 2016).

In policy design and agenda-setting, a broader set of social-ecological feedbacks can be modelled to identify multiple societal transformation pathways to achieving long-term visions, ensuring that the impact of interventions on nature on people inform future decisions (e.g., how benefits of protected areas inform societal decisions on spatial planning, land tenure or subsidy schemes) (Sze *et al.*, 2021; Alava *et al.*, 2022; Pacheco and Meyer, 2022). Here, modelling the key feedbacks in social-ecological systems with interventions on indirect drivers is essential in developing scenarios with robust strategies (Akçakaya *et al.*, 2016; Brotons *et al.*, 2016; Keys *et al.*, 2019; PBL, 2019b, 2019a) (Figure 4).

3.2 Scenario analysis in state space and policy space

For scenario analyses to support policy using the NFF, a single policy can be scored and mapped in the Nature Futures policy space to assess how the system did and will evolve along the three perspectives (Figure 2b). Another example is to look at how different management options play out over time, given, for example, the impact of climate change (Palacios-Abrantes *et al.*, 2022; Parmesan, C. *et al.*, 2022) or a change in fishery regulation (Halouani *et al.*, 2016). Although most policies will impact the system across the three value perspectives, some policies may particularly favour one perspective over the others (see Figure 1, Table 1). When it is done well in consultation and discussion with stakeholders, assigning equitable interventions to different nature value perspectives allows us to evaluate the consequences of different preferences and priorities inherent in decision options (Pascoe, Plagányi and Dichmont, 2017).

Furthermore, a combination of policies can be tested through models and indicators and analyze how the key levers/interventions can progress the system along the three axes in the state space and eventually towards the Nature Futures Frontier (Figure 2a) (Palacios-Abrantes *et al.*, 2022; Haga *et al.*, 2023). For example, marine protected areas (representing NN when it excludes people from conservation areas) (Brown *et al.*, 2001; Sala and Giakoumi, 2018), other effective area based management (emphasising NC with traditional management practices) (Schmidt and Peterson, 2009;

Nemogá, Appasamy and Romanow, 2022) and sustainable harvest from fisheries (NS with direct instrumental benefit from sustainable management) (Asche *et al.*, 2018; Hilborn *et al.*, 2021) can be assessed in the policy space (Figure 2b) or together with other sustainability and conservation interventions (e.g., banning plastics and oil drilling, restoration of coral reefs) in an integrated way in the state space (Figure 2a, Figure 4) (see Section 3.1). A modelling framework can be developed (as shown in Figure 4) to assess the state and changes of the key social-ecological system in the Nature Futures scenarios (see Section 3.2). Further, a range of variables and indicators can be selected to quantify Nature Futures scenarios in the state space (as illustrated in Table 1), which can be generated from data or models (see Section 3.3).

This means that to represent the evolution of the system quantitatively in a three-dimensional state space, some projections of indicators with a single score per axis are needed on the three Nature Futures axes (NN, NS, NC) (Figure 2a). There can be indicators commonly used across all Nature Future scenarios (so called 'cross-cutting' or 'common' indicators) and indicators that are specific to each of the three value perspectives (so called 'specific' indicators) (see Table 1 for examples). Then the overall score for each of the three nature value perspectives can be calculated by deriving an index across all indicators associated with each scenario. To generate common or specific indicators, an individual to a suite of models is needed to assess the impacts of drivers and associated interventions on nature, nature's contributions to people and eventually the quality of life, retrospectively or prospectively (Figure 4).

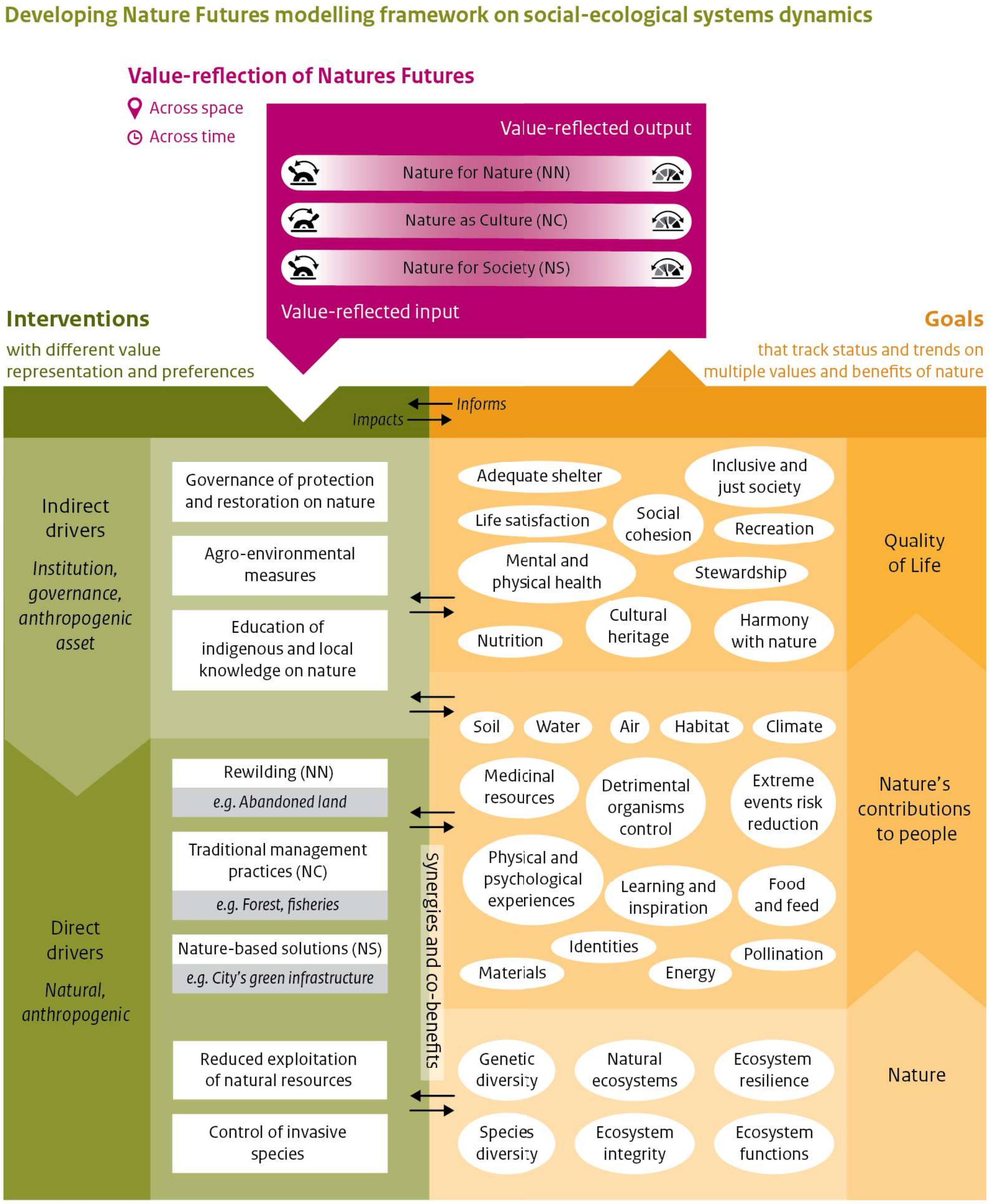

Figure 4. An illustrative modelling framework on the sustainable sea and land use using components of the IPBES conceptual framework with interventions on indirect and direct drivers (left panel) and goals on nature, nature's contributions to people and quality of life (right panel). The Nature Futures scenarios can combine different degrees of nature values through interventions (input) to assess their consequences on nature and people (output). A few illustrative interventions on direct drivers are rewilding abandoned land (primarily for Nature for Nature), traditional forest and fishery management practices (primarily for Nature as Culture) and nature-based solution such as city's green infrastructure (for Nature for Society) as value reflected interventions into modelling, further supported by indirect drivers including governance, implementation subsidy measures and education. The state of nature, nature's contributions to people, and quality of life are ideally measured using multiple indicators that represent diverse roles, values and benefits of nature. The Nature Futures scenarios emphasize identifying synergistic interventions with co-benefits that can reinforce key social-ecological feedbacks onto the pathways to the Nature Futures Frontier.

3.3 Key remaining challenges to modelling Nature Futures scenarios

Most modelling approaches have not incorporated multiple values of nature or only do so in a limited fashion (Brown, Seo and Rounsevell, 2019). This is particularly true for the relational values of nature. As illustrated, integrating diverse value perspectives in modelling the Nature Futures scenarios is essential for a more comprehensive assessment of the impact of societal decisions on nature and people. (Table 1, Figure 4).

Time-series monitoring data in impact models of direct drivers on biodiversity and ecosystem services remains a key challenge (Rosa *et al.*, 2020). Most existing biodiversity models use space for time replacement in the calibration of models (Walters and Scholes, 2017). This is relevant for the retrospective policy evaluation where time-series data are prerequisites for impact evaluation or evidence synthesis (Rodrigues and Cazalis, 2020). Furthermore, historical observation data and empirical evidence are fundamental for developing rigorous models for predicting the future (Urban *et al.*, 2022).

An increasing suite of models, variables and indicators are being made available for the assessment of biodiversity and nature's contributions to people (Tittensor *et al.*, 2017; Kim *et al.*, 2018; Chaplin-Kramer *et al.*, 2020; Willcock *et al.*, 2020). However, a broader range of drivers and interventions, in particular of those with positive impacts on nature and people, needs to be represented in models for screening and identifying policy interventions that are critically called for in Nature Futures scenarios (Leclere *et al.*, 2018; IPBES, 2019; PBL, 2019b; CBD Secretariat, 2022).

New models are in development that incorporates social-ecological feedbacks reflecting the impacts of biodiversity and ecosystem services provision on the economy and vice versa (Banerjee *et al.*, 2020; Johnson *et al.*, 2020). However, scenarios and models need to fully consider cross-scale interactions (e.g., connections between local, regional, and global dynamics and outcomes), social-ecological feedbacks, and tipping points/regime shifts if they are to inform policy effectively (Keys *et al.*, 2019; PBL, 2019a; Rocha *et al.*, 2020).

The Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP) scenario frameworks have been used extensively in biodiversity and climate research (IPCC, 2015; IPBES, 2019). The biodiversity and ecosystem services model intercomparison carried out for the IPBES Global Assessment revealed that all SSP/RCP scenarios except for the most sustainable combination SSP1/RCP2.6 would result in biodiversity loss and ecosystem degradation across the globe, with increasing climate impact in the coming decades (IPBES, 2019; H. M. Pereira *et al.*, 2020). Given that the RCP/SSP scenarios have been developed for the IPCC process and thus have a strong climate change and mitigation focus, their adaptation to the NFF will be challenging.

The NFF may be only relevant as extensions of the SSP1, or the world could start from different SSPs and the NFF is used to identify diverse pathways onto positive future (IPBES, 2021, 2022a). The recent 6th IPCC Assessment Reports highlight some of the new scenario approaches, including the Climate Resilience Development Pathways and Illustrative Mitigation Pathways, which, together with the Nature Futures Framework, can help co-develop new scenarios for climate and biodiversity (IPCC 2022a, IPCC 2022b). Still, a continued joint effort is needed in developing future scenarios with interventions on relevant drivers reflecting diverse values of nature and worldview are tested in conserving biodiversity, mitigating climate impact, and ensuring human well-being, justice and intergenerational equity.

Furthermore, uncertainties need to be explored in Nature Futures scenarios, including the models and their structures, methodologies, assumptions, parameters, data and indicators, and from epistemological and ontological differences across sectors, disciplines and cultures (Regan, Colyvan and Burgman, 2002; Dunford, Harrison and Rounsevell, 2015, p. 201; Rounsevell *et al.*, 2021). Common definitions, modelling protocols, standard data format, and further guidance on the application of the NFF will support more consistent scenarios and modelling practices (Pereira *et al.*, 2013; Wilkinson *et al.*, 2016; Urban *et al.*, 2022). Importantly, uncertainties associated with Nature Futures scenarios and modelling should be communicated clearly and transparently to the end users (IPBES, 2016).

4. Moving towards Nature Futures

To date, scenarios and models in environmental assessments have tended to focus on representing human impacts on ecosystems and lacked positive futures for nature and people (IPBES, 2016; Rosa *et al.*, 2017; Pereira *et al.*, 2021). Scenarios and models can integrate a broad set of the social-ecological systems and key feedbacks that are of relevance and importance to biodiversity conservation, climate mitigation and human wellbeing (L. M. Pereira *et al.*, 2020). To achieve this, the existing models on biodiversity, ecosystem services need to be mapped and coupled with models on human systems and norms to develop comprehensive frameworks that integrate potential key feedbacks across them (Arneth, Brown and Rounsevell, 2014), improving the representation of globally connected social-ecological systems that exhibit cross-scale interactions (Leadley *et al.*, 2014; Keys *et al.*, 2019). Furthermore, relational values of nature need to be reflected better in the models and indicators, notably improved capacity in modelling how environmental changes alter human behaviour, institutions, and culture and vice versa (Elsawah *et al.*, 2020; O'Neill *et al.*, 2020).

Model algorithms developed based on observed data are crucial to projecting changes into the future (Mouquet *et al.*, 2015; Urban *et al.*, 2016), enhancing the rigor and credibility of models. We can use a wide range of observation data and correlations based on observed trends in drivers to forecast responses of biodiversity and ecosystems under different policy interventions (Petchey *et al.*, 2015). High-resolution remote-sensing and other observational evidence ("big data"), jointly with advanced machine learning technologies and cloud-based computing (Pereira *et al.*, 2013; Willcock *et al.*, 2018; Fernandez, In review), can contribute significantly to increasing the predictive power of changes in biodiversity and nature's contributions to people (Willcock *et al.*, 2020; Urban *et al.*, 2022). Making Nature Futures scenarios truly nature and people positive thus presents a critical challenge to broader research communities to shift the conventional impact modelling of negative anthropogenic drivers to positive anthropogenic drivers (e.g., biodiversity and people's positive contributions to nature) on nature and people in a full circle.

As elaborated in this paper, the NFF aims to support transformative change towards sustainable futures by placing human-nature relationships at the centre. It bridges knowledge systems and communities of practices through continuous dialogue, creating a culture of stakeholder-driven scenario development and their co-implementation while maintaining minimum consistency and comparability (Lundquist *et al.*, 2017; Rosa *et al.*, 2017). In the coming years, we expect that the Nature Futures approach will enable scientific and broader stakeholder communities to identify policy and management interventions that reflect diverse ways people can value nature more than we have until now. To achieve this, a participatory approach is being promoted to engage stakeholders in developing narratives, engineering models and building evidence bases for solutions to conservation and sustainability issues (PBL, 2019a, 2019b; L. M. Pereira *et al.*, 2020). This inclusive approach is meant to ensure that the information generated from Nature Future scenarios is relevant and is used by the stakeholders to initiate and amplify necessary societal transformations. Addressing interlinkages, co-benefits and trade-offs between sectors, such as food, biodiversity, water and energy with so-called nexus approaches, will be vital to finding pathways towards achieving multiple societal goals (Liu *et al.*, 2018; Singh *et al.*, 2018). The Nature Futures is also expected to contribute to the ongoing assessments of IPBES on "transformative change" and "nexus", which were initiated at the eighth IPBES Plenary session in June 2021.

The ambition of Nature Futures is to help expand the integration of nature in policy-making across sectors and better link the efforts of scientists and knowledge holders to values and associated decisions for nature and people. In an era where combined global environmental changes are at play, marine, terrestrial, and freshwater biodiversity is imperilled. The spread of COVID-19 has transformed intricately coupled nature and human systems, pressing new norms on all societies, and bringing a sense of extreme urgency to build back better and greener. The Nature Future Framework presented in this paper is expected to stimulate that development through scenarios and models that can inform the realization of multiscale policy frameworks such as the UN CBD Kunming-Montreal Global Biodiversity Framework, UNFCCC Paris Agreement, UN Sustainable Development Agenda, and the latest UN Ocean Treaty, thereby bringing the world onto the pathways towards more ecological, liveable, and just futures.

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Figure1

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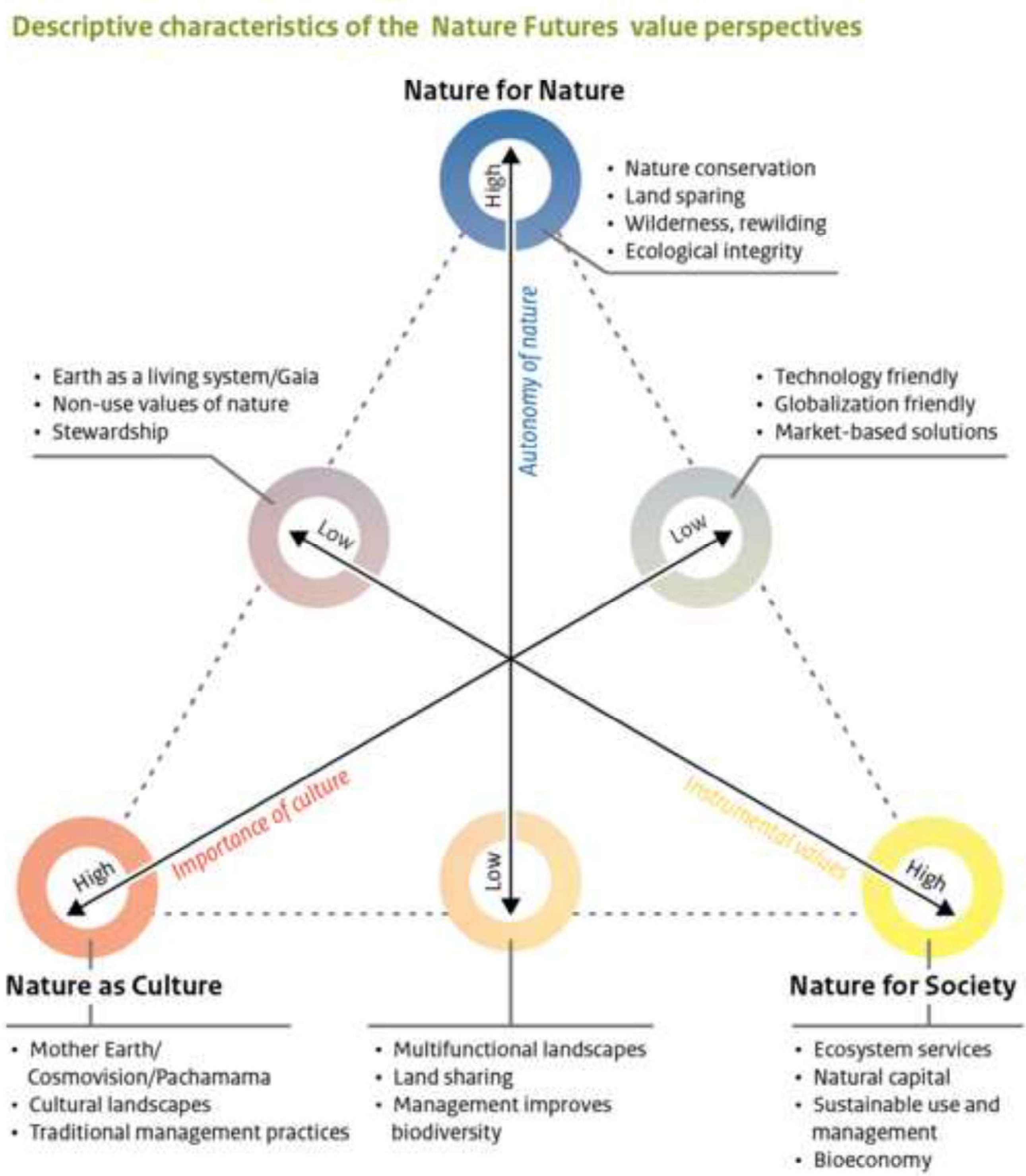
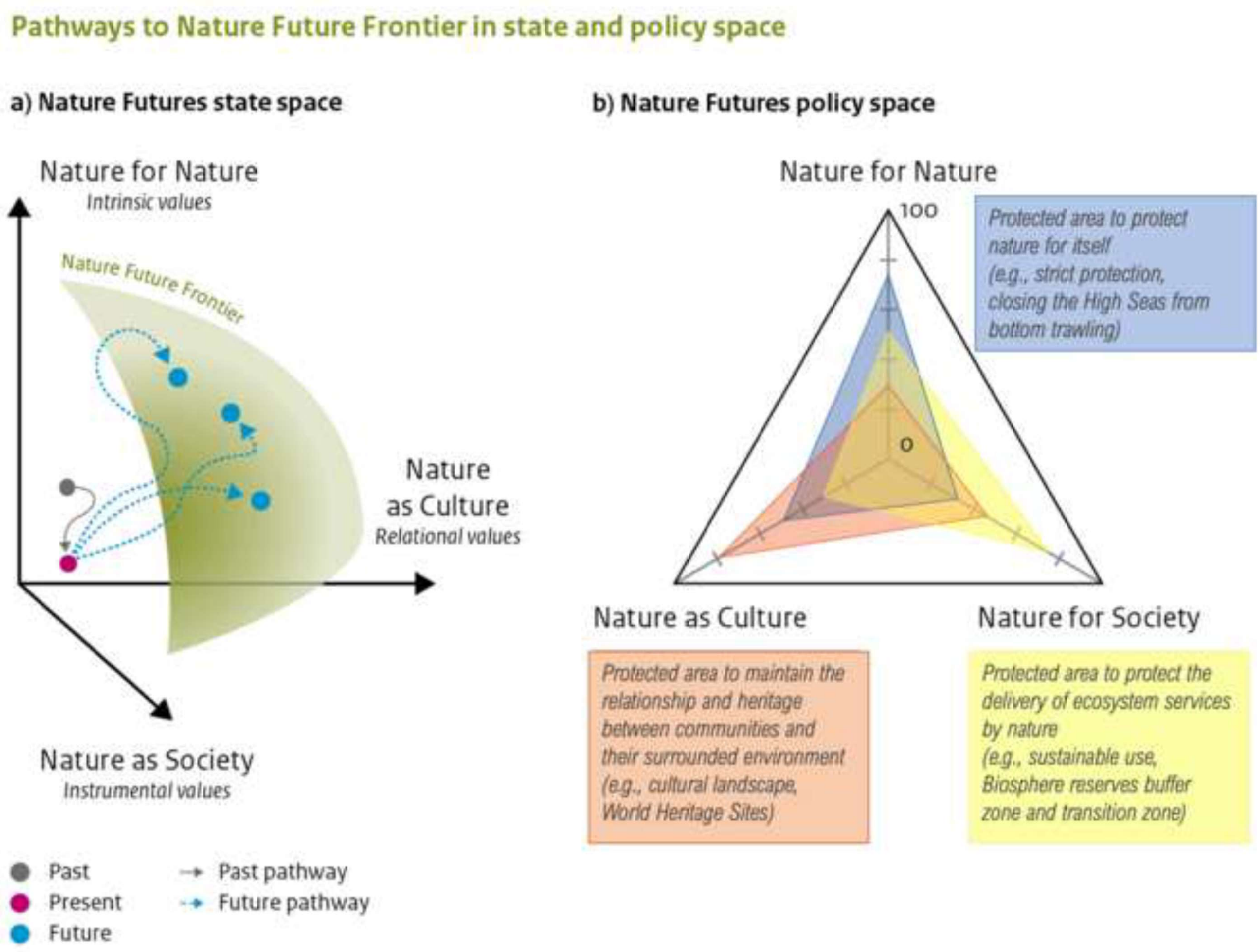


Figure2



Pathways to Nature Future Frontier in state and policy space
a) Nature Futures state space
Nature for Nature
Intrinsic values
Nature Future Frontier
Nature
as Culture
Relational values
Nature as Society
Instrumental values
Past
Present
Future
Past pathway
Future pathway
b) Nature Futures policy space
Nature for Nature
100
0
Protected area to protect nature for itself (e.g., strict protection, closing the High Seas from bottom trawling)
Nature as Culture
Nature for Society
Protected area to maintain the relationship and heritage between communities and their surrounded environment (e.g., cultural landscape, World Heritage Sites)
Protected area to protect the delivery of ecosystem services by nature (e.g., sustainable use, Biosphere reserves buffer zone and transition zone)

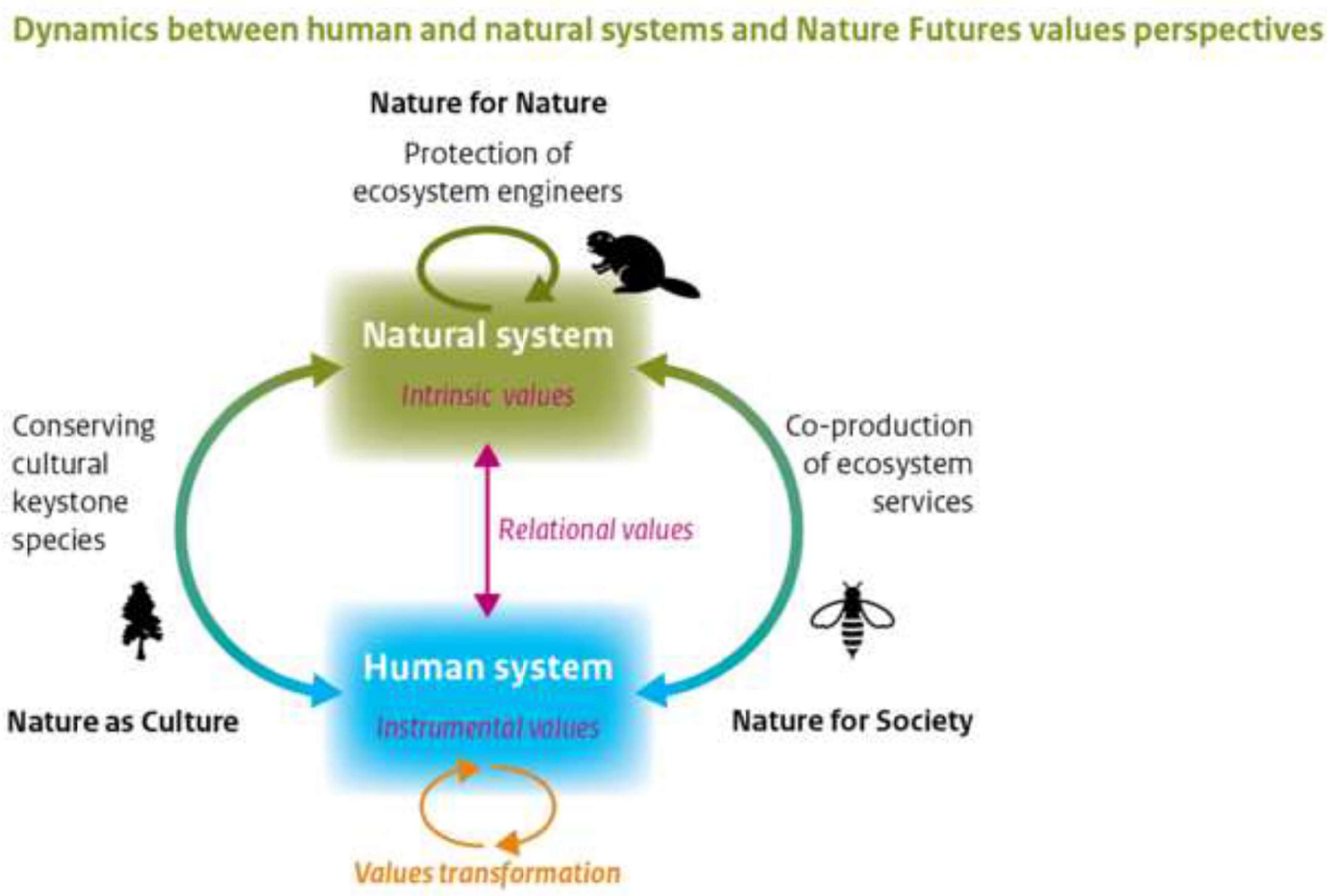

Dynamics between human and natural systems and Nature Futures values perspectives
Nature for Nature
Protection of ecosystem engineers
Natural system
Intrinsic values
Relational values
Human system
Instrumental values
Values transformation
Conserving cultural keystone species
Nature as Culture
Co-production of ecosystem services
Nature for Society

Figure4

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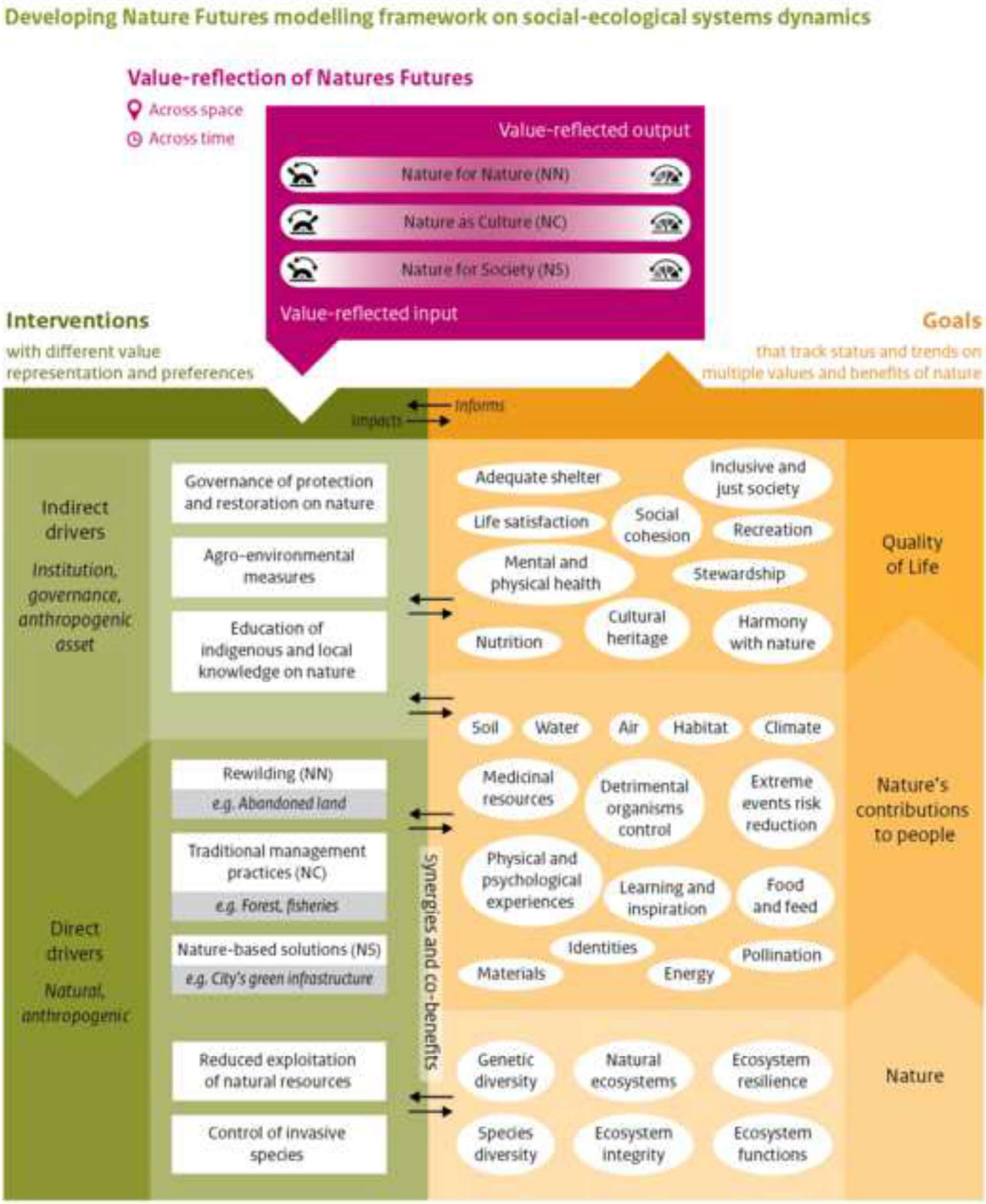

Graphical Abstract

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