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SPECIAL FEATURE: ORIGINAL ARTICLE

Operationalizing the Nature Futures Framework to Catalyze the Development of Nature-Future Scenarios

Mapping the shared socio-economic pathways onto the Nature Futures Framework at the global scale

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Abstract

The Nature Futures Framework (NFF) was developed for the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) to explore scenarios that represent a diversity of positive relationships between humans and nature. Widely used in global environmental assessments, the shared socio-economic pathways (SSPs) in combination with the representative concentration pathways (RCPs) were developed for climate change assessments. However, the relationship at a global level between the SSP–RCP scenario outcomes and the framing of the NFF around three value perspectives—Nature for Nature, Nature for Society, and Nature as Culture—has not been established. Here, we demonstrate a method to map onto the NFF value perspectives results from alternative SSP scenarios, each paired with an RCP consistent with the SSP storyline. For each of the NFF value perspectives, multiple elements were identified, each represented by one or more nature-focused indicators. Values for these indicators, for the different SSP scenario outcomes, were derived from an existing application of a global land system model, LandSyMM. A score for each indicator is estimated by comparing the indicator values against a normative target range. We find that only SSP1 provides greater benefits for Nature as Culture and Nature for Society relative to a 2010 baseline. Overall, the SSP scenarios provide fewer benefits for Nature for Nature, consistent with a bias towards the provision of material over non-material ecosystem services. The results demonstrate that the SSP–RCP scenario framing captures some, but not all, of the dimensions of nature and that alternative scenario framings, such as the NFF, are needed to study a broader range of biodiversity and ecosystem related questions as well as exploring positive futures.

Keywords Climate change · Land use · NFF · Scenario · Sustainability · Values

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Introduction

Scenario analysis is a powerful tool to explore the consequences of human (in)action within different socio-economic assumptions in the context of an uncertain future. The climate change community has used this successfully for decades, and developed and refined a set of exploratory storylines that describe plausible but diverse futures (Table 1) (Ebi et al. 2014; O'Neill et al. 2014; van Vuuren et al. 2014). The currently most widely used are representative concentration pathways (RCPs) describing alternative greenhouse gas concentration trajectories, coupled with the shared socio-economic pathways (SSPs) describing alternative socio-economic trajectories (O'Neill et al. 2020). Global integrated assessment models (IAMs) have then been used to quantify the implications of these storylines for different sectors of the economy. IAM outputs (such as greenhouse gas emissions or land use

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Table 1 A comparison of the SSP and NNF scenario framings

Scenario characteristic	Shared Socio-economic Pathways (SSPs)	Natures Futures Framework (NFF)
Objective	To evaluate the future consequences of climate change and the capacity of society to either mitigate or adapt to climate change threats.	To develop scenarios and models of desirable futures for nature and people, and evaluate trade-offs and co-benefits arising from the different values underpinning these scenarios.
Scenario logic	A 2-dimensional matrix comprising challenges for climate change mitigation and adaptation. Identifies 5 zones within the matrix (see below): SSP1, SSP2, SSP3 SSP4 & SSP5.	A triangular space comprising three value perspectives on nature – Nature for Nature, Nature for Society, and Nature as Culture (see below) – to represent a diversity of futures.
Visual representation		
Scenario type	Exploratory: describes trajectories from the present to some future point in time	Normative (or at least aspirational) based on achieving the 3 value perspectives
Qualitative/quantitative	Initial qualitative narrative storylines, complemented with quantitative model outputs	Mostly qualitative, although an emerging number of quantitative studies
Geographic extent	Initially global, but with regional and national interpretations	No specific definition of geography. Intended to be applicable at different scales
Temporal dimension	Narrative defined through time-slices. Time-steps specified through model outputs	Not specified
Accounting for climate change	Through the scenario matrix, as well as use in combination with the RCPs	Not specified
Accounting for biodiversity	Not specified	Through the nature for nature value perspective
Key references	(Ebi et al., 2014; O'Neill et al., 2014; van Vuuren et al., 2014)	(Kim et al., 2023; Pereira et al., 2020)

change) have been applied in, e.g. earth system models to compute global, spatially resolved impacts on the climate system or in ecosystem models to explore global, spatially resolved implications for natural and managed ecosystems (Frieler et al. 2015; O'Neill et al. 2016; Popp et al. 2017; Riahi et al. 2017; Rosenzweig et al. 2014).

This well-established and widely used approach to investigate the magnitudes and impacts of global climate change has in recent years faced increasing criticism. In addition to climate change, a broader set of sustainability challenges, such as biodiversity loss, have come into focus, which are difficult to address methodologically in a climate

change framing. Criticisms of IAM scenarios include that the magnitude and speed of uptake of land-based mitigation scenarios is unprecedented in human history, and the related consequences such as loss of habitats, and biodiversity, negative impact on food production and security, and harms to freshwater ecosystems (Bonsch et al. 2016; Henry et al. 2018; Kreidenweis et al. 2016; Rounsevell et al. 2014; Searchinger et al. 2017; Turner et al. 2018). Additionally, the simulated carbon uptake potential in forests or via bioenergy crops in IAMs cannot be reproduced with dedicated carbon cycle models (Harper et al. 2018; Krause et al. 2020).

To some degree, these challenges arise from the storylines and scenarios used in the climate change community, with their singular focus on greenhouse gas emissions and other climate change forcers, and ways towards reducing these. The strong economic focus of IAMs also makes it difficult to integrate the multiple societal perceptions and values of ecosystem services, beyond those where markets exist (Lamperti et al. 2021; Ramanathan et al. 2022; Rising et al. 2022; Uden et al. 2021). Over recent years, the emerging consensus is that addressing multiple development objectives at once, and the need to explore both synergies and possibly unavoidable trade-offs between achieving these requires a new set of storylines, which are normative ('goal-seeking') in that they describe desired futures and have non-monetary goals as their outcomes (Arneth et al. 2019; Otero et al. 2020; Rosa et al. 2017). Closely related to these necessary developments are models that can simulate the pathways (sensu "a description of the time-dependent actions required to move from today's world to a set of future visions" (Arneth et al. 2019)).

Scientists contributing to the Intergovernmental Science-Policy Platform on Ecosystem Services and Biodiversity (IPBES) have responded to these needs by developing the Nature Futures Framework (NFF) (Kim et al. 2023; Pereira et al. 2020). Unlike the SSP–RCP climate change scenarios, the storylines and visions underpinning the NFF were co-designed iteratively with a broad range of non-academic stakeholders and experts, starting with a joint workshop (Lundquist et al. 2017), and distilled into the current NFF that seeks to consider a plurality of perspectives along the three axes "Nature for Nature", i.e. the intrinsic values of nature; "Nature for Society", i.e. the instrumental values of nature; and "Nature as Culture", i.e. the relational values (Table 1) (Kim et al. 2023; Pereira et al. 2020). Kim et al. (2023) provide a first review of the possibilities and challenges of translating NFF storylines into quantitative modelling outcomes, based on existing modelling tools, with Durán et al. (2023) describing alternative, indicative narratives across the NFF value perspectives.

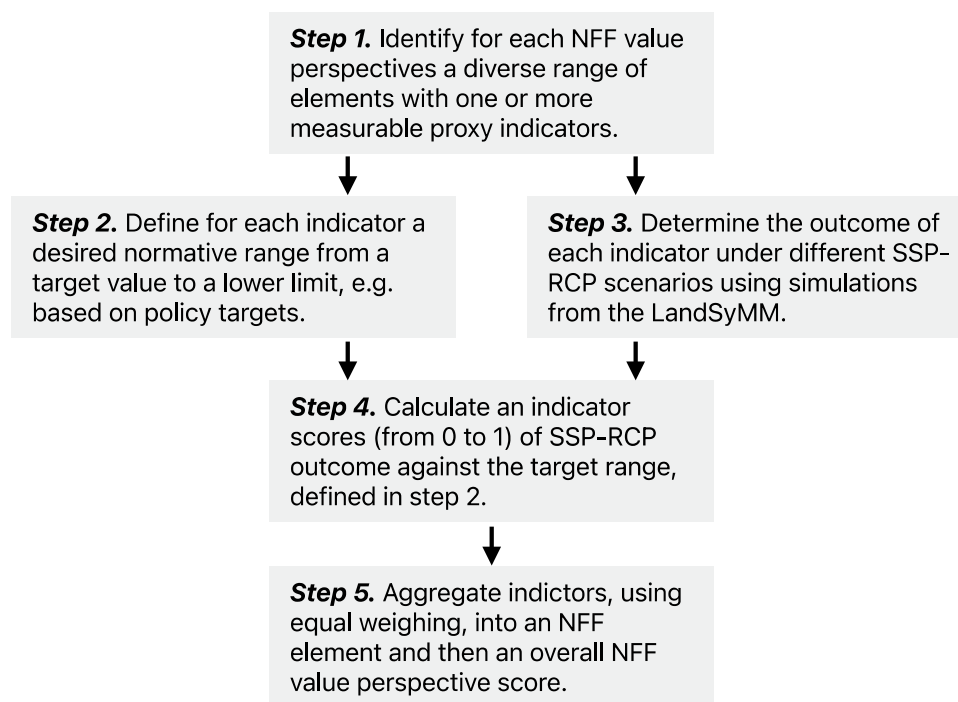There are both fundamental differences and some similarities, between the SSP and NFF scenario framings (Table 1). This means that although comparing scenarios across these two different paradigms is challenging, there is value in doing this to evaluate the extent and consequences of these difference and similarities. Given the different 'issue' focus of both framings (i.e. climate change and biodiversity), it is also useful to compare the approaches to draw more generic conclusions about outcomes that are relevant to both issues. Mapping one framework onto another, i.e. addressing both the climate change and biodiversity crises, is important as these have previously been treated independently. The interconnections between biodiversity and climate change are important as climate change exacerbates risks to biodiversity, while ecosystems and their biodiversity play a key role in greenhouse gas fluxes and climate adaptation (Pörtner et al. 2021). Furthermore, the SSPs are older than the NFF and so have been used extensively within the literature. While the NFF is still developing through further testing and refinement in research studies and with stakeholder communities, comparison with the more established SSP framework is useful in providing insights to support the direction for these developments. However, to date, a comparison between SSP scenario outcomes and the NFF value perspectives has not been conducted.

We explore in this study how outputs simulated under different SSP scenarios, with an RCP scenario consistent with the storyline, from a state-of-the-art model of the land system (LandSyMM; Alexander et al. 2023; Henry et al. 2022; Rabin et al. 2020)) could be interpreted with respect to the NFF value perspectives. The mapping of one framing onto the other also seeks to explore to what extent the SSPs cover the scenario space that is represented by the NFF, and to what extent they do not. The analysis is based on existing, exploratory scenarios and is intended to support further applications of the NFF and contribute to multiple ongoing development efforts in the IPBES community (Kim et al. 2023; Pereira et al. 2020). The work also responds to an invitation from IPBES to discuss opportunities for the NFF (IPBES 2022) and a call for studies that operationalise the NFF (Lundquist et al. 2021).

Materials and methods

Five steps (Fig. 1) were undertaken to produce an aggregate global score for each NFF value perspective under the SSP scenarios at 2100, as well as for a current baseline. The "Middle of the road" SSP2 scenario was not included, since data were not available for this scenario from existing, published studies. As described below, the steps progressed from identifying elements of the NFF value perspective with one or more proxy indicator, to scoring these indicators against target values and finally to aggregating the individual scores for an NFF value perspective.

Fig. 1 Diagram of the steps applied to derive a score for an NFF value perspective under an SSP-RCP scenario

Step 1. Identify for each NFF value perspectives a diverse range of elements with one or more measurable proxy indicators.

Step 2. Define for each indicator a desired normative range from a target value to a lower limit, e.g. based on policy targets.

Step 3. Determine the outcome of each indicator under different SSP-RCP scenarios using simulations from the LandSyMM.

Step 4. Calculate an indicator scores (from 0 to 1) of SSP-RCP outcome against the target range, defined in step 2.

Step 5. Aggregate indictors, using equal weighing, into an NFF element and then an overall NFF value perspective score.

Identifying elements of value perspectives and proxy indicators

A range of proxy indicators were identified relating to a range of elements for each NFF value perspective. These proxy indicators were selected as a pragmatic combination of values where data were available for future scenarios and to provide as broad a coverage as possible of the aspects of each value perspective that were consistent with the existing NFF framework (Kim et al. 2023; Pereira et al. 2020). Five different elements were selected for Nature for Nature and Nature as Culture, and four elements for Nature for Society (Table 2). Each of these elements had between 1 and 7 proxy indicators, with the total number of indicators being 11 for Nature for Nature, 12 for Nature for Society, and 17 for Nature as Culture.

Defining indicator target value range

Target values were ascribed to each proxy indicator, to represent a normative, desirable future (Table 2). Existing publications and policy targets were used to define these targets where possible, e.g. planetary boundaries (Steffen et al. 2015), EAT-Lancet diet (Willett et al. 2019), and international agreements such as the Bonn Challenge and New York Declaration on Forests (Dave et al. 2019). An assumption of no further change was made in cases where no clear target could be identified, for example, in the case of cultural landscapes targets included no further loss of extensive pasture, unmanaged forest, and other natural areas. Additionally, an

indicator level with poor or 'bad' outcomes was also defined using the same approach. This allowed a scale of values to be described from the desired future outcome to a lower threshold. For example, in the Forest Area (N1.1, Table 2), the target indicator range was determined to be from 4222 Mha corresponding to the Bonn Challenge, to a lower limit of 3377 Mha. A future area at or above 4222 Mha would score the maximum 1 ('good') for this indicator and a forest area at or below 3377 Mha would score a 0 ('bad') (see Sect. 2.4 for further details of scoring the indicators using the target ranges).

Assessing indicator outcomes for each SSP

Existing simulations for the SSP scenarios using LandSyMM (Alexander et al. 2018; Rabin et al. 2020) (https://landsymm.earth/) were used to assess the outcomes for each of the proxy indicators at 2100. SSPs were paired with RCPs consistent with the SSP storyline: SSP1 with RCP4.5, SSP3 and 4 with RCP6.0, and SSP5 with RCP8.5. While multiple RCPs are potentially consistent with an SSP (and vice versa), some combinations are considered more likely (Engström et al. 2016). Each SSP scenario was paired with the RCP considered to be most likely according to the descriptions within the scenario narrative. LandSyMM is a state-of-the-art global land use model that couples a dynamic global vegetation model (LPJ-GUESS) (Smith et al. 2014) with a land system and international trade model (PLUM) (Alexander et al. 2018; Rabin et al. 2020). LandSyMM combines

Table 2 Proxy indicators for each Nature Future Framework value perspective

	Element of value perspective	Proxy indicator	Units	Baseline value	Target level	Lower limit ('Bad') level	Description and justification of target
Nature for Nature (intrinsic value)	N1. Terrestrial habitat availability	N1.1. Forest area	Mha	3872	4222	3377	Bonn challenge and New York Declaration on Forests: 350 Mha by 2030. Lower limit from 20% range in land cover
		N1.2. Tundra area	Mha	838	838	670	Target no further loss of Tundra. Lower limit from 20% range in land cover
		N1.3. Other vegetation area	Mha	2944	3562	2850	Target to increase forest from present to meet planetary boundary. Lower limit from 20% range
		N1.4. Land area with no change in biome	Mha	13,018	13,018	10,414	Target no further change. Lower limit from 20% range in land cover
	N2. Pollution impacts	N2.1. N loss to water	Tg N	45	34	45	Using methane loss to air from planetary boundary assessment as target value and giving today mid score
	N3. Impacts on freshwater habitats	N3.1. Irrigation use as a fraction of runoff	% of runoff	2.4	1.8	3.0	Highly spatially variable, but planetary boundary indicates a central value of 30% abstraction from river flows for intermediate PB, and we are currently within the PB for water use (65% to the PB)
	N4. Biodiversity hotspots	N4.1. Conservation International hotspots (plant species)+CSLF area	Mha	1395	1395	1116	Area of primary vegetation lost in CI hotspot cells. Target is current/baseline area. Lower limit from 20% range in land cover
	N5. Species richness	N5.1. Amphibians	Mha	1012	1012	810	Area of natural land in top 10% of richest areas for biodiversity. Target is to lose no more natural area in these locations. Lower limit from 20% range in land cover
		N5.2. Birds	Mha	1290	1290	1032	As above
		N5.3. Mammals	Mha	1372	1372	1098	As above

Table 2 (continued)

Element of value perspective	Proxy indicator	Units	Baseline value	Target level	Lower limit ('Bad') level	Description and justification of target
Nature for Society (provisioning and regulating services)						
S1. Food provisioning	S1.1. Fruit and veg	Mt	1492	SSP1 2014, SSP3 3595, SSP4 2625, SSP5 2178	SSP1 1007, SSP3 1797, SSP4 1312, SSP5 1089	Target consistent with EAT-Lancet diet. Lower threshold (i.e. 'bad' value) 50% of that amount. *
	S1.2. Cereals	Mt	1800	SSP1 1062, SSP3 1998, SSP4 1476, SSP5 1188	SSP1 531, SSP3 999, SSP4 738, SSP5 594	As above
	S1.3. Oil crops and pulses	Mt	174	SSP1 356, SSP3 661, SSP4 490, SSP5 379	SSP1 178, SSP3 330, SSP4 245, SSP5 189	As above
	S1.4. Starchy roots	Mt	437	SSP1 126, SSP3 231, SSP4 170, SSP5 139	SSP1 63, SSP3 115, SSP4 85, SSP5 69	As above
	S1.5. Sugar crops	Mt	929	SSP1 548, SSP3 1021, SSP4 752, SSP5 585	SSP1 274, SSP3 510, SSP4 376, SSP5 292	As above
	S1.6. Monogastrics (e.g. pork, chicken. and egg)	Mt	1119	SSP1 548, SSP3 984, SSP4 738, SSP5 593	SSP1 274, SSP3 492, SSP4 369, SSP5 296.535	As above
	S1.7. Ruminants (e.g. beef and lamb)	Mt	2566	SSP1 2335, SSP3 4182, SSP4 3310, SSP5 2489	SSP1 1167, SSP3 2091, SSP4 1655, SSP5 1244	As above
S2. Timber provisioning	S2.1. Managed forest area	Mha	1445	1445	1156	No current shortfall in the provision of timber. Lower limit from 20% range in land cover
S3. Climate regulation	S3.1. C sequestration as fraction of fossil and industrial emissions	% of fossil CO_2 emissions	6	20.0	6.0	Target C sequestration of 20% fossil and industrial emissions from land. Lower limit no change from baseline
	S3.2. N loss to the atmosphere	Tg N	28	23	33	Using methane loss to air from planetary boundary assessment as target value, and giving today mid score (De Vries et al. 2013)

Table 2 (continued)

Element of value perspective	Proxy indicator	Units	Baseline value	Target level	Lower limit ('Bad') level	Description and justification of target
S4. Water regulation	S4.1. Area–time in drought risk	%	2.90	1.5	4.4	% of cell-years below 5th percentile of baseline annual runoff, weighted by land area. Baseline can be < 5% because it's only looking at the last 30 years (so, for baseline: 1981–2010). Target 50% reduction, lower limit 50% increase
	S4.2. Area–time in flood risk	%	4.99	2.5	7.5	% of cell-months above 95th percentile of baseline monthly runoff, weighted by land area. Looking at last 30 years of each time period. Target 50% reduction, lower limit 50% increase
Nature as Culture (cultural services and health)	C1. Cultural landscapes C1.1. Extensive pasture area	Mha	2076	2076	1661	Target no further change. Lower limit from 20% range in land cover
	C1.2. Unmanaged forest area	Mha	2160	2614	2091	Increase in forest area to achieve the planetary boundary. Lower limit from 20% range in land cover
	C1.3. Other natural area	Mha	4053	4904	3923	As above
	C1.4. Area with no land use change	Mha	13,018	13,018	10,414	Target no further change. Lower limit from 20% range in land cover
	C1.5. Cropland N fertiliser application	Mt	153	115	191	Reduction required in total N from present to meet the planetary boundary. 'Bad' threshold giving today use a mid-score

Table 2 (continued)

Element of value perspective	Proxy indicator	Units	Baseline value	Target level	Lower limit ('Bad') level	Description and justification of target
	C1.6. Cropland management intensity	Index	40,415	28,291	40,415	Target 30% reductions in intensity of production to allow reductions in pesticide and machinery use. 'Bad' threshold assumes baseline conditions
	C1.7. Pasture management intensity	index	136	95	136	As above
C2. Aesthetic quality	C2.1. Cropland area	Mha	1574	1574	1259	No further change, assuming current use has accepted aesthetic values. Lower limit from 20% range in land cover
	C2.2. Primary vegetation area	Mha	7658	7658	6126	No further change, assuming current use has accepted aesthetic values. Lower limit from 20% range in land cover
C3. Recreation	C3.1. Minimum natural area for population	%	97.60	97.6	92.7	Sufficient natural land for recreational use of resident population (least 1 hectare per thousand people) % of global population with sufficient access, Target value is 100% of people have access to sufficient natural space, with 95% as lower threshold. Using SSP spatial population projections, baseline is SSP2 2010

Table 2 (continued)

Element of value perspective	Proxy indicator	Units	Baseline value	Target level	Lower limit ('Bad') level	Description and justification of target
C4. Physical health (diet)	C4.1. Population underweight	% of pop	13	7.8	13	Target 40% reduction. Based on the global nutrition targets with targets ranging from 30%-50% reduction in malnutrition metrics (WHO 2014) 'Bad' is no improvement in levels of underweight individuals
	C4.2. Population overweight	% of pop	25	25	30	Target is no increase in proportion of overweight individuals in the population, as per current WHO obesity targets. 'Bad' is increasing current rates by 20%
	C4.3. Population obese	% of pop	10	10	12	Target is no increase in proportion of obese individuals in the population, as per current WHO obesity targets. 'Bad' is increasing current rates by 20% (Lobstein and Brinsden 2020)
	C4.4. Fruit and vegetable consumption	kcal/person/day	232	345	172.5	Target consistent with EAT-Lancet diet. Lower threshold (i.e. 'bad' value) 50% of that amount
	C4.5. Red meat composition	g/person/day	250	204	306	Target consistent with EAT-Lancet diet. Lower threshold (i.e. 'bad' value) 150% of that amount
C5. Health and pollution	C5.1. N loss to water	Tg N	45	34	56	Reduction required in total N from present to meet the planetary boundary value and giving today mid score
	C5.2. N loss in the atmosphere	Tg N	28	23	33	Using methane loss to air from planetary boundary assessment as target value, and giving today mid score (De Vries et al. 2013)

Target values are also given as a percentage of the baseline (2001–2010 mean)

*Target varies by SSP for food production due to differences in population sizes under these scenarios

spatially explicit, biophysically derived yield responses with socio-economic scenario data to project future land use and management inputs. LandSyMM improves upon existing global land use models by having a more detailed spatial representation of crop yields and the responses of crops to intensity of production (Maire et al. 2022). Additionally, food demand is price elastic, responding both to country level incomes and the endogenously modelled prices, using a modified, implicit, directly additive demand system (MAIDADS) (Gouel and Guimbard 2018). LandSyMM runs on a 0.5° spatial grid and uses a dynamic global vegetation model, LPJ-GUESS (Smith et al. 2014), to estimate crop yields at a given location in response to climate change, irrigation, and fertiliser application rates. Agricultural intensity is represented by three factors: nitrogen fertiliser application rate, irrigation water use, and a management intensity index (representing, e.g. pesticide use, phosphorous and potassium fertiliser, controlling of soil pH and increased use of machinery or labour). The outputs of land use and management from PLUM for scenarios are fed into a final LPJ-GUESS run to produce projections of multiple, ecosystem service indicators, such as water runoff and N loss.

Many of the values used for the proxy indicators are produced directly through the LandSyMM simulations and have been previously published. This includes the area of different land covers, e.g. unmanaged forest, cropland areas, the food production and food provisioning values, N losses, and water runoff (Alexander et al. 2018; Rabin et al. 2020). Other indicator values were derived from these published simulations. The biodiversity and species richness indicators were calculated using the approach of Henry et al. (2019) that overlays projected land use change with maps of biodiversity species richness, e.g. conservation international (CI) biodiversity hotspots (Arneth et al. 2023; Myers et al. 2000). The proxy indicator for access to recreational area considers the proportion of locations (on a 0.5-degree grid) where there is sufficient natural land cover for there to be 1 ha per thousand residents in that area. That limit was chosen, as the Natural England's Accessible Natural Greenspace Standard (ANGSt) recommends that everyone should have an accessible natural greenspace including a minimum of one hectare of statutory local nature reserves per thousand population (Natural England 2010). C sequestration for each period was calculated as the change in total terrestrial C from the beginning to the end of the period; this was then divided by the total anthropogenic CO_2–C emissions from fossil fuels and other industrial sources (IPCC 2013). The proportion of the global population in different body mass index (BMI) categories was calculated from dietary intake using the method of Henry et al. (2022).

Calculating indicator scores against targeted values

The values for each indicator and scenario were then translated to a linear indexed score between 0 and 1, using the target ('good') and lower ('bad') levels, where 'good' and 'bad' refer to the outcomes for each NFF value perspective. A value of 1 implies achieving or exceeding the targeted level, and conversely a value of 0 means at or worse than the 'bad' level (Table 2). Most of the scoring ranges have high values being 'better', e.g. forest area (N1.1), but others have lower values than the target, e.g. irrigation use as a fraction of runoff (N3.1). The indicator scores were limited to a range of 0–1, so that overshooting the target or undershooting the lower bound was not represented.

To illustrate the approach, the first element of Nature for Nature is 'Terrestrial habitat availability' (N1) and the first proxy indicator is Forest area (N1.1). The baseline forest area is 3872 Mha and the target range is from a lower limit of 3377 Mha to 4222 Mha (Sect. 2.1). The LandSyMM simulation for SSP1 at 2100 has a 116 Mha (3%) drop in forest area, to 3756 Mha (Rabin et al. 2020). This is 0.59 on the linear scale between 3377 and 4222 Mha; therefore, this is taken as the score for that indicator and SSP.

Aggregating indicator scores

The individual indicators were aggregated with equal weights to provide a mean score for each element of the NFF value perspective. These elements were in turn averaged in the same manner to derive an overall score for the NFF value perspective under each SSP. The supplementary material provides a spreadsheet showing these calculations.

Results

Proxy indicator results

The proxy indicator results showed a wide range of outcomes as well as variability across the SSPs (Fig. 2). The selected normative scale ranges, from a target value to the lower bound 'bad' level, were exceeded in many cases, predominately at the negative end of the range. For example, the area of land with change in biome (N1.4) and N loss to water (N2.1) were worse than the lower bound for all SSPs. Conversely, some indicators were found to have a more positive outcome. The food provisioning indicators (S1.1-7) generally had high scores across all SSPs, with SSP4 achieving the target score across all 7 food groups.

Fig. 2 Indicator scores and normative scoring ranges for **a** Nature for Nature, **b** Nature for Society, and **c** Nature as Culture. Values are shown for SSPs 1, 3, 4, and 5 and 2010 baseline conditions. The minimum and maximum values are the lowest and highest values that occur in the scenarios or in the normative ranges

a) **Nature for Nature (intrinsic value)**

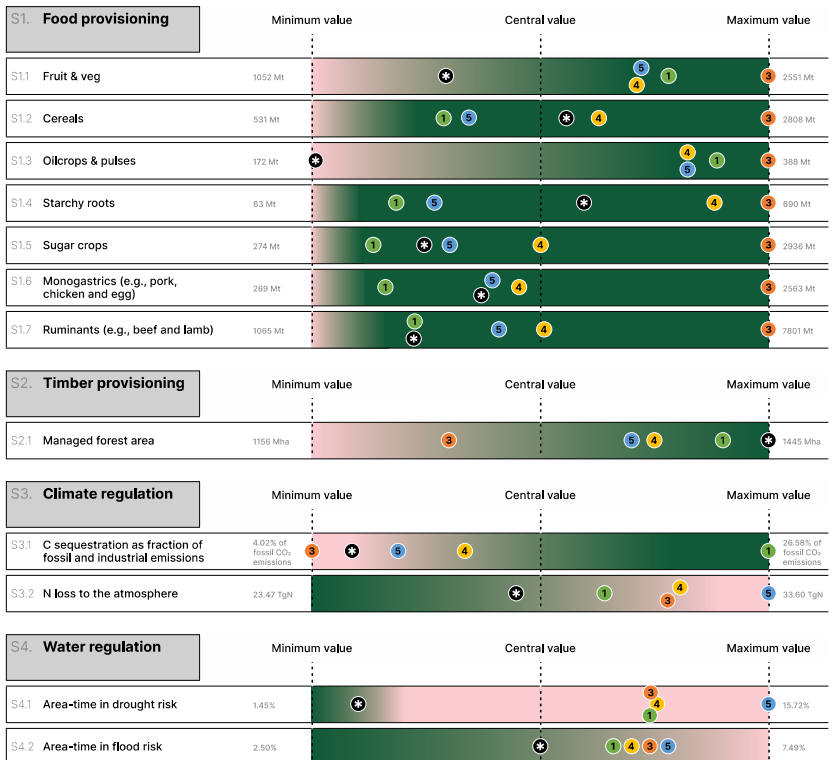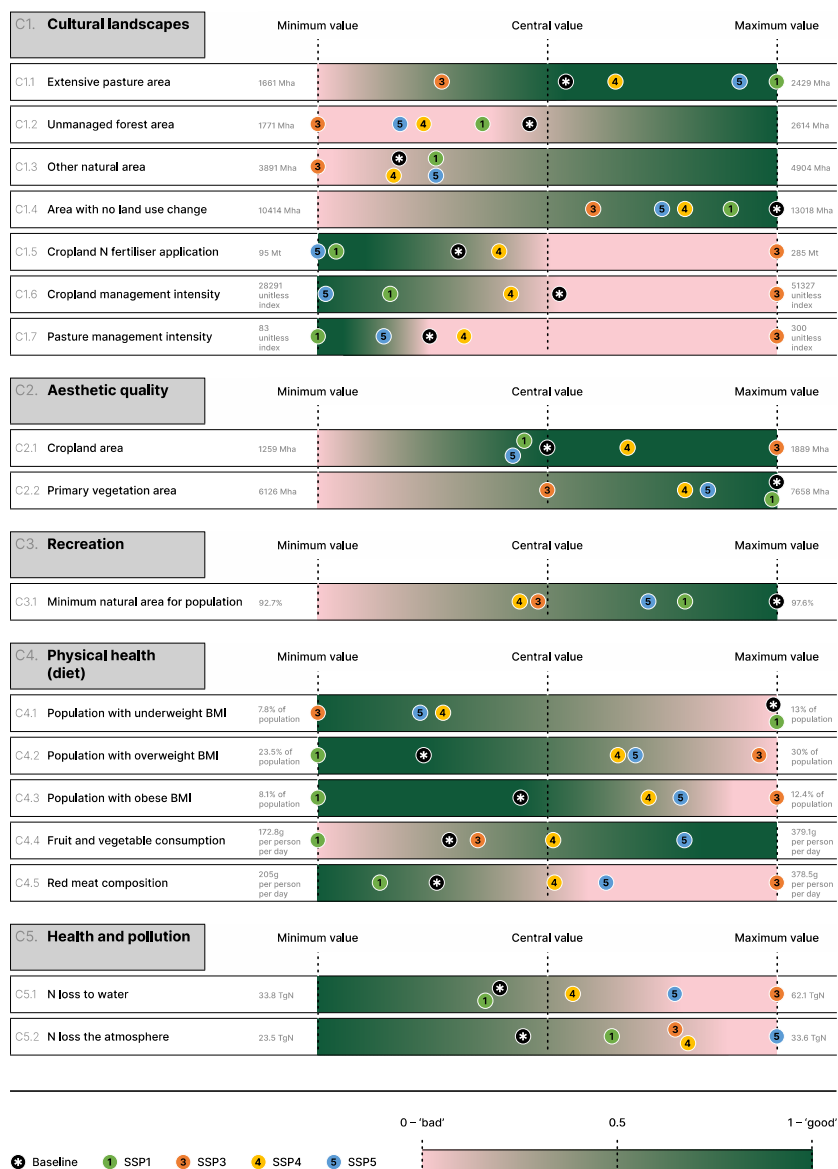b) **Nature for Society (provisioning and regulating services)**

Fig. 2 (continued)

c) **Nature as Culture (cultural services and health)**

C1. Cultural landscapes — Extensive pasture area, Unmanaged forest area, Other natural area, Area with no land use change, Cropland N fertiliser application, Cropland management intensity, Pasture management intensity. C2. Aesthetic quality — Cropland area, Primary vegetation area. C3. Recreation — Minimum natural area for population. C4. Physical health (diet) — Population with underweight BMI, Population with overweight BMI, Population with obese BMI, Fruit and vegetable consumption, Red meat composition. C5. Health and pollution — N loss to water, N loss the atmosphere.

Legend: Baseline, SSP1, SSP3, SSP4, SSP5. Scale: 0 – 'bad', 0.5, 1 – 'good'.

Element of value perspective results

The score for the elements of each NFF value perspective (Table 3) also showed wide variations. Pollution impacts (N2) scored negatively across the SSPs and baseline, with only SSP1 receiving a score above 0, of 0.08. Terrestrial habitat availability (N1) was assessed as moderately high in the baseline (0.68), but dramatically decreased in all future scenarios. The lowest overall scores from Nature for Society and Nature as Culture related to water regulation (S4) and Health and pollution (C5), respectively. Both declined substantially from an intermediate baseline score. For each NFF value perspective, there was one element that had scored consistently highly. Impacts on freshwater habitats (N3) showed improvements in all SSPs from the baseline

for Nature for Nature. Food provisioning (S1) in Nature for Society, and aesthetic quality (C2) in Nature as Culture both scored highly for all scenarios. Food provisioning scores reflected that sufficient food was produced to fulfil the EAT-Lancet diet. However, healthier products such as fruit, vegetables, and pulses were undersupplied (Fig. 2, Table 3). The health outcomes from the relative oversupply of food compared to nutritional requirements were included in Nature as Culture and showed the substantial and growing problem of the global population becoming overweight and obese.

Overall NFF value perspective results

The desired goal is to score a maximum 1 for each of the NFF value perspective totals (Table 3). This would be

Table 3 Aggregated scores for NFF value perspectives and each of their value elements

	Element of value perspective	Baseline	SSP1	SSP3	SSP4	SSP5
Nature for Nature	N1. Terrestrial habitat availability	0.680	0.238	0.089	0.158	0.182
	N2. Pollution impacts	0.000	0.080	0.000	0.000	0.000
	N3. Impacts on freshwater habitats	0.540	1.000	0.660	1.000	1.000
	N4. Biodiversity hotspots	1.000	0.900	0.050	0.500	0.650
	N5. Species richness	1.000	0.800	0.000	0.367	0.233
	Total perspective score	**0.644**	**0.604**	**0.160**	**0.405**	**0.413**
Nature for Society	S1. Food provisioning	0.776	1.000	0.799	0.863	0.972
	S2. Timber provisioning	1.000	0.900	0.300	0.750	0.700
	S3. Climate regulation	0.250	0.642	0.065	0.248	0.081
	S4. Water regulation	0.500	0.170	0.130	0.150	0.110
	Total perspective score	**0.631**	**0.678**	**0.323**	**0.503**	**0.466**
Nature as Culture	C1. Cultural landscapes	0.395	0.688	0.157	0.343	0.638
	C2. Aesthetic quality	1.000	0.945	0.750	0.900	0.850
	C3. Recreation	1.000	0.800	0.480	0.440	0.720
	C4. Physical health (diet)	0.581	0.754	0.293	0.463	0.476
	C5. Health and pollution	0.500	0.412	0.065	0.199	0.010
	Total perspective score	**0.695**	**0.720**	**0.349**	**0.469**	**0.539**

represented as a triangle filling the space of the radar diagram shown in Fig. 3; conversely, the worst possible outcome would be a dot in the centre indicating achievement of none of the targets for all three values perspectives. The baseline scores were already failing to meet these objectives, indicating that we are operating outside of planetary boundaries with negative consequences for environmental and societal objectives. The SSPs were also not able to achieve these normative goals. Only in SSP1 ("sustainability—taking the green road") do any of the NFF value perspective scores increase, with Nature for Society and Nature as Culture both increasing relative to the baseline, although with a decline in the score for Nature for Nature. SSP3 ("regional rivalry—a rocky road ") saw the most dramatic decline in all the NFF value perspectives. SSP4 and SSP5 both had substantial declines in all value perspectives' scores.

Discussion

The study seeks to quantify from the NFF value perspectives the outcomes under different SSP scenarios. The focus is on the three values perspectives (the corners of the NFF triangle, Table 1) rather than other locations in the triangular space, as the approach uses the NFF perspectives as lenses to evaluate the outcomes for each SSP scenario. The NFF is not being used here to create the scenarios, and therefore intermediate points on the NFF space would only be numerical averages of those considered. This contrasts with potential studies where the NFF is used in a 'goal-seeking' scenario framework. In such cases, it would be critical to consider

other points in that spaces, as important trade-offs and co-benefits could occur that need to be captured and explored.

SSP1 is consistently the best of the SSPs in terms of coming closest to filling the NFF triangle, indicating that each of the value perspectives would have reached their maximum level (i.e. the corners of the triangle, Fig. 3a). SSP3 is consistently the worst scenario, followed by SSP4 and SSP5, which have quite similar outcomes falling between SSP3 and SSP1. All SSPs performed worst for Nature for Nature and all the SSPs are worse than the baseline except for Nature as Culture and Nature for Society in the SSP1 scenario, and in these cases SSP1 is only slightly better than the baseline. Some bias towards the provision of material over non-material ecosystem services was evident with higher scores for Nature for Society than for Nature for Nature, including food provisioning indicators (S1.1–7) having high scores across all SSPs.

The poor performance of SSP3 relative to the baseline likely reflects limitations arising from the largely dysfunctional socio-economic development trajectory. However, since even SSP1 (an environmentally friendly and equitable scenario) performs worse than the baseline in Nature of Nature, this implies another limitation relative to the baseline. This limitation could derive from the adverse effects of climate change, which occurs across all SSP–RCP combinations and for which the consequences appear mostly to be negative, as might be expected. Indeed, SSP1 was associated with lower levels of climate change (RCP4.5), which could partly explain why it performs better than the other SSPs (e.g. SSP5 with RCP8.5), in addition to its relatively benign (i.e. low environmental

Fig. 3 NFF value perspectives scoring plotted as a radar plot; **a** the 2010 baseline with the maximum possible scores on all value perspectives, as well as the lowest possible scores; **b** the outcomes from SSP scenarios and the 2010 baseline
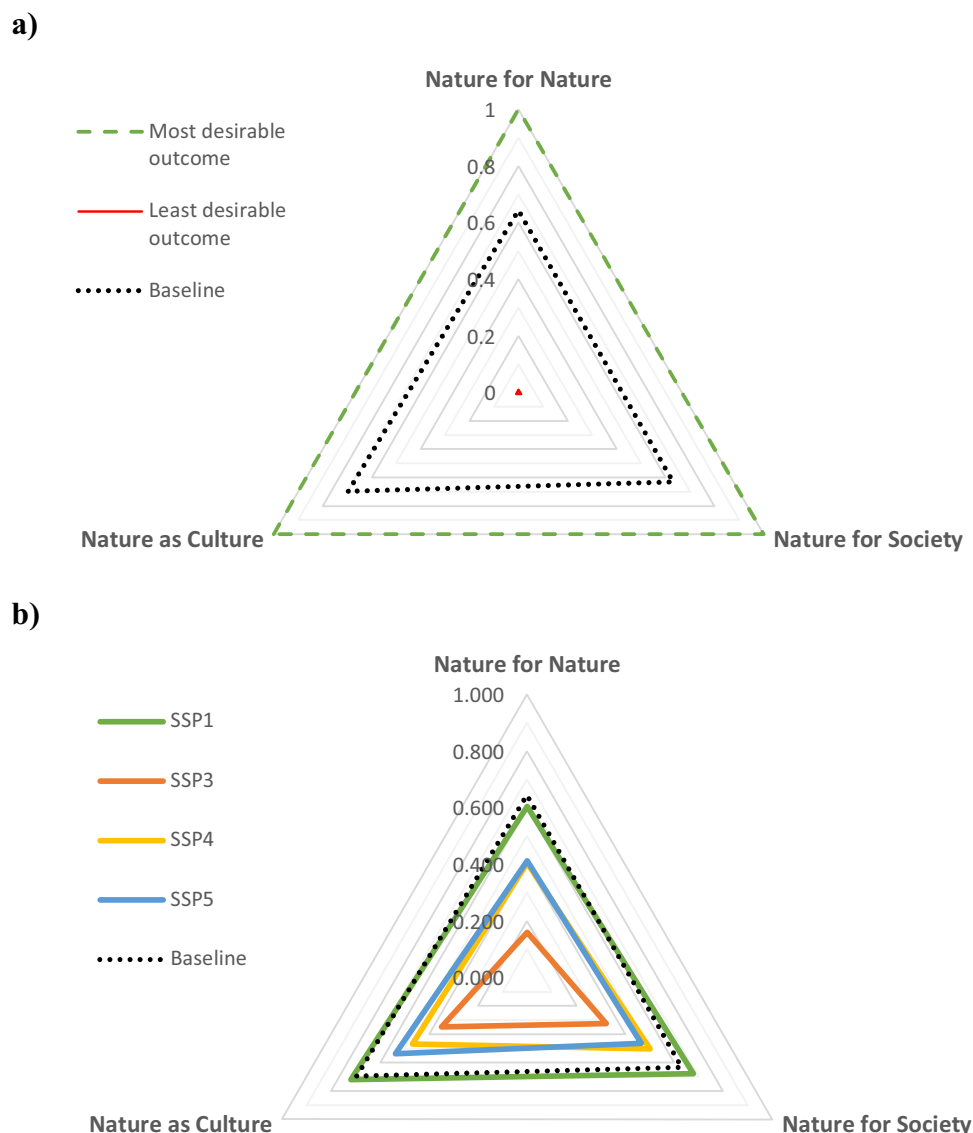
impact) socio-economic conditions. However, SSP3 is also combined with RCP4.5, which suggests that whilst climate change is a contributing factor, it is not as important as the socio-economic scenario assumptions. Increases in bio-energy demand and the associated land use are a further pressure in all SSPs that contribute to worse outcomes relative to the baseline (Popp et al. 2017).

Actions to mitigate climate change would still have significant benefits for nature, especially in combination with actions to limit the negative impacts of other human-mediated drivers. These results also suggest that the SSPs have limitations when used for nature-based studies, since with a strong climate change focus, they lack narratives that are relevant to addressing biodiversity issues (Pereira et al. 2020). The results also suggest legacy effects, meaning that we are already committed to nature losses, and the SSPs simply reflect these legacy trends, since they are not goal-seeking.

Subjective judgement and values in this study

As elements in the assessment are necessarily subjective there is no single objectively correct NFF value perspective scores for an SSP along each of the 3 NFF dimensions. However, the relative positions of the SSPs for each NFF, as well as through time and therefore in comparison to the baseline, are likely to be more robust. The method presented here required the specification of normative targets to scale each indicator of an NFF value perspective. In setting these levels and choosing the indicators, we have attempted to be as evidence based as possible using published literature sources, but nonetheless the work contains elements of value judgements. For example, to represent the aesthetic quality of agricultural landscapes (C2) is derived in part from cropland area (C2.1), which to many people in rural communities are an important reflection of their sense of

place and appreciation of managed rural environments. Whilst such sentiments may not be shared by everyone, we have attempted to include a diversity of normative values in the often challenging representing the subjective concept of aesthetic quality. Soliciting a broad range of perspectives through stakeholder engagement would represent a better way of determining alternative values (Blair et al. 2023; Kok et al. 2019). However, values are highly context dependent, and application of the method to different locations or regions (below the global level) would likely lead to very different values, and thus diverse outcomes for the mapping of the SSPs–RCPs onto the NFF.

Additionally, we have made methodological choices, about how to aggregate the indicators. Here, we chose to apply equal weighting of elements within the NFF value perspective scores as well as for indicators within each element. This was an explicit choice and avoids the need to select a range of weighting parameters. Applying weights (other than equal weights) has the potential to result in quite different outcomes. We could have applied a non-equal weighting to compare with the equal weighting approach, but the selection of such weights is subjective and judgemental. Assigning weights to indicators based on their quantifiable or perceived importance is extremely difficult in practice and would almost certainly require the application of values based on personal choices about what is, or is not, important for nature. This then raises the question of whose values and how should these values be defined, which is a common challenge in normative scenario approaches such as the NFF.

Values implicit in SSPs

Taking this a step further, we could also surmise about the values embedded within the SSP storylines themselves. The SSP storylines reflect contrasting, and quite divergent, worldviews, so should a normative vision for nature be specified differently for these different worldviews? For example, should SSP1 give more weight to Nature for Nature and Nature as Culture, whereas SSP5 with a more materialistic worldview should give more weight to Nature for Society? In this study, the normative targets were determined independently from the SSPs; however, weighting and scoring the NFF value perspectives differently for each SSP would give different outcomes.

Values not included in the NFF

Also pertinent to a discussion of values is that the NFF only considers values perspectives related to nature and does not account for other individual and societal values. This could include, for example, social justice and equity, economic and wealth development, or a focus on technological solutions to environmental problems (Blair et al. 2023). In principle,

further such dimensions could form part of the NFF, extending it from a triangle with three dimensions reflecting three nature value perspectives to a polygon with multiple dimensions. Such an approach might well avoid the criticism of the NFF that it is too nature focused, which, as we discussed previously, mirrors criticism levelled at the SSPs for being too climate change focused.

Limitations and potential future work

In addition to questions around values, it is important to reflect on the limits of models and their indicators to adequately reflect the complexities of the natural world. The approach presented here was based on a limited number of modelled indicators that will only ever cover a part of the system of study. Selection of proxy indicators is subjective and usually constrained by the availability of data from model simulations. Therefore, future work to comprehensively capture themes and indicators from published NFF descriptions and narratives (e.g. Durán et al. 2023; Kim et al. 2023) would potentially require model developments. Indicators for Nature as Culture are particularly challenging at a global scale, and further contributions of anthropologists and other social scientists to assist with defining suitable indicators would be beneficial. Additional further work could also focus on the implications for inequality both within and between countries and regions, including using the spatial representation of LandSyMM. Moreover, it would be beneficial to include a fuller representation of the uncertainties associated with models and their parameters that are used to quantify alternative scenarios, including uncertainty between the association with SSP and RCP (Brown and Rounsevell 2021; Rounsevell et al. 2021).

Conclusions

This study demonstrates that the NFF can be used effectively at a global level to assess outcomes from other scenario frameworks against a broad range of nature-related perspectives. Further work is required to model desirable futures for nature and people based on such a pluralism of values, i.e. to have global 'goal-seeking' modelling using the NFF. In such work, it would be critical to consider outcomes from objectives across the triangular NFF space, to explore the trade-off and synergies arising between these objective values and the consequences for other perspectives. There is also a need to further develop modelling methods to better represent the normative framing of the NFF. For example, it is unclear whether current models adequately represent the narrative assumptions describing very different future worlds, especially if models are calibrated on past and present data. Models also need to be adapted to account for

different scenario worlds, which implies a change in the model structure itself, rather than simply modifying model parameters to represent different scenarios, as has been proposed for more behaviour-based modelling approaches (Brown and Rounsevell 2021; Rounsevell et al. 2021).

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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