




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

# Modeling desirable futures at local scale by combining the nature futures framework and multi-objective optimization

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## Abstract

Envisioning positive scenarios that recognize the multiple values of nature is fundamental for designing transformative changes in local socio-ecological systems. This study developed a protocol with three specifications for operationalizing the Nature Futures Framework (NFF) in a landscape scenario analysis using a multi-objective optimization framework composed of: (1) exploring nature-positive futures, (2) seeking alternative pathways for targets satisfying visions of plural values, and (3) screening key direct drivers to achieve the targets. This research conducted a case study of a rural landscape in northeastern Japan. First, 110 strategies of landscape management options were simulated from 2015 to 2100 using a forest landscape model, LANDIS-II. The simulation developed a data frame of four integrated indicators of the NFF values for each year and strategy. Second, nature-positive strategies were screened using the common values. Pareto optimal strategies were then identified to obtain equally good solutions. Finally, the key response options to achieve good nature-positive futures were identified using decision tree analysis. Our protocol identified (1) multiple, but few nature-positive and Pareto optimal strategies that satisfied NFF visions, (2) nature-positive, but not Pareto optimal strategies, and (3) non-nature-positive strategies. In most Pareto optimal strategies, the maximized value perspectives changed over time. Our protocol also identified key response options to achieve three different NFF value perspectives in the case study area: (1) clear or selective cutting in forestry and (2) solar PV installation on abandoned pastureland in agriculture and energy sectors. We discussed the implication for local landscape management, localizing NFF narratives to develop future scenarios and modeling practice of NFF. The protocol does not depend on a specific model and indicator. Thus, our scalable protocol can be applied to scenarios and model practices in any region to support envisioning plausible, feasible, and positive futures, and designing future stakeholder collaboration.

**Keywords** Scenario analysis · Forestry · Agriculture · Forest landscape model · Nature positive

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## Introduction

A holistic and integrated approach is essential for preventing biodiversity decline (IPBES 2019; Leclère et al. 2020; Secretariat of the Convention on Biological Diversity 2020). Maintaining ecological systems in good condition is essential to achieving sustainable development goals (SDGs) because it is a prerequisite for a sustainable social system that avoids overshooting and shortfalls (Raworth 2017; Rockström et al. 2009). Countermeasures to climate change and biodiversity degradation have been considered in individual fields such as the Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Pörtner et al. 2021). However, in recent years, nature-based solutions have become a central issue in climate change mitigation and adaptation (Chausson et al. 2020; Seddon et al. 2020, 2021). In 2021, the IPCC and IPBES jointly reported that climate change and biodiversity problems are inextricably connected (Pörtner et al. 2021). Degradation of ecological systems is a wicked problem; thus, identification of critical levers and leverage points to trigger the transformation of the entire socio-ecological system is an urgent and important task (Abson et al. 2017; Chan et al. 2020; Meadows 1999).

A place-based scenario analysis that considers interactions between site-specific socio-ecological systems is helpful in designing local transformations (TNFD 2022; Wu 2013, 2021). Therefore, a large number of previous studies have conducted scenario analyses of landscape and ecological management at local scales worldwide (Ren et al. 2019; Shifley et al. 2017; Verburg et al. 2004). However, the comparison and integration of knowledge from each scenario analysis were difficult because the scenarios were developed for each local-specific context (Rosa et al. 2017). Shared socio-economic pathways (SSPs) are frequently used in biodiversity studies. However, a global assessment report demonstrated that even SSP1-RCP2.6, which is the most sustainable scenario, cannot halt biodiversity degradation (IPBES 2019).

Thus, to explore nature-positive futures (CBD 2021), the IPBES task force on scenarios and models developed a framework for designing multiscale and integrative nature–people scenarios: the Nature Futures Framework: a flexible tool to support the development of scenarios and models of desirable futures for people, nature, and Mother Earth (henceforth the NFF) (Schoolenberg et al. 2020; Okayasu et al. 2019a, b; Pereira et al. 2020; Rosa et al. 2017). This is a framework for scenario development that enables comparisons between case studies of desirable futures, while also considering the local context in collaboration with stakeholders. The NFF is characterized

by (1) expressing the value of nature from three perspectives: Nature for Nature (NN) (intrinsic value), Nature for Society (NS) (instrumental value), and Nature as Culture/One with Nature (NC) (relational value); (2) identifying a set of solutions rather than a specific solution to a desired future vision; (3) including social and ecological system interactions; and (4) application at the local scale (Pereira et al. 2020).

Several studies have conducted qualitative scenario analyses of ecosystem services using the NFF by identifying the key direct and indirect drivers of biodiversity loss (Rosa et al. 2020). Sarkar et al. (2020) reviewed the drivers of the changes in tropical wetlands in India and Brazil. They found common drivers of agricultural intensification, infrastructure development, and lack of concrete policies, while some drivers differed between countries. Moreover, 20 indicators of wetland values were classified into three value perspectives of NFF; there were both common indicators among value perspectives and specific indicators for each value perspective (Sarkar et al. 2020). Siqueira-Gay et al. (2020) described the drivers of current deforestation in the Amazon using the Driver, Pressure, State, Impact, and Response (DPSIR) framework, and qualitatively envisioned the changes in nature's contributions to people (NCP) under alternative future scenarios. Resende et al. (2020) also described the drivers of changes in water quality and quantity using the DPSIR framework, and qualitatively evaluated the future direction of a business as usual (BaU) and four alternative scenarios. Lembi et al. (2020) graphically visualized three alternative future socio-ecological systems in urban areas in Brazil by applying the NFF concept. All these studies qualitatively draw the interlinkage between indirect drivers, such as population and socio-economic conditions, direct drivers, such as land use and land cover (LULC) change, natural resource management, climate change, and natural ecosystems. Narratives of SSP scenarios in climate change research have been translated into quantitative socio-economic status using gridded population models and LULC change models (Chen et al. 2020; Shi et al. 2021). Thus, establishing a scenario simulation methodology that quantitatively translates NFF narratives using models that simulate the impacts of a wide variety of drivers is a key task.

There are two expected tasks for NFF modeling at the local scale. One is to simulate all the key indirect and direct drivers to represent the holistic transformation of socio-ecological systems, considering the diversity of value, learning, and ecosystem management activities between stakeholder agents (Kim et al. 2021; Pereira et al. 2020). This task requires the integration of landscape change models and socio-economic dynamics models and the implementation of stakeholder agents into the integrated model (Chopin et al. 2019). The other task is to inform interlinkages between the three different value

perspectives of the NFF to strengthen and catalyze collaboration between stakeholders (Pereira et al. 2020). This information is useful for considering key leverage points and levers in a landscape (Pasalodos-Tato et al. 2013; Pereira et al. 2020; Scheller 2020). Thus, this study focused on the second task, in which the existing landscape change models can contribute to developing a protocol for modeling the NFF in a landscape. The following section describes the specific requirements of the developed protocol.

**Specification 1.** Exploring nature-positive futures: This protocol explores solution sets that satisfy plausible, nature-positive, and NFF visions using landscape change models, which can simulate various human interventions.

**Specification 2.** Seeking alternative pathways for targets satisfying visions of plural values: This protocol visualizes multiple alternative pathways to reach an agreed-upon target in the NFF state space. The protocol also visualizes

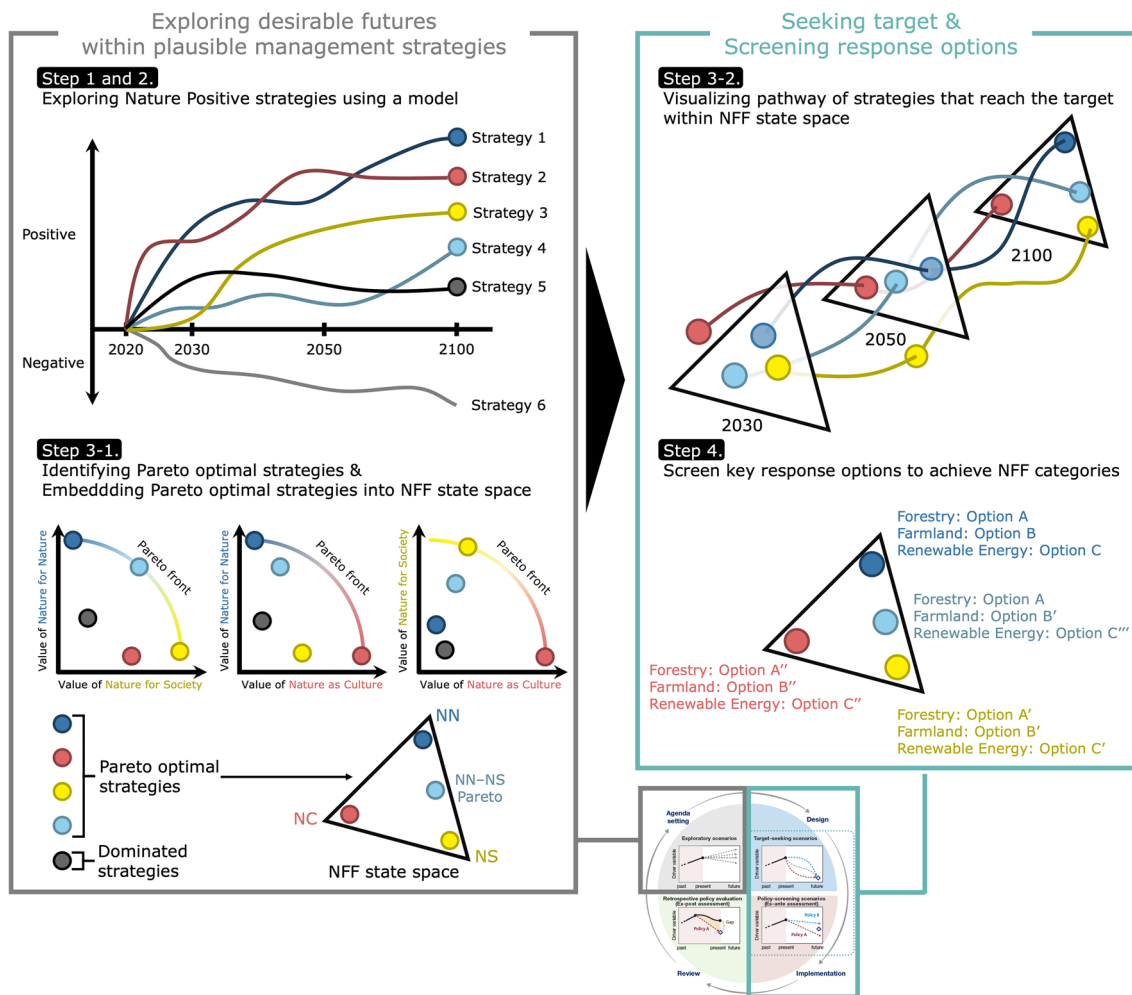
the interlinkages between the three value perspectives of the NFF.

**Specification 3.** Screening key direct drivers to achieve targets: This protocol identifies the conditions of direct drivers to achieve all pathways identified in Specification 2.

This study conducted an NFF modeling case study in Japan to assess the utility of the protocol. In this paper, we discuss whether our protocol can inform collaborations among stakeholders with diverse values; we also discuss research needs to expand the applicability of NFF in a certain landscape context.

## Materials and methods

This study modeled the NFF-based scenarios by applying the concept of multi-objective optimization and a landscape change model to explore desirable futures, seek targets in the NFF state space, and screen response options

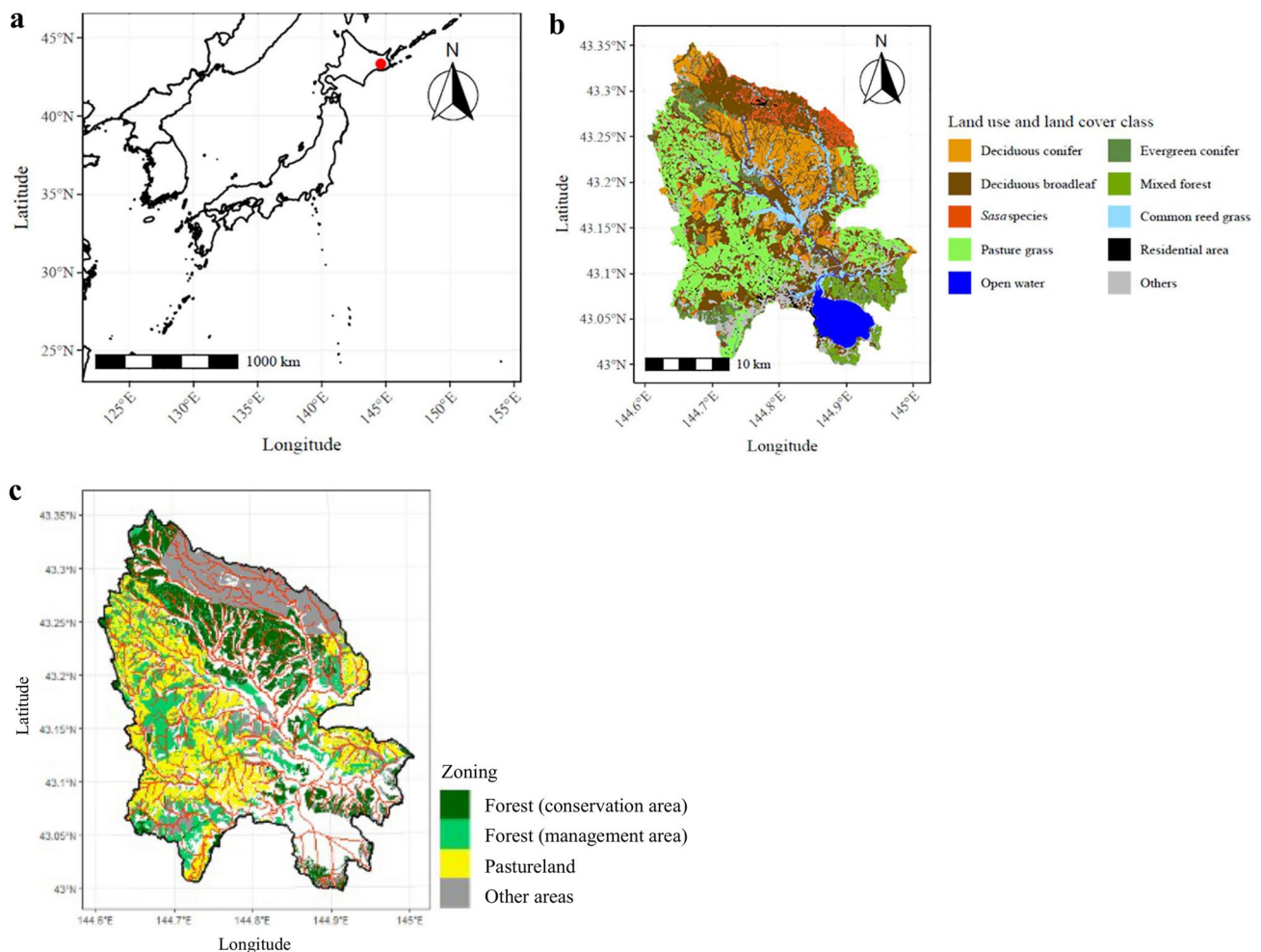


**Fig. 1** Overall protocol developed by this study. The right bottom figure was modified from the description of scenarios by Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (<https://ipbes.net/scenarios>)

for reaching these targets in the Bekambeushi River watershed in northeastern Japan (Fig. 1). First, a landscape change model simulated changes in NFF indicators toward 2100 under plausible landscape management strategies (hereafter, plausible strategies) (Step 1). Second, strategies that satisfied the nature-positive constraints (hereafter, nature-positive strategies) were extracted (Step 2). Third, Pareto optimal strategies and dominated strategies among NN, NS, and NC indicators were identified to embed them in the NFF state space (Kim et al. 2021) (Step 3–1). Then, our protocol identified how values of each nature-positive strategy transitioned in the NFF state space toward 2100 (Step 3–2). Finally, the key response options to reach a certain condition in the NFF state space were identified (Step 4). All analyses and visualizations for this process were conducted using R v4.1.2 (R Core Team 2021) and Julia v1.6 (Bezanson et al. 2017).

## Site description

The Bekambeushi River watershed in northeastern Japan was selected as the case study area (Fig. 2A). The total area of the watershed is 700 km<sup>2</sup>, with a small difference in elevation from 0 to 141 m (GSI 2019). The current monthly mean air temperature ranges from −8 to 20 °C, and the annual precipitation is 1200 mm (Esgf-CoG 2017). Forest and pasturelands cover 70% and 20% of the watershed, respectively (Fig. 2B; Biodiversity Center of Japan 2017). The Bekambeushi River wetland, located in the middle of the watershed, was listed in the Ramsar Convention in 1993 (Akkeshi Town 2019a). In the national forest in the northern areas, the dominant species for tree plantation is *Larix kaempferi* (Lamb.) Carrière. In the private forest in the southern areas, the dominant species are Sakhalin fir (*Abies sachalinensis* (F. Schmid) Mast.) for tree plantation and a natural mixed forest of Sakhalin fir and Japanese oak (*Quercus crispula* Blume). The



**Fig. 2** Description of the study area. **a** Location of the Bekambeushi River watershed (red dot), **b** vegetation distribution, and **c** zoning of the study area

Bekambeushi River flows from the north into Lake Akkeshi, a 32 km<sup>2</sup> brackish water lake, connecting Akkeshi Bay and the Pacific Ocean through a narrow ~400 m-wide channel. Upstream land use changes in the watershed affect the water quality and productivity of the lake and bay through nutrient concentration changes in the river water (Nakaoka et al. 2018).

The main industries in the watershed are dairy farming, tourism, forestry in the national and private forests, and fisheries and aquaculture in the bay, lake, and offshore area (Akkeshi Town 2018). The watershed stakeholders include local ecosystem managers, such as foresters and farmers, and those who use local ecosystems, such as citizens, local governments, and tourists (Tajima et al. 2021). One of the stakeholders' concerns is the impact of LULC changes in the watershed on river water quantity and quality, which may affect fundamental industries such as fisheries and aquaculture. Moreover, the total residential population in the watershed was 8604 in 2010 and is projected to decrease to 4980 by 2050 (NIPSSR 2018). This depopulation has affected local ecosystem management. The areas of clear-cutting and thinning of larch and Sakhalin fir for timber and pulp production have decreased in recent years (Hokkaido Prefecture 2019). Local administrative documents reflect the concern that the abandonment of pastureland will increase because of the declining population (Akkeshi Town 2019b). However, other administrative documents plan to maintain or expand dairy farming (Akkeshi Town 2014). As these contrasting plans suggest, it is uncertain whether the future direction of land use management will be toward land sharing or land sparing (Immovilli and Kok 2020).

The study area has been subjected to multiple scenario analyses. Tajima et al. (2021) conducted a questionnaire survey of residents and found that the objects supporting local identity differed depending on the stakeholders. Objects related to marine ecosystems, such as fisheries, oysters, kelp, clams, and Pacific saury, produced capitals, such as the Akkeshi Bridge and roadside stations, and landscapes and livelihoods, such as dairy farming, were found to support local identities (Tajima et al. 2021). On the other hand, modeling studies have shown that changes in local land use and forest management intensities as populations decline would alter ecosystem services, such as vegetation distribution, carbon fixation, wood supply, and pasture supply using the LANDIS-II model (Haga et al. 2019). Moreover, another study has suggested that the introduction of renewable energy as a climate change mitigation measure would decrease the habitat of the mountain hawk eagle and Blakiston's fish owls within the area (Haga et al. 2020). Based on these studies, this study translated the stakeholder's preferences (Tajima et al. 2021) into an NFF perspective and used the LANDIS-II model to visualize the interlinkages, such as trade-offs or synergies, among different values.

## Step 1. Developing an NFF indicator data frame using a model

### Model description

This study simulated LULC change and vegetation succession using the LANDIS-II model (Scheller et al. 2007) under different forest and pastureland management scenarios at a 100 m resolution under climate change. LANDIS-II is one of the leading forest landscape models (e.g., Petter et al. 2020; Scheller et al. 2011; Shifley et al. 2017; Thompson et al. 2016) that has already been localized in this area, as described previously. A significant difference from the other land use change models, which simulate discrete state space transitions (e.g., Estman 2022), is that LANDIS-II simulates the impact of anthropogenic interventions on vegetation dynamics in each grid cell. LANDIS-II is a raster-based spatially explicit model that represents an entire landscape as a collection of grid cells and computes the vegetation dynamics of each plant cohort in each grid cell. The model calculates spatially explicit plant cohort recruitment due to seed dispersal from surrounding grids, natural disturbances, forest management, growth, competition, mortality, above-ground biomass, and ecosystem carbon and nitrogen cycles influenced by climate change. The model requires initial forest vegetation and climate conditions, life history, functional data by tree species, and landscape management options. The model outputs time-series changes in biomass by tree species, carbon sequestration rate, and timber and pasture production. This study used LANDIS-II NECN Succession extension v6.4 (Scheller et al. 2011) (hereafter, NECN v6.4), which can represent responses to climate change according to the traits of each plant species. The calculation process is detailed both in Scheller et al. (2011) and the GitHub repository of the simulation model (<https://landis-ii-foundation.github.io/Extension-NECN-Succession/>). A previous study has described the parameterization, calibration, and validation of the model (Haga et al. 2019, 2020). The list of simulated species is shown in Table S1 in the Supplementary Materials.

Table 1 describes the major direct drivers and response options, i.e., human interventions, which could be simulated using the LANDIS-II model. The LANDIS-II Biomass Harvest extension v4.1 calculates harvesting methods and timing for plant cohorts at the stand level and harvesting plans based on zoning at the landscape level. Clearing, thinning, and selective cutting can be simulated by setting the type and amount of trees to be harvested and the timing of harvesting in each forest stand. Even in pasturelands, model users can control the timing of vegetation succession owing to seed dispersal from the surrounding area.

We used the RCP2.6, which is expected to minimize the impacts of climate change on biodiversity, because the NFF

**Table 1** Direct drivers and response options, which LANDIS-II can simulate. The response options refer to the PANCES Project (PANCES Project 2022)

Ecosystems	Direct drivers	Player	Response options
Forest	Landscape level: Zoning Stand level: Clear-cut Selective cutting Thinning Planting Site preparation Rotation period	Forest manager Local government Forest owner Power generation company	Promotion of sustainable forest management Formulation of forest zoning Promotion of plantation forest management Guidance from a single-storied forest to a multi-storied forest Guidance to a natural forest Introduction of forest environment tax to manage abandoned forests Support for new employment in forestry and training of leaders Promotion of utilization of woody biomass
Pastureland	Continuous management Pastureland abandonment Solar PV installation on abandoned pastureland Plantation of trees on abandoned pastureland	Farmer Local government Land owner Power generation company	Promotion of direct payment system to agricultural workers Consolidate and increase the scale of agricultural land Promotion of mechanization in the agricultural sector Diversion of abandoned cultivated land (natural regeneration or tree plantation) Promotion of solar PV installation

assumes desirable visions of future human–nature relationships (Pereira et al. 2020). The same bias-corrected RCP2.6 future climate data of the CMIP5 MRI-CGCM3 model were used, as in previous studies (Haga et al. 2019, 2020). Under these climate conditions, the average temperature in the region would increase by 1.4 °C by 2100 (Haga et al. 2019, 2020). The remaining environmental conditions were the same as those described by Haga et al. (2020). The simulation period was 85 years, from 2015 to 2100, with time steps for material cycling set to one month and seed dispersal and ecosystem management set to one year.

### Designing plausible direct human interventions to nature

First, in all plausible strategies, conservation areas where human intervention should be avoided and management areas where ecosystem management is conducted were determined according to the current policy of forest and pastureland management in the area (Fig. 2C). Forests were first zoned into conservation areas and management areas by forest stands, referring to the forest register database

and regional forest plans (Akkeshi Town 2017; Hokkaido Prefecture 2017a, 2017b, 2017c; MAFF 2017). The current conservation practices on the current protected forests for disaster prevention and mitigation and wildlife conservation will be continued until 2100. Other forests intended for timber production were designated as management areas. The pasturelands were zoned into two areas based on geographical, topographical, and social factors: the conservation areas to be guided to the natural forest after abandonment, and management areas to support instrumental or relational values. First, we identified pasturelands that were topographically and socially difficult to manage, likely to be abandoned, and used these to simulate the expansion of abandoned land (Haga et al. 2020). For pasturelands abandoned in management areas, a grid search was conducted to determine whether solar PV should be introduced after abandonment or whether biomass energy should be used by converting pastures into forests after abandonment. Solar PV was introduced from abandoned pasturelands located far from the forest edge. See Haga et al. (2020) for a detailed algorithm for abandoned pastureland expansion.

Second, combinations of plausible forest and pastureland management in the management areas, i.e., plausible strategies (Fig. 3 and Supplementary Materials S2), were designed. Individual forest and pastureland management options are plausible and difficult to determine superior or inferior relationships from the viewpoint of plural values of nature. Therefore, we conducted a grid search over the 110 combinations of plausible strategies comprising two contrasting groups: 21 land-sparing-oriented strategies, which decrease timber production and maintain or rewild pastureland as the population decreases (Fig. 3 orange and Table S2-1), and 89 land-sharing-oriented strategies, which continue landscape management despite depopulation to maintain a supply of NCPs from the landscape (Fig. 3 green, Tables S2-2, and S2-3). The forest management in this study refers to standard practices as follows (Akkeshi Town 2017; Hokkaido Prefecture 2017c). The older forest stand that reached the standard harvest period was harvested first. We limited the maximum clear-cut area of each operation to 20 ha for biodiversity conservation, referring to the standard practice. To conserve and expand riparian forests, abandoned pastureland within 300 m of the river was rewilded by natural regeneration. In addition, pasturelands that were once wetlands in the past were not used as a source of renewable energy because

they were considered to have the potential to become wetlands (Kaneko et al. 2008; Morimoto et al. 2017).

### Indicator selection by translating visions and values of NFF to the local context

We assumed that whether the study area is nature positive can be evaluated by the condition of the fundamental landscape structure and ecosystem functioning. Thus, we selected five common indicators to quantitatively evaluate four values (Table 2). The visions and values of each vertex of the NFF were translated into the local context and mapped to variables that could be output by the LANDIS-II model (Table 2 and Supplementary Materials S3). In this study, we set up common visions and values to evaluate nature-positive criteria, which is the basic idea of NFF, and specific visions and values to enable the quantitative evaluation of the value each vertex aims for. First, we assumed that the nature-positive state recovered fundamental landscape structures and ecosystem functions by the 2030s and 2050s compared to the current level (Locke et al. 2021). For this purpose, we calculated the Dissimilarity-based Satoyama Index (DSI) (Yoshioka et al. 2017) and proportion of non-artificial landscape area to evaluate landscape structure, net ecosystem productivity (NEP) as regulating NCP, vegetation biomass, and its diversity (Table 2).

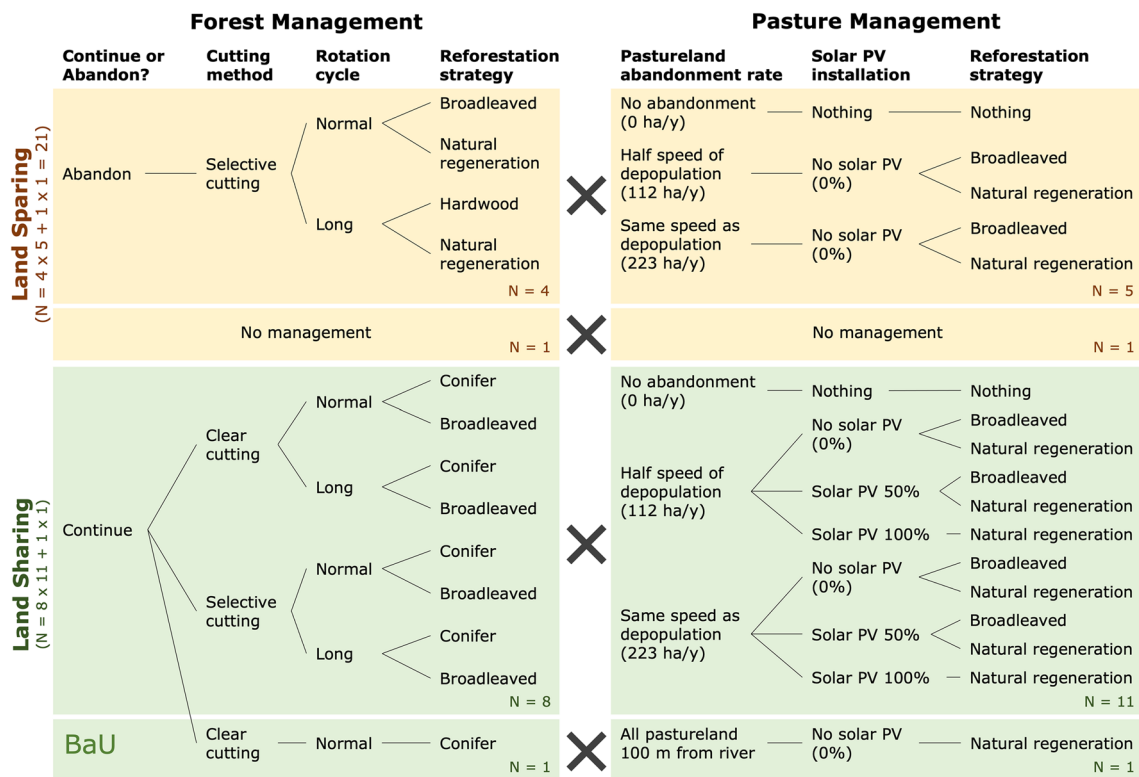


Fig. 3 Combinations of forest and pastureland management strategies

**Table 2** Indicators for evaluating the common value and three NFF values. The Supplementary Materials describe the calculation of each indicator

Category	Vision	Value	Indicator which can be calculated from LANDIS-II output	Stakeholder (Tajima et al. 2021)
Common	Fundamental landscape characteristics and ecosystem function will be maintained	Landscape structure	Dissimilarity-based Satoyama Index (DSI) (Yoshioka et al. 2017)	Forest, land, and marine
		Landscape structure	Area of natural landscape (ha)	Forest, land, and marine
		Regulating NCP	Net Ecosystem productivity (NEP) (g-C y <sup>-1</sup> )	Forest, land, and marine
		Biomass of plant species	Total aboveground biomass of trees in the watershed (g-dry weight)	Forest, land, and marine
		Diversity of plant species	Simpson's diversity index of aboveground biomass of trees in the watershed	Forest, land, and marine
Nature for Nature	Preserve nature's diversity and functions	Habitat of fauna	Habitat suitability index of Blakiston's fish owl (Yoshii et al. 2018) Habitat suitability index of the mountain hawk eagle (Itoh et al. 2012)	Forest
		Amount of flora	Aboveground biomass of native tree species (g-dry weight) (Editorial Committee of History of Akkeshi Town 2012)	Forest
Nature for Society	Maintain or maximize instrumental values of nature	Yield of agriculture and forestry	Pasture yield (g-dry weight y <sup>-1</sup> )	Forest, land, and outside the area
			Timber yield (g-dry weight y <sup>-1</sup> )	Forest, land, and outside the area
		Energy production	Energy production of woody biomass (J y <sup>-1</sup> ) Energy production of solar PV (J y <sup>-1</sup> )	Forest, land, marine, and outside the area
Nature as Culture/ One with Nature	Maintain the livelihoods and the natural landscape which support local identity and culture	Supporting local identities and learning and inspiration	Proportion of the natural landscape in the viewshed from residential areas and roads	Forest and land
		Eco-tourism (physical and psychological experiences)	Proportion of the natural landscape in the viewshed from tourism resources: canoe route, local cultural heritage, and natural park	Land
		Connectivity of dairy farming and aquaculture (regulation of freshwater and coastal water quality)	Biomass of riparian forests (g-dry weight), which regulates water quality	Land and marine

Scenario-specific indicators were introduced by considering each of the three value perspectives of the NFF. The NN primarily aims to preserve biodiversity and ecosystem functions (Pereira et al. 2020). In this study, this narrative was translated as encouraging a rewilding by withdrawing from human intervention in forest and pastureland as the population declined. Thus, the value of

NN was evaluated using the habitat suitability index (HSI) for rare representative species in the area and native plant species biomass (Table 2). For the fauna, Blakiston's fish owl (*Ketupa blakistoni blakistoni*) (Yoshii et al. 2018), which uses riparian forests, and the mountain hawk eagle (*Spizaetus nipalensis orientalis*), which uses forest edges (Itoh et al. 2012), were selected.



NS and NC primarily aim to maintain the provision of NCPs: instrumental values in NS and relational values in NC (Immovilli and Kok 2020; Pereira et al. 2020). Thus, the NS vision in this area was to maximize the supply of grass, timber, and renewable energy by managing landscapes through mechanization, efficiency, and land consolidation, even under population decline. The provision of instrumental value in NS was evaluated by timber and pasture production and the potential of solar power generation on abandoned land and renewable energy from woody biomass of woody plants (Table 2).

However, NC emphasizes the relational values of a region (Immovilli and Kok 2020; Pereira et al. 2020). For this reason, NC's vision is to maintain the local identity supported by local livelihoods. A previous study revealed that local identities in this area are provided by fisheries and unique natural terrestrial landscapes that support tourism and dairy farming (Tajima et al. 2021). Thus, the proportion of the natural landscape in the viewshed from residential areas and roads and from tourism resources, such as canoe routes, local cultural heritage sites, and natural parks, and the biomass of riparian forests, which regulate water quality, were used as indicators.

Finally, the 15 indicators in Table 2 were summarized into four categories to develop a time-series NFF indicator data frame (four indicators  $\times$  110 strategies  $\times$  85 years) (Fig. 1). First, each individual indicator was min–max normalized timewise. Then, integrated indicator time series by categories were calculated as the arithmetic mean of the min–max normalized indicators for each year and category as follows:

$$Y_{\text{integ}_{c,y}} = \frac{\sum_{i=1}^{N_c} w_{c,i} \times Y_{c,i,y}}{\sum_{i=1}^{N_c} w_{c,i}},$$

where  $Y_{\text{integ}_{c,y}}$  are the integrated indicators of category  $c$  in year  $y$ ,  $N_c$  is the number of individual indicators within category  $c$ , and  $Y_{c,i,y}$  is the min–max normalized individual indicator  $i$  within category  $c$  in year  $y$ .  $w_{c,i}$  is the weight of indicator  $i$  within category  $c$ . It should be noted that the higher indicator values show better conditions. We assume that each indicator has the same weight ( $w_{c,i} = 1$ ) to demonstrate how our protocol performs. Sensitivity analysis of  $w_{c,i}$  are shown in the supplementary materials S7.

## Step 2. Screening nature-positive strategies using the simulated common integrated indicator

Step 2 screened nature-positive strategies from 110 management strategies using the common integrated indicator. The post-2020 target aims to stop the net decline in biodiversity loss by 2030 and sufficiently recover by 2050 compared with

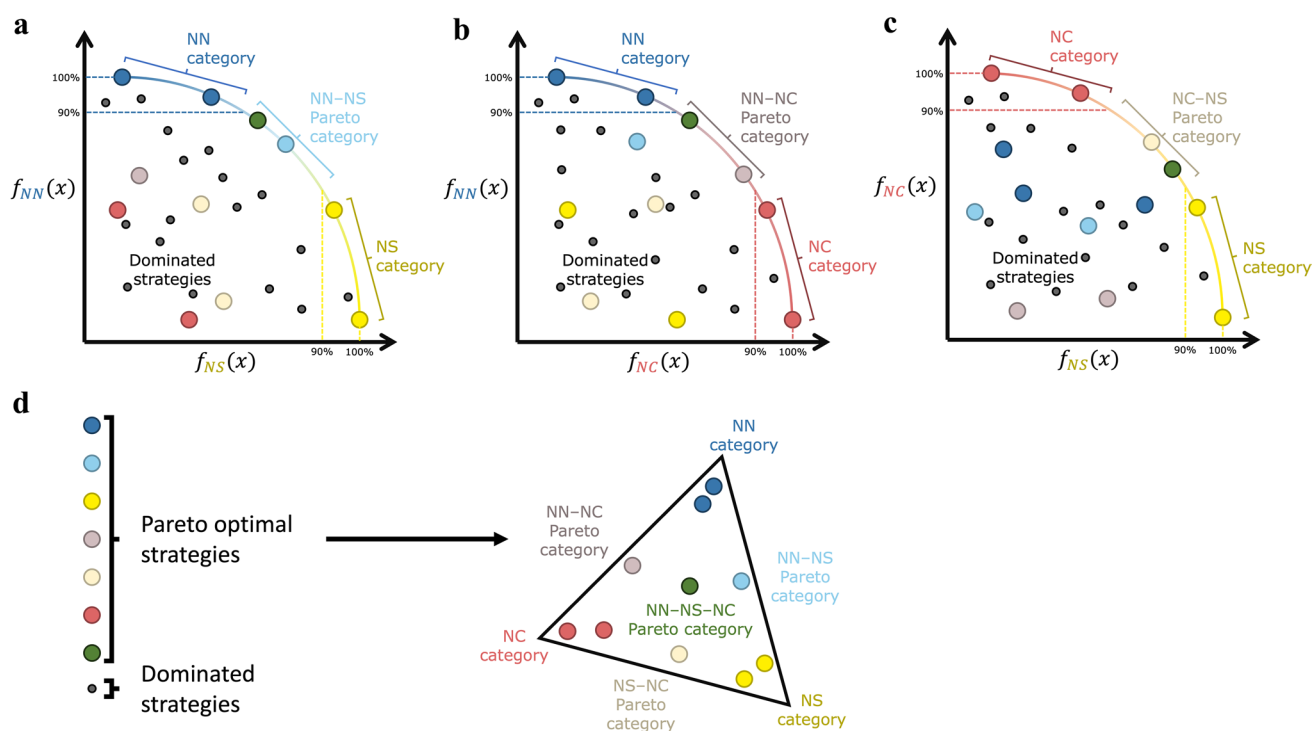
2020 (CBD 2021). Therefore, we herein define “nature-positive strategies” as strategies that indicate higher values of common indicators in both the 2030s and 2050s than the mean common indicator value from 2015 to 2029.

## Step 3. Embedding nature-positive strategies to NFF state space by identifying the Pareto front

All vertices of the NFF state space are plausible and desirable futures, although the values differ among them (Kim et al. 2021; Pereira et al. 2020). Therefore, combinations of vertices that can achieve different values simultaneously, which show trade-off relationships, or strike a balance between different values, can exist. This information about the interlinkages between different values of NFF state space will visualize local problems in landscape management and suggest possible collaboration between stakeholders. Therefore, this study visualizes the interlinkages between the values of each vertex of the NFF state space (Kim et al. 2021) using the concept of multi-objective optimization for the 2030s, 2050s, and 2090s.

All scenario narratives drawn in the NFF are desirable futures (Pereira et al. 2020; IPBES 2022), i.e., there are no superior or inferior relationships between scenarios, but each scenario is better than the others in at least one value of nature. Therefore, exploring management strategies resulting in such scenarios is equal to exploring Pareto optimal solutions (Benson 2009) in the three-dimensional NFF state space (Kim et al. 2021; IPBES 2022). An example is shown in Fig. 4. In the NN and NS plane, plots on the colored curve in Fig. 4A are Pareto optimal strategies: there are no other strategies that increase NN or NS value without decreasing the other value. The colored curve is called the Pareto front, a set of Pareto optimal strategies, which shows trade-offs between the two values. The other colored plots and black plots in Fig. 4A are dominated strategies: there is at least one strategy in which both NN and NS values are better. Repeating this procedure for the NN and NC plane and NC and NS plane as shown in Fig. 4B, C, all nature-positive strategies can be classified into two groups: (1) Pareto optimal strategies in which there are no other strategies that increase an NFF value without decreasing another value or (2) dominated strategies in which there is at least one strategy with higher three NFF values than themselves (Fig. 4D left).

Next, our protocol classified the Pareto optimal strategies into seven NFF categories to show which NFF perspectives will be achieved (Fig. 4D). The Pareto optimal strategies with top 10% values of each integrated indicator (Fig. 4A–C) were classified to be the categories which can achieve the vertices of NFF triangles: NN category, NS category, and NC category. The remaining Pareto optimal strategies were classified into the categories that balance multiple value perspectives: NN–NS Pareto category, NS–NC Pareto category,



**Fig. 4** How to embed the nature-positive strategies (hereinafter, nature-positive strategies) into the Nature Futures Framework (NFF) state space. All nature-positive strategies are plotted in **A** NN and NS, **B** NN and NC, and **C** NC and NS planes. Large colored plots are the

Pareto optimal strategies; small black plots are dominated strategies. The Pareto optimal strategies are then classified into the NFF categories shown in **D**

NN-NC Pareto category, and NN-NS-NC Pareto category. As a result, the Pareto optimal strategies can be embedded in a three-dimensional state space of NFF integrated indicators (hereafter, NFF state space (Kim et al. 2021)).

#### Step 4. Identifying pathways to achieve NFF category

Step 3 labels the non-nature-positive strategies, dominated strategies, and seven NFF categories for each management strategy defined in Step 1. Therefore, decision tree analysis was used to visualize the key response options to reach each NFF category avoiding non-nature-positive conditions. From the results, the critical indirect drivers, leverage points, and levers behind them were also discussed.

## Results

### Step 1. Summary of the NFF indicators time-series data frame

The summary of the four integrated indicators of 110 strategies organized according to time horizon shows that the indicator values diverged into decreasing or increasing trends

over the 2050s and 2090s, depending on ecosystem management strategies (Table 3). The mean and median values for each category increased moderately through the 2050s and

**Table 3** Summary of four integrated indicators by category and time horizon for all 110 strategies

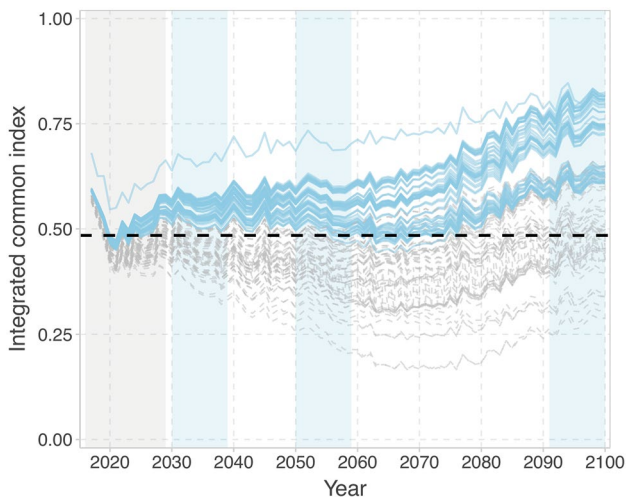
Category	Year	Mean $\pm$ SD	Min	Median	Max
Common	Current	0.49 $\pm$ 0.05	0.39	0.49	0.68
	2030s	0.50 $\pm$ 0.06	0.32	0.50	0.69
	2050s	0.48 $\pm$ 0.09	0.20	0.48	0.73
	2090s	0.59 $\pm$ 0.14	0.24	0.61	0.85
NN	Current	0.31 $\pm$ 0.04	0.24	0.30	0.55
	2030s	0.36 $\pm$ 0.05	0.22	0.37	0.61
	2050s	0.35 $\pm$ 0.08	0.12	0.35	0.62
	2090s	0.51 $\pm$ 0.13	0.22	0.50	0.83
NS	Current	0.32 $\pm$ 0.09	0.04	0.32	0.57
	2030s	0.32 $\pm$ 0.12	0.00	0.31	0.67
	2050s	0.38 $\pm$ 0.15	0.06	0.35	0.69
	2090s	0.42 $\pm$ 0.18	0.12	0.40	0.75
NC	Current	0.69 $\pm$ 0.03	0.57	0.69	0.81
	2030s	0.71 $\pm$ 0.06	0.49	0.72	0.87
	2050s	0.66 $\pm$ 0.13	0.21	0.70	0.89
	2090s	0.7 $\pm$ 0.2	0.2	0.8	1.0

further through the 2090s. The common, NN, and NC indicators showed that the maximum value increased through the 2090s, whereas the minimum value decreased, indicating that the ecological condition diverged due to human intervention. However, the results of NS showed that the minimum, mean, median, and maximum values monotonically increased over the 2090s, suggesting an increasing trend in every strategy.

## Step 2. Screening nature-positive strategies by common indicators

By screening 110 strategies in which the common integrated indicator increased from the current to the 2030s and 2050s, 51 nature-positive strategies were identified, which were positive in all three time horizons (blue lines) (Fig. 5 and S4). Our sensitivity analysis also identified  $50 \pm 10$  nature-positive strategies (Supplementary Material S7). Nature-positive strategies in blue lines show a recovery from the current state to the 2030s, followed by an increase through 2090. The DSI, proportion of natural landscape, and total tree biomass were high in these nature-positive strategies (Fig. S4).

However, as indicated by the gray dashed line, the majority were labeled as non-nature-positive strategies (Figs. 5 and S4): non-positive in the 2030s ( $N=2$ ), non-positive in the 2050s ( $N=10$ ), non-positive in the 2030s and 2050s ( $N=23$ ), and non-positive in the three time horizons ( $N=23$ ). In the non-nature-positive strategies, the recovery in the mean indicator values from the current



**Fig. 5** Common integrated indicator by 110 management strategies. Black horizontal line shows the mean value from 2016 to 2029 of business as usual (BaU). Blue lines show nature-positive strategies whose mean values for the 2030s and 2050s are higher than the black horizontal line ( $N=51$ ); gray dashed lines show non-nature-positive strategies ( $N=59$ )

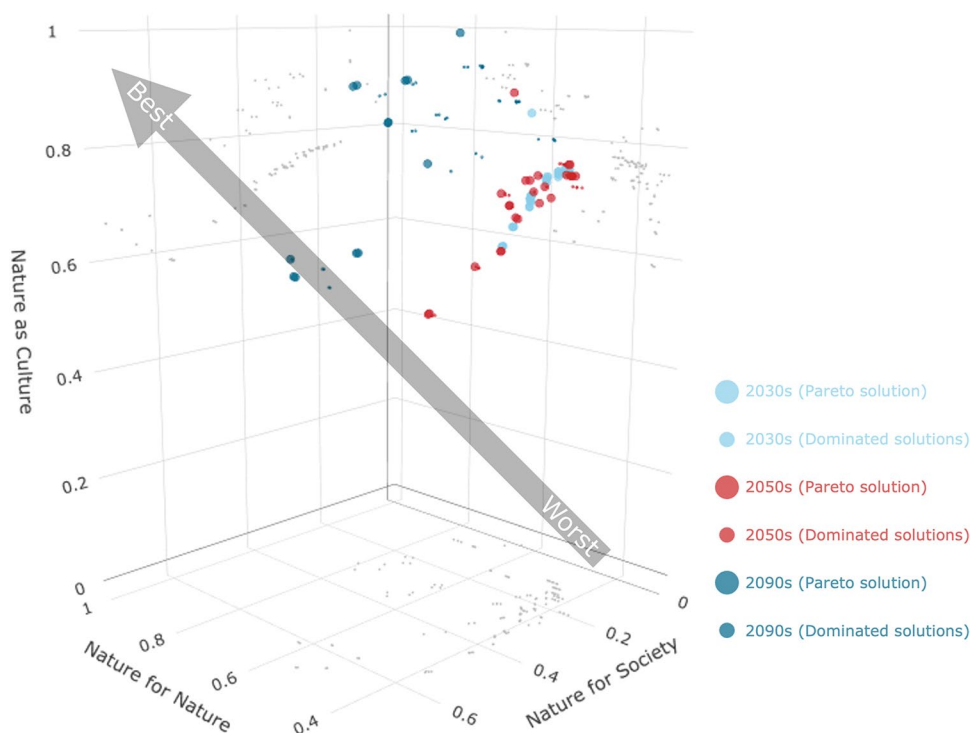
to the 2030s was small, and the mean of the indicator values decreased from the 2030s to the 2070s (Fig. 5). For individual indicators, DSI was lower than in the nature-positive strategies, the natural landscape was monotonically decreasing, and the other indicators were lower than those of the nature-positive strategies (Fig. S4).

## Step 3-1. Identifying Pareto optimal strategies

The nature-positive strategies in the three-dimensional NFF state space show synergies and trade-off relationships among the three value perspectives (Figs. 6, 8). The dominated strategies (Fig. 6 small colored plots and Fig. 7 small black plots) are nature-positive strategies, but are inferior to the Pareto optimal strategies (Fig. 6 large colored plots and Fig. 7 large colored plots). For all indicator combinations, the Pareto optimal strategy and the set of dominated strategies separated by the year approached 2100, and a trade-off relationship between the indicators emerged (Fig. 7). The correlation coefficients between (1) NN and NS indicators and (2) NS and NC indicators were consistently negative and the Pareto front was confirmed, suggesting a trade-off between these indicators (Fig. 7, 1st column). On the other hand, the NN and NC indicators were positively correlated for all time horizons, but a Pareto front emerged in the 2090s, suggesting a trade-off (Fig. 7, 3rd column).

6–18% of the nature-positive strategies were Pareto optimal strategies by three time horizons and were classified into six NFF categories (Table 4). Five of the categories were predetermined, as shown in Fig. 4B: the vertex categories of NN, NS, and NC, the NN–NS Pareto category, and the NN–NC Pareto category (Table 4), whereas the NS–NC Pareto category and NN–NS–NC Pareto category were not identified. In addition, an unexpected category, the NN and NC bundle category, was identified that maximized NN and NC indicators simultaneously (Table 4). This category appeared because the NN and NC indicators showed a synergy relationship in the 2030s and 2050s. In the 2090s, the trade-off between NN and NC indicators emerged (Fig. 7, 3rd column); then this NN and NC bundle category was changed into the NC category (Fig. 8). The number of Pareto optimal strategies varied from 20 to 7 over time (Table 4). The sensitivity analysis also showed that only 30–60% of the nature-positive strategies were classified as Pareto optimal strategies on average (Supplementary Material S7). The majority were classified as the NN–NS Pareto category. Only one or two strategies were classified as NN, NS, and NC categories for each time horizon, suggesting that the feasible solution space to reach each NFF vertex is very small.

**Fig. 6** Visualization of Nature for Nature (NN), Nature for Society (NS), and Nature as Culture/One with Nature (NC) integrated indicators in the 2030s, 2050s, and 2090s in three-dimensional space. The light blue, red, and blue plots show 51 nature-positive strategies in the 2030s, 2050s, and 2090s. Large and small plots denote the Pareto optimal and dominated strategies, respectively. All indicators are the minimum at the right bottom origin O (0, 0, 0) and the maximum at the left top (1, 1, 1). The small gray plots show the projection of the 51 strategies on each plane surface of NN, NS, and NC



### Step 3-2. Embedding Pareto optimal strategies to the NFF state space

Approximately 50% of the nature-positive strategies transitioned to other NFF categories or dominated strategies over time (Fig. 8A). The NN category in the 2030s transitioned to the dominated strategy after the 2050s. Strategies classified as NN and NC bundle category in the 2030s and 2050s, which achieved NN and NC simultaneously, were classified as NC category in the 2090s. In the NN–NS Pareto category ( $N=16$ ), most strategies were inferior after the 2050s. The remainder of the NN–NS Pareto category transitioned to the NN or NN–NC Pareto categories in the 2090s. Later, 12% of dominated strategies in the 2030s and 2050s also moved to Pareto optimal strategies.

The NFF classification results for the 2090s were embedded in the three-dimensional NFF state space, as shown in Fig. 8B. The Euclidean distances between the vertices of (1) NN and NC, (2) NN and NS, and (3) NS and NC were (1) 0.28, (2) 0.58, and (3) 0.81, respectively, unlike the equilateral triangle shape assumed in Fig. 4A. This indicates that the visions of NN and NC are in close space in the NFF state space, while NS is isolated, reflecting how similar the visions are.

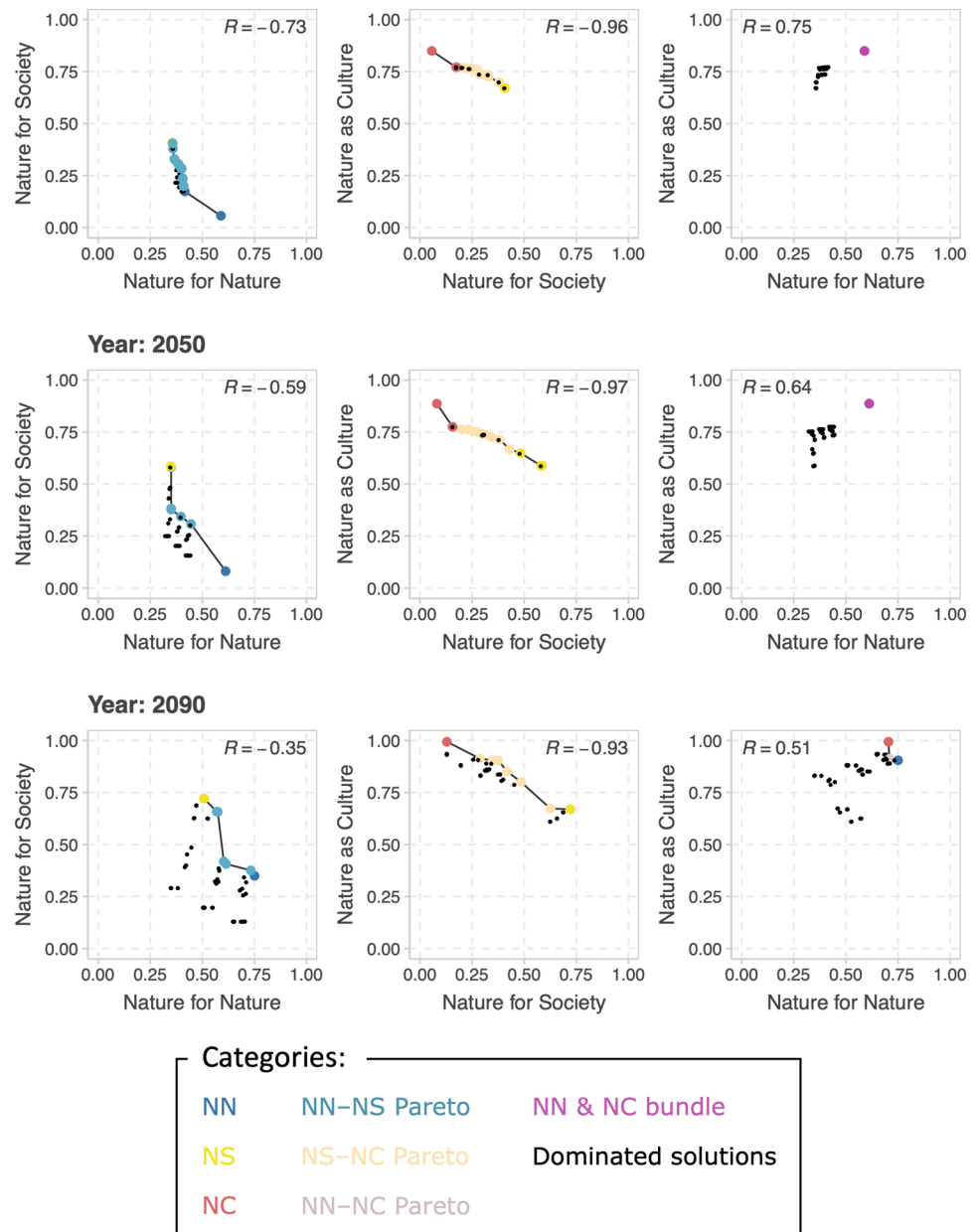
### Step 3-3. What will alternative nature futures be like?

Twenty-four strategies were Pareto optimal strategies in at least one or more time horizons, with each arriving at

a different nature future (Fig. 9). In all strategies, the NN-integrated indicator increased through the 2030s, plateaued through the 2050s, and then showed a monotonically increasing trend (Fig. 6). The HSI of Blakiston's fish owl increased monotonically through 2100, because there was no development or deforestation near the river (Fig. S5-1). The HSI of the mountain hawk eagle decreased in the long term as forest edges decreased due to the conversion of abandoned pasturelands to forest lands (Fig. S5-1). The total biomass of native trees decreased after 2040, but increased thereafter (Fig. S5-1). The NS-integrated indicator showed that the supply of timber and pasture grasses varied widely from year to year, but in some strategies increased, others remained flat, and in others decreased until 2100 (Fig. 6). The NC-integrated indicator showed an increase in 2030, leveling off in 2040, and a monotonically increasing trend thereafter (Fig. 6). The total biomass of riparian forests decreased after 2040, but increased thereafter (Fig. S5-1). The proportion of natural landscapes decreased with the introduction of renewable energy (Fig. S5-1). Because the NS indicator has a trade-off relationship with both the NN and NC indicators (Fig. 8), NS indicators were low in strategies where NC was maximized at a certain time horizon; conversely, NC indicators were low in strategies where NN and NS indicators were high (Fig. 9, left and middle panels).

Only three strategies were Pareto optimal strategies in all three time horizons (Fig. 9 left panels). The majority of the NFF category transition pattern was that the NN–NS Pareto category in the 2030s shifted to the dominated strategy in

**Fig. 7** Visualization of NN-, NS-, and NC-integrated indicators in the 2030s, 2050s, and 2090s in two-dimensional space. Large colored and small black plots denote the Pareto optimal and dominated strategies in each two-dimensional area, respectively. The colors show the NFF category (Fig. 4b). Black solid lines show the Pareto front. Numbers in each panel show the Pearson correlation coefficient



both the 2050s and 2090s ( $N = 11$ ) (Fig. D1 right panels). In strategies classified as the NS category in the 2030s and the NN-NS Pareto category in later years, the NC indicator decreased through the 2050s, indicating a significant trade-off. On the other hand, each indicator was maintained at a moderate level in the NN-NS Pareto category in all time horizons. Although this strategy was not a Pareto optimal strategy in terms of the NC indicator, it was almost a balanced solution between the three value perspectives. The most frequent strategies were NN-NS Pareto in the 2030s, and the dominated strategies in the 2050s and 2090s ( $N = 11$ ) (Fig. 9 right panels). These results suggest that ecosystem management goals in the short term are not sufficient to manage changes in mid- and long-term ecosystem values.

Thus, short-, mid-, and long-term milestones for ecosystem management are important for reducing uncertainty.

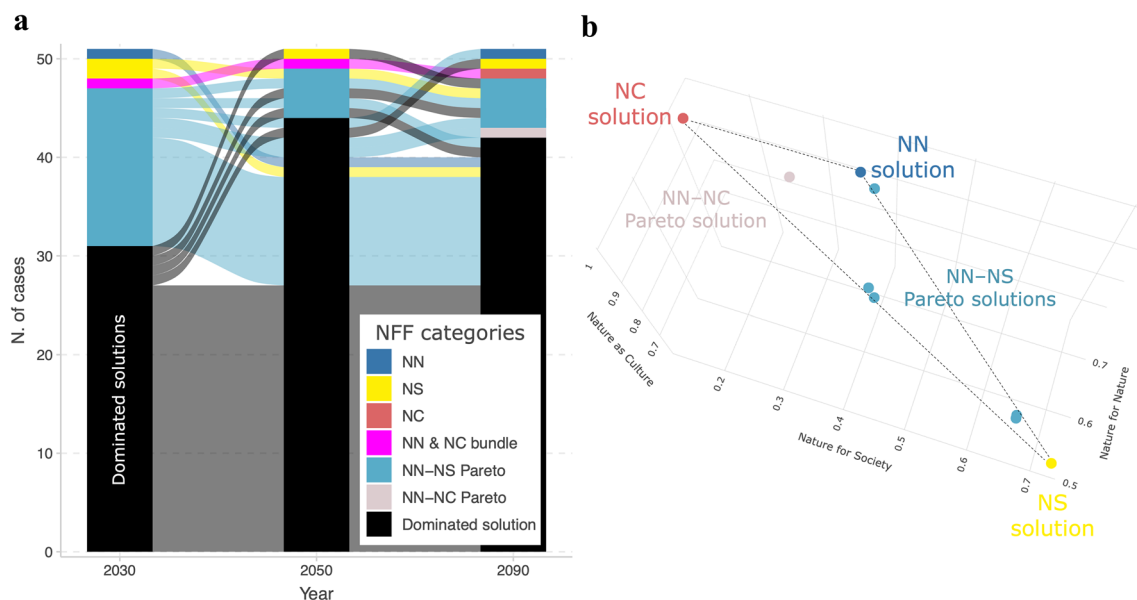
#### Step 4. Key direct driver identification

Although the rules for classifying NFF categories differed by decade, the forest harvesting method and percentage of solar PV on abandoned pastureland were critical explanatory variables (Fig. 10 and Supplementary Material S6). Here, we show the decision tree for the 2090s, as discussed in Fig. 8B as an example (Fig. 8). First, the final cutting method of the forest stands was divided into two groups: one containing nature-positive strategies and the other containing non-nature-positive strategies (Node 1). The clear-cutting generally resulted

**Table 4** Summary of the NFF category by time horizon

NFF category	Number of strategies and mean value of NN-, NS-, and NC-integrated indicators		
	2030s	2050s	2090s
NN	$N=1$ (0.42, 0.17, 0.77)	$N=0$ (NA)	$N=1$ (0.75, 0.35, 0.90)
NS	$N=2$ (0.36, 0.41, 0.67)	$N=1$ (0.35, 0.59, 0.59)	$N=1$ (0.51, 0.72, 0.67)
NC	$N=0$ (NA)	$N=0$ (NA)	$N=1$ (0.70, 0.13, 0.99)
NN and NC bundle	$N=1$ (0.59, 0.06, 0.85)	$N=1$ (0.61, 0.08, 0.89)	$N=0$ (NA)
NN–NS Pareto	$N=16$ (0.39, 0.29, 0.73)	$N=5$ (0.38, 0.40, 0.70)	$N=5$ (0.62, 0.50, 0.77)
NN–NC Pareto	$N=0$ (NA)	$N=0$ (NA)	$N=1$ (0.71, 0.26, 0.91)
Total	$N=20$ (0.40, 0.29, 0.74)	$N=7$ (0.41, 0.38, 0.71)	$N=9$ (0.64, 0.44, 0.81)

The numbers indicate the number of strategies belonging to each NFF category. The numbers in parentheses indicate the mean value of integrated indicators within each category for NN, NS, and NC, respectively



**Fig. 8** **a** Transition of NFF category of 51 nature-positive strategies from the 2030s to the 2090s. **b** Embedded NFF classification results of the 2090s in the NFF state space. Colors show the NFF categories

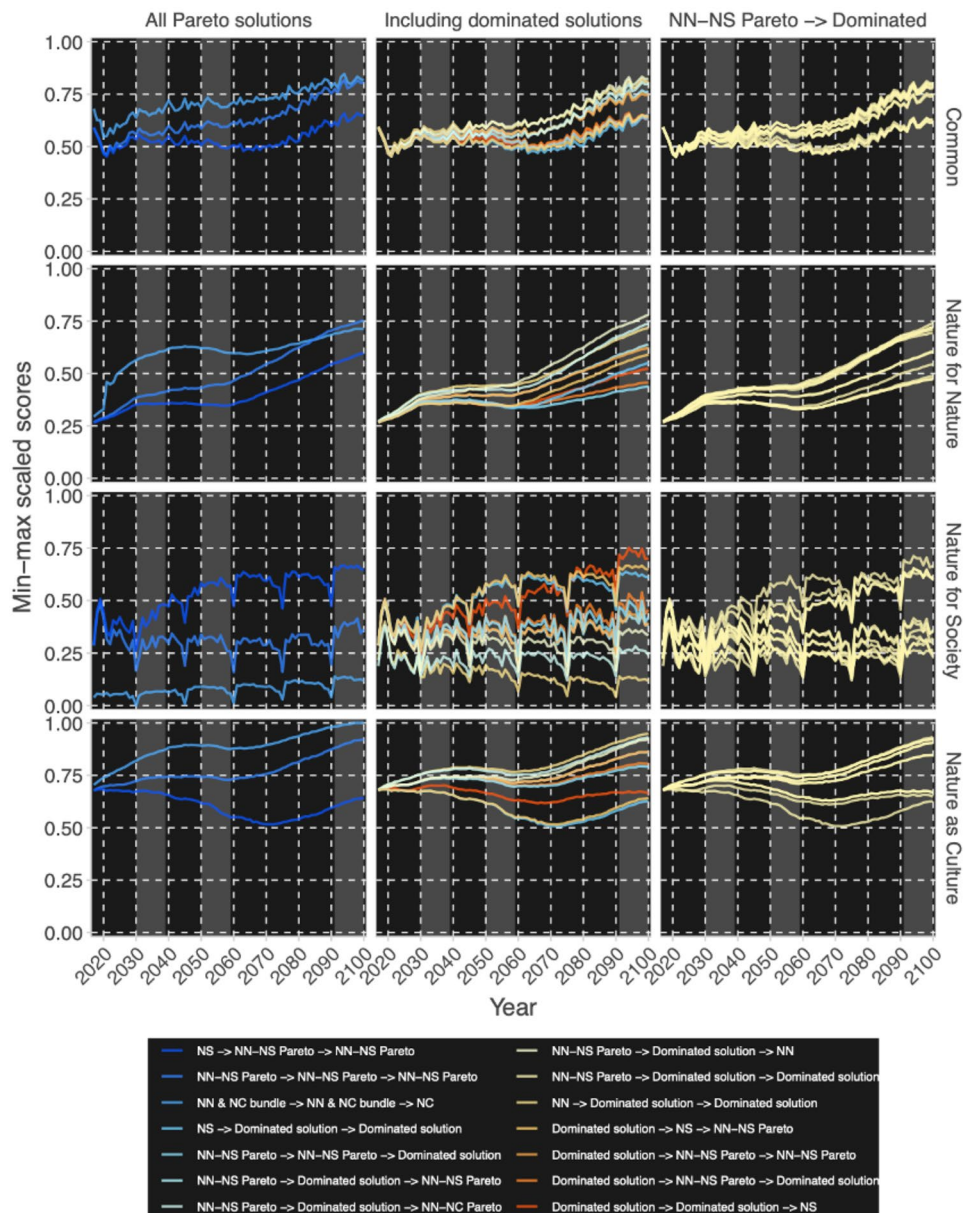
in non-nature-positive strategies, whereas the strategies with gradually withdrawn clear-cutting in forests but maintained pastureland were selected as NCs (Node 25). Next, the use of woody biomass without introducing solar PV on abandoned pastureland resulted in the NN–NC Pareto ( $N=1$ ), NN ( $N=1$ ), and dominated strategy ( $N=35$ ) categories (Node 2 left). The strategy with solar PV installed on all abandoned pasturelands was classified as non-nature-positive strategies (Node 10 right). On the other hand, a mix of solar PV and woody biomass use resulted in 10 nature-positive strategies, some of which were NS solutions ( $N=1$ ) or the NN–NS Pareto

category ( $N=2$ ) (Node 10 left). The rotation period of forestry, as well as the method of reforestation after final cutting and the expansion speed of abandoned pastureland, all contributed to the divergence of these individual strategies.

## Discussion

By simulating a combination of plausible management strategies, this study was able to indicate the range of nature-positive futures (Specification 1), while simultaneously

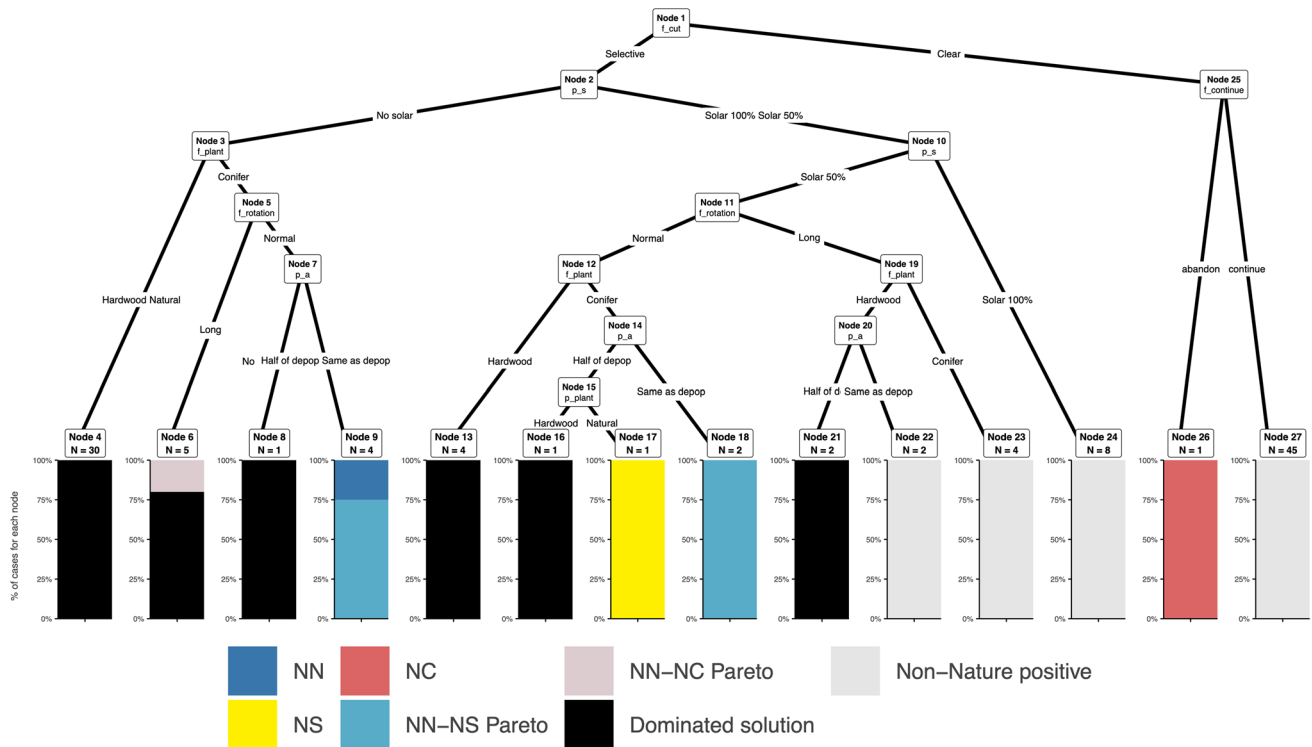
**Fig. 9** Strategies where one or more of the nature-positive strategies were classified as Pareto optimal solutions in at least one or more time horizons ( $N=24$ ). The line colors indicate the transition pattern of NFF categories in the 2030s, 2050s, and 2090s. The left panel represents strategies with Pareto optimal strategies in all years ( $N=3$ ), the right panel represents strategies classified as the NN–NS Pareto category in the 2030s, which shifted to the dominated strategy in both the 2050s and 2090s ( $N=11$ ), and the middle panel represents the other strategies ( $N=10$ )



identifying the desired targets in terms of NFF, pathways to those targets (Specification 2), and key response options (Specification 3). This study defined NFF categories at each vertex and edge of the NFF triangle as Pareto optimal strategies between NFF indicators. This definition can contribute to the quantification of diverse desirable alternatives in NFF. Moreover, this study found that NFF categories transition over time, demonstrating that the values in each management strategy were unstable in the future. Some of the nature-positive futures were classified as the vertex or edge of the NFF triangle (Figs. 7, 9), but the number of these strategies was only 25 out of 110 (Fig. 9). The sensitivity analysis also showed the strategies that satisfy the NFF visions are limited regardless of the weight  $w_{c,i}$  (Supplementary Material S7).

An ecosystem management option did not always guarantee maximizing or maintaining the same value in all time horizons.

Several landscape models have applied a multi-objective optimization framework to visualize Pareto fronts between agricultural production and environmental indicators, as well as between forest carbon fixation, biomass, and yield (Coleman et al. 2017; Marques et al. 2020). This study shows that NFF can be applied to existing landscape change modeling to analyze the interlinkages between different visions constrained by biodiversity conservation goals. Our protocol is scalable because it is not dependent on a specific model or landscape. Furthermore, to propose various candidates for nature future scenarios, it is encouraged to exhaustively test



**Fig. 10** Decision tree of the 2090s

the combinations of ecosystem management. In this study, we performed a grid search over 110 pre-defined strategies: all strategies assumed stakeholders will not change strategy toward 2100 to reduce iterations because of the limitations of our computational resources. However, metaheuristic optimization, such as evolutionary algorithms, would also be useful to explore optimal strategies from a huge number of combinations (Groot and Rossing 2011).

In the following, we discuss: (1) implications for local policy design and (2) future scenarios and modeling of the NFF to support a transformative change in socio-ecological systems in local communities.

## Implications for local agenda setting and policy design

### Can our protocol help identify alternative policy options?

The final cutting in forests and utilization of abandoned pastureland contributed to the classification of NFF categories (Figs. 10 and S6), suggesting that nature future scenarios are oriented by a combination of response options. In Japan, coniferous plantation forests expanded post-WWII (Tanimoto 2006), but the conversion to broadleaf forests is considered throughout the country for biodiversity conservation (Forest Agency 2021). The forest plan for this area also describes the conversion to broadleaf forests through

selective cutting (Akkeshi Town 2017; Hokkaido Prefecture 2017c). The results of this study suggest that the use of forest management practices to balance timber production and ecosystem conservation will contribute to the nature-positive future of plantation forests. Among the response options identified in the PANCES Project (see Table 1), the following should be considered: promotion of sustainable forest management, formulation of forest zoning, promotion of plantation forest management, guidance from a single-storied forest to a multi-storied forest or natural forest, introduction of forest environmental tax to manage abandoned forests, support for new employment in forestry, and training of leaders (PANCES Project 2022).

In terms of pastureland management, the features of the Pareto optimal strategies were: (1) pastureland is maintained, or if pastureland is abandoned, it is (2) converted to forest by natural regeneration, or (3) a mix of solar PV and natural regeneration is installed. Depopulation and outflow from rural areas to urban areas (NIPSSR 2018) and the introduction of renewable energy to the landscape for decarbonization (METI 2021) are current megatrends in Japan. Thus, the priority areas for agricultural landscape management and renewable energy should be identified, reflecting the local characteristics and stakeholders' interests. Response options for agriculture, such as the promotion of a direct payment system, consolidating and increasing the scale of agricultural land, and promoting mechanization in the agricultural



sector, should be implemented to maintain the agricultural landscape while at the same time carefully designing the conversion of abandoned pastureland (Table 1). Thus, our process successfully identified policy implications to achieve desirable futures that avoid non-nature-positive states by treating the direct drivers among multiple sectors in a landscape change model.

### Can our approach draw insights to transform indirect drivers?

Indirect drivers in multiple sectors, such as forestry, dairy farming, the energy industry, and fisheries, influence the direct drivers that lead to the divergence of nature futures. Therefore, cross-sectoral cooperation among stakeholders with different value perspectives is a key lever in this study area (IPBES 2019). The vertices of the NN and NC were similar in the NFF state space (Table 4 and Fig. 8B) without a clear trade-off relationship. The reason why NN and NC indicators did not show the trade-off, i.e., Pareto front, was the similarity of indicators. In this region, the previous questionnaire survey to stakeholders revealed that local identities (Akkeshi-ness) were supported by fisheries, agriculture, and tourism resources closely related to natural landscapes evaluated by NN indicators (Tajima et al. 2021). Two habitat suitability indices of NN and two watershed indicators of NC decreased with increasing installation of solar PV (Fig. S5). Moreover, the aboveground biomass of native tree species and that of riparian forests showed similar dynamics (Fig. S5). Thus, both NN and NC indicators increased at the same time and did not show the Pareto front (Fig. 7). The result suggested that it is possible to design win–win cooperation among the forest, land, and marine stakeholders in the region who have different visions: (1) preserve nature's diversity and functions and (2) maintain the livelihoods and the natural landscape which support local identity and culture (Table 2).

In contrast, the NS indicator showed a clear trade-off relationship with the NC and NN indicators. Thus, if the stakeholders of an ecosystem service are outside the region, there may be hidden conflicts with the stakeholders in the watershed. In particular, unplanned renewable energy installations cause conflicts between energy production, local communities, and local SDG (Akita et al. 2020; Schumacher 2017; Schwanitz et al. 2017). Therefore, cross-sectoral cooperation among stakeholders inside and outside the region is another important lever. For example, these levers should work on the following leverage points (IPBES 2019):

1. Unleash values by discussing local identities and embracing diverse visions of a good quality of life

through sharing central value perspectives among stakeholders.

2. The supply of energy, which alters the landscape structure and influences the NN, NC, and NS indicators, should be community driven to internalize externalities and telecoupling. Moreover, to minimize the ecological impacts, energy demand within the region should be reduced in line with future population decline and decarbonization measures.

Our results also demonstrate that balancing intrinsic and instrumental values in the short term does not always guarantee long-term balanced futures. For example, the majority of strategies classified as the NN–NS Pareto category in the 2030s resulted in the dominated strategy category after the 2050s. Furthermore, rural areas in Japan are expecting an increase in migration and related populations, who continuously have relationships with a specific region against depopulation (Hori et al. 2021; Naitou et al. 2019). Thus, the structure and relationships of stakeholders in the future assumed in the NFF might differ from the current situation. For envisioning long-term nature future scenarios, the inclusion of future generations' voices is also essential to consider changes in stakeholders (Rana et al. 2020).

### Implications for future scenarios and models of the NFF

#### Localizing NFF narratives consistent with local policies

When developing NFF visions, values, and indicators at local scales, such as those shown in Table 2, mapping to various existing local strategies is necessary. The 2020s is a decade of action; for example, in Japan, local municipalities are developing plans to achieve the SDGs, climate change mitigation and adaptation, and biodiversity conservation (CAO 2022; MOE 2021, 2022). Since these existing environmental and sustainability policies might overlap with the visions and values described in the NFF, a procedure for translating them into the NFF context will help a local administrator operationalize the NFF.

Variety in the definition of a desirable future should also be considered in future research. This study used the narrative of nature positive as a constraint to select positive strategies, but the degree of recovery is also important. Moreover, there are other candidates for the constraints, such as area-based conservation measures, decarbonization targets, and other socio-economic targets, such as food self-sufficiency, labor, and financial requirements. Considering local nature futures with global-, regional-, or national-scale megatrends as boundary conditions is important. The sub-national-scale SSP scenario narratives and their spatially explicit

socio-economic dataset can be used as the constraints of NFF modeling (Chen et al. 2020; NIES 2021).

The indicators used to evaluate NFF visions and values are multidimensional (Sarkar et al. 2020; Siqueira-Gay et al. 2020); thus, it is necessary to develop a local reference indicator set to analyze these trade-offs. Our 15 NFF indicators were developed from administrative planning documents and previous studies that can be evaluated by LULC, biomass, and other outputs of landscape change models. The challenge is to evaluate relational values ascribed to nature, such as a way of life and sense of place (Saito et al. 2022). In addition, the state variables of the social system that influence stakeholders' values and behaviors, such as localized SDG indicators, are another challenge.

Moreover, this study calculated the integrated indicator value as the arithmetic means of the min–max scaled indicators for the Common, NN, NS, and NC categories with equal  $w_{c,i}$ . The sensitivity analysis showed that the number of nature-positive strategies and Pareto optimal strategies are both sensitive for the  $w_{c,i}$  values with complex interactions (Supplementary Material S7). The use of analytic hierarchy process (AHP) for integrating indicators is one option to reflect different current stakeholders' preferences (e.g., Abelson et al. 2021). However, in mid- to long-term simulation, (1) the choice of indicators and (2) setting a plausible stakeholders' preference, i.e.,  $w_{c,i}$ , for each decade (2030s, 2050s, and 2090s) are important issues for future research because the stakeholders themselves are also dynamic. Another option is to identify Pareto optimal solutions among all individual indicators to visualize trade-off and bundle relationships (e.g., Groot et al. 2010; Hu et al. 2015).

### Coupling landscape models and indirect driver models

A major limitation of this study was that only direct drivers were modeled. Thus, policy implications for indirect drivers, leverage points, and levers are limited to those closely related to ecosystem management activities. In climate change research, a broad range of indirect drivers are discussed, including lifestyle changes and food system transformation. For example, the identification of hotspots with a high impact on CO<sub>2</sub> emissions enabled the design of levers and leverage points for lifestyle changes using a participatory approach at the city scale (IGES 2019; Koide et al. 2021a, b).

Some landscape modeling studies have incorporated agents of ecosystem managers to simulate feedback between socio-ecological systems (Kim et al. 2021). These studies have primarily focused on agent-based landscape change modeling (Gibon et al. 2010; Sotnik 2018; Sotnik et al. 2021), which focuses on specific stakeholders such as forestry and agricultural workers. For example, an extension of LANDIS-II can simulate the social learning of agents and

impact spatially explicit forest management (Sotnik et al. 2021). Including citizen agents of the target landscape and stakeholder agents outside the region will allow for an evaluation of the influence of indirect factors.

On the other hand, connecting with the models of indirect drivers helps quantify the pathway to transform entire socio-ecological systems. For example, the discussion of socio-economic changes in climate change research is supported by integrated assessment models that connect global climate models with socio-economic models. A local-scale study successfully coupled a macro socio-economic model and an optimization model of renewable energy installation and visualized the future (Hori et al. 2020). Off-line coupling of the local landscape change models and socio-economic factors through the social demand of nature's value and social resource constraints will enable a more comprehensive implication for transforming socio-ecological systems.

## Conclusion

The NFF is a tool that can evaluate nature from different perspectives: intrinsic, instrumental, and relational values. This study developed a protocol for applying NFF to scenarios and models at a landscape scale. We used the nature-positive concept as a constraint to filter plausible and feasible solutions, evaluated Pareto optimality in the three value aspects of the NFF, and identified pathways to reach the vertices and edges of the triangle. Ecosystem management strategies that reached the vertices and edges of the NFF triangles existed, but the number of these strategies was small. Selective cutting of forestry was the important key response option to achieve nature-positive futures. The response options to achieve Pareto optimal strategies differed between NFF visions. Not only forestry and pastureland management, but also renewable energy installation altered the consequences. In addition, only a few strategies were able to consistently maximize or maintain the same value perspectives, suggesting the importance of setting visions for landscape management that can be sustained medium to long term. These results also imply the potential for stakeholder collaboration within the region. Further local practices in scenarios and modeling that explicitly incorporate changing stakeholder values and indirect drivers are needed to envision nature-positive and holistic transformative changes.

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**Data availability** Input data and analysis scripts have deposited in our GitHub repository: <https://github.com/hagachi/Project-bekambe-NFF>. Redistribution of the forest registers, which were used for initializing landscapes, are restricted by the Forest Management Bureau of Hokkaido Prefecture. Requests to access the datasets should be directed to the bureau: <https://www.rinya.maff.go.jp/hokkaido/keikaku/map/map.html> (in Japanese).

The authors have no relevant financial or non-financial interests to disclose.

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