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Exploring the contribution of nature-based solutions for environmental challenges in the Netherlands

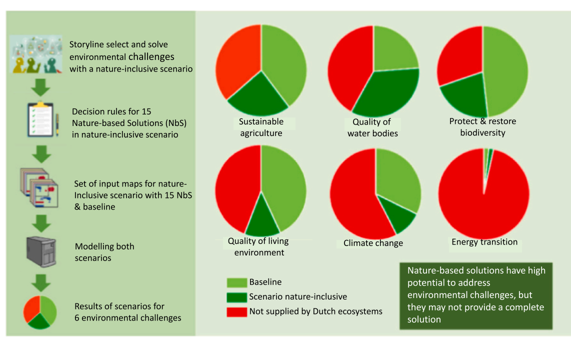
Bart De Knegt [a,b,*], Bas C. Breman [a], Solen Le Clec'h [b], Arjen Van Hinsberg [c], Marjolein E. Lof [b], Rogier Pouwels [a], Hans D. Roelofsen [a], Rob Alkemade [b,c]

[a] Wageningen Environmental Research, Wageningen University & Research, Wageningen, the Netherlands
[b] Earth Systems and Global Change Group, Wageningen University & Research, Wageningen, the Netherlands
[c] PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands

HIGHLIGHTS

- Evaluating the effectiveness of Nature-Based Solutions (NbS) is critically needed.
- Assessing a future scenario with the widespread implementation of NbS.
- We evaluated a nature-inclusive scenario using ecosystem services models.
- NbS significantly contribute to solve environmental challenges and policy targets.
- NbS have high potential to solve environmental challenges, but are no full solution.

GRAPHICAL ABSTRACT



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ABSTRACT

Nature-based solutions (NbS) offer a promising and sustainable approach to addressing multiple environmental challenges, including climate change, pollution, and biodiversity loss. Despite the potential of NbS, their actual effectiveness in solving these challenges remains uncertain. Therefore, this study evaluates the contribution of NbS implemented in a nature-inclusive scenario for six environmental challenges and associated policy targets in the Netherlands. Fifteen different NbS were applied in the scenario in urban, agricultural, aquatic, and protected nature areas, with measures like flower field margins, green roofs, groundwater level management, and river restoration. The spatially-explicit Natural Capital Model was used to quantify the effectiveness of all applied NbS at a national-scale. Results show NbS significantly contribute to simultaneously solving all six assessed environmental challenges. The most significant impact was seen in improving the quality of water bodies (+34 %), making agriculture more sustainable (+24 %), and protecting and restoring biodiversity (+22 %). The contribution of NbS to address the quality of the living environment (+13 %), climate change (+10 %), and the energy transition was less effective (+2 %). Furthermore, NbS can help to achieve sectoral policy targets at the global, EU, and national levels, including those related to the Birds Habitats Directives, carbon emission, and pesticide reduction targets. This study highlights the potential of NbS to effectively address multiple environmental

* Corresponding author at: Droevendaalsesteeg 3-3 A, 6708 PB Wageningen, the Netherlands.
E-mail addresses: bart.deknegt@wur.nl (B. De Knegt), bas.breman@wur.nl (B.C. Breman), solen.leclech@wur.nl (S. Le Clec'h), arjen.vanhinsberg@pbl.nl (A. Van Hinsberg), marjolein.lof@wur.nl (M.E. Lof), rogier.pouwels@wur.nl (R. Pouwels), hans.roelofsen@wur.nl (H.D. Roelofsen), rob.alkemade@pbl.nl (R. Alkemade).

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challenges, although they do not provide a complete solution, and suggests that future research could focus on identifying even more effective ways to implement NbS, and to mainstream their use in policy and practice.

1. Introduction

Climate change, pollution and loss of biodiversity are among the most urgent environmental pressures that affect human well-being (Steffen et al., 2015), but until now policy makers have not been able to tackle these interrelated challenges simultaneously and effectively. There is an urgent need to solve these challenges to avoid further loss of human well-being and biodiversity.

International organizations such as IPCC and IPBES call for urgent and drastic action and a transformative change to address the challenges that negatively affect human well-being (IPBES, 2019; Pörtner et al., 2021). Policy makers have set sustainability and biodiversity targets, such as those embodied in the Aichi Biodiversity Targets and the 2030 Agenda for Sustainable Development (UN, 2015), to tackle societal challenges at a global and national scale. So far, actions to achieve these targets have not been sufficient (IPBES, 2019). Future projections based on current trajectories of international sustainability and biodiversity targets, indicate that most of the targets will not be achieved (IPBES, 2019). Consequently, the IPBES in its recent global assessment states that ongoing rapid declines of biodiversity, ecosystem functions and services can only be countered with a transformative change of multiple economic sectors and at multiple scales (IPBES, 2019). An important element of this change is to address the interdependent challenges in an integrated way to avoid negative trade-offs and unintended feedbacks (Larrosa et al., 2016).

Nature-based solutions (NbS) are a promising integrative concept to help solve environmental challenges simultaneously and sustainably (Keesstra et al., 2018). Several definitions of NbS exist, e.g., stemming from IUCN, EC and UNEA (Cohen-Shacham et al., 2016; European-Commission, 2015; UNEA, 2022)). Common core features of NbS across these definitions are interventions that: (1) are inspired and powered by nature; (2) address societal challenges or resolve problems; (3) provide multiple services/benefits, including human well-being and biodiversity gain; and (4) are of high effectiveness and economic efficiency (Sowińska-Świerkosz and García, 2022). This study delves into each of these four critical attributes.

Many scholars relate NbS to the concept of ecosystem services (ES) and natural capital (Cohen-Shacham et al., 2016). ES are considered to be the multiple beneficial flows powered by nature offering provisioning, regulating and cultural goods and services, and hence contributing to human well-being (De Groot et al., 2012). For instance, ecosystems play a crucial role in mitigating the impacts of climate change by sequestering carbon and fostering adaptation to a rapidly changing environment, vegetation can help to purify the air from pollutants. Flower field margins can enhance the presence of natural enemies in agricultural landscapes that control pests and reduce the use of pesticides. In other words NbS are actions aimed to solve these environmental challenges by maintaining and enhancing the supply of ES (Albert et al., 2019).

Although evidence on the effectiveness of NbS is increasing rapidly, the full potential of NbS on multiple environmental challenges at national scale, has not been rigorously assessed. Firstly, most studies are qualitative by nature and do not measure the extent of the contribution of NbS (Sowińska-Świerkosz and García, 2022). The quantitative evidence that is available in the literature does suggest that NbS is effective (Keesstra et al., 2018; Paulin et al., 2020) and is a necessary addition besides more technical solutions (Girardin et al., 2021). Secondly, integrated studies that assess multiple NbS on multiple environmental challenges and policy targets are still limited (Brears, 2020). Previous research has primarily focused on the (co-)benefits of NbS within the context of a single ES, policy target, or environmental challenge (Veerkamp et al., 2021). Finally, most studies are performed on a local or regional scale, which leaves the effects on policy targets, that are mostly formulated at the national level, less studied (Schröter et al., 2016). Currently, there is a notable lack of comprehensive studies that combine these aforementioned aspects and quantitatively assess the extent of NbS contributions to multiple environmental challenges and policy targets at the national level.

Yet, there is a critical need for knowledge to integrate evidence-based NbS into international, national and local policies and to support key stakeholders in adopting NbS on their lands (Seddon et al., 2020). Knowledge gaps exist regarding approaches to landscape planning with NbS, enabling stakeholders and policy to formulate effective policy strategies, while concurrently giving clarity on where and how NbS interventions can be most impactful. Key steps, including understanding the challenges, making visions and scenarios, assessing of potential impacts and formulating solution strategies are important steps to facilitate planning of NbS and provide further steps towards mainstreaming (Albert et al., 2021).

This study aims to quantify the national scale impact of utilizing NbS of a nature-inclusive scenario to address multiple environmental challenges. We collaboratively developed the narrative and spatially explicit maps for this scenario in close consultation with key stakeholders at the national level. This scenario is grounded in the widespread implementation of a range of advanced yet proven NbS. Then we assessed this scenario on the contribution to environmental challenges and associated policy targets via the delivery of ES using the Natural Capital Model (De Knegt et al., 2022). The six assessed environmental challenges were: transition to a sustainable agriculture, protection and restoration of biodiversity, good quality of waterbodies, good quality of the living environment, climate change mitigation and adaptation and the transition to the production of renewable energy. The assessed policy targets were: Dutch targets to decrease the ecological footprint and to increase the amount of renewable energy, EU targets of the Birds and Habitats Directives, the Water Framework Directive, the reduction of pesticides, the improvement of pollinator species, the reduction of greenhouse gasses and the improvement of human health by reducing air pollution.

2. Materials and methods

2.1. Framework and relation between key concepts

The framework we used builds upon Albert et al. (2019) (Fig. 1). It incorporates the four core features of NbS namely: powered by nature, address sustainability challenges, multifunctionality and assesses efficiency as an outcome (Sowińska-Świerkosz and García, 2022).

First, NbS are powered by nature and enhance ecosystem elements and structures that influence ecological processes and functions in order to deliver multiple ES (Cohen-Shacham et al., 2016). The potential supply of ES is defined as the amount of service that can be generated by an ecosystem independent of demand for the service (Hein et al., 2016). To increase the supply of ES, policy and practice can implement NbS that affect ecosystem type, extent, quality and functioning. The demand for ES is characterized as both consumption and desire, aligning with distinct ES categories—an approach consistent with the perspective presented by Wolff et al. (2015). The demand for the majority of provisioning services, along with a few cultural services, is reflected in consumption. In contrast, the demand for most regulating services and cultural amenities can be gauged through desires, incorporating preferences and the imperative for risk prevention. ES mismatches are defined as the differences in quality or quantity that occur between ES supply and demand (Geijzendorffer et al., 2015). ES mismatches may cause actual demand for specific ES to be unsatisfied (Wei et al., 2017).

The second aspect of NbS that was assessed is the challenges they can solve via the delivery of provision, regulating, and cultural ES. Since we assessed the challenges within the environmental domain, we called them environmental challenges after UNEA (2022). NbS and ES are the connections within the social-ecological system. For many, but not for all environmental challenges policy formulated specific policy targets. For instance for climate adaptation, quality of the living environment and to make agriculture more sustainable, no overarching policy targets have been formulated in the Netherlands.

The third aspect we examined regarding NbS was its multi-functionality. We evaluated how NbS may impact twelve ES and six environmental challenges, including biodiversity. This assessment provides valuable insights into whether synergies or trade-offs exist between these ES and challenges.

The final facet of the NbS definition pertains to its efficiency. We employed models to gauge the potential effectiveness of NbS in addressing environmental challenges.

2.2. Study area

The Netherlands is located in north-western Europe and has a low-lying elevation and flat topography, with only about 50 % of its land exceeding 1 m above sea level. The Netherlands is a typical delta area, with three major rivers - the Rhine, Meuse and the Scheldt - flowing through it into the North Sea. The northern and western half of the Netherlands is characterized by clay (8000 km^2) and peat soils (3000 km^2) and with shallow groundwater levels prevailing in much of the area. The central, southern and eastern half is characterized by sand (14,000 km^2) and loess soils (900 km^2), with shallow to relatively deep groundwater levels. Currently, about 50 % of the surface area is agricultural land, 20 % is "semi-natural" area and forest, 15 % is urban and infrastructure area and 10 % is surface water. While the Netherlands host some nearly pristine ecosystems, the majority are either man-made or significantly shaped and influenced by human activities. Biodiversity is mostly associated with semi-natural ecosystems that have limited degrees of naturalness. With a population of 17.6 million people, living within a total land area of 33,500 km^2, the Netherlands is the 16th most densely populated country in the world and the second-most densely populated country in the European Union. Although it is a small country, agricultural input and output are high. The Netherlands has been selected as a study area due to its status as a prime example of an industrialized country. Generalization of the method and output apply to other highly industrialized countries, for instance for other countries in Europe. The decision is further supported by the abundance of high-resolution data, the availability of detailed ES models for assessing scenario impacts, and the Dutch government's ambitious commitment to integrating NbS into both policy and practice.

2.3. Five step approach

PBL Netherlands Assessment Agency, in collaboration with Wageningen University & Research is responsible for providing policy and decision makers with insight into the future of Dutch nature every four years. For this edition we followed a five-step approach to quantify the contribution of large-scale deployment of NbS on environmental challenges and associated policy targets (Fig. 2). In the first step a storyline was developed in close collaboration with key actors from policy and practice for a nature-inclusive future of the Netherlands. Secondly, a selection was made of the most relevant environmental challenges and associated policy targets in the Netherlands for which nature could potentially offer a solution. Thirdly, we identified several proven, promising and innovative NbS for each of the selected challenges, with the goal of addressing as much of the challenges as possible. In the fourth step we developed a spatially explicit scenario for the future of nature in which the selected NbS were implemented at a large scale throughout the Netherlands. Soil and hydrology maps, along with maps indicating the absence of ES, were employed to identify the most promising locations where NbS effectiveness is anticipated to be high. In the fifth and final step, the contribution of all NbS to solve environmental challenges and policy targets was estimated at national level using the Natural Capital Model (NC-Model) (De Knegt et al., 2022) for the current situation (baseline) and the nature-inclusive scenario.

In our study, we proceed with the premise of relatively stable climate conditions for NbS and consistent policy targets throughout the study period. However, we justify this assumption by acknowledging the dynamic and evolving nature of ecosystems, often experiencing rapid changes in response to climate shifts. The unpredictability stemming from these climate-induced alterations emphasizes the need for a nuanced understanding of ecosystems. Additionally, while our fixed policy targets provide a framework, it is essential to recognize that addressing the climate-dynamic aspect of ecosystems requires ongoing adaptability and responsiveness in policy formulation.

2.3.1. Step 1: development of storyline for a nature-inclusive future

A storyline was developed in close cooperation with key stakeholders to lay down the focus and principles for a normative future scenario for the Netherlands in 2050. This storyline was based both on interviews and a workshop with key stakeholders. Twenty-four interviews were conducted with key actors from the field of nature, landscape and water management. These organizations and key actors were selected based on their prominent roles, expertise, and influence in the domains of nature,

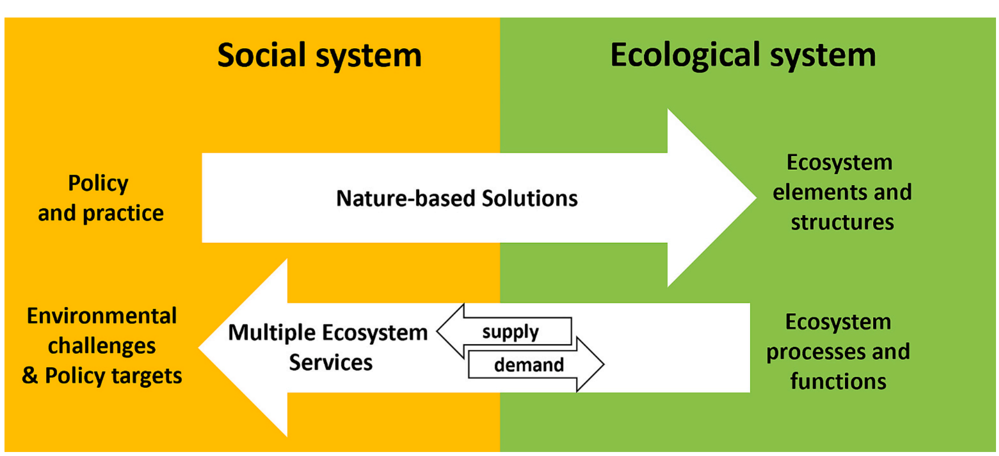

Fig. 1. Nature-based Solutions are actions that enhance ecosystem services to address environmental challenges and meet policy targets in socio-ecological systems (modified from Albert et al. (2019)).

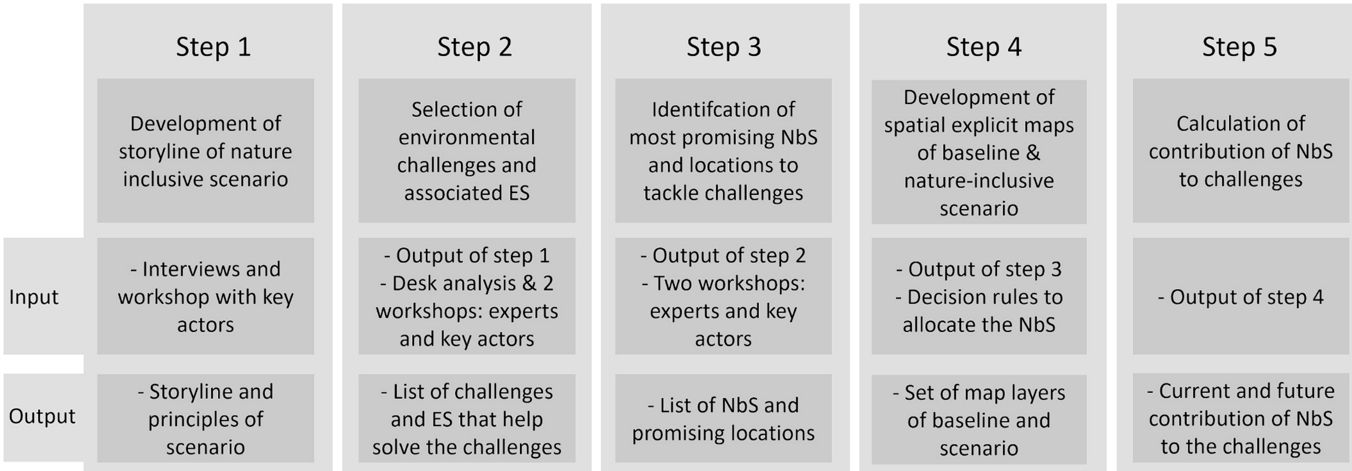

Fig. 2. Five steps of the general approach.

landscape, and water management, aiming to capture a comprehensive understanding of the subject through the twenty-four conducted interviews. Questions were focussed on their view on nature, current challenges, solutions, and what is important for the future of nature. Interviews were semi-structured and lasted for 60–90 min each. The key actors represented a diverse range of entities, including seven representatives from ministries on the national scale (e.g., the Ministry of Agriculture, Nature, and Food Quality, and the Ministry of Economic Affairs and Climate Policy), six representatives of provincial governmental organizations (such as the Province of Zuid-Holland and the Province of Noord-Brabant), five representatives from nature conservation organizations (The State Forestry Department, the Society for the Preservation of Nature Monuments in the Netherlands, WWF), four farmer organizations (such as the Land and Horticulture Organization and Farm Nature), and two representatives from regional water authorities. Results of the interviews were analysed to draw meaningful results. This involved sorting the data into categories and looking for patterns and trends. This semi-structured interview approach provided an ideal framework for obtaining open-ended data and insights. The results were discussed in a workshop of two and a half hours with the interviewees using the World Café Method (Brown, 2010), and these results were further refined. The key stakeholders shared their perspectives on a voluntary basis, and the entire process spanned a duration of six months.

A nature-inclusive storyline was developed (Pouwels et al., 2020)and based on the concept of land sharing, contrasting with a previous scenario that focused on achieving biodiversity targets through land sparing, which designates specific conservation areas for biodiversity conservation separated from agricultural area (Locke, 2014; Wilson, 2016). The concept of nature-inclusiveness revolves around the concept of land sharing, a narrative that encourages development practices to integrate with and support nature (Tscharntke et al., 2012). It highlights the importance of simultaneously protecting and utilizing nature to meet societal needs. This concept is preferred over traditional land-sparing approaches, as it promotes a holistic and harmonious coexistence between human activities and natural ecosystems, fostering long-term environmental and societal benefits. The storyline provides inspiration for policy makers to embrace a more sustainable approach to development, with a focus on protecting and using nature as a sustainable way to meet the needs of society.

This nature-inclusive scenario utilizes NbS in urban, agricultural, and also protected nature areas to tackle environmental challenges (Breman et al., 2022). Nature-inclusiveness refers to an approach that integrates and incorporates nature and natural processes into various sectors and aspects of society, including urban planning, agriculture, and protected nature areas. The scenario also aims at preserving biodiversity both within and outside protected nature areas, and ensuring that human activities remain within planetary boundaries (Rockström et al., 2009). A nature-inclusive approach seeks a future in which both people and the natural world mutually benefit. Additionally, the scenario promotes a diet that includes a higher proportion of plant-based proteins instead of animal-based proteins, which decreases the need for agricultural area, reduces nitrogen and CO_2 emissions and promotes human health. Nature and biodiversity are not framed as restrictive to economic activities, but are seen as essential for a sustainable economy (Obrecht et al., 2021). The scenario relies on a transformative change of land use and management (European-Commission, 2019) and to live in harmony with nature (UN, 2010).

2.3.2. *Step 2: selection of environmental challenges and associated ES*

A compilation of the most pertinent and pressing environmental challenges for the Netherlands was accomplished through a comprehensive approach involving interviews, literature review, expert insights, and two workshops. Firstly, the series of twenty four interviews (see Section 2.3.1) were analysed in a semi-structured way and yielded a list of environmental challenges and associated policy goals, and the number of times it was mentioned by the interviewees. In addition, an analysis of the existing environmental policy objectives was carried out by compiling the most topical policy targets for the Netherlands from policy literature and prior policy evaluation studies.

Eight senior experts in ecology, who work at the science-policy interface within the WUR and PBL organization, identified the most important ES in a workshop to address each of the above mentioned environmental challenges, drawing from recent literature and their expert knowledge. These experts had backgrounds in terrestrial ecology and aquatic ecology, soil and water systems, agro-ecology, urban ecology and ES.

The list of environmental challenges and policy targets from the interviews and the ES that were identified by the experts were discussed in a two and a half hour workshop with the key actors mentioned in Section 2.3.1. This resulted in the final set of environmental challenges, policy targets and associated ES.

2.3.3. *Step 3: identification of promising NbS*

To identify the most promising NbS for addressing the identified environmental challenges, the MAYA principle, which stands for 'Most Advanced, Yet Acceptable,' was applied. NbS were selected based on their innovative and proven effectiveness ('Most Advanced') with consideration for their potential for large-scale implementation in the future ('Yet Acceptable'). The most promising NbS for each of the selected environmental challenges were determined through a two-step workshop process.

In the first three-hour workshop, a group of eight senior experts (mentioned in Section 2.3.2) put forth a list of NbS options for each environmental challenge. Initially, they independently suggested NbS through a desk study and expert knowledge, aligning with the MAYA principle for each challenge. Subsequently, they engaged in a group discussion to arrive at a final list of NbS for each environmental challenge. For instance, strip cropping, a method proven to be effective in natural pest control, was recognized as a promising NbS for use on arable lands to promote sustainable agriculture in the scenario (Labrie et al., 2016).

A second workshop of two and a half hours was conducted with the previously mentioned group of key actors (see Section 2.3.1), enabling them to provide feedback (stickering and group discussion) and reflect on the proposed lists of NbS for each environmental challenge.

2.3.4. Step 4: development of scenario GIS maps

Two sets of GIS map layers were prepared, one for the current situation (baseline) from 2020 and one for the nature-inclusive scenario (Table 1). The set of maps includes three types of map layers: a) land cover and land use maps, b) maps with abiotic conditions, such as a soil map, water table, soil pH, atmospheric nitrogen deposition, climate and c) other relevant maps, such as the number of inhabitants and the location of buildings. Specifically these maps were the input for the calculations of the set of ES. To create the set of nature-inclusive scenario maps, the baseline maps were utilized as a foundation and subsequently modified to align with the principles of the nature-inclusive scenario, emphasizing the extensive implementation of NbS. Then, the identified NbS of the previous step were added to the land-use map.

The most logical locations for the NbS were chosen considering the current soil and water system and where the demand for ES is highest. The Landscape Soil and Hydrology Map (LSHM) was used to select areas logic from the soil and water system perspective (Delft and Maas, 2015). For instance, the NbS to raise the ground water table on peat soils to decrease CO_2 emissions were placed on soils with a thick peat layer with a low water table. In addition, maps with mismatches between the supply and demand were used to optimize the allocation of NbS, thereby contributing to the resolution of environmental challenges. As an example, the NbS aimed at creating additional forests and parks to address the shortage of outdoor recreation were positioned in proximity to densely populated regions with limited opportunities for leisure activities. The complete list of 563 decision rules governing the placement of NbS, along with details on the resulting land allocation in hectares, can be found in the supplementary material.

The identified NbS could be a change in the current land use (e.g., agricultural practices), land cover (e.g., type of vegetation) or abiotic condition (e.g., water level). For example, current agriculture was changed to the NbS of strip cropping at arable field on sandy and clay soils, since strip cropping on these soils will decrease the need to use pesticides (Labrie et al., 2016). Dairy farming on peat soils with low groundwater levels are rewetted to stop soil subsidence, reduce CO_2 emissions and stop the loss of biodiversity (Günther et al., 2020). Within cities, urban parks and forest patches were added to increase possibilities for outdoor recreation in areas where demand exceeds supply. Mismatches were pinpointed through a spatial assessment, comparing the demand for recreational areas for walking and bicycling around residential areas with the supply of greenspace for these activities. The type, amount and location of NbS were saved as a set of hierarchical decision rules within a scenario tool called the "Multi-reclass Tool" (Breman et al., 2022; De Knegt et al., 2022). This tool resulted for the scenario in a set of consistent and aligned maps of land cover, land use and matching environmental data with a resolution between 0.5 m and 25 m. All decision rules, detailing the formulation and application of the nature-inclusive scenario, is comprehensively presented in the supplementary material and summarized in Table 2.

2.3.5. Step 5: calculation of contribution of NbS to environmental challenges

The NC-Model was used to estimate twelve ES by quantifying the extent of the match or mismatch between ES supply and demand for both the baseline and nature-inclusive scenario (De Knegt et al., 2022). Each ES had its demand assessed; for example, pollination-dependent crop production was considered. The demand is dictated by the needs of pollinator-dependent crops, while the surrounding landscape ecosystems supply the required pollination service. A mismatch between ES supply and demand arises when there is a potential harvest loss due to insufficient provision of pollinators around the crops. The NC-Model is briefly described in Appendix 1 and is comprehensively described, including equations, inputs, outputs, uncertainty, validation, model assumptions of each ES model in De Knegt et al. (2022).

The NC-Model classifies ES using the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2012), namely wood production, drinking water production, energy production from biomass, air quality regulation, urban cooling, pest control, pollination, carbon sequestration, water storage, water purification, outdoor recreation and natural heritage. Table 2 presents indicators that were spatially quantified by use of each ES model.

To establish the scientific credibility of the NC-Model, 27 relevant model aspects, including sensitivity, uncertainty, and validation, are thoroughly elaborated upon for each ES model. This approach ensures the development of the NC-Model as a robust and reliable tool for estimating the supply and demand of ES in the baseline and nature-inclusive scenarios.

2.4. Analysis of results

First, results were calculated per ES as maps of supply, demand and use at the national level. The model outcomes across supply, demand and use are in the same unit per ES and are presented as a percentage of supply compared to the demand in order to calculate the indicators and distance to policy targets (Table 2). Secondly, the degree to which environmental challenges were solved was calculated by averaging all percentages of ES equally that contribute to solve the challenge. Some ES contribute to more than one environmental challenge. For policy targets, results are presented in terms of percentage achievement of policy targets.

Results were presented and discussed with the group of stakeholders mentioned in Section 2.3.1., in parliament and with diverse other expert and policy organizations.

3. Results

3.1. Environmental challenges in the Netherlands

The interviews and workshops with key actors yielded six environmental challenges, associated policy targets and relevant ES that could address these challenges:

1. Transition to a sustainable agriculture

Key actors unanimously acknowledge that one of the foremost challenges lies in the transition towards sustainable agriculture. Current practices, marked by monocultures and intensive land management, contribute to issues like eutrophication and pollution. This harms biodiversity in agriculture and surrounding protected nature areas, while imported fodder increases the ecological footprint beyond Dutch borders, although the ecological footprint is not quantitatively assessed in this study. Lowering groundwater for high agricultural production worsens soil subsidence, emitting carbon dioxide.

Actors propose enhancing regulating ES for sustainable agriculture and co-benefits. This involves increasing wild bee pollination and mainstreaming natural pest control to reduce pesticides, boost crop

Table 1
List of input maps, sources and resolution of the maps that were developed for the baseline and scenario to calculate the ES.

Group	Map name	Source	Resolution (m)	Wood production	Drinking water production	Energy from forests	Air quality regulation	Urban cooling	PestControl	Pollinatin	Carbon sequestration forest	Carbon sequestration peat	Water storage	Water purification	Outdoor recreation	Natural heritage
Land cover/Land use	Land cover	Ecosystem type map of the Netherlands, 2020 (https://www.cbs.nl/nl-nl/maatwerk/2022/49/ecosysteemtypenkaarten-2013-2020), with 107 categories	25		x	x	x	x	x	x	x		x		x	
	Vegetation	Vegetation cover map of trees, shrubs and grass of the Netherlands, 2019 (https://www.nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/89611780-75d6-4163-935f-9bc0a738f7ca), % cover per cell	10					x					x			
	Nature management	Nature types and management of protected areas in the Netherlands 2018 (https://www.bij12.nl/onderwerpen/natuur-en-landschap/productencatalogus/kaarten/landelijke-beheertypenkaart/) , with 75 categories	25	x		x					x					x
	Crop type	Netherlands Enterprise Agency (https://www.pdok.nl/downloads/-/article/basisregistratie-gewaspercelen-brp-), with 147 categories	10						x	x						
	SkyViewFactor	SkyViewFactor of the Netherlands, (https://dataplatform.knmi.nl/dataset/svf-nl-3#:~:text=An%20important%20variable%20to%20calculate,surroundings%20of%20a%20given%20location.), with 0-1 cover per cell	0.5					x								
	Urbanisation level	Urbanisation level (https://research.wur.nl/en/publications/basisbestand-natuur-en-landschap), with 5 categories	10					x								
	Water purification measures	Nature-inclusive interventions: marsh buffers, nature-friendly banks, reed beds, manure-free zone (De Knegt et al., 2022), in % per measure	nvt											x		
Abiotic conditions	Water level	Groundwater level: highets, lowest, in spring (https://edepot.wur.nl/409366), continous in cm minus groundlevel	25	x								x				x
	Soil map	Soilmap, 2012 (https://www.wur.nl/nl/show/Bodemfysische-Eenhedenkaart-BOFEK2020.htm), with 79 categories	25	x								x	x			
	Nitrogen deposition	Atmospheric nitrogen deposition map of the Netherlands 2019 (https://www.rivm.nl/publicaties/grootschalige-concentratie-en-depositiekaarten-nederland-rapportage-2019), continous in mol/ha	25													x
	Air pollution	Concentration fine dust particles (PM 2.5), 2018 (https://www.rivm.nl/bibliotheek/rapporten/2019-0170.pdf), continuous in ug/m3	10				x									
	Soil pH	Soil pH map of the Netherlands 2019 (Wamelink et al. 2019), continous on pH scale	25													x
Other maps	Inhabitants	Number of inhabitants and etnicity in the Netherlands, 2020 (https://cbsinuwbuurt.nl/#vierkant100m2020_aantal_inwoners), continous in inhabitants per gridcell	25				x	x					x		x	
	na_bag	m2 buildings per cell (https://www.geobasisregistraties.nl/basisregistraties/adressen-en-gebouwen), continuous 0-100	10					x								
	Drinking water infiltration areas	mask ligging inzijggebieden (file:///C:/Users/knegt005/Downloads/Bescherming+Nationale+Grondwater+Reserves.pdf), shape	2.5		x											

yields, and conserve biodiversity. Sustainable land use in drinking water areas ensures clean water, while raising the water table cuts carbon emissions from peat soils. Policy targets aim to reduce pesticides by 50 % by 2030, halt pollinator decline, limit peat soil emissions to 1 Mton CO_2/year, and enhance agricultural biodiversity.

2. Protection and restoration of biodiversity

The second challenge, identified by the key actors as another significant challenge, is the imperative to safeguard and restore biodiversity. Actors acknowledge that biodiversity constitutes the foundation of our economy and needs urgent protection. Various factors, including climate change, desiccation, eutrophication, fragmentation, habitat loss, and invasive species, were highlighted as principal contributors to the concerning decline in biodiversity.

Most actors were calling for more rigorous action, since current policy actions were not sufficient to halt the loss of biodiversity. The ES natural heritage aims to preserve existing biodiversity and ensure its sustainable conservation for future generations. Actors believe this objective can be achieved by the sustainable management and utilization of resources and to maintain good environmental conditions for ecosystems and species, thereby safeguarding their long-term viability. The most important policy objectives that were ratified by Dutch government comes from the Convention on Biological Diversity and the European Birds and Habitats Directive.

3. Good quality of waterbodies

The third challenge, broadly recognized by key actors, is to attain a good quality of water bodies. Actors highlight that the majority of water

Table 2
List of indicators and associated policy targets per ES that were calculated using the NC-Model.

ES category	ES	Indicator	Policy target
Provisioning services	Drinking Water Production	% surface area of 100 years zone around water extraction point with sustainable land use (hectare)	-
	Wood Production	% wood production versus wood demand (m3 wood equivalents without bark/yr)	Dutch target to half the ecological footprint by 2050.
	Biomass for Energy Production	% energy production from forest compared to total energy production (PJ/yr)	Dutch Energy agreement: 40% renewable in 2030
Regulating services	Urban Cooling	% avoided temperature rise of the UHI during a heat wave by vegetation (degree Celsius/capita)	-
	Water purification	% surface area of waterbodies with good chemical conditions (nitrate & phosphor) (hectare)	EU Water Framework Directive: all waterbodies in good condition in 2027
	Pest Control	% density of natural enemies in agricultural crops that are susceptible to pests (0-100)	EU Farm to Fork Strategy: 50% reduction of chemical pesticides by 2030
	Pollination	% avoided production loss of pollination dependent crops by natural pollinators (kg/ha)	EU Nature restoration Law: stop the decline of pollinator populations by 2030 and realise an increase thereafter
	Carbon Sequestration (forest & peat soils)	% sequestration of CO_2 by forest and decrease of emission by peatland compared to total CO_2 emission (Mton CO_2 eq/yr)	1) Paris Climate Agreement 2030 49% reduction, 2050 no net emissions, 2) Dutch Climate Agreement 0.4-0.8 Mton CO_2/year for forest & 1 Mton/year CO_2 emission reduction for peat
	Air Quality Regulation	% people under the WHO norm for PM 2.5 fine dust (10 ug/m3)	50% improvement of human heath by inland emissions in 2030 compared to 2016
	Water Retention	% people living at places with a water retention capacity greater than 6mm/hour of saturated soils (mm/hour)	-
Cultural services	Outdoor Recreation	% people with enough green space in their living environment (number of places for recreation for walking and bicycling)	-
	Natural Heritage	% species which have good environmental and spatial conditions to guarantee their sustainable occurrence (# species that could occur sustainably)	1) CBD target no species threatened with extinction, 2) EU/Dutch target no species of Birds and Habitat Directives and no Habitattypes threatened with extinction

Please note that this study did not quantitatively assess the ecological footprint of imported goods from abroad.

bodies fall short of the desired water quality standards. They emphasize concerns not only about the chemical aspects of water quality, such as concentrations of nutrients and pollutants but also the ecological quality and the overall suitability of water for drinking and safe swimming.

Helophyte-based water purification is the ES that can contribute to reach the challenge to achieve good conditions, mainly by lowering nitrate and phosphate concentrations in the water. Associated policy targets are set by the Water Framework Directive to achieve good conditions for all waterbodies by 2027.

4. Good quality of the living environment

The fourth challenge identified by the key actors is to ensure a high quality of the living environment. The actors note that the majority of the population in the Netherlands resides in urban areas, and there is a growing demand to construct at least one million more houses in the coming years. Actors emphasize the significance of fostering healthy cities, characterized by good air quality, a reduced risk of flooding, sufficient green spaces for recreation, and ample greenery to mitigate heat during heatwaves.

ES that contribute to solve this challenge key actors mention are air quality regulation, outdoor recreation, water retention and urban cooling. While specific policy targets have been set for air quality (10 μg/m3 PM2.5), there are currently no established targets for addressing the other aspects mentioned.

5. Climate change mitigation and adaptation

The fifth challenge requiring attention, as indicated by the key actors, is the imperative to mitigate and adapt to a changing climate. Actors emphasize that the impacts of climate change are particularly pertinent to the Netherlands, given that a significant portion of its population resides in a delta region situated below sea level. Actors underscore that weather extremes, including peak discharges following heavy rainfall, droughts, sea level rise, and the challenges posed by heat stress during heatwaves, exert profound effects on biodiversity, as well as on the livelihoods and well-being of many individuals.

The main ES contributing to climate mitigation and adaptation are carbon sequestration, water retention and urban cooling in cities. At European scale, a policy target of a 49 % reduction of carbon emissions by 2030 has been agreed upon and no net emissions in 2050. At the national Dutch level, an emission reduction target was agreed of 1 Mton CO_2/year for peat soils and an extra sequestration of 0.4–0.8 Mton CO_2/year for forest. No policy targets are operational for coping with heat stress or water retention.

6. Transition to the production of renewable energy

The last challenge key actors mention is the transition to produce energy from renewable sources. This challenge is driven by the growing demand for renewable energy as an alternative to fossil fuels and nuclear sources.

The ES of biomass for energy is classified as an ES, since it can be obtained from ecosystems. Energy from solar and wind power are considered as abiotic provisional services in the extended version of the CICES classification (see CICES 5.1). Policy target is to produce 40 % of total energy consumption from renewable sources (including sun and wind).

3.2. NbS for environmental challenges

Key actors and experts identified a variety of NbS, which differ in the type of interventions they entail (Table 3). These include changes to land cover through the greening of urban areas and increasing forested areas, restoration of water and soil systems, and changes to the management of agricultural and natural areas. Furthermore, the area covered by these interventions also varies.

3.3. Nature-inclusive scenario

Fig. 3 shows the main land use type maps of the baseline and the nature inclusive-scenario.

Fig. 4 shows the proportion of each land-use category in the baseline scenario and under the nature-inclusive scenario. 6 % of current agricultural areas is changed into natural areas, and the remaining agricultural areas are under management based on agroecological principles. 7 % of agricultural grassland areas are converted to croplands. To accommodate the need for housing in 2050 the urban area increased with 30.000 ha.

3.4. Contribution of NbS for environmental challenges

Fig. 5 shows the effects of the NbS on ES and on the environmental challenges in the current situation (light green) and the nature-inclusive scenario (dark green). Fig. 5 illustrates the continued mismatch between supply and demand (depicted in red) that persists despite the implementation of NbS. In this study we did not assess if this red part is be solved by technical alternatives, imported from abroad or be a real unmet demand. Appendix 2 lists the results for ES and the environmental challenges for the baseline and the scenario.

1. Transition to a sustainable agriculture

The NbS implemented in the scenario, to enhance ES that support a sustainable agricultural production enhanced the ES pollination, pest control, drinking water production, and the avoided emission of carbon emissions on peat soils. The baseline scenario shows that ES already address an average of 40 % of the environmental challenges. The NbS of the nature-inclusive scenario combined solve another 24 % to the total challenge, which leaves 36 % of the challenge still unmet.

The results for the different ES contributing to this challenge vary. Wild pollinators were enhanced mainly by adding flower field margins, which results in an decrease of avoided crop loss of 82 % to 98 %. The density of natural enemies that control pests in crops, increased almost fourfold (385 %) mainly by the introduction of strip cropping on arable fields and by adding flower field margins and hedgerows in this new cropping system. The sustainable production of drinking water has increased to a level to guarantee the sustainable production of drinking water (from 62 % to 100 %). This is largely attributed to the extensification of agriculture and the reduction of pesticides and fertilizer residues entering drinking water infiltration areas. Higher groundwater tables of agricultural grasslands on peat soils, reduce the CO_2 emissions from 6.5 Mton CO_2/year to 5 Mton CO_2/year. The national sectoral goals to reduce emissions with 1 Mton CO_2/year are thus easily met, although the avoided CO_2 emission is still only a fraction of the total Dutch carbon emission (approx. 1 %).

2. Protection and restoration of biodiversity

The implementation of all NbS across natural, agricultural, and urban areas combined resulted in significant co-benefits for biodiversity. This has also improved the conditions in protected nature areas neighbouring agriculture, resulting in a three-fold increase in the total population sizes of all species. These NbS improve the conditions that are important for the sustainable occurrence of species from 48 % to 70 % for all species. Specifically, the favourable conditions for species protected under the EU Birds and Habitats Directives to prevent extinction have increased from 54 % to 77 %. Moreover, the ecological footprint (the area abroad required to support the Dutch economy) has slightly decreased due to increased wood and food production, making the Netherlands more self-sufficient and reducing the need for imports from abroad. This progress contributes to the policy target of halving the ecological footprint by 2050.

3. Good quality of water bodies

The area of waterbodies with good chemical conditions for nitrogen and phosphorous, as formulated by the Water Framework Directive, has increased from the current 24 % to 58 % of waterbodies through the ES water purification. In this scenario, helophyte filters, swamp buffer strips, nature-friendly banks and manure-free zones help to retain nutrients from the water and create an improvement of the chemical water quality.

4. Good quality of the living environment

The nature-inclusive scenario's NbS have improved the quality of the living environment in urban areas, but the effectiveness of the NbS varies across different ES, including outdoor recreation, water retention, urban cooling, and air purification. In the baseline scenario, ES had already contributed to solving this challenge by 43 %. On average, the NbS implemented in the nature-inclusive scenario provided an additional 13 % improvement, leaving 44 % of the challenge yet to be addressed.

The shortage of outdoor recreation space, which stood at 77 % in the baseline scenario, was almost entirely resolved (99 %) by the increase in recreational parks in new and existing urban areas. While water retention increased in the scenario, with the percentage of greenspace in urban areas increasing from 69 % to 80 %, it still remains insufficient to prevent flooding for 20 % of the population. During heat waves, urban temperatures decreased significantly by 27 % to 43 % due to the increase in vegetation cover in the new urban areas built with a nature-inclusive approach. However, in existing urban areas, limitations of available free space to increase vegetation cover limits the potential supply of the service. Despite the increase of vegetation in cities, there is only a small positive impact on air quality (from 0.4 % to 1.0 %), still most of the population still lives in areas that exceed the WHO norms for good air quality.

5. Climate change mitigation and adaptation

The nature-inclusive scenario contributes substantially to mitigating and adapting to climate change, but the scenario was not able to solve the total challenge. Due to the NbS within the nature-inclusive scenario that increase groundwater levels in peat soils and increase the amount of forest, less carbon is emitted and more carbon is stored. This results in halving the net carbon emissions. Sectoral policy targets of the Dutch Climate Agreement on carbon sequestration for forest (0.4–0.8 Mton/year) and peat (1 Mton/year) are easily met in the scenario with increases of 1Mton/year for forest and 1.5Mton/year less emission for peat. Peat soils still emit CO_2 and contribute to climate change (3 % of total emissions). Adapting to climate change by increasing water infiltration to prevent flooding is also increased by about 10 %, with 20 % of people still living in flood-prone areas. The Urban Heat Island effect is mitigated quite strongly (from 27 % to 43 %) due to increased vegetation cover in the nature-inclusive scenario.

6. Transition to the production of renewable energy

The effectiveness of the implemented NbS in meeting the biofuel needs of our society is limited. The production of biomass increases by

Table 3
NbS applied in the nature-inclusive scenario, the area they cover and the environmental challenges they target.

Category	NbS	Land use	Change in area compared to Baseline (ha)	Change in area compared to Baseline (%)	Environmental challenges: Climate change: mitigation	Climate change: adaptation	Quality of the living environment	Agricultural transition	Energy transition	Quality of water bodies	Protect and restore biodiversity
Greening urban area				Change in area compared to urban area of Baseline							
	Ecological management of urban green areas	semi-natural woodlands and grasslands	65	28%			■				■
	increase green roofing	green roofs	21	8.7%		■	■				■
	create recreational parks near cities	parks, woodlands, grasslands and water	8	3.4%	■	■	■				■
	increase amount of trees near infrastructure	woodland	1	0.6%	■	■	■				■
	increase green walls	green walls	-	-		■	■				■
Restoring water and soil system				Change in area compared to land area of Baseline							
	raise ground water table on clay and sandy soils	arable fields with field margins, semi-natural grasslands	244	72.4%	■						■
	restore streams (rivers & brooks) for water retention	riverine woodlands, semi-natural grasslands	103	30.7%		■					■
	raise ground water table on peat soils	agricultural grassland, semi-natural grasslands, marshlands	77	22.8%	■						■
	retention of nutrients from water bodies	helophytes in and near waterbodies	-	-	■					■	■
Changing management of agricultural areas				Change in area compared to agriculture of Baseline							
	strip cropping on clay and sandy soils	arable fields with semi-natural grassland strips	849	38.0%				■			■
	increase extensive grassland (decrease in live stock)	semi-natural grasslands	316	14.1%				■			■
	increase (agro)forest(ry)	semi-natural forests and agriculture	23	1.0%	■			■			■
	natural banks of ditches, canals and streams	semi-natural grasslands	-	-				■		■	■
	natural borders of land plots	flower field margins, hedgerows	-	-				■			■
Increase natural (protected) areas				Change in area compared to natural area of Baseline							
	Nature restoration: quality impulse of existing nature	all types of natural land use	278	75.1%							■
	Increase of natural areas (and water retention)	all types of natural land use	83	22.4%		■			■		■

13 % in the scenario compared to the baseline situation. However, this is still a very small percentage of the total national energy consumption (approx. 1 %). Most of the increase in forest biomass was allocated for carbon sequestration, thus only residual forest products such as branches were used for energy production.

3.5. Effectiveness of NbS

The results show a clear correlation between the amount of NbS applied and the effectiveness of the NbS. More NbS resulted in greater contributions towards solving the challenges. The effectiveness of NbS varied across different ES, with natural pest control showing the greatest improvement, with the density of natural enemies increasing fourfold compared to the baseline. Energy from forest showed the smallest improvement, with only a 13 % increase. These increases corresponded to the relative increase of the NbS; the number of natural elements in the agricultural landscape quadrupled, while the increase of forest from which forest products are derived to generate energy increased also with about 13 %.

Furthermore, the effectiveness of NbS in enhancing ES seems to depend on level of the baseline situation. In general, NbS tends to be more effective for ES with lower baseline values compared to those with higher values. For example, NbS to increase water retention resulted in a 17 % increase (from 69 % to 80 %), whereas the urban heat island was reduced by 60 % (from 27 % to 43 %) and air purification was improved by 250 % (from 0.4 % to 1.0 %). Similarly, in agricultural landscapes, the implementation of NbS such as hedgerows and flower field margins resulted in a 28 % increase in pollination (from 77 % to 99 %) and a 285 % increase in pest control (from 14 % to 55 %) for areas with low baseline values.

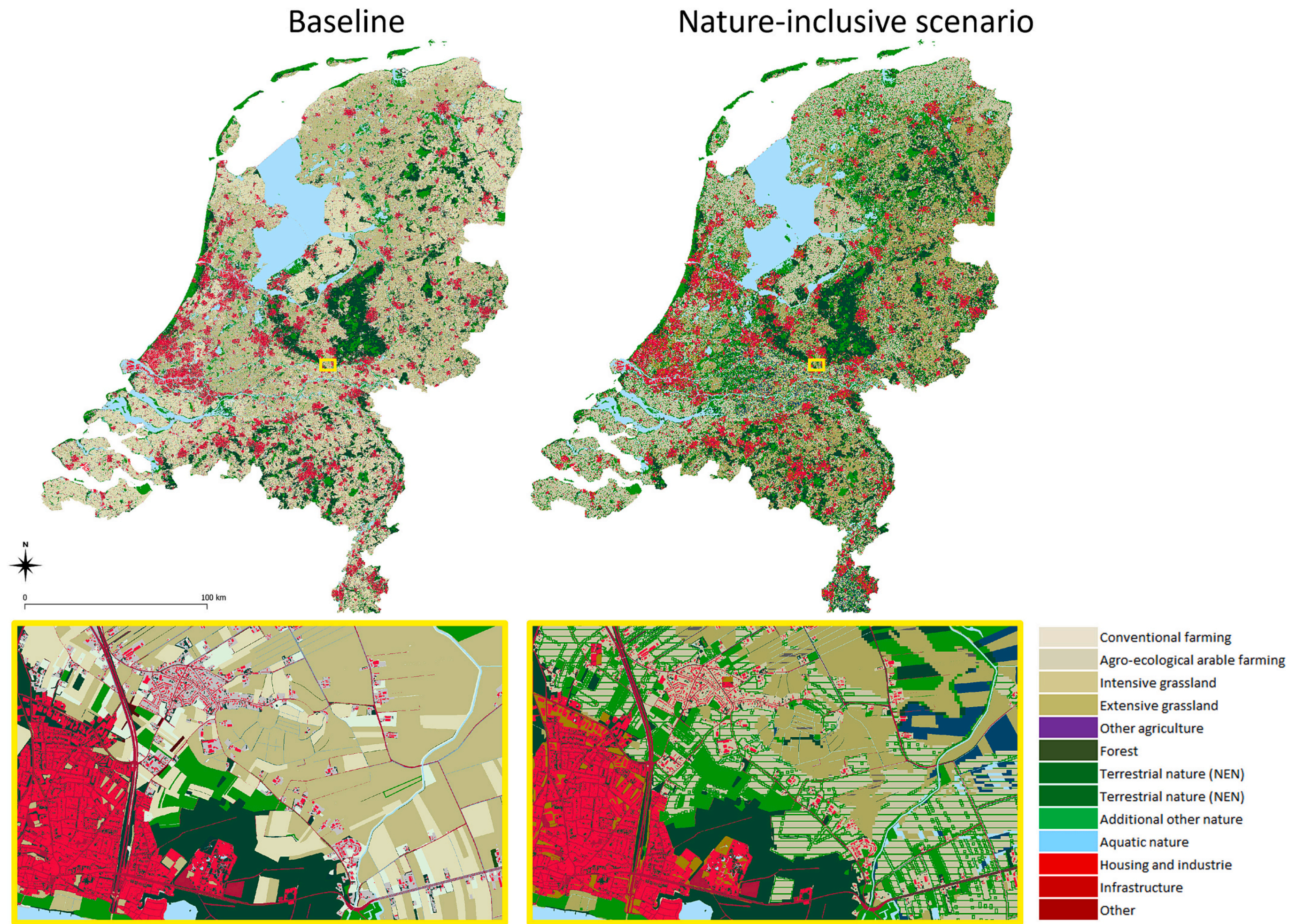

Fig. 3. Map and cut-outs (yellow squares) of the Netherlands with main land use categories of the baseline (left) and nature-inclusive scenario (right). In the zoomed cut-out around the city of Rhenen the allocation of some NbS is illustrated. Conventional farming of the baseline is transformed to agro-ecological arable farming using strip cropping with flower field margins and hedgerows in the nature-inclusive scenario (right corner), the management of grasslands is more extensive in the (centre) or transformed to more natural areas or forest on soils and with water conditions unfavourable for conventional farming (top right), green spaces in cities are managed less intensive and are more focussed on biodiversity (left).

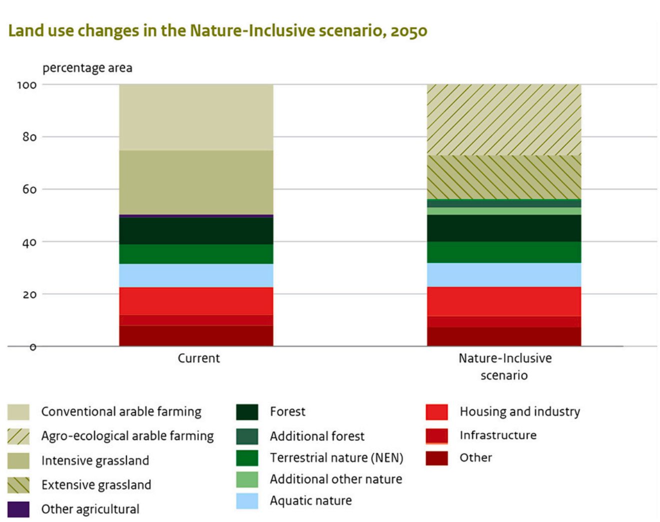

Fig. 4. Area per land use category for the current situation and for the nature-inclusive scenario.

4. Discussion

4.1. NbS help solve simultaneously environmental challenges

In this study, we quantified the contribution of large-scale implementation of NbS in a nature-inclusive future scenario for six environmental challenges and ten associated policy targets in the Netherlands. Results show that NbS contribute to the solution of all these challenges and associated policy targets. However, the magnitude differs greatly among the assessed challenges and policy targets. Although NbS have significant benefits via the delivery of ES, they are not sufficient to solve the challenges completely under this scenario. On average half of all environmental challenges remain to be solved even though the proposed NbS were already quite drastic.

According to the nature-inclusive scenario, NbS are most effective in addressing three environmental challenges: enhancing water quality, a more sustainable agricultural production, and conserving and restoring biodiversity. However, their impact on mitigating climate change, improving the quality of living environments, and transitioning to sustainable energy sources is relatively limited compared to the other challenges. The nature-inclusive scenario consequently has positive effects on sectoral policy targets at Global, EU, and national level. Examples include the biodiversity targets of the Birds and Habitats Directives, the Convention on Biological Diversity, the Water

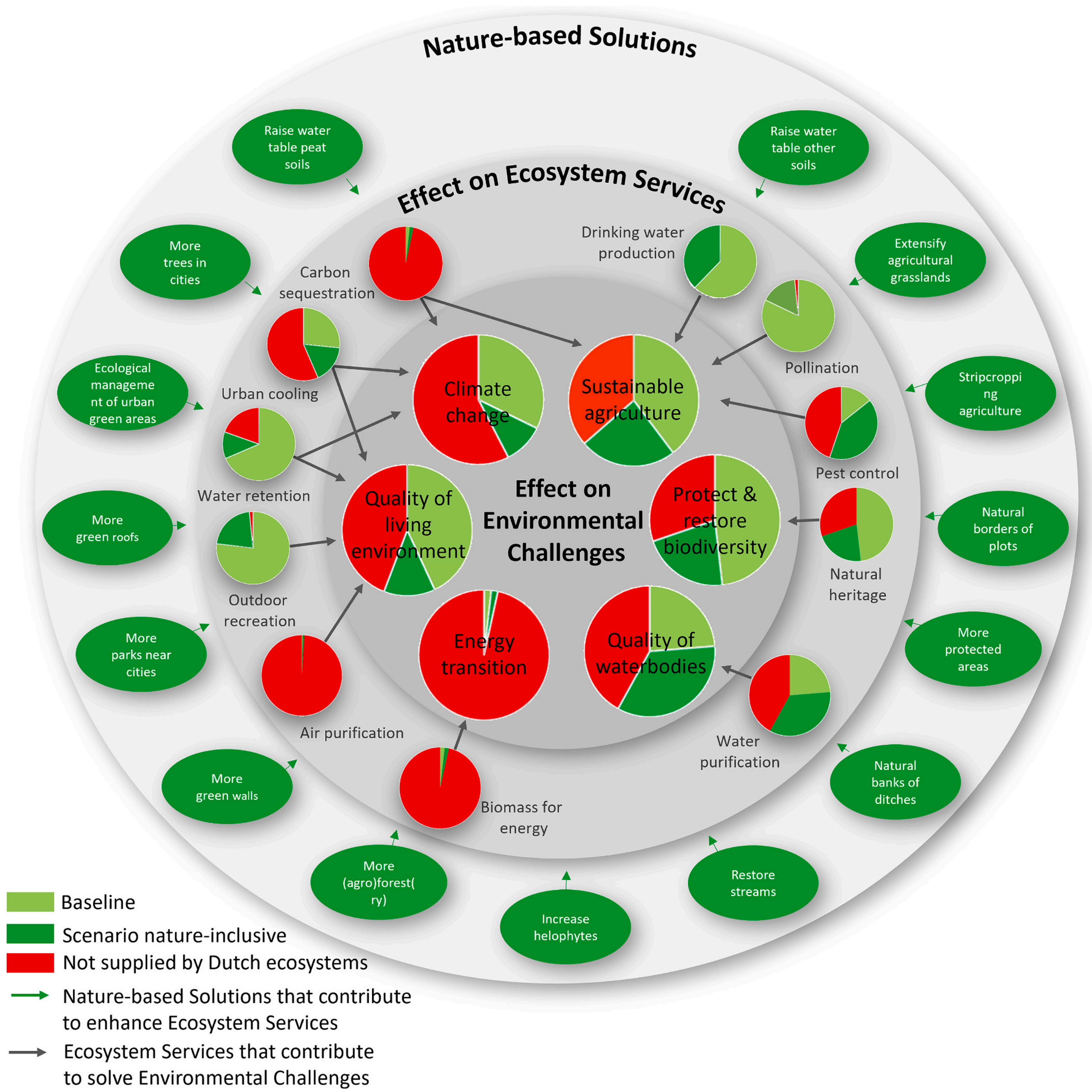

Fig. 5. Outer ring: the selected NbS that contribute to enhance ES to solve environmental challenges. Middle ring: the (mis)match between supply and demand per ecosystem service for the current situation (light green) and for the nature-inclusive scenario (light green + dark green). Red corresponds to the part that is still not supplied after implementing the NbS by Dutch ecosystems (mismatch between supply and demand). Inner ring: the contribution of ES to solve the six selected environmental challenges calculated as the average of all contributing ES. An overview of the results per ES and per environmental challenge is given in Appendix 2.

Framework Directive, nationally targeted carbon emission reductions, the reduction of pesticide use, and protection of pollinator populations. Furthermore, the results highlight a clear correlation between the quantity of applied NbS and their effectiveness, with increased NbS showing greater contributions in addressing challenges; additionally, the efficacy of NbS in enhancing ES is influenced by the baseline situation, generally proving more effective in areas with lower baseline values than those with higher values. This is likely due to the principle of diminishing returns, as noted also by (le Clech et al., in press).

Other studies have demonstrated the effectiveness of NbS for improving the quality of waterbodies, making agriculture more sustainable and protecting and restoring biodiversity. Literature highlights the potential for improving water quality through nutrient retention, with reported ranges of 46–90 % for phosphorus and 16–84 % for nitrogen (Malaviya and Singh, 2012). However, it should be noted that the effectiveness of nutrient retention can vary widely between different NbS, as demonstrated by Malaviya and Singh (2012). Numerous studies have reported positive effects when examining the use of NbS as a means of promoting agricultural sustainability. Natural pest control, by introducing natural elements in the agricultural landscape was found effective in many occasions (Bianchi et al., 2006). (Rusch et al., 2016). Zhang et al. (2019) estimated that in a mix cropping system on arable land, diseases were suppressed and Zhu et al. (2000) reported a reduction incidence of diseases. These results are in the same range of the results of this study. NbS that promote pollination like adding flower field strips are reported to be a 'win–win–win' balance between crop production, farm income, and the environment (Catarino et al., 2019). Literature suggests that the rewetting of peatland is an effective strategy for reducing, stopping and even reversing carbon emissions from peat soils depending on the amount rewetted and water table depth, as highlighted by Bonn et al. (2014), Tan et al. (2022) and Günther et al. (2020). While rewetting and restoration may increase CH4 emissions in the short-term, this generally does not offset the immediate benefits of reducing oxidative carbon losses, nor the long-term benefits of enhanced CO_2 sequestration (Bonn et al., 2014; Günther et al., 2020). For the environmental challenge to restore biodiversity many studies have shown the positive effects of specific NbS on biodiversity loss, but few studies assessed the net effects of a nature-inclusive scenario on country level and policy targets.

An increasing number of studies indicate the effectiveness of NbS in addressing climate change, improving the quality of the living environment, and facilitating the transition to sustainable energy production. Climate mitigation, by decreasing sources and increasing sinks of greenhouse gases through terrestrial ecosystem stewardship and improvements in agriculture, are widely recognized as having the potential to provide around 30 % of what is needed to keep warming below 2 °C by 2030 (Griscom et al., 2017; Quéré et al., 2018). However, a more recent analysis and involving tighter model constraints (e.g. on where ecosystem regeneration can take place) indicates that this figure is overestimated, and emphasizes the need to explore this potential on a national level (Griscom et al., 2017). Our study found a lower effectiveness of climate change mitigation at 2 %. This could be explained because the Netherlands have CO_2 emissions from organic soils far above average (Ritchie et al. 2020) and a lower potential for carbon sequestration because of low forest cover and limited space to increase it. Furthermore, greenhouse gas emissions from mineral soils and reductions of other sectors were not included in our assessment. Including these sectors would also increase the effectiveness for climate mitigation. For the reduction of the urban heat island effect, other studies found a 10 % increase in forest-vegetation resulted in a decrease of about 0.83 °C in surface temperature (Kong et al., 2014), while Steeneveld et al. (2011) reports a 0.58 °C change. This is higher compared to our study where the effect of a 10 % increase in vegetation result in an decrease of temperature of 0.35 °C. The lower effectivity of the results in this study could possibly explained by differences in size and location of the cities studied, the type and density of vegetation, and the local climate conditions (Salmond et al., 2016). Many studies of the effectivity of NbS to improve the quality of the living environment report positive effects of NbS on water retention, air filtration, urban cooling, outdoor recreation and biodiversity. Results of these studies are comparable in magnitude to our study (Gattringer et al., 2021; Manso and Castro-Gomes, 2015; Nowak et al., 2014; Paulin et al., 2020; Shukri, 2010), although quantitative comparisons are difficult because of differences in indicators and the applied types and amounts of NbS. Alves et al. (2019) report positive co-benefits for recreational activities of increasing green space and planting trees. Looking at the energy transition, our results are fairly low, since energy production could only be originate form residual forest-products, since the rest of the wood is used either for construction or carbon sequestration.

This study provides further evidence of the multiple benefits of NbS, which is consistent with previous research (Castellari et al., 2021; Somarakis et al., 2019). NbS is an attractive alternative to traditional engineering solutions due to its ability to provide multiple co-benefits, while traditional solutions often aim at single objective with negative external effects (Reid et al., 2018). Our study found that all assessed ES, environmental challenges, and associated policy targets benefited from the implemented NbS. At least at the national level, there seems to be no trade-offs between ES, challenges, or policy targets. The lack of trade-off relations could be explained by the strategic placement of NbS in the nature-inclusive scenario, which are located in areas where soil and water systems and ES mismatches were most apparent. While realizing the nature-inclusive scenario requires a big effort and a transformative change in land use and management, it offers many win-win results.

4.2. Limitations of study

The approach presented in this study provides a valuable contribution to the assessment of NbS as a tool to address environmental challenges and policy targets. By selecting relevant challenges and policy targets, identifying NbS that can enhance ES and applying ES models, this study enables a credible and reproducible ex-ante assessment of NbS potential at a national level. The involvement of relevant stakeholders throughout the project ensured a reflective and impactful utilization of the results. The method and tools presented here can serve as a basis for further research and practical applications of NbS in environmental policy and planning.

Despite the strengths of our approach, four main limitations exist. Firstly, the set of twelve ES that were assessed in this study, while encompassing provisioning, regulating, and cultural services, is not exhaustive. Other regulating services, such as soil fertility, erosion control, and coastal protection, were not included in our analysis but could play important roles in sustainable agriculture and climate change adaptation. To enhance the robustness of our findings, future research could prioritize the inclusion of missing ES models. Adding the missing ES is expected to strengthen our conclusion on the multiple benefits of NbS, since no trade-offs are observed among the ES that were already analysed. Moreover, Lee and Lautenbach (2016) have observed that regulating ES exhibit predominantly positive correlations. Hence, expanding especially the number of regulating and cultural ES is likely to yield more synergetic interactions, further highlighting the potential of NbS to address environmental challenges.

Secondly, modelling ES comes with uncertainties (Hamel and Bryant, 2017). The applied ES models that make up the NC-Model are based on best available scientific knowledge and each ES model calculates the (mis)match between both supply and demand, uses high quality data at a fine resolutions. However, models are simplifications of reality and the assumptions, limitations, and uncertainties should be taken into consideration when interpreting the results. The model quality of each ES within the NC-Model is assessed concerning 27 aspects including uncertainty, sensitivity and validation. Current research is actively validating both the models and application of NbS in the field through the use of empirical data. These aspects are all comprehensively described in De Knegt et al. (2022). Also ES are modelled in an independent way, without considering the feedback loops that might occur when enhancing the supply of one ES. For instance, the positive effects of increased natural pest control on the use of pesticides which can have beneficial effects on pollinator populations were not taken into consideration. Also we assume relatively stable climate conditions for NbS and consistent policy targets throughout the study period, while we know ecosystems are dynamic and can experiencing rapid changes in response to climate shifts. Considering the remaining wishes to increase the reliability and robustness of the ES models, the results should be taken carefully, and not as precise estimations. The given percentage should be seen as order of magnitude of relative changes of the scenario compared to the baseline situation is a way to take the uncertainties into account. Future research should focus on continuously enhancing model quality, preferably by drawing insights from real-life case studies, and assessing the robustness and uncertainties of the used models quantitatively.

Thirdly, this study used a straightforward and simple approach to calculate the contribution of ES in addressing environmental challenges, by averaging all relevant ES. In this study, we assigned equal weights to all selected ES due to the lack of supporting arguments or data to differentiate their importance. However, stakeholders may have varying perspectives and priorities of the challenges, which could influence the relative importance of individual ES and therewith the outcomes. Future research could investigate alternative lists of relevant ES for the challenges, consider weighting methods that incorporate stakeholder perspectives, and evaluate how the relationships between NbS, ES, and environmental challenges may vary across specific contexts.

Fourthly, despite the multiple benefits and synergies of NbS identified in this study, this study did not consider the potential negative effects and trade-offs of NbS in real-world implementation. For example, within cities, planting exotic drought-resistant trees and creating green spaces can help cool urban areas, and reduce the urban heat island effect, but may also lead to a loss of biodiversity if non-native species are chosen for these projects (Gulsrud et al., 2018). Additionally, NbS may have unintended consequences, such as the spread of weeds and rodents in cropping areas or the creation of shadow on crop fields by hedgerows that are intended to improve pest control and pollination ES (Uyttenbroeck et al., 2016). Therefore, it is important to carefully consider and address these potential negative effects and trade-offs when implementing NbS, taking into account the local context. Future research could aim to develop strategies that maximize the benefits of NbS while minimizing their potential drawbacks.

4.3. Implications for landscape design, planning, management and policy

Our study highlights the potential of NbS for addressing environmental challenges. However, the inflexibility, and sectorial approach of current governance models may hinder the widespread implementation of NbS (Finewood, 2016). Van der Jagt et al. (2020) highlighted constraints in mainstreaming NbS within the urban context in the Netherlands and surrounding countries. These constraints likely have broader applicability. The challenges include a lack of coordination and collaboration, insufficient professional knowledge, limited engagement from the private sector, gaps in policy development and implementation, competition for space, and financial limitations.

Fortunately, policymakers recognize the significance of integrating NbS into policy frameworks as a means to address policy objectives and promote sustainable solutions (European-Commission, 2019; IPO et al., 2022; UNEP, 2020). This can pave the way for mainstreaming NbS in landscape design, planning, management, and policy. The results of this study have already found their way in the Dutch policy arena. Dutch policy is busy formulating new policy goals, funding initiatives and embracing the principles of this nature-inclusive scenario and NbS (I&W, 2022; NL2120, 2023).

The results of our study provide valuable insights and options for practitioners and policymakers looking to enhance the role of NbS in addressing environmental challenges and achieving policy targets. Three potential strategies are identified to effectively help solve the environmental challenges: increasing the effectiveness of NbS, reducing demand for specific ES, and optimizing the synergy of NbS to achieve multiple challenges and targets. Firstly, landscape designers and managers could optimize vegetation type and configuration, to improve the delivery of ES. To maximize the effectiveness of NbS it is important to also consider the baseline level of ES; with higher effectivity at locations with low baseline levels. Secondly the demand for ES could be decreased for ES that are not as effective or costly to implement. For example reducing emissions of fine dust particles in urban areas by the electrification of transportation, while considering the trade-offs of electrification has on the demand for scarce minerals in ecologically vulnerable areas abroad. Lastly, optimizing the multiple benefits of NbS can be accomplished through the use of tools such as Pareto frontier calculations to identify and achieve multiple targets (Seppelt et al., 2013).

A notable next step would be to perform an economic cost-benefit analysis linked to the mainstreaming of implementation of NbS. While the study now addresses technical feasibility, a comprehensive cost-effectiveness evaluation can help policymakers even better informed decisions regarding investment in NbS. Economic considerations are paramount for policymakers, as they require a clear understanding of the financial implications and returns associated with such large-scale initiatives. Examining the results in the context of cost-benefit considerations can be essential for bridging the gap between theoretical feasibility and the practical implementation of NbS policies.

The NC-Model, which consists of sub-models per ES, can be used by practitioners and policymakers to evaluate different scenarios with alternative configurations of NbS in landscape design, planning, management, and policy. By incorporating multiple ES, trade-offs, and synergies between them, these models can provide an effective means of understanding the potential contribution of NbS to address multiple environmental challenges. This knowledge can then be used to support the use of the best available scientific knowledge in assessments and policy support, empowering stakeholders, policymakers, and spatial planners to make informed decisions (Santoro et al., 2019). As such, the use of scenarios and models plays a complementary role in landscape design, planning, management, and policy, allowing practitioners to explore possible futures and translate those scenarios into projected consequences for environmental challenges and policy targets. This gives stakeholders, policy and spatial planners insight into the outcomes of interventions like NbS beforehand so they can steer towards achieving their goals. Models are particularly useful for ex-ante assessments, because they are able to assess the complex and multiple effects of NbS on different ES while taking into account the synergies and trade-offs between them (Sang, 2020). With growing demand for these methods and models, we believe that they have great potential to drive the mainstream adoption of NbS.

5. Conclusion

NbS are proving to be a promising alternative to conventional technical solutions for addressing multiple environmental challenges simultaneously. Our study shows that NbS can significantly contribute to addressing all six assessed environmental challenges and associated policy targets. Although the magnitude of the contributions may differ among challenges, NbS seems most effective for improving the quality of waterbodies, making agriculture production more sustainable, and protecting and restoring biodiversity.

In addition to its effectiveness, NbS can also help achieve sectoral policy targets at the global, EU, and national levels. For instance, the use of NbS can help achieve targets under the Birds Habitats Directives, the Convention on Biological Diversity, the Water Framework Directive, sectoral carbon emission targets, and reducing the application of pesticides, among others.

The NC-model is a publicly available state-of-the-art reproducible tool that can be used to assess the effectiveness of NbS for addressing specific environmental challenges and policy targets via modelling of ES. This tool enables policymakers and practitioners to perform ex-ante scenario studies to evaluate the effects of interventions on a large group of ES and NbS using high resolution data. The NC-model also enables practitioners to identify alternative scenarios of specific contexts or locations, which can help find even more effective NbS.

Working with nature through NbS allows us to design a more sustainable future, while avoiding the negative side effects associated with conventional technical solutions. This study provides evidence that NbS can play a crucial role in addressing multiple environmental challenges in a sustainable way. The findings of this study hold significant policy relevance, and are already playing a role in elevating the priority of NbS within the national policy agenda. Furthermore, they have been instrumental in guiding the planning, design, and execution of NbS initiatives for policy and practical applications in the Netherlands (Paulin et al., 2023; Paulin et al., 2022; Paulin et al., 2020). We strongly encourage policymakers, practitioners, and scientists to adopt the NC-model and mainstream NbS as a promising, sustainable complement to conventional technical solutions.

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CRediT authorship contribution statement

Bart De Knegt: Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Bas C. Breman:** Writing – review & editing, Project administration, Investigation, Conceptualization. **Solen Le Clec'h:** Writing – review & editing, Supervision. **Arjen Van Hinsberg:** Conceptualization. **Marjolein E. Lof:** Software, Methodology. **Rogier Pouwels:** Writing – review & editing, Investigation. **Hans D. Roelofsen:** Software, Methodology. **Rob Alkemade:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.172186.

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