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Research article

Growing mismatches of supply and demand of ecosystem services in the Netherlands

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ABSTRACT

A sufficient supply of goods and services from ecosystems is vital to ensure human well-being. This study evaluates whether the demand for goods and services within the Netherlands is met by Dutch ecosystems, could otherwise be provided through technology and/or by imports, or remains (partially) unmet. Additionally, this study shows the dynamics of supply and demand of these services over time. The results reveal that no ecosystem service supply is fully meeting the total demand provided by Dutch ecosystems. Additionally, for the majority of the services (10 out of 17), the gap between supply and demand widened over the last two decades, indicating a growing mismatch. Imports and technology only partly close the gap between supply and demand. The growing mismatch between supply and demand is expected to lead to increasing negative impacts on human well-being, such as poor air and water quality, heat stress in urban areas, increasing flood risks, limiting opportunities for outdoor recreation and loss of biodiversity. Our findings show that current policy goals to maintain and restore ecosystem services are not on track in the Netherlands. Urgent action is necessary to enhance the sustainable utilization of natural resources and to optimize the balance between supply and demand. Priority should be given to goods and services facing unmet demand where imports or technological solutions are not feasible, particularly those where the gap between supply and demand is widening.

1. Introduction

There is a growing recognition that nature is fundamental to our existence and economy (IPBES, 2019). Ecosystems provide essential goods and services such as clean water, fertile soil for agriculture, and regulation of climate through carbon sequestration. However, anthropogenic activities leading to, for example to habitat degradation, climate change, and pollution affect biodiversity and the vital goods and services it provides (IPBES, 2019). Urgent policy and conservation actions are needed to secure the supply of essential goods and services, especially given the expected increase in resource needs driven by population and economic growth and climate change (IPBES, 2019; Pörtner et al., 2023).

Policies have established goals and targets at the global, European, and national level, to achieve a sustainable future and secure human well-being by both preserving and enhancing the benefits we derive from nature. For instance, section F of the Global target of the Convention on Biological Diversity's (CBD) Kunming-Montreal Global Biodiversity Framework ambitions to value, conserve and restore biodiversity and ecosystem services (ES) globally for all people. (CBD, 2022). In Europe the European Biodiversity Strategy, under the European Green Deal, has specific targets for sustainable natural capital management, such as reversing pollinator decline, increasing organic farming, implementing agro-ecological practices, developing urban greening plans, and promoting international natural capital accounting initiatives (European-Commission, 2020). National governments, including the Dutch government, have agreed upon these international agreements and are actively contributing at the national level to achieve the goals set forth within them (IPO et al., 2022; Rijksoverheid, 2023).

To evaluate the efficacy of these policy goals, understanding the dynamics of ES supply and demand over time and space is crucial (Su et al., 2024). It is particularly critical to assess these dynamics at the national scale to enable policymakers to make informed decisions with nationwide impact and to develop effective remediation strategies (González-García et al., 2020; Schirpke et al., 2019; Wei et al., 2017). Despite the abundance of national ES assessments, almost none of these

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assessment have a quantitative character, nor are they compared to a defined goal. The Eritrean, French, UK, and Lithuanian national ES assessments are a couple of many examples of qualitative assessments (Adem Esmail et al., 2023; Crouzat et al., 2019; Gomes et al., 2021; Watson et al., 2011). Moreover, some countries only assessed a small set of ES, leading to an incomplete understanding of the benefits derived from nature and of the impact of policies on natural resources (Vári et al., 2024). In their national assessment for instance the Czech Republic assessed 5 ES, Denmark 9 ES, Estonia 10 (Vári et al., 2024), Eritrea 9 ES (Adem Esmail et al., 2023), Spain 10 (Vári et al., 2024) and China 12 ES (Chen and Chi, 2022). While most studies tend to assess either demand or supply independently, they often overlook the crucial aspect of determining whether there is a match or mismatch between them. Within countries of Europe only a minority (48%) explicitly account for the demand into their national assessments (Vári et al., 2024). As a result, it remains unclear whether ES are effectively provided (Dworczyk and Burkhard, 2021; Vári et al., 2024). Finally, only few studies assessed whether mismatches are accommodated by other means such as imports or technological alternatives (Kleemann et al., 2020; Schröter et al., 2016). Consequently, only a limited number of assessments have quantitatively evaluated the status and trends of mismatches for a comprehensive range of ES at the national level (Feurer et al., 2021; Jacobs et al., 2016; Vári et al., 2024; Wei et al., 2017). The integration of these aforementioned aspects - quantitative assessment of multiple ES, and the identification of supply-demand mismatches at the national scale - is essential for a full understanding of ES supply. This holistic approach is the key contribution of our study to both science and policy, providing critical insights into national trends and enabling the development of informed, effective strategies to address these mismatches on a nationwide level.

Capturing (mis)matches of ES requires assessing the potential supply, i.e., the amount of service that can be generated by an ecosystem independent of demand for the service and the demand, i.e., consumption and desire. Consumption predominantly reflects the demand for provisioning services, alongside some cultural services, whereas the demand for regulating services and many cultural amenities can be inferred through direct use or expressed preferences, incorporating desires and risk prevention imperatives (Dworczyk and Burkhard, 2021; Wolff et al., 2015). ES are facilitated through the linkage between ES supply and demand, enabling the transfer of goods and services from areas where they are provided to those where they are needed (Serna-Chavez et al., 2014; Syrbe and Walz, 2012). ES mismatches are defined as the differences that occur between ES supply and demand (Geijzendorffer et al., 2015). ES mismatches are also referred to as unmet or unsatisfied demand when they are not fulfilled through other means such as technology or imports (Wei et al., 2017).

Besides supply from ecosystems, technology and imports are pivotal in meeting the demand for goods and services, thus averting unmet demand (Fitter, 2013). Despite their initial promise, however, these solutions often bring unintended adverse consequences, such as increased reliance on finite natural resources and heightened ecological footprints in other areas (Borucke et al., 2013; Schröter et al., 2016). Genuine unmet demand arises when ecosystems, technology, and imports fail to meet the desired levels of goods and services, a situation frequently observed in regulating and cultural services. This underscores the critical need for sustainable strategies to bridge the gap between supply and demand, particularly in cases where technology or imports cannot viably provide specific goods and services (Fitter, 2013; Palomo et al., 2018). Such strategies are essential for ensuring sustainable resource management and safeguarding ecosystem functions upon which human well-being depends.

The aim of this study is to assess whether supply-demand (mis) matches for a representative set of ES provided by Dutch ecosystems occur and how they change over time, and to analyse the extent to which imports and technology have reduced mismatches. Our study helps track progress towards sustainability policy objectives. It also offers strategies for policymakers and decision-makers on how to ensure a sustainable delivery of goods and services from ecosystems to society. We employed a mixed-method approach, relying on statistics, modelling, and literature review. We assessed seventeen ES, covering a broad set of production services, regulating services and cultural services. Our study provides two readily applicable indicators for tracking the status and trends of ES at national level. In this study, the Netherlands serves as a model for similar industrialized countries for assessing supply-demand mismatches of ES, benefiting from ample high-resolution data.

2. Materials and methods

2.1. Overall approach

The approach of this study comprises four parts. Firstly, we assessed a set of seventeen ES to determine whether matches or mismatches between supply and demand occur. Secondly, we quantified whether the mismatch between supply and demand of ES is mitigated through technical alternatives, imports, or if it remains an unmet demand in 2020. We focused on 2020 for assessing the current situation to capture the most recent and up-to-date snapshot of ES supply and demand and because assessing trends from older maps, such as those from 2000, has proven very difficult due to methodological inconsistencies and limitations. Thirdly, trends in supply and demand were evaluated annually from 2000 to 2020. Finally, the uncertainty of ES mismatches and trends was evaluated by considering both the completeness and reliability of the indicators used. All steps were conducted at the national level. The supply, demand and their changes over time were assessed separately for every ES.

2.2. Study area

The Netherlands, situated in north-western Europe, features predominantly low-lying, flat terrain with just 50% of its land exceeding 1 m above sea level. It's a delta region, traversed by three major rivers—Rhine, Meuse, and Scheldt—flowing into the North Sea. The northern and western regions are characterized by clay and peat soils with shallow groundwater, while the central, southern, and eastern parts have sand and loess soils with varying groundwater levels. Currently, 62% of the land is dedicated to agricultural use, 15% to semi-natural and forested areas, 18% to urban and infrastructure development, and 5% to surface water (Fig. 1). The Netherlands, with a population of 17.6 million, is the 16th most densely populated country globally and the second-most densely populated in the European Union (Eurostat, 2024; Worldbank, 2024). The Netherlands boasts one of the most productive agricultural areas globally. The landscape in the Netherlands is largely man-made. The Netherlands has long been recognized as a pioneer in grey infrastructure and technologies, such as constructing dikes, dams, and reclaiming land from the sea. However, there is a growing shift towards considering and implementing nature-based solutions as alternatives (Keesstra et al., 2018). Initiatives such as the Room for Rivers program (Rijke et al., 2012) and the commitment to achieving sustainable provision of goods and services derived from ecosystems exemplify this trend (IPO et al., 2022; Rijksoverheid, 2023).

2.3. Targeted Ecosystem Services

We focussed on quantifying seventeen indicators of ES, as classified in the CICES (Common International Classification of Ecosystems Services (Haines-Young and Potschin, 2012);): four provisioning ES, namely non-drinking water, drinking water, wood and energy from biomass; ten regulating services, namely: soil fertility, erosion prevention, water retention, coastal protection, prevention of heat islands, water purification, air quality regulation, pest control, pollination, carbon sequestration; and three cultural services: outdoor recreation,

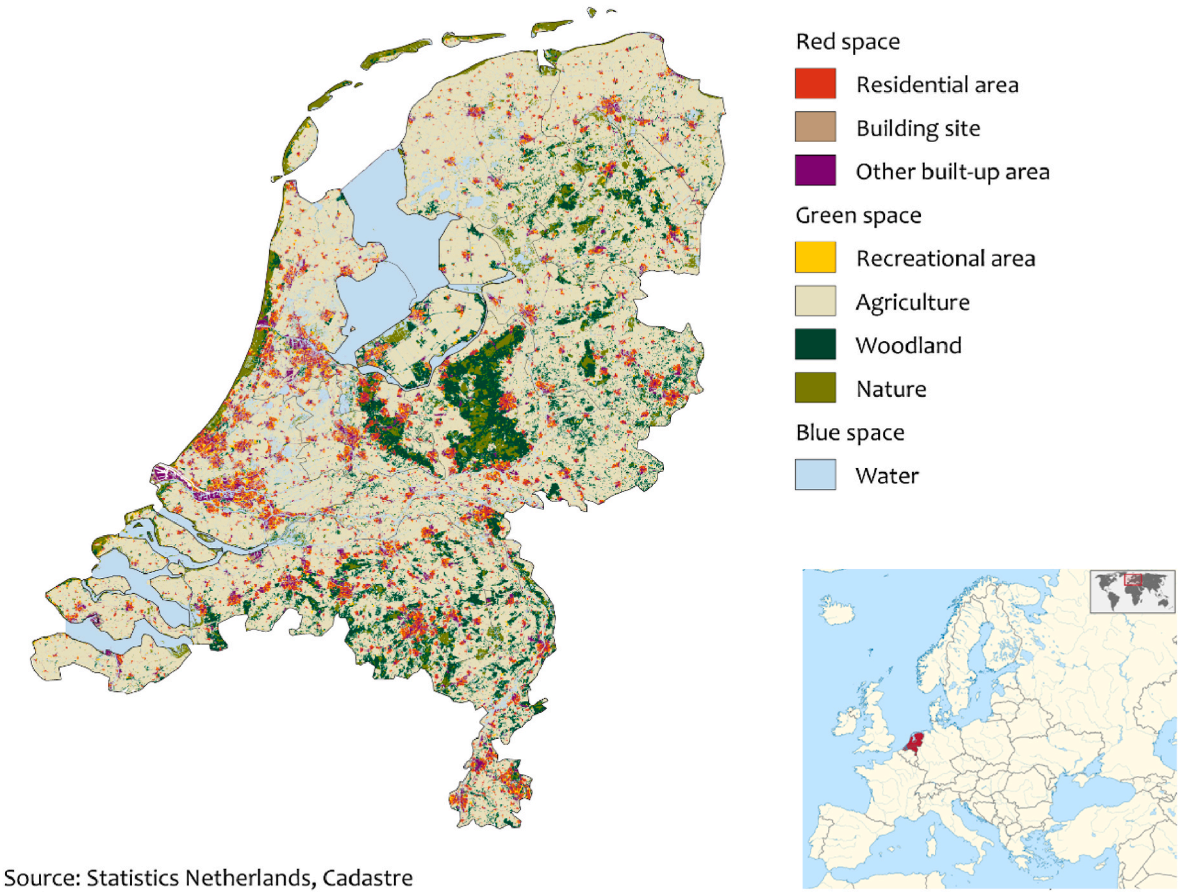

Fig. 1. Map of the Netherlands with main land use categories.

natural heritage and symbolic value of nature (Fig. 2).

These seventeen ES were selected based on their direct relevance to pressing environmental challenges in the Netherlands (De Knegt et al., 2024). For sustainable agriculture, key ES include soil fertility, pest control, pollination, and erosion prevention, all of which support the productivity and sustainability of agricultural systems. Climate change mitigation and adaptation rely on regulating services such as carbon sequestration, coastal protection, and water storage, which help buffer against rising sea levels and extreme weather events. The quality of the living environment is enhanced through cultural services like outdoor recreation, and the symbolic value of nature, which play vital roles in improving mental and physical well-being, particularly in densely populated urban areas. Biodiversity protection and restoration are supported by natural heritage and the symbolic value of nature. The quality of waterbodies is safeguarded by regulating services such as water purification, ensuring clean and healthy water systems. Lastly, the energy transition is supported by provisioning services like energy from biomass, which is a key renewable resource, aiding the shift towards sustainable energy solutions. Each of these services plays a vital role in addressing these environmental challenges, aligning with national sustainability and conservation goals.

This set of seventeen ES is a well-balanced selection, representing provisioning, regulating, and cultural services. There is sufficient availability of data and models to quantify these services. Moreover, this set is relevant in the Dutch context and for policymakers, and it is expected to evolve over time in response to shifts in land use, environmental pressures, and demographic changes (De Knegt et al., 2024; le Clech et al., 2024; Paulin et al., 2020a,b). Their inclusion offers a comprehensive perspective on the country's current and possible future environmental needs.

2.4. Match of supply and demand, technical alternatives, imports and unmet demand

2.4.1. Conceptual framework and key definitions

The conceptual framework for assessing supply-demand dynamics consists of six main concepts (Table 1): *supply*, *demand*, *(mis)match*, *technology*, *import*, and *unmet demand*. *Supply*, referring to potential supply or capacity, is determined by the current ecosystem structure, function, and management (Vallecillo et al., 2019), irrespective if the supply is actually used (Dworczyk and Burkhard, 2021; Jones et al., 2016). *Match* is variably defined as actual use, i.e. when it aligns with societal demand, flow, or benefit (Geijzendorffer et al., 2015). A *mismatch* is the difference in quality or quantity between the supply and demand of ES (Geijzendorffer et al., 2015). *Import* refers to goods brought into one country from another for sale or use, and is typically well-defined and measurable (Schröter et al., 2018; Wei et al., 2017). In addition to supply from ecosystems or imports, goods, and services can also be provided by *technology* (Fitter, 2013; Wei et al., 2017). For example, in drinking water production, natural ecosystems can play a significant role in purifying water, in addition to technologies such as using UV-light, membranes and using chemicals can play a significant role. *Unmet demand*, sometimes termed unsatisfied demand (Geijzendorffer et al., 2015; Wei et al., 2017), occurs when ES from ecosystems, technology, or imports fail to adequately meet societal needs (see Table 2).

We quantitatively assessed the supply, the demand and their (mis) match for the year 2020, for all seventeen ES independently. If the demand for one ES exceed its supply, a mismatch occurs (Eq .(1). In case of a mismatch, further analysis was conducted to determine whether technology and imports fulfilled the remaining demand or revealed genuine unmet demand (Eq. (2)).

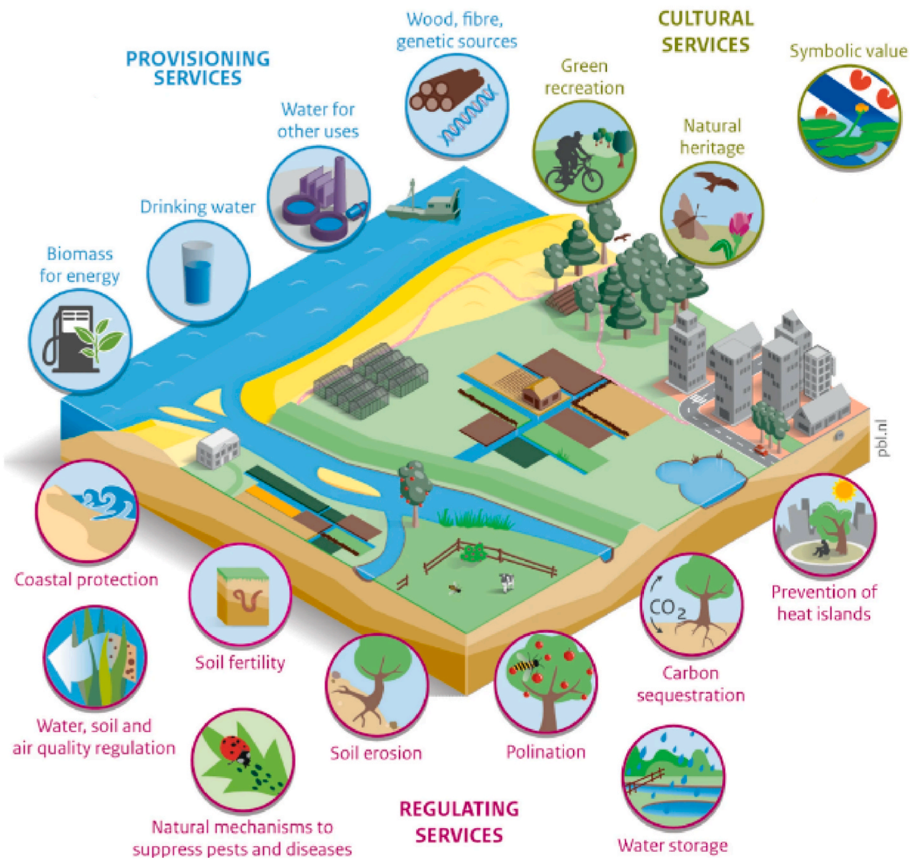

Fig. 2. Overview of the seventeen ES included in the assessment. Note that water purification and air quality regulation are considered separately in this assessment.

Table 1
Definitions of the concepts of the analysis.

Component	Definition	Example (pollination)
(potential) Supply	The potential amount of goods and services that ecosystems can generate independently of the demand for the service.	Availability of pollination by wild pollinators from ecosystems.
Demand	The amount of goods and services required by society, particular stakeholder groups or individuals.	Pollination dependent crops.
Match/ mismatch	Matches and mismatches of potential supply and demand for goods and services signify the alignment, use or flow (match) or disparity (mismatch) respectively between the potential supply and demand.	Match is when no harvest losses occur, mismatch is when harvest loss occurs due to lack of availability of pollinators for pollinator dependent crops.
Technology	The contribution of technology to meet the demand for goods and services.	Pollination by hand, pollination by domesticated bees that could not survive without humans.
Import	The contribution of import to meet the demand for goods and services.	Pollination is a services cannot be imported. On the contrary: wood products can be imported.
Unmet demand	The situation where the desired level of goods and services is not met due to insufficient supply by either ecosystems, technology or import.	Harvest loss due to pollination deficit by wild pollinators or technology.

$$\text{(Mis)match}_i\ (\%) = \text{ES}_i\ (\text{demand}) - \text{ES}_i\ (\text{supply}) / \text{ES}_i\ (\text{demand}) \times 100 \quad (1)$$

(Mis)match, demand and supply were assessed for each ES independently.

$$\text{Unmet demand}\ (\%) = \text{ES}\ (\text{demand}) - (\text{ES}\ (\text{supply}) + \text{technology} + \text{import}) / \text{ES}_i\ (\text{demand}) \times 100 \quad (2)$$

With *ES(demand)*, the societal need for those goods or services, *ES (supply)* being the ecosystem's potential to provide goods or services; *(Mis)match*, the difference between demand and supply; *technology*, the contribution of technological solutions; *import*, goods or services brought in from abroad; and *Unmet demand*, the remaining demand after accounting for supply, technology, and imports.

2.4.2. *Quantifying supply and demand*

The ES indicators are listed in Table 1, where each indicator represents the percentage of total demand supplied by Dutch ecosystems, technology, imports, or unmet demand. Using percentages enhances comparability across ES that vary in units.

Depending on the specific characteristics of each ES, three primary methods are utilized to quantify a (mis)match: statistical analysis, modelling techniques, and literature review (Fig. 3). Statistical analysis involve examining statistical data from national monitoring programs, e.g., wood consumption, production and import. Modelling techniques involve using spatial explicit mathematical models to simulate ES dynamics, e.g., predicting natural pest control with land use data and environmental variables. Literature review involve synthesizing recent literature, e.g., analysing the harvest losses due to lack of pest control. An more detailed overview of the general approach can be found in Appendix A.

Table 2
Indicators to assess the supply, demand and supply by ecosystems, technology, import and the remaining unmet demand.

ES category	Indicators			
	ES (CICES 5.3 code)	Supply & demand	Unit	Match of demand and supply by ecosytems
Provisioning services	Non-drinking water production (1.2.2.1)	Clean water for non-drinking purposes	Million liter	% of wateruse cleaned by ecosystems for non-drinking purposes
	Drinking water production (1.1.2.1)	Clean water for drinking purposes	Million m^3	% of wateruse cleaned by ecosystems for drinking purposes
	Wood production (1.1.1.2)	Volume of wood	Million m^3 wood equivalents without bark	% wood production versus wood demand
	Biomass for energy production (1.1.1/3.3)	Energy production	PJ	% energy production from biomass compared to total energy production
Regulating services	Prevention of heat islands (2.3.6.2)	Reduction of UHI	°C/capita	% reduction of UHI by vegetation
	Water purification (2.3.5.1)	Reduction of nitrate & phosphor	1.000 oxygen demanding units	% reduction of chemical conditions (nitrate & phosfor) for good water quality
	Pest control (2.2.3.1)	Reduction of pests in agricultural crops	0–100	% density of natural enemies in agricultural crops that are susceptible to pests
	Soil fertility (2.3.4.1/2/3)	Fertile agricultural soils with good soil hydrology	Million tons dry matter	% avoided production loss of crops by fertile soils defined by their hydrology
	Erosion prevention (2.2.1.1/2)	Eriosion free agricultural soils	1.000 ha	% of area of soils with high soil erosion risk with vegetation
	Pollination (2.3.2.1)	Sufficient pollination	10.000 tons	% avoided production loss of pollination dependent crops by natural pollinators
	Coastal protection (2.2.3.2)	Protection of coast to flooding	Kilometer	% of the coastline with natural ecosystems
	Carbon sequestration (2.3.6.1)	Sequestration of CO_2	Mton	% sequestration of CO2 by forest and decrease of emission by peatland compared to total CO2 emission
	Air quality regulation (2.1.1.2)	Clean air where people live (PM2.5 concentration lower than 10 μg/m^3)	100.000 people	% people under the WHO norm for PM 2.5 fine dust
	Water retention (2.2.2.2)	No risk of flooding where people live (Infiltration capacity >6 mm/h)	100.000 people	% people living at places with a water retention capacity greater than 6 mm/h of saturated soils
Cultural services	Outdoor recreation (3.1.1.2)	Enough opportunities for outdoor recreation	100.000 people	% people with enough green space in their living environment
	Natural heritage (3.2.2.1/2)	No species threatened with extinction (Red List)	Species	% of species that can occur sustainably
	Symbolic value of nature (3.4.1.1)	Healthy populations of symbolic plants and animals	Index (0–100)	% of population of species with high symbolic value compared to natural reference

2.4.3. *Methodology per ES*

The following paragraphs provide brief descriptions for each ES, outlining the methods used to quantify the indicators. For more information refer to the Appendices: Appendix B provides a detailed description of the method, and Appendix C provides the data used for each ES. A comprehensive method description is available in De Knegt et al. (2020, 2022).

Non-drinking water production is a provisioning service, to produce water for activities such as cleaning, irrigation, and industrial processes (CICES code 1.2.2.1). Demand for non-drinking water equals the amount of consumption of non-drinking water for domestic, agricultural and industrial uses which are derived from national statistics. The supply from Dutch ecosystems and technology was assessed based on the number and type of purification steps used by drinking water companies, such as filtration, chemical treatments, or UV treatment, to achieve the desired water purity. Literature was used to quantify water imports and unmet demand.

Drinking water production, serves to meet the demand for potable water (CICES code 1.1.2.1). To assess supply and demand by Dutch ecosystems, technology and imports the same methodology was used as for non-drinking water, but now related to potable water. Therefore, the total consumption, the amount of sources and purifications steps used to produce drinking water differ, since a higher water quality is needed for drinking water compared to non-drinking water purposes, as well as the extent of technological purification steps required to attain the desired water quality.

Wood products play a crucial role across multiple sectors,

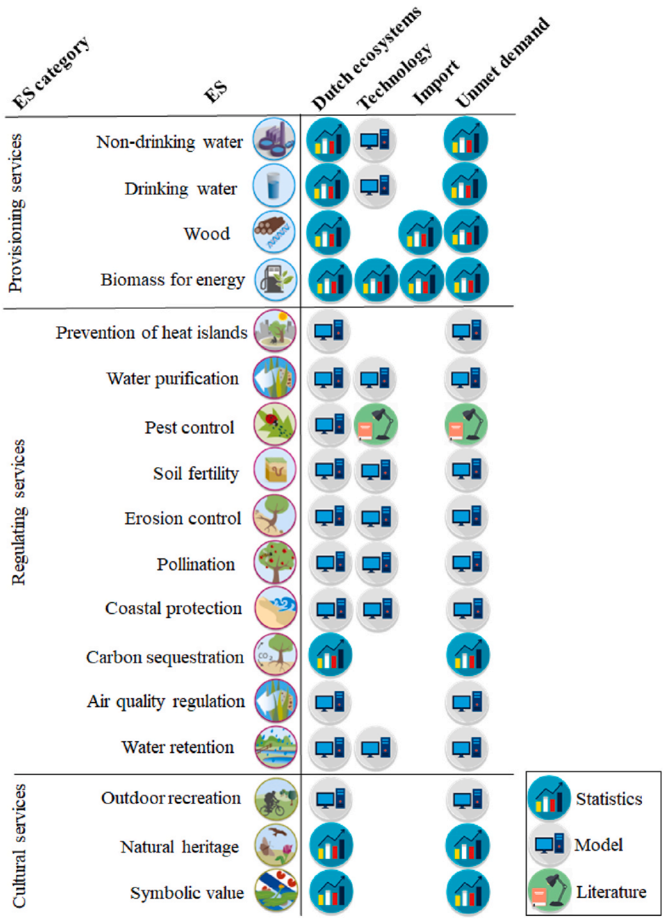

Fig. 3. General method (statistics, models, literature) used per ES to quantify the supply and demand by Dutch ecosystems, technology, imports and unmet demand. Some ES are exclusively provided by ecosystems, while others may be fulfilled by technology, imports, or a combination thereof. Empty cells are assumed to be of neglectable importance.

encompassing construction and furniture production among others (CICES code 1.1.1.2). The demand for wood products is derived through national statistics, specifically measuring the total cubic meters (m^3) of wood consumption in the Netherlands. Similarly, national statistics are used to collect data on supply, sourced from Dutch ecosystems as well as imports and exports. While technological alternatives to wood are readily accessible, we currently do not evaluate them, as our definition of demand remains centered on wood-based materials.

Biomass for energy production, a provisioning ES, reflects the growing need for sustainable energy sources compared to fossil fuels (CICES code 1.1.1/3.3). Demand for renewable energy from biomass is derived from national statistics of annual survey data, which is based on a comprehensive survey sent to all primary wood processors and roundwood exporters in the Netherlands. The supply assessment considers biomass contributions from agricultural and urban ecosystems, with adjustments made for the frequently imported agricultural products and other materials, such as wooden furniture, as derived from literature. Imports and technological alternatives of energy, such as nuclear power, geothermal energy, and energy from the sun, wind and from fossil fuels, are also derived from national statistics.

Soil erosion control is a regulating ES, particularly critical in agricultural landscapes. Demand for soil erosion regulation arises in areas susceptible to wind or water erosion, such as arable land on loess soils or on slopes (CICES code 2.2.1.1/2). The supply consists of various measures aimed at combating erosion at soil erosion prone areas, like the area having permanent vegetation preventing erosion by the retention of soil of root systems of plants. Both supply and demand were derived from a spatially explicit model that includes land use, slope, soil and presence of vegetation. Data were then averaged at the national level. Technological alternative, involve non-living components to combat erosion such as using plastic were derived from literature.

Soil fertility is a regulating service to support and enhance agricultural production (CICES code 2.3.4.1/2/3). It encompasses the chemical, biological, and physical conditions supporting optimal crop growth. Demand for fertile soils is assumed for all land (hectares) that is used for agricultural production. Supply is determined mostly by the natural ability of soils to provide nutrients, air and good moisture conditions for agricultural crops. The information of the natural soil fertility of soils is derived from the spatially explicit that provides the capacity of soils to avoid harvest losses based on hydrology (Mulder et al., 2018). Data were then averaged at the national level. Technology to boost soil fertility on soils that are less suitable for agricultural production involves practices like fertilization and drainage. It is assumed that these measures are implemented wherever there is a risk of harvest loss to mitigate potential agricultural losses.

Prevention of heat islands, recognized as a climate adaptation service, focuses on lowering the temperature in cities in cases of heat waves (CICES code 2.3.6.2). The demand is defined by the rise of temperatures in cities due to the Urban Heat Island (UHI) effect. The supply is quantified by the impact of vegetation in lowering the temperature using the spatially explicit NC-Model (De Knegt et al., 2022). Data sources include parameters such as sky-view factor, wind speed, radiation, temperature and the amount of vegetation in cities. Although technology is possible for this service, for instance using air conditioners for indoor use, they are not assessed since we focus on the outdoor temperatures.

Water purification is a critical ES aimed at maintaining water quality of water bodies by removing pollutants (CICES code 2.3.5.1). The demand for water purification arises from existing nutrient concentrations and to comply with the Water Framework Directive standards. Supply is determined by the natural purification capacity of ecosystems, that is influenced by vegetation cover and land management (mowing and removing biomass). Utilizing the spatially explicit NC-Model (De Knegt et al., 2022), this model estimates the impact of vegetation and land use on nutrient levels, particularly nitrate and phosphate, in Dutch surface water bodies. Additionally, the assessment extends to the technological purification of water carried out by water purification plants.

Natural pest control is an ES to suppress pest in agricultural crops (CICES code 2.2.3.1). The demand for pest control arises from the need to mitigate crop damage caused by pests, while supply is determined by the abundance of natural enemies such as hoverflies and parasitic wasps coming from flower field margins and other suitable habitats. The spatially explicit NC-Model (De Knegt et al., 2022) was used to assess the landscape suitability to supply natural enemies, such as crawling predators and flying nectivores, that can control pest populations in agricultural crops. By integrating habitat suitability and dispersal abilities of natural enemies, the model calculates natural enemies that control pests, thereby reducing dependence on harmful synthetic pesticides. The study also assesses the influence of technology and identifies areas of unmet demand through literature research.

Pollination is a relevant ES for agricultural crop production (CICES code 2.3.2.1). Demand arises from pollinator-dependent crops requiring insect mediated pollination for successful or enhanced fruit or seed set, while supply is determined by the availability of suitable nesting habitats and floral resources. We estimated this service using the spatially explicit NC-Model (De Knegt et al., 2022) through the contribution of wild pollinators, such as bees and hoverflies, to crop pollination. By assessing wild pollinator abundance and visitation rates, this service enhances agricultural productivity. Domesticated bees are considered a technological alternative, since they are introduced species that depend on humans for their housing, feeding and healthcare.

Coastal protection is an ES aimed at mitigating the risk of flooding and erosion along coastal areas (CICES code 2.2.3.2). Demand for coastal protection stems from the need to safeguard the hinterlands from flooding. It is defined as the length of the total coastline. Supply is provided by the percentage of the coastline that consists of natural features such as dunes and higher grounds, which act as natural buffers against storm surges. The percentage of the coastline that consists of dams and dykes is considered as a technological alternative for coastal protection.

Carbon sequestration is an ES vital for mitigating climate change impacts (CICES code 2.3.6.1). Demand arises from the need to reduce carbon emissions from all sources and combat climate change, while the supply is determined by the capacity of natural ecosystems to store and accumulate carbon in biomass (Berkel et al., 2021). The total amount of carbon emissions (demand) is derived from national statistics. The supply is determined by land use data with carbon sequestration rates. The contribution of technological alternatives, such as carbon sequestration through for instance Direct Air Capture, is derived from literature. Import and export of emission rights within the EU ETS is derived from literature.

Air quality regulation is an ES aimed at improving ambient air quality and thereby safeguarding human health (CICES code 2.1.1.2). Demand arises from the need to reduce the concentration of fine dust particles below regulatory thresholds for good air quality, while supply is provided by the absorption of fine dust particles by vegetation. The spatially explicit NC-Model (De Knegt et al., 2022) was used to assesses the capacity of vegetation to remove particulate matter (PM 2.5) from the atmosphere. By considering factors such as deposition velocity, resuspension of particles, and vegetation coverage, this service quantifies the contribution of ecosystems to air quality improvement. The contribution of technical alternatives are assessed by literature review.

Water retention is an ES for reducing the risk of flooding in cities due to peak discharges of water from rain storms (CICES code 2.2.2.2). Demand arises from the imperative to prevent flooding and maintain water balance in urban and rural areas, while supply is determined by soil type, moisture content, and vegetation cover. Utilizing the spatially explicit NC-Model (De Knegt et al., 2022), this model estimates the capacity of ecosystems to retain and infiltrate rainwater, thus preventing flooding. By integrating infiltration rates of soils and interception capacity of vegetations and litter, this service quantifies the contribution of ecosystems to water retention. Technological alternatives like runoff of water through the sewer system are estimated using literature.

Outdoor recreation is an ES that provides opportunities for leisure and physical activity in natural environments, contributing to individual well-being and societal quality of life (CICES code 3.1.1.2). The demand for outdoor recreation arises from the desire for recreational activities on a daily basis such as hiking, cycling, and nature exploration, in the living environment. Supply is determined by assessing the accessibility and availability of natural areas suitable for outdoor activities, including parks, forests, and green spaces. The spatially explicit NC-Model (De Knegt et al., 2022) was used to assess if supply and demand align. Technical alternatives like recreation outside the direct living environment or tourism to and from abroad are not considered since we focus on daily recreation in the local living environment.

Natural heritage encompasses the cultural values associated with wild species, ecosystems, and landscapes, representing a vital aspect of societal identity and heritage (CICES code 3.2.2.1/2). In the context of ES, natural heritage combines the 'existence' and 'bequest' services. Demand for natural heritage arises from the need to sustainably conserve and protect native species and habitats, as mandated by various conservation directives and targets. Supply is quantified by assessing the survival prospects of native species across different taxonomic groups, considering threat status and rarity as assessed by national Red List assessments. Technological means to protect wild species are considered as not feasible.

The symbolic value of nature includes elements with spiritual or religious significance, whose existence and conservation is important to people (CICES code 3.4.1.1). In the CICES classification system, symbolic value of nature falls under the category of cultural services. While demand for symbolic value is challenging to quantify directly, we assume that the absence or decline of symbolic species or ecosystems that originally occur in the Netherlands is negatively perceived. The supply of symbolic value is quantified through the mean species abundance, measuring the average presence of species within ecosystems and reflecting the cultural significance and symbolic meaning attributed to pristine landscapes. Technical alternatives are considered not feasible.

2.5. *Trend of supply and demand*

The changes of every ES over the last 20 years was assessed for supply and demand separately. Table 3 lists the sources and indictors used for the trend of both supply and demand for every ES. Trends were indexed with the year 2000 as a baseline and then modelled using a second-degree polynomial function, with the slope (direction coefficient) and coefficient of determination (R^2) provided for each graph. Variations within $\pm 5\%$ are considered stable, whereas variations of $\pm 5\%$ or greater are classified as significant changes. Indicators used for the yearly trends were selected to closely approximate demand, as annual spatial data were not always available. For instance, for the demand in 2020 of water retention we calculated the infiltration capacity needed to prevent flooding, while for the trend in demand we used data of the number of days with heavy rainfall (annual number of days with >50 mm) in the last twenty years.

2.6. *Uncertainty assessment*

We conducted an evaluation to assess both the uncertainties surrounding the match of supply and demand, as well as the trends of each ES. Building upon the criteria outlined by van Oudenhoven et al. (2018) for assessing the scientific credibility of ES indicators, we focused on five key aspects. A scientifically credible indicator, according to their framework, must be endorsed by scientific experts, supported by existing literature, integrated into a conceptual framework, quantifiable, and represent a valid depiction of the subject. Given that the first four criteria were already addressed (endorsement, literature, framework, quantifiable), we delved into the remaining criterion of representativity, i.e., we assessed the extent to which the indicators accurately portray the ES. Our evaluation involved a qualitative assessment conducted by ES experts (see below), wherein we evaluated the completeness of the indicators utilized and the reliability of the data used. Completeness was determined by comparing the description of each ES, with the definitions of the ES used in the CICES framework, with the indicators employed. Each ES was then assigned a score on a three-level scale, indicating the comprehensiveness of the indicators utilized: High: encompassing all aspects and is complete; Medium: comprising essential elements but is not complete; Low: encompassing some aspects and thus is not complete. Regarding reliability, the quality and representativeness of the data utilized for the indicators were categorized into three levels: High: based on comprehensive surveys or precise measurements; Medium: relying on moderately representative data or estimates derived from a mix of measurements and published sources; Low: relying on limited measurements, expert judgment, factual information, or extrapolation.

The uncertainty quantification relies on expert judgement to evaluate the completeness and reliability of ES indicators. At least five specialists were assigned to each ES, selected from a total of thirty-one experts. These experts, drawn from Wageningen University and The Netherlands Environmental Assessment Agency (PBL), independently scored both the status and trends of the indicators, evaluating their completeness and reliability. The independent scoring approach helped minimize bias by allowing each expert to provide their assessment without influence from others. The scores were then averaged and rounded to create the final score. However, when significant

Table 3
Indicators and sources used to assess the trend of supply and demand.

ES category	ES	Trend demand	Trend supply
Provisioning services	Non-drinking water production	Trend water use agriculture, businesses and private individuals (CBS, 2023c)	Trend water production agriculture, businesses and private individuals (CBS, 2023c)
	Drinking Water Production	Trend water use drinking water (CBS et al., 2020)	Trend production of drinking water (CBS et al., 2020)
	Wood Production	Trend use of wood (PROBOS, 2021)	Trend of production of wood (PROBOS, 2021)
	Biomass for Energy Production	Trend total energy use (CBS et al., 2024c)	Trend final consumption of renewable energy (CBS et al., 2024i)
Regulating services	Prevention of heat islands	Trend number of days with temperature above 25 C (CBS et al., 2024h)	Trend hectares green space in cities (CBS, 2024k)
	Water purification	Trend of surface water pollution (Emissieregistratie, 2023)	Literature (De Knegt et al., 2020)
	Pest Control	Trend of area crops sensitive to pests (CBS, 2024k)	Literature (Kleijn et al., 2018)
	Soil fertility	Literature (De Knegt et al., 2020)	Trend hectares agriculture (CBS, 2024k) and literature (De Knegt et al., 2020)
	Erosion prevention	Literature (De Knegt et al., 2020)	Literature (De Knegt et al., 2020)
	Pollination	Trend of hectares of pollinator dependent crops (CBS, 2024k)	Trend of number of red list of bees (Reemer, 2018)
	Coastal protection	Trend of sealevel rise (CBS et al., 2024j)	Length of coast with natural ecosystems (dunes, higher grounds) (De Knegt et al., 2020)
	Carbon Sequestration (forest & peat soils)	Trend emission carbon dioxide (CBS et al., 2024b)	CO_2 emissions following LULUCF (Arets et al., 2020)
	Air Quality Regulation	Trend fine dust particles PM2.5 (CBS et al., 2024d)	Trend hectares green space in cities (CBS, 2024k)
	Water Retention	Trend of number of days with heavy rainfall (CBS et al., 2024f)	Trend hectares green space in cities (CBS, 2024k)
Cultural services	Outdoor Recreation	Trend population growth (CBS, 2023b)	Trend hectares green space in cities (CBS, 2024k)
	Natural Heritage	Constant	Trend of number of red list species (CBS et al., 2024g)
	Symbolic value of nature	Constant	Trend of 28 species with high symbolic value (CBS, 2023a; De Knegt et al., 2020)

disagreements arose—defined as a difference of two categories or more—the experts engaged in group discussions to resolve discrepancies. Through these discussions, the group could reach consensus on a final score, ensuring that the assessment reflected collective expert judgment while also addressing any uncertainties.

3. Results

3.1. Match of supply and demand

Ecosystems in the Netherlands, fulfil an average of 36% of the total demand for goods and services. Dutch ecosystems provide 32% of provisioning services, 31% of regulating services, and 57% of cultural services. The extent of the (mis)match of supply and demand vary widely among the assessed ES (Table 4, Fig. 4). For none of the assessed ES, Dutch ecosystems supply fully met the total demand. For five ES, Dutch ecosystems manage to supply more than half of the demand, namely for non-drinking water (used for household tasks, irrigation, and industrial purposes), pollination, soil fertility, outdoor recreation, and natural heritage. For other ES, such as biomass for energy, regulation of air quality and carbon sequestration none or only a fraction of the demand is supplied by ecosystems. More detailed statistics and spatially explicit model results can be found in Appendix D.

The uncertainty analysis shows that five out of seventeen ES scored high on the aspect of completeness, one (soil fertility) scores low and the rest (n = 11) scored medium. For reliability, all ES except for two achieved a medium score.

3.2. Technology, imports and unmet demand

Technology contributes to meet on average 27% to the total demand, encompassing (non-) drinking water, energy production, pollination, soil fertility, erosion prevention, water storage, water purification, coastal protection, and pest control. The extent to which technology supply goods and services varies across provisioning, regulating, and cultural services (Fig. 5). It accounts for 47% of production services, 28% of regulating services, and 0% of cultural services.

Import fulfils 5% of the demand for provisioning services, particularly for wood and biomass for power generation. 83% of wood and approximately 2% of biomass for power generation are imported to meet the national demand in the Netherlands. However, for regulating and cultural services, importation is not possible, resulting in no contribution from imports.

Despite the contribution of technological alternatives and imports to meet current demands, an unmet demand remains for seven ES. On average, this percentage stands at 32%, for production services at 0%, for regulating services at 41%, and for cultural services at 43%. An example of a ES that has no unmet demand is wood production: only 17% of the demand is supplied by Dutch ecosystems and the rest is imported. An example of an ES that has a partially unmet demand is outdoor recreation: still 39% of people have not enough space in their surroundings to satisfy their need for outdoor recreation. An example of an ES where demand is fully unmet is carbon sequestration: ecosystems in the Netherlands are a net emitter of carbon into the atmosphere and contribute to the problem instead of the solution.

3.3. Trends in supply and demand 2000–2020

For 10 out of 17 ES, the net trend between 2000 and 2020 has been negative, meaning that the supply hasn't been keeping pace with demand (Fig. 6, Appendix E). Out of these 10 ES, water storage, prevention of heat islands, and outdoor recreation, present an increase in both supply and demand, but for the other three ES the increase in supply is much less compared to the increase of the demand. For two ES (wood production and natural heritage) the mismatch between supply and demand remains the same, and for five ES (biomass for energy, water

Table 4
Supply and demand of ES in the Netherlands (2020).

ES	Indicator	Unit	Demand 2020	Supply 2020
Carbon sequestration	Sequestration of CO_2 by forest and peatland	Mton	155	−3
Regulation air quality	Reduction of number of people living in areas with PM2.5 concentration lower than 10 μg/m^3 by vegetation	100.000 people	139	1
Prevention of heat islands	Reduction of UHI by vegetation	°C/capita	6	2
Symbolic value of nature	Average population index of symbolic plants and animals	index (0–100)	100	34
Water storage	Reduction of number of people living in areas with Infiltration capacity >6 mm/h by soil and vegetation	100.000 people	174	63
Erosion prevention	Avoided risk of soil erosion by vegetation	1.000 ha	233	109
Outdoor recreation	Number of people with no shortage of opportunities for outdoor recreation	100.000 people	174	130
Natural heritage	Number of species not on the Red List	Species	1771	1.077
Pest control	Density of natural enemies in agricultural crops that are susceptible to pests	0–100	100	9
Water purification	Reduction of waterbodies with unfavourable chemical conditions (nitrate & phosphor) by vegetation	1.000 oxygen demanding units	33.133	2.518
Biomass for energy	Energy production from biomass compared to total energy production	PJ	1.850	30
Wood production	Wood production	million m^3 wood equivalents without bark	20	4
Coastal protection	Coastal protection by dunes and higher grounds	Kilometer	1.833	383
Drinking water	Drinking water produced by ecosystems	Million m^3	58	28
Non-drinking water	Non-drinking water produced by ecosystems	Million liter	1.283	759
Soil fertility	Avoided production loss of agricultural soils by maintaining good soil hydrology	Million tons dry matter	3	2
Pollination	Avoided production loss of pollination dependent crops by natural pollinators	10.000 tons	41	33

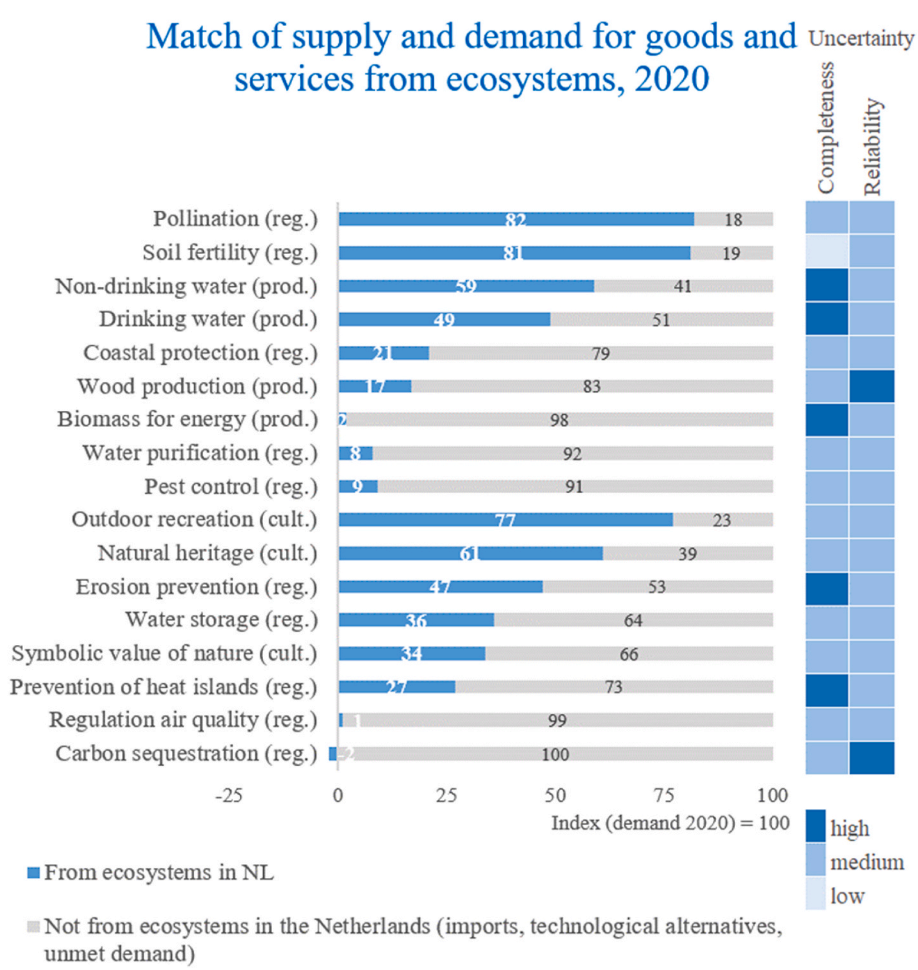

Fig. 4. The match of supply and demand (0–100) of ES in 2020 in the Netherlands for seventeen ES. The uncertainty analysis consists of completeness in comparison to the CICES definitions and reliability of the indicators used. Numbers indicate the percentage of demand that is supplied by ES.

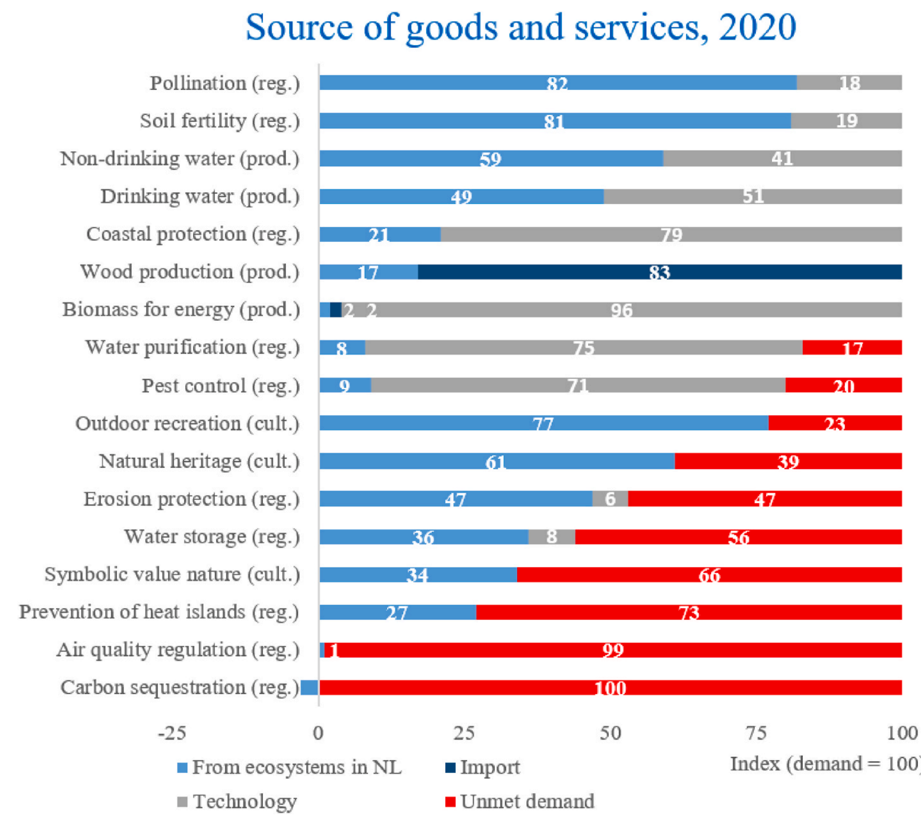

Fig. 5. The sources of goods and services (blue = from ecosystems, green = from import, grey = from technology) and the remaining unmet demand (red). Numbers on the bars indicate the percentage of the demand that is supplied by each of the categories.

purification, air quality regulation, carbon sequestration, and symbolic value of nature) the discrepancy is decreasing.

Results for the trend of the demand shows eight ES have increased (non-drinking water, drinking water, wood production, water storage, coastal protection, prevention of heat islands, erosion control, outdoor recreation), four have decreased (pest control, water purification, air quality regulation, and carbon sequestration), and five have been stable (pollination, soil fertility, biomass for energy, natural heritage, symbolic value of nature).

Results for the trend of the supply of ES show increases for eight ES (wood production, biomass for energy, water storage, prevention of heat islands, regulation of air quality, carbon sequestration, outdoor recreation and symbolic value of nature). For four ES the supply has decreased (non-drinking water, pollination, soil fertility, pest control). No changes have been observed for the supply in drinking water production, erosion prevention, water purification, coastal protection and natural heritage.

The uncertainty analysis shows there are no ES with a low score. Seven out of seventeen ES received high scores for completeness, while ten scored a medium level. Thirteen out of seventeen ES scored high for reliability, with the four remaining ES scoring medium.

4. Discussion

4.1. Key findings

This paper examines the dynamics of seventeen ES in the Netherlands, assessing the (mis)matches between supply and demand in 2020 and their change over the past two decades. The findings uncover that Dutch ecosystems contribute to the supply of many valuable goods and services to society. Nevertheless, for none of these goods and services supply by Dutch ecosystems can solely meet the entirety of demand. Trend analysis indicates that this disparity between supply and demand has been widening over time. Although imports and technology solve part of the mismatch between supply and demand, unmet demand still remained in 2020.

The seventeen goods and services of this study can be divided into two groups based on having unmet demand or not. The first group includes the seven goods and services without unmet demand. These ES rely on technology or imports to fill the mismatch, as the contribution of the ecosystem alone is not sufficient to fully address the demand. Our results are largely consistent with those conducted at national, subnational and global levels (Chen and Chi, 2022; de León and del Álamo, 2011; IPBES, 2019; Jacobs et al., 2016; Maes et al., 2020; Watson et al., 2011). Within these studies mismatches are in general least frequently observed for provisioning services, and most frequently for regulating and cultural ES. Trends in the Netherlands indicate that five out of seven ES in this group without unmet demand are moving unfavourably: the gap between supply by Dutch ecosystems and demand is widening. A widening gap for these ES was also observed in the aforementioned studies, caused by a simultaneous increase in demand and decrease in supply. One possible explanation for the similarity in the results is that the drivers influencing demand and supply—such as population growth, climate change, land use intensification, and pollution—operate on a global scale. Failing to reverse this widening gap could heighten reliance on imports and technology. This could potentially lead to unmet demand in the future, especially against the backdrop of the expectation of increased demand due to population growth and climate change (Pörtner et al., 2023; Vollset et al., 2020).

Despite the absence of unmet demand in this group of seven goods and services, concerns persist regarding the reliance on technology and imports to fulfil the demand. Goods and services like timber can be transported and are currently imported in the Netherlands to meet national demand, thereby increasing reliance on ecosystems outside the Netherlands and expanding the ecological footprint of 4 times the surface area of the Netherlands outside of the county (Footprint Data Foundation, downloaded 10 june 2024; van Vuuren and Smeets, 2000).

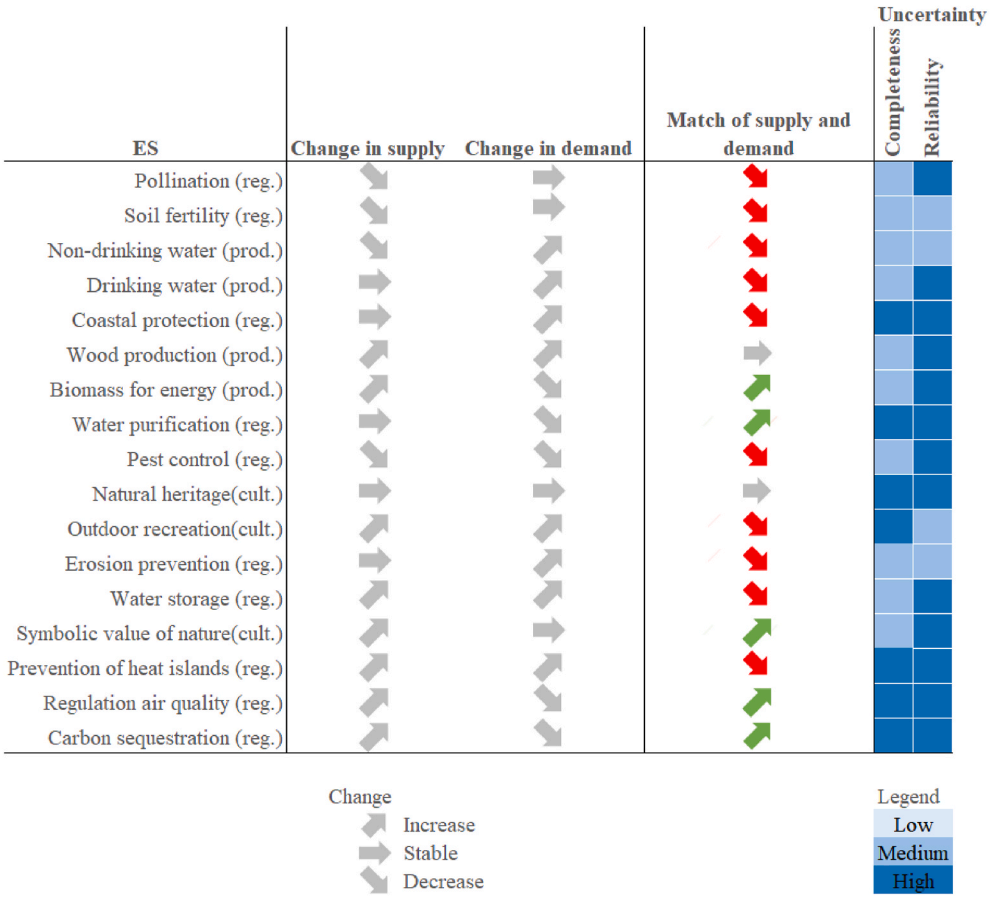

Fig. 6. The trend of change in supply and demand of the 17 ES between 2000 and 2020 in the Netherlands and uncertainty related to the choice of the indicators.

Another example is the use of fertilizers to enhance crop productivity. It adversely affects biodiversity within and outside agricultural landscapes (Dudley and Alexander, 2017). Reliance on domestic bees for pollination is reported to have negative impacts on wild pollinators (Mallinger et al., 2017).

The second group encompasses the goods and services with unmet demand. This group consists solely of regulating and cultural ES, which need to be supplied at the location of demand, or cannot be substituted making technology or import less feasible (Fitter, 2013). The average of unmet demand is 55% in this group, highlighting pressing concerns as this unmet demand detrimentally affects human well-being (Winkler et al., 2021). For instance, insufficient water purification leads to polluted water systems, adversely affecting aquatic fauna, flora, and human health. Additionally, the absence of natural pest control in agriculture results in harvest losses when no pesticides are used, compounding the already detrimental effects of pesticides on human health and ecosystem well-being (Rani et al., 2021). Some goods and services in this category can only be supplied by ecosystems, as imports or technology are not possible (Batabyal et al., 2003; Fitter, 2013; Sandhu et al., 2016). Examples of this include natural heritage, outdoor recreation, the symbolic value of nature, prevention of heat islands, and air quality regulation in cities. Trends indicate that the gap between supply and demand is either stagnant or widening for the majority (6 out of 10) of goods and services, as also confirmed by other studies (Chen and Chi, 2022; de León and del Álamo, 2011; IPBES, 2019; Jacobs et al., 2016; Maes et al., 2020; Watson et al., 2011).

4.2. Factors driving supply and demand

There are several possible explanations for the observed changes in supply of ES. The supply of ES has overall declined in the Netherlands, and is mainly related to physical factors (Chen and Chi, 2022). This decline is likely due to the overall deteriorating conditions of ecosystems by pollution, climate change, and overexploitation (Maes et al., 2020). The provision of non-drinking water, soil fertility, pollination, and pest control have declined, suspected to be mainly caused by agricultural intensification. In the case of non-drinking water, agricultural intensification has led to higher efforts to achieve proper water quality and closures of water production units (Pronk et al., 2021). Regarding soil fertility, the decrease in agricultural area combined with reduced water availability due to climate change has led to a diminished supply of fertile soils for agricultural production (De Knegt et al., 2020). Agricultural intensification including pesticide use have led to decreases of populations of insect populations that are beneficial for pollination and pest control (Biesmeijer et al., 2006; Hallmann et al., 2017). On the other hand ES such as water storage, climate regulation in cities, air quality control, and opportunities for outdoor recreation have seen an increase due to a slight expansion of green spaces in urban areas (De Knegt et al., 2020).

Various factors contribute to the observed changes in the demand for ES. Besides climate change, anthropogenic factors (i.e., population density, economic development, built-up area, and land use intensity) are considered to be closely related to ES demand (Chen and Chi, 2022). For ES such as (non-)drinking water, water storage, coastal protection, prevention of heat islands and erosion prevention the growing demand seems to be driven by population growth and climate change (Boithias et al., 2014; Pyrgou et al., 2020; Scholes, 2016). With hotter and dry summers, more heavy rain showers and rising sea levels the demand for these ES has increased and is likely to continue to increase in the future (Pörtner et al., 2023). The demand for outdoor recreation has increased mainly because the urban population has grown, especially in the biggest cities (Van Steen et al., 2016). The demand for wood, pest control, water purification, air quality regulation and carbon sequestration has declined. For the last three ES the decline in demand was due to lower emissions of pollutants and CO_2 by less polluting production processes (CBS et al., 2024a; 2024b; 2024d). However, given the persistent and significant drivers such as population growth, climate change, and agricultural practices, the pressures on the ecological system are expected to remain high (IPBES, 2019). These enduring pressures will likely lead to increased demand for ES while simultaneously decreasing their supply, creating a challenging scenario for the future.

4.3. Limitations

This study has several limitations that future research can address. Firstly, although we examined a wide array of ES representing provisioning, regulating, and cultural functions across both terrestrial and aquatic domains, our assessment did not cover all ES. It is recommended for future research to assess the full spectrum of ES to ensure comprehensive coverage. Although we did not miss any major ES, adding more ES is expected to reinforce the patterns have already observe. Secondly, ES are complex and interconnected, exhibiting significant spatial and temporal variability, which introduces inherent uncertainties in their quantification and assessment (Hamel and Bryant, 2017; Hou et al., 2013). Despite incorporating the latest scientific knowledge, uncertainties persist, particularly for regulating and cultural services, where data limitations and gaps in ecosystem condition models increase uncertainty. Due to the lack of quantitative data on uncertainty and sensitivity analysis, we relied on expert judgment to assess and quantify them. While in the uncertainty assessment most ES scored medium for completeness and reliability in the supply-demand match, completeness remains a concern, potentially impacting the accuracy of mismatch estimates. However, the results presented in this study are considered robust as they are presented as national totals. Regarding supply-demand trends, nearly half of the ES scored high for completeness, with most showing high reliability, indicating that while trends are more reliable, completeness gaps may affect long-term projections. Although the estimates presented in this study are based on the latest scientific knowledge, they should be viewed as approximations rather than precise values. The discrepancies in several ES, such as carbon sequestration, air quality regulation, and wood production, are so substantial that they fall well within the expected range of statistical uncertainties. Future efforts should focus on quantifying uncertainties more rigorously and improving model accuracy and monitoring networks to follow progress towards policy goals (Karp et al., 2015). Thirdly, feedback from policymakers on earlier versions of the indicators highlighted the complexity arising from the integration of various aspects such as status, trends, supply and demand, imports, technology, and inherent uncertainties. Efforts were made to balance the richness and complexity of the data with the need for simplicity and transparency to enhance communication and uptake in policy and decision-making processes. As a result, improvements were made to the figures presented. Future research could evaluate whether these enhancements have indeed improved clarity among diverse stakeholder groups.

4.4. Implications for policy and decision-making

The findings of this study have several implications for policy and decision-making. Firstly, the indicators on mismatches, trends, and the match of supply and demand, alongside considerations of technical alternatives, imports, and unmet demand, give insight on the progress towards policy goals on sustainable resource use and preservation of ES. The infographic (Fig. 2) is widely used by other national and international institutions and in scientific and popular publications. The presented indicators became part of Dutch policy cycle and are for instance now input for the IUCN national dashboard on the state and trend of the environment in the Netherlands (IUCN, 2024). As a result, frequent update of the indicators is demanded by the Statutory Research Tasks Unit for Nature & the Environment which is funded by the Dutch Ministry of Economics, Agriculture and Innovation in the Netherlands. The outcomes of the indicators reveal an unmet demand and a widening gap between the supply and demand of essential goods and services that technical substitutes or imports fail to address. A deeper exploration of long-term trends in these ecosystem imbalances, both globally and locally, would enhance the analysis, providing a clearer view of potential policy interventions needed to address these gaps. This indicates that the Global Biodiversity Framework policy target to maintain and enhance nature's benefits and restore current declines is not on track, underscoring the pressing need to address these issues. The effect of this unmet demand poses significant risks to human well-being, such as poor air and water quality, urban heat islands, heightened flood risks, and limited recreational opportunities. Given projections of population growth and the escalating impacts of climate change, monitoring these mismatches becomes increasingly important for tracking policy progress and prioritizing adaptive management approaches.

Secondly, the type of information provided in this study can help to prioritize restoration efforts. Restoration efforts should focus on goods and services crucial for human well-being, exhibiting unmet demand, widening gaps between supply and demand, and where imports or technology are not feasible. Already six ES meet all of these three criteria (pest control, natural heritage, outdoor recreation, erosion protection, water storage, prevention of heat islands). Considering the already large ecological footprint, importing goods and services, as well as using technology, requires careful scrutiny. Detailed case analysis of these six services, examining both the reasons behind the supply-demand imbalances and the feasibility of proposed solutions, would further substantiate these recommendations. Promoting a circular economy (MacArthur, 2013) and embracing short supply chains (Renting et al., 2003) should be considered to reduce adverse effects and decrease the ecological footprint.

Thirdly, the results of supply-demand (mis)matches identify potential solutions for policymakers and decision-makers seeking to close the gap between the supply and demand for essential goods and services (Chen and Chi, 2022; González-García et al., 2020; Wei et al., 2017). Strategies involve increasing supply, reducing demand, or spatially optimizing both. Increasing the supply can be achieved by enhancing the capacity of ecosystems to provide desired ES bundles through increasing the amount of specific ecosystems or improving the condition of ecosystems by decreasing environmental pressures. Reducing demand is an option for ES where ecosystems may not be very effective to supply the desired services, for instance the effectivity of regulation of air quality is limited in the Netherlands. This necessitates actions like reducing the production of fine dust particles, for example, by electrifying transportation, especially in densely populated urban areas. Optimizing the spatial alignment of supply and demand, particularly for regulating services, could be highly effective in addressing mismatches where supply needs to match demand spatially. To include comparative data and specific case studies from other countries could provide a more nuanced understanding of how different regions have approached these issues. Exploration of nature-based solutions is strongly recommended as they target multiple ES including biodiversity, represent long-term adaptive investments, reduce the ecological footprint and can address various drivers of change (Keesstra et al., 2018).

Fourthly, to effectively support policy and practice, specific attention should be given to implementing sustainable practices at national, regional, and local levels. In agriculture, incentivizing sustainable farming could enhance key ES like pest control and water retention, while urban planners can prioritize nature-based solutions to address issues such as heat islands, air quality regulation, flood risks and providing enough room for outdoor recreation. Engaging and aligning diverse stakeholders—from national agencies focusing on large-scale goals like flood reduction, to local communities involved in small-scale initiatives—will be crucial for success. Though funding mechanisms and legislation were not the primary focus of this study, further research into these areas, alongside stakeholder consultations, would strengthen policy implementation efforts.

5. Conclusion

This study reveals a widening gap between the supply and demand of ES in the Netherlands, posing significant challenges to human well-being and sustainability policy goals. Despite mitigation efforts through imports and technology, unmet demand persists, underscoring the urgent need for immediate action. Prioritizing Nature-based Solutions and optimizing the supply and demand of high-priority ES can foster a more sustainable relationship between society and nature. Continuous monitoring and adaptive management are crucial to maintaining and enhancing the benefits provided by ecosystems for future generations. By integrating these strategies, we can work towards achieving biodiverse and resilient ecosystems that supports human well-being and sustainable development.

CRediT authorship contribution statement

Bart de Knegt: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Marjolein E. Lof:** Writing – review & editing, Software. **Solen Le Clec'h:** Writing – review & editing, Supervision. **Rob Alkemade:** Writing – review & editing, Supervision.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.123442.

Data availability

Data will be made available on request.

References

Adem Esmail, B., Cortinovis, C., Wang, J., Geneletti, D., Albert, C., 2023. Mapping and assessing ecosystem services for sustainable policy and decision-making in Eritrea. Ambio 52 (6), 1022–1039.
Arets, E., Lesschen, J.P., Lerink, B., Schelhaas, M., Hendriks, C., 2020. Information on LULUCF Actions, The Netherlands Reporting in Accordance to Article 10 of Decision No 529/2013/EU.
Batabyal, A.A., Kahn, J.R., O'Neill, R.V., 2003. On the scarcity value of ecosystem services. J. Environ. Econ. Manag. 46 (2), 334–352.
Berkel, J.V., Bogaart, P., Driessen, C., Hein, L., Horlings, E., Jong, R.D., Schenau, S., 2021. Natural capital accounting in the Netherlands: technical report.
Biesmeijer, J.C., Roberts, S.P., Reemer, M., Ohlemuller, R., Edwards, M., Peeters, T., Schaffers, A., Potts, S.G., Kleukers, R., Thomas, C., 2006. Parallel declines in pollinators and insect-pollinated plants in Britain and The Netherlands. Science 313 (5785), 351–354.
Boithias, L., Acuña, V., Vergoñós, L., Ziv, G., Marcé, R., Sabater, S., 2014. Assessment of the water supply: demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. Sci. Total Environ. 470, 567–577.
Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J.C., Wackernagel, M., Galli, A., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework. Ecol. Indicat. 24, 518–533.
CBD, 2022. COP 15: four goals, 23 targets for 2030. https://www.cbd.int/article/cop15-cbd-press-release-final-19dec2022.
CBS, 2023a. Meetprogramma's voor flora en fauna. Kwaliteitsrapportage NEM over, 2022.
CBS, 2023b. Statline: regionale kerncijfers nederland. https://opendata.cbs.nl/statline/#/CBS/nl/dataset/70072ned/table?dl=65A84.
CBS, 2023c. Statline: Watergebruik bedrijven en particuliere huishoudens; nationale rekeningen. https://opendata.cbs.nl/#/CBS/nl/dataset/82883NED/table.
CBS, 2020. Productie van drinkwater, 1950-2020 (indicator 0045, versie 15, 15 juni 2022). PBL, RIVM, & WUR. www.clo.nl.
CBS, 2024a. Belasting van het oppervlaktewater vanuit riolering en rioolwaterzuivering, 1990-2021 (indicator 0515, versie 19, 24 oktober 2023). PBL, RIVM, & WUR. www.clo.nl.CentraalBureauvoordeStatistiekCBS. Den Haag; PBL Planbureau voor de Leefomgeving, Den Haag; RIVM Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven; en Wageningen University and Research, Wageningen.
CBS, 2024b. Emissies broeikasgassen, 1990-2022 (indicator 0165, versie 42, 29 maart 2024. PBL, RIVM, & WUR. www.clo.nl.
CBS, 2024c. Energieverbruik per sector, 1990-2021 (indicator 0052, versie 24, 30 augustus 2022). PBL, RIVM, & WUR. www.clo.nl.
CBS, 2024d. Fijnere fractie van fijn stof (PM2,5) in lucht, 2009-2022 (indicator 0532, versie 08, 23 juni 2023). PBL, RIVM, & WUR Den Haag; PBL Planbureau voor de Leefomgeving, Den Haag; RIVM Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven. en Wageningen University and Research, Wageningen. www.clo.nl.CentraalBureauvoordeStatistiekCBS.
CBS, 2024f. Neerslagextremen in Nederland, 1910-2022 (indicator 0590, versie 03, 15 augustus 2023). PBL, RIVM, & WUR. www.clo.nl.
CBS, 2024g. Rode Lijst Indicator, 1995-2022 (indicator 1521, versie 16, 17 mei 2023). PBL, RIVM, & WUR. www.clo.nl.
CBS, 2024h. Temperatuurextremen in Nederland, 1906-2022 (indicator 0589, versie 03, 15 augustus 2023). PBL, RIVM, & WUR. www.clo.nl.
CBS, 2024i. Verbruik van hernieuwbare energie 1990-2022 (indicator 0385, versie 39. PBL, RIVM, & WUR. www.clo.nl. (Accessed 4 April 2024).
CBS, 2024j. Zeespiegelstijging langs de Nederlandse kust en mondiaal, 1890-2018 (indicator 0229, versie 11, 1 oktober 2020). PBL, RIVM, & WUR. www.clo.nl.
CBS, 2024k. Statline: Landbouw; gewassen, dieren en grondgebruik naar regio. https://opendata.cbs.nl/#/CBS/nl/dataset/80780ned/table?ts=1721303097716.
Chen, W., Chi, G., 2022. Spatial mismatch of ecosystem service demands and supplies in China, 2000–2020. Environ. Monit. Assess. 194 (4), 295.
Crouzat, E., Zawada, M., Grigulis, K., Lavorel, S., 2019. Design and implementation of a national ecosystem assessment–insights from the French mountain systems' experience. Ecosystems and People 15 (1), 288–302.
De Knegt, B., Biersteker, L., van Eupen, M., van der Greft, J., Heidema, N., Koopman, R., Jochem, R., Lof, M., Mulder, M., van Rijn, P., 2022. Natural Capital Model, pp. 2352–2739.
De Knegt, B., Breman, B.C., Le Clec'h, S., Van Hinsberg, A., Lof, M.E., Pouwels, R., Roelofsen, H.D., Alkemade, R., 2024. Exploring the contribution of nature-based solutions for environmental challenges in The Netherlands. Sci. Total Environ. 929, 172186.
De Knegt, B., van der Aa, M., van Gerven, L., Hendriks, K., Koopmans, S., Lof, M., Riksen, M., Roelofsen, H., de Vries, S., Woltjer, I., 2020. Graadmeter Diensten van Natuur, update 2020: Vraag, aanbod, gebruik en trend van goederen en diensten uit ecosystemen in Nederland, pp. 2352–2739.
de León, del Álamo, J.B., 2011. Evaluación de los ecosistemas del milenio de España. El Ecol. 71, 27–29.
Dudley, N., Alexander, S., 2017. Agriculture and biodiversity: a review. Biodiversity 18 (2–3), 45–49.
Dworczyk, C., Burkhard, B., 2021. Conceptualising the demand for ecosystem services–an adapted spatial-structural approach. One Ecosyst.: ecology and sustainability data journal 6 (2021), e65966, 6.
Emissieregistratie, 2023. Overzichtstabel belasting naar oppervlaktewater. https://www.emissieregistratie.nl/data/overzichtstabellen-water/belasting-naar-oppervlaktewater.
European-Commission, 2020. In: EU (Ed.), Bringing Nature Back to Our Lives: EU Biodiversity Strategy for 2030, COM (2020) 380 Final, p. 25. Brussels.
Eurostat, 2024. Population density by NUTS 3 region. https://ec.europa.eu/eurostat/databrowser/view/DEMO_R_D3DENS_custom_672158/bookmark/table?lang=en&bookmarkId=48e7b1e4-7d8d-45db-8717-b7bfd36182a0.
Feurer, M., Rueff, H., Celio, E., Heinimann, A., Blaser, J., Htun, A.M., Zaehringer, J.G., 2021. Regional scale mapping of ecosystem services supply, demand, flow and mismatches in Southern Myanmar. Ecosyst. Serv. 52, 101363.
Fitter, A.H., 2013. Are ecosystem services replaceable by technology? Environ. Resour. Econ. 55, 513–524.
Geijzendorffer, I.R., Martín-López, B., Roche, P.K., 2015. Improving the identification of mismatches in ecosystem services assessments. Ecol. Indicat. 52, 320–331.
Gomes, E., Inácio, M., Bogdzevič, K., Kalinauskas, M., Karnauskaitė, D., Pereira, P., 2021. Future scenarios impact on land use change and habitat quality in Lithuania. Environ. Res. 197, 111101.
González-García, A., Palomo, I., González, J.A., López, C.A., Montes, C., 2020. Quantifying spatial supply-demand mismatches in ecosystem services provides insights for land-use planning. Land Use Pol. 94, 104493.
Haines-Young, R., Potschin, M., 2012. Common International Classification of Ecosystem Services (CICES, Version 4.1), vol. 33. European Environment Agency, p. 107.

Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLoS One 12 (10), e0185809.
Hamel, P., Bryant, B.P., 2017. Uncertainty assessment in ecosystem services analyses: seven challenges and practical responses. Ecosyst. Serv. 24, 1–15.
Hou, Y., Burkhard, B., Müller, F., 2013. Uncertainties in landscape analysis and ecosystem service assessment. J. Environ. Manag. 127, S117–S131.
IPBES, 2019. The Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform. IPBES Secretariat, Bonn, Germany.
IPO, S.B.B., Natuurmonumenten, N.L.L., Lnv, 2022. Interprovinciaal overleg, staatsbosbeheer, natuurmonumenten, landschappen NL. Ministerie van LNV. De eerste agenda Natuurinclusief.
IUCN, 2024. Dutch national dashboard for biodiversity. https://dashboardbiodiversiteit.nl/.
Jacobs, S., Spanhove, T., De Smet, L., Van Daele, T., Van Reeth, W., Van Gossum, P., Stevens, M., Schneiders, A., Panis, J., Demolder, H., 2016. The ecosystem service assessment challenge: reflections from Flanders-REA. Ecol. Indicat. 61, 715–727.
Jones, L., Norton, L., Austin, Z., Browne, A., Donovan, D., Emmett, B., Grabowski, Z., Howard, D., Jones, J.P., Kenter, J., 2016. Stocks and flows of natural and human-derived capital in ecosystem services. Land Use Pol. 52, 151–162.
Karp, D.S., Tallis, H., Sachse, R., Halpern, B., Thonicke, K., Cramer, W., Mooney, H., Polasky, S., Tietjen, B., Waha, K., 2015. National indicators for observing ecosystem service change. Global Environ. Change 35, 12–21.
Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610, 997–1009.
Kleemann, J., Schröter, M., Bagstad, K.J., Kuhlicke, C., Kastner, T., Fridman, D., Schulp, C.J., Wolff, S., Martínez-López, J., Koellner, T., 2020. Quantifying interregional flows of multiple ecosystem services–A case study for Germany. Global Environ. Change 61, 102051.
Kleijn, D., Bink, R., ter Braak, C., Grunsven, R.v., Ozinga, W., Roessink, I., Scheper, J., Schmidt, A., de Vries, M., Wegman, R., 2018. Decline of Insect Populations in the Netherlands: Trends, Causes and Knowledge Gaps, vol. 2871. Alterra-rapport-Wageningen University and Research Centre.
le Clech, S., van Bussel, L.G., Lof, M.E., de Knegt, B., Szentirmai, I., Andersen, E., 2024. Effects of linear landscape elements on multiple ecosystem services in contrasting agricultural landscapes. Ecosyst. Serv. 67, 101616.
MacArthur, E., 2013. Towards the Circular Economy, Economic and Business Rationale for an Accelerated Transition, vol. 1. Ellen MacArthur Foundation, Cowes, UK.
Maes, J., Teller, A., Erhard, M., Conde, S., Vallecillo, S., Barredo, J.I., Paracchini, M.-L., Abdul Malak, D., Trombetti, M., Vigiak, O., 2020. Mapping and Assessment of Ecosystems and Their Services: an EU Wide Ecosystem Assessment in Support of the EU Biodiversity Strategy. EUR.
Mallinger, R.E., Gaines-Day, H.R., Gratton, C., 2017. Do managed bees have negative effects on wild bees?: a systematic review of the literature. PLoS One 12 (12), e0189268.
Mulder, M., Hack-ten Broeke, M., Bartholomeus, R., van Dam, J., Heinen, M., van Bakel, J., Walvoort, D., Kroes, J., Hoving, I., Holshof, G., 2018. Waterwijzer Landbouw: instrumentarium voor kwantificeren van effecten van waterbeheer en klimaat op landbouwproductie. Stowa.
Palomo, I., Willemen, L., Drakou, E., Burkhard, B., Crossman, N., Bellamy, C., Burkhard, K., Campagne, C.S., Dangol, A., Franke, J., 2018. Practical solutions for bottlenecks in ecosystem services mapping. One Ecosyst. 3, e20713.
Paulin, M., Remme, R., de Nijs, T., Rutgers, M., Koopman, K., de Knegt, B., van der Hoek, D., Breure, A., 2020a. Application of the natural capital model to assess changes in ecosystem services from changes in green infrastructure in Amsterdam. Ecosyst. Serv. 43, 101114.
Paulin, M., Remme, R., Van der Hoek, D., De Knegt, B., Koopman, K., Breure, A., Rutgers, M., De Nijs, T., 2020b. Towards nationally harmonized mapping and quantification of ecosystem services. Sci. Total Environ. 703, 134973.
Pörtner, H., Roberts, D., Adams, H., Adler, C., Aldunce, P., Ali, E., Ara Begum, R., Betts, R., Bezner Kerr, R., Biesbroek, R., 2023. SPM-summary for Policymakers.
PROBOS, 2021. HOUTPRODUCTIE EN -GEBRUIK IN NEDERLAND IN 2021.
Pronk, T., Hofman-Caris, R., Vries, D., Kools, S., ter Laak, T., Stroomberg, G., 2021. A water quality index for the removal requirement and purification treatment effort of micropollutants. Water Supply 21 (1), 128–145.
Pyrgou, A., Hadjinicolaou, P., Santamouris, M., 2020. Urban-rural moisture contrast: regulator of the urban heat island and heatwaves' synergy over a mediterranean city. Environ. Res. 182, 109102.
Rani, L., Thapa, K., Kanojia, N., Sharma, N., Singh, S., Grewal, A.S., Srivastav, A.L., Kaushal, J., 2021. An extensive review on the consequences of chemical pesticides on human health and environment. J. Clean. Prod. 283, 124657.
Reemer, M., 2018. Basisrapport voor de Rode Lijst Bijen. Rapportnummer EIS2018-06. EIS Kenniscentrum, Leiden.
Renting, H., Marsden, T.K., Banks, J., 2003. Understanding alternative food networks: exploring the role of short food supply chains in rural development. Environment and planning A 35 (3), 393–411.
Rijke, J., van Herk, S., Zevenbergen, C., Ashley, R., 2012. Room for the River: delivering integrated river basin management in The Netherlands. Int. J. River Basin Manag. 10 (4), 369–382.
Rijksoverheid, 2023. Beleidskompas. https://www.kcbr.nl/beleid-en-regelgeving-ontwikkelen/beleidskompas/hulppaginas/actueel.
Sandhu, H., Wratten, S., Porter, J.R., Costanza, R., Pretty, J., Reganold, J., 2016. Mainstreaming ecosystem services into future farming. Solutions 7 (2), 40–47.
Schirpke, U., Candiago, S., Vigl, L.E., Jäger, H., Labadini, A., Marsoner, T., Meisch, C., Tasser, E., Tappeiner, U., 2019. Integrating supply, flow and demand to enhance the understanding of interactions among multiple ecosystem services. Sci. Total Environ. 651, 928–941.
Scholes, R.J., 2016. Climate change and ecosystem services. Wiley Interdisciplinary Reviews: Clim. Change 7 (4), 537–550.
Schröter, M., Albert, C., Marques, A., Tobon, W., Lavorel, S., Maes, J., Brown, C., Klotz, S., Bonn, A., 2016. National ecosystem assessments in Europe: a review. Bioscience 66 (10), 813–828.
Schröter, M., Koellner, T., Alkemade, R., Arnhold, S., Bagstad, K.J., Erb, K.-H., Frank, K., Kastner, T., Kissinger, M., Liu, J., 2018. Interregional flows of ecosystem services: concepts, typology and four cases. Ecosyst. Serv. 31, 231–241.
Serna-Chavez, H., Schulp, C., Van Bodegom, P., Bouten, W., Verburg, P., Davidson, M., 2014. A quantitative framework for assessing spatial flows of ecosystem services. Ecol. Indicat. 39, 24–33.
Su, R., Duan, C., Chen, B., 2024. The shift in the spatiotemporal relationship between supply and demand of ecosystem services and its drivers in China. J. Environ. Manag. 365, 121698.
Syrbe, R.-U., Walz, U., 2012. Spatial indicators for the assessment of ecosystem services: providing, benefiting and connecting areas and landscape metrics. Ecol. Indicat. 21, 80–88.
Vallecillo, S., La Notte, A., Zulian, G., Ferrini, S., Maes, J., 2019. Ecosystem services accounts: valuing the actual flow of nature-based recreation from ecosystems to people. Ecol. Model. 392, 196–211.
van Oudenhoven, A.P., Schröter, M., Drakou, E.G., Geijzendorffer, I.R., Jacobs, S., van Bodegom, P.M., Chazee, L., Czúcz, B., Grunewald, K., Lillebø, A.I., 2018. Key criteria for developing ecosystem service indicators to inform decision making. Ecol. Indicat. 95, 417–426.
Van Steen, P.J., Pellenbarg, P.H., Groote, P.D., 2016. Population growth of cities in The Netherlands. Journal of Economic and Social Geography 107 (1), 126–128.
van Vuuren, D.P., Smeets, E.M., 2000. Ecological footprints of Benin, Bhutan, Costa Rica and The Netherlands. Ecol. Econ. 34 (1), 115–130.
Vári, Á., Adamescu, C.M., Balzan, M., Gocheva, K., Götzl, M., Grunewald, K., Inácio, M., Linder, M., Obiang-Ndong, G., Pereira, P., 2024. National mapping and assessment of ecosystem services projects in Europe–Participants' experiences, state of the art and lessons learned. Ecosyst. Serv. 65, 101592.
Vollset, S.E., Goren, E., Yuan, C.-W., Cao, J., Smith, A.E., Hsiao, T., Bisignano, C., Azhar, G.S., Castro, E., Chalek, J., 2020. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. Lancet 396 (10258), 1285–1306.
Watson, R., Albon, S., Aspinall, R., Austen, M., Bardgett, B., Bateman, I., Berry, P., Bird, W., Bradbury, R., Brown, C., 2011. UK National Ecosystem Assessment.
Wei, H., Fan, W., Wang, X., Lu, N., Dong, X., Zhao, Y., Ya, X., Zhao, Y., 2017. Integrating supply and social demand in ecosystem services assessment: a review. Ecosyst. Serv. 25, 15–27.
Winkler, K.J., Dade, M.C., Rieb, J.T., 2021. Mismatches in the ecosystem services literature—a review of spatial, temporal, and functional-conceptual mismatches. Current Landscape Ecology Reports 6, 23–34.
Wolff, S., Schulp, C., Verburg, P., 2015. Mapping ecosystem services demand: a review of current research and future perspectives. Ecol. Indicat. 55, 159–171.
Worldbank, 2024. Population density (people per sq. km of land area). https://www.worldbank.org/en/home.