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# Towards nationally harmonized mapping and quantification of ecosystem services

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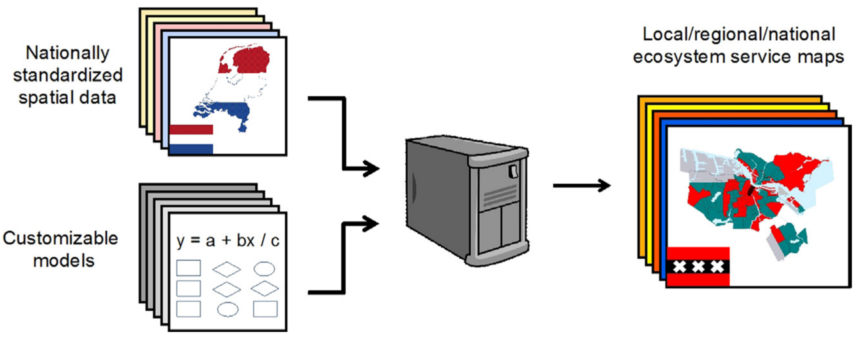
## HIGHLIGHTS

- Nationally harmonized approaches for assessing ecosystem services are needed.
- The NC-Model comprises harmonized Dutch ecosystem service assessment models.
- Models use a standard set of high-resolution and publicly-available input data.
- Its application illustrates the distribution of supply and use in high detail.
- Scale-specific assessment approaches support inclusive, equitable decision-making.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The EU 2020 Biodiversity Strategy requests EU Member States to map and assess ecosystem services within national territories, and to promote and integrate these values into policy-making. This calls for standardized and harmonized data, indicators, and methods to assess ecosystem services within national boundaries. Current approaches for assessing ecosystem services often oversimplify cross-scale heterogeneity, sacrificing the spatial and thematic detail required to support the needs and expectations of decision-makers at different levels. Hence, nationally harmonized models for mapping and quantifying ecosystem services are needed. This paper presents the Natural Capital Model (NC-Model), a spatially-explicit set of models for quantifying and mapping ecosystem services within the Netherlands. Its aim is to support the integration of ecosystem services within spatial planning and policy-making at the national level, contributing to the fulfilment of national and international environmental policy targets. Models introduce previously unexplored combinations of explanatory variables for modelling ecosystem functions and the socioeconomic benefits they accrue, making use of publicly-available and high-resolution spatial data. To capture spatial and thematic heterogeneity across the urban-rural gradient, the NC-Model comprises a subset of ecosystem service models tailored to the urban environment. To demonstrate the model's application, we expand on six urban ecosystem service models and implement them to quantify and map ecosystem services for Municipality of Amsterdam. High-resolution ecosystem supply and use maps provide detailed spatial information useful for supporting spatial planners and decision-makers who wish to optimize the allocation of natural elements while supporting the needs

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of citizens. They paint a picture on the interlinkages that exist between natural elements, ecological functions, and socioeconomic well-being in a friendly manner, tailored to various audiences with differing priorities. Their open-access nature enables their customization, supporting the sharing of knowledge and data to endorse ecosystem service modelling efforts by external parties within and outside the Netherlands.

## 1. Introduction

Ever since the release of the Millennium Ecosystem Assessment (MEA, 2005), the need to integrate ecosystem services within policy-making has gained prominence, targeted by initiatives such as the Convention on Biological Diversity (CBD, 2010), Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES; Pascual et al., 2017), and U.N. Sustainable Development Goals (SDGs; U.N., 2017). At the global scale, Aichi Biodiversity Targets 14 and 15, formulated under the CBD, call for the protection and enhancement of ecosystem services by ratifying parties (CBD, 2010). At the EU level, the EU 2020 Biodiversity Strategy called EU Member States to map and assess ecosystem services within national territories, and to promote and integrate these values into national accounting and reporting at the national and EU level (EC, 2011). At the urban level, Target 2 from the Strategy calls Member States to maintain and enhance ecosystem services by restoring and promoting green infrastructure (EC, 2013, 2019). To monitor developments towards these objectives, standardization and harmonization of data, indicators, and methods to assess ecosystem services, are necessary (Schröter et al., 2016). This is instrumental for systematically monitoring the impact of policies on ecosystems and the socioeconomic benefits they support (Zulian et al., 2014).

Despite the need for a common evidence base, a "one-size-fits-all" approach is difficult to attain due to scale-dependent conditions (Schröter et al., 2016; Martínez-López et al., 2019). The urban-rural and local-global gradients are characterized by heterogeneous landscape structures, land-uses, climates, administrative structures, and demographic variability (Larondelle and Haase, 2013; Martín-López et al., 2012; Schram-Bijkerk et al., 2018). This leads to variations in the performance of ecosystem functions (i.e., ecological structures and processes that satisfy human needs; De Groot et al., 2002; Potschin and Haines-Young, 2011) as well as in socioeconomic factors that determine the exposure to and consumption of ecosystem services (Keeler et al., 2019). This cross-scale heterogeneity is often oversimplified within standardized ecosystem service assessment approaches, sacrificing the spatial and thematic detail associated with different geographical locations and extents (Derkzen et al., 2015; Martínez-López et al., 2019). This calls for scale-dependent harmonization, supporting the needs and expectations of decision-makers at different levels (Martínez-López et al., 2019; Hauck et al., 2013). Harmonization at different scales is especially useful when it can lead to better informing decision-makers and integrating ecosystem services within policy-making and spatial planning (Breure et al., 2012).

Contributing to this need, recent years have seen a rise in the number of tools and guidelines for conducting ecosystem service assessments at different geographical locations and extents. At the large scale, tools such as InVEST (Integrated Valuation of Ecosystem Services and Trade-offs; Tallis and Polaski, 2011), ARIES (Artificial Intelligence for Ecosystem Services; Villa et al., 2014), and IMAGE (Integrated Model to Assess the Global Environment; Doelman et al., 2018) have received broad attention and uptake (Bagstad et al., 2013). At the EU-level, approaches for assessing ecosystem services at the pan-European and regional scales are under development through initiatives such as MAES (Mapping and Assessment of Ecosystems and their Services), ESMERALDA (Enhancing ecoSysteM sERvices mApping for poLicy and Decision mAking), and ESTIMAP (Ecosystem Services Mapping Tool) (Maes et al., 2015; Vihervaara et al., 2019; Zulian et al., 2014). Despite their usefulness at relatively large scales, most of these approaches lack the level of spatial and thematic detail required to conduct assessments at the regional and local level (Hauck et al., 2013; Derkzen et al., 2015; Martínez-López et al., 2019). Customizable ecosystem service models provide a useful solution to this issue (Villa et al., 2014; Maes et al., 2015), yet customization requires (i) readily-available place-specific knowledge and data that can directly substitute pre-set knowledge and data; or (ii) readily-available models integrating place-specific knowledge and data to directly substitute pre-designed models (Martínez-López et al., 2019). Recognizing these needs, governments are (i) establishing platforms for data harmonization and sharing (EC, 2007; Cetl et al., 2017; VROM, 2010), and (ii) developing approaches for assessing ecosystem services within national boundaries (UK NEA, 2011; EME, 2012, 2014; NOU, 2013; de Knegt, 2014, 2019; Rugani et al., 2014).

In this paper, we present the Natural Capital Model (NC-Model), a spatially explicit set of models for quantifying and mapping ecosystem services within the Netherlands at the local, regional, and national level. The aim of the NC-Model is to support the integration of ecosystem services within spatial planning and policy-making within the Netherlands, contributing to the fulfilment of national and international environmental policy targets (EZ, 2013; EC, 2011, 2013, 2019; CBD, 2010). The model is continuously under development and improvement by a collaboration of Dutch knowledge institutes (i.e., National Institute of Public Health and the Environment, RIVM; Wageningen ENvironmental Research, WENR; Netherlands Environmental Assessment Agency; PBL), fostering knowledge exchange and reducing overlapping modelling efforts within national borders. The first models were originally translated from ecosystem service models developed for Flanders by the Belgian knowledge institute VITO (Staes et al., 2017; Jacobs et al., 2016) and applied to the Netherlands to develop maps for the Netherlands Atlas of Natural Capital (Remme et al., 2018; Paulin et al., 2019; https://www.atlasnaturalcapital.nl).

Key methodological advantages of the NC-Model include (i) its contribution to universal models for quantifying and mapping ecosystem services, and (ii) its consideration of spatial and thematic detail and heterogeneity relevant at the regional and local (e.g., urban, rural) level. The NC-Model builds on existing process-based approaches for quantifying and mapping ecosystem services by introducing previously unexplored combinations of explanatory variables for modelling ecosystem functions and the socioeconomic benefits they accrue. All ecosystem service models make use of standard publicly-available input datasets, and can be customized for their use by parties within or outside the Netherlands. Spatial detail is considered by making use of fine-detail local data, including population and remotely-sensed vegetation maps at a high resolution (10 × 10 m). Accounting for thematic detail requires considering scale-specific linkages between ecological and socioeconomic factors that determine the production and consumption of ecosystem services (Martínez-López et al., 2019; Keeler et al., 2019). The model realizes this by assimilating quantitative relationships between ecological, social, and economic parameters within the Netherlands, established within empirical studies. To account for the heterogeneity that characterizes ecosystem service production and consumption patterns across the urban-rural gradient, the NC-Model additionally comprises a subset of ecosystem service models tailored to the urban environment, namely the Urban Natural Capital Model (Urban NC-Model; Remme et al., 2018).

In this paper, we (i) describe the NC-Model, (ii) present six completed urban ecosystem service models, and (iii) demonstrate their application within the Municipality of Amsterdam. Section 2 describes the mechanism behind the NC-Model and delves into models for the ecosystem services: Air Quality Regulation, Physical Activity, Property Value, Urban Cooling, and Urban Health. Section 3 presents and analyses quantification and mapping results, and expands on their potential use to support decision-making. Section 4 presents the concluding remarks.

## 2. Materials and methods

The NC-Model comprises an extensive set of models for quantifying and mapping ecosystem services, classified according to the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018). These include the recreational potential provided by natural landscapes, natural pollination, natural pest control, and water purification, among others. Output (i.e., ecosystem service maps and total quantities) is produced by use of algorithms combining formulas and input data, including (i) a standardized set of spatial data and (ii) reference values obtained from empirical studies capturing linkages between variables. Reference values are incorporated into algorithms either directly by incorporating them into formulas, or through their prior integration into look-up tables. Detailed input data and model descriptions, including stepwise procedures for their direct replication, are found in the Supplementary Material (Appendices 1 and 2). All codes and model outputs are available from the authors upon request. As all input necessary for model implementation is readily available, key user requirements include thorough knowledge of spatial modelling and coding. Model customization additionally requires a deep understanding of ecosystem functions and their relationships with socioeconomic parameters relevant for the model under customization, as well as spatial data and reference values to substitute custom input. Customization may be desirable for improving model inaccuracies, integrating novel insights and data, developing scenarios to support decision-making, or for translating models into different spatial contexts (Zulian et al., 2014; Martínez-López et al., 2019).

We present six models for mapping and quantifying ecosystem service supply and use in urban areas. Urban models are highly relevant in the Netherlands, where the population is expected to increase from roughly 17 million in 2018 to 18.4 million inhabitants in 2060, and where most of the population is concentrated in urban areas (https://opendata.cbs.nl/; Stoeldraijer, et al., 2017). Fig. 1 presents a schematic diagram illustrating the interlinkages between supply and use indicators, as well as key input variables that influence their quantity and distribution. Supply proxy indicators capture the performance of ecosystem functions, such as the filtration of atmospheric concentrations of particulate matter by vegetation and water. Use indicators capture realized social or economic benefits that result from the performance of ecosystem functions. Social benefits include the contribution of green space to human health or to people's inclination to engage in outdoor physical activity, among others. Economic benefits reflect either the direct contribution of natural capital to economic markets (e.g., the effect of vegetation and water on property value) or the translation of social benefits into monetary units (e.g., economic gains from enhanced health due to the presence of green space). Descriptions for all indicators in Fig. 1 are provided in Table 1.

To ensure consistency in model output for all applications, all ecosystem service models use a standard set of spatial data as input (Table 2). Most datasets are publicly available at standard international data repositories, such as the INSPIRE (https://inspire-geoportal.ec.europa.eu/) and ESRI geoportals (http://esrinl-content.maps.arcgis.com/), and all datasets can be found at governmental data registries. Since spatial datasets are difficult to attain for the same year, we included the most recent versions of datasets or versions that align well with the general dates of all datasets. In addition to land use data (*Ecosystem Unit Map, EUM*) and given its subjectivity at the local scale (Rabe et al., 2016), the NC-Model makes use of high-resolution ($10 \times 10$ m) vegetation maps as intermediate input. Vegetation maps are derived using the national digital elevation model (*Actueel Hoogtebestand Nederland, AHN3*), based on LiDAR (Light Detection and Ranging), and high-resolution ($25 \times 25$ cm) aerial photography (*Luchtfoto*; Remme et al., 2018). National digital elevation data is used to derive a layer with the height of objects. The red and infrared bands from the aerial photograph of the Netherlands are used to derive a Normalized Difference Vegetation Index (NDVI) layer, which distinguishes between vegetation and other objects (Huang et al., 2008). Next, an overlay operation is performed to obtain vegetation height. This results in three separate layers, including low vegetation (<1 m high), shrubs and bushes (1–2.5 m high), and trees (>2.5 m high). Another key intermediate input for various models is the high-resolution ($10 \times 10$ m) population map, which captures the human component of such models and directly influences ecosystem service supply and use. The population map is derived by assigning neighbourhood-specific population statistics (*Wijk- en Buurtkaart*) to housing units (*Basisregistratie Adressen en Gebouwen, BAG*). Within the Supplementary Material, we provide (i) additional information on the contents and availability of input datasets (Appendix 1), and (ii) a stepwise procedure for developing vegetation and population maps (Appendix 2).

To demonstrate the NC-Model's application and its use to support decision-making, all six models were applied to quantify and map ecosystem services for the Municipality of Amsterdam. Amsterdam is the capital of the Netherlands and its most populated city, with more than 850,000 inhabitants and a population density of roughly 5200 inhabitants/km$^2$ (https://www.amsterdam.nl/ois) (Fig. 2). Its surface area covers 219 km$^2$, distributed among water bodies (24.9%), built-up areas (e.g., residential and commercial buildings; 35.8%), semi built-up areas (e.g., dump sites and cemeteries; 5.6%), agricultural areas (e.g., greenhouses; 11.6%), recreational areas (e.g., sport grounds and allotment gardens; 11.8%), woodland and nature (2.7%), and transport infrastructure (7.6%). We applied the urban models here presented to provide an overview of ecosystem service values generated by Amsterdam's green and blue infrastructure, to support the 'Quality Impulse Green' (*KwaliteitsImpuls Groen*; Amsterdam Municipality, 2017). The Quality Impulse Green is a spatial plan developed by the Municipality of Amsterdam, which aims to strengthen green and blue infrastructure (i.e., vegetation and water) in alignment with the municipality's demographic trends and economic ambitions (Amsterdam Municipality, 2017). Input maps showing the distribution of vegetation, water, and inhabitants, are displayed in Fig. 3. The values for total tree, bushes/shrubs, and grass coverage in the municipality are 5%, 2%, and 20% respectively. Algorithms were written in Python programming language, using the PCRaster software to per-

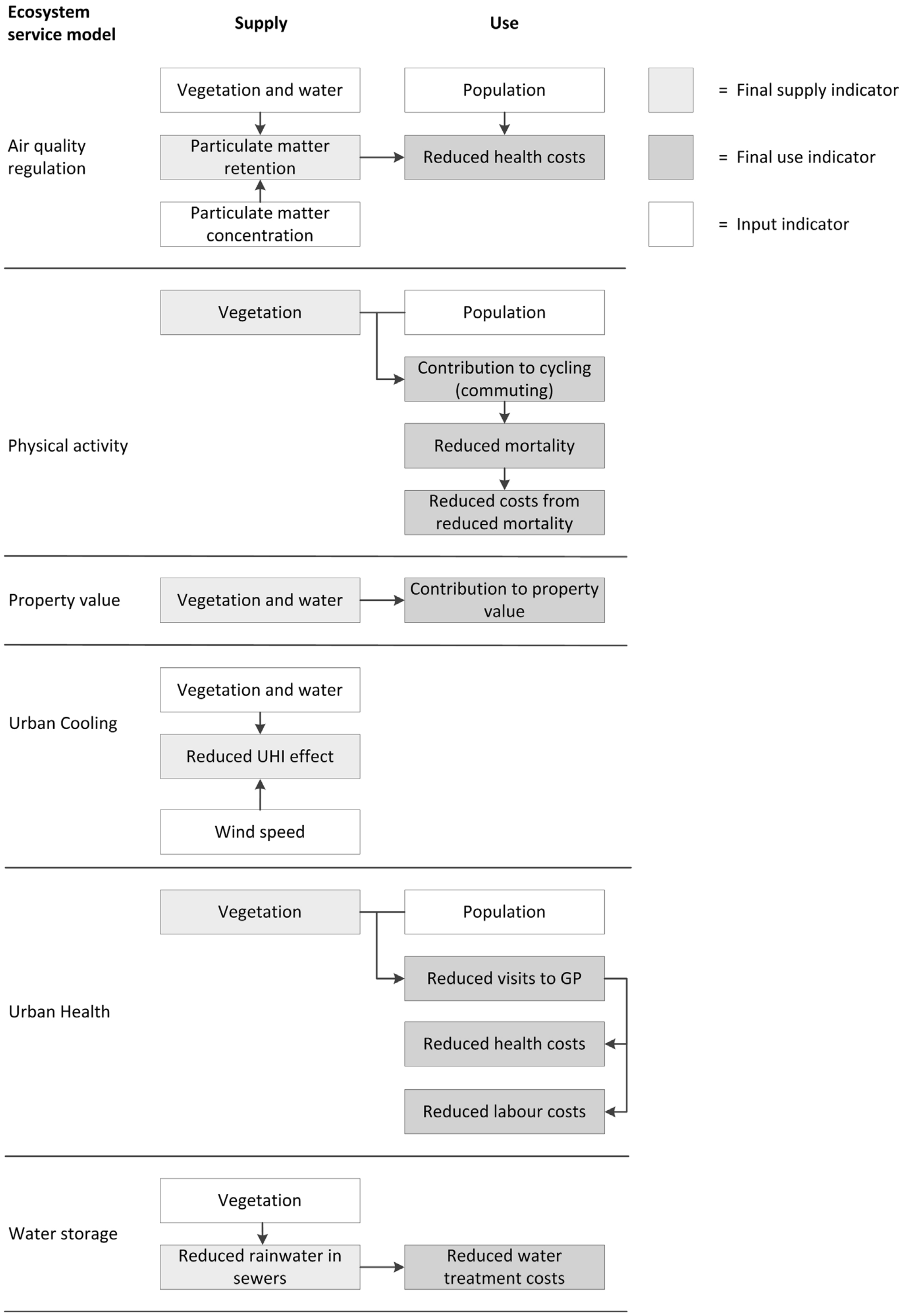

**Fig. 1.** Schematic overview of six ecosystem service models from the Urban NC-Model. Indicators presented (white boxes) either directly or indirectly influence the final supply (light grey) or final use (dark grey) of ecosystem services.

form spatial calculations (https://www.python.org/; http://pcraster.geo.uu.nl/). All models are described in brief below and more extensively in the Supplementary Material (Appendix 2).

### 2.1. Air Quality Regulation

Air pollution is a common problem within cities, caused by factors such as traffic and industry. The most harmful component of air pollution for human health is particulate matter, which is associated with respiratory and cardiovascular diseases, as well as mortality (Derkzen et al., 2015; Santibañez et al., 2013). The ability of particles to enter the human body is determined by their diameter, with smaller particles entering the lungs and airways with more ease. Once entering the body, particulate matter with a diameter of up to 10 µm ($PM_{10}$) can cause cardiovascular disease (Cassee et al., 2013; Gerlofs-Nijland et al., 2019). Because of the roughness of their surface, different types of vegetation can contribute to cap-

**Table 1**
Main input and output indicators for six urban ecosystem services, based on Fig. 1 (cell size = 10 × 10 m).

| Indicator | Input/Output | Unit | Description |
|---|---|---|---|
| Contribution to cycling (commuting) | Output (use) | minutes/year | The contribution of green space surrounding a household to the time individuals spend cycling for commuting purposes |
| Contribution to property value | Output (use) | € | Contribution to residential property value by surrounding green areas and water |
| Outdoor physical activity | Output (use) | minutes/year | The contribution of green space surrounding a household to the time individuals spend on all moderate and vigorous physical activities that can be done outdoors, including physical activity for commuting purposes and leisure time, walking, cycling, gardening, and outdoor sports |
| $PM_{10}$ concentration | Input | μg/year | $PM_{10}$ atmospheric $PM_{10}$ concentration |
| $PM_{10}$ retention | Output (supply) | kg/year | Amount of atmospheric $PM_{10}$ retained by vegetation and water |
| Population | Input | Inhabitants | Number of inhabitants per cell |
| Reduced costs from reduced mortality | Output (use) | €/year | The economic benefit of avoided premature deaths from reduced all-cause mortality, based on the European default value of a statistical life (VSL) (Kahlmeier et al., 2017) |
| Reduced health costs | Output (use) | €/year | Savings in health costs due to reduced years of lost life (YOLL) as an effect of reduced atmospheric $PM_{10}$ concentrations (CE-Delft, 2017) |
| Reduced mortality | Output (use) | avoided deaths/year | The number of avoided premature deaths from the reduced risk of all-cause-mortality from cycling |
| Reduced health costs | Output (use) | €/year | Reduced public health costs resulting from urban-green related health enhancements |
| Reduced labour costs | Output (use) | €/year | Reduced labour costs from urban-green related enhancements to the health of employees |
| Reduced rainwater in sewers | Output (supply) | $m^3$/year | The amount of water that is stored by vegetation and hence does not end up in the drainage system |
| Reduced UHI effect | Output (supply) | °C/year | The cooling effect of vegetation and water in the direct surroundings of a location (30 m) |
| Reduced visits to GP | Output (use) | visits/ year | Reduced number of visits to general practitioner per year as a result of the amount of green space surrounding an area |
| Reduced water treatment costs | Output (use) | €/ year | The reduction in water treatment costs associated with reductions of rainwater in the drainage system |
| Vegetation and water | Input/Output (supply) | Percentage cover | The percentage of a cell that is covered by vegetation (trees, bushes/ shrubs, and low vegetation) or water |
| Wind speed | Input | m/s | Average wind speed at 100 m height |

$PM_{10}$ = Particulate matter up to 10 μg, UHI = urban heat island, GP = general practitioner.

**Table 2**
Standard input spatial data for modelling six ecosystem services at the urban scale. Extensive details on dataset content, sources, and availability is found in the Supplementary Material (Appendix 1).

| Dataset name | Description | Resolution | Year |
|---|---|---|---|
| Actueel Hoogtebestand Nederland (AHN3) | Elevation data | 0.5 × 0.5 m | 2015 |
| Basisregistratie Addressen en Gebouwen (BAG) | Basic registry of addresses and buildings | 10 × 10 m | 2016 |
| Basisregistratie Gewaspercelen (BRP) | Agricultural areas of the Netherlands | 10 × 10 m | 2017 |
| Bevolkingskernen | Contour of populated areas | 10 × 10 m | 2011 |
| Ecosystem Unit Map (EUM) | Land use map | 10 × 10 m | 2017 |
| Fijnstof 2017 (pm10) | Concentration of particulate matter up to 10 μg | 50 × 50 m | 2017 |
| Luchtfoto | High resolution aerial photograph | 0.25 × 0.25 m | 2017 |
| Top10NL | Topographic map of the Netherlands | 5 × 5 m | 2017 |
| Wijk- en Buurtkaart | District and neighbourhoods data | 10 × 10 m | 2017 |
| Windsnelheden op 100 m hoogte (m/s) | Average wind speed at 100 m altitude | 2.5 × 2.5 km | 2015 |
| WOZ-waarde | Real estate value | 10 × 10 m | 2016 |

turing particulate matter (Remme et al., 2018; Janhäll, 2015). The urban Air Quality Regulation model estimates the contribution by water and different vegetation types to reductions in atmospheric $PM_{10}$ concentrations in Dutch cities. It considers three important factors as determinants for atmospheric self-depuration: the deposition velocity and resuspension of suspended particles, and the total concentration of $PM_{10}$ in the air. The deposition velocity is the speed with which particulate matter deposits to the natural surface (Chen et al., 2012). Resuspension occurs when deposited particles are re-emitted into the air due to various factors (e.g., physical characteristics of the contaminated surface, physicochemical nature of the contaminant, meteorological conditions), leading to the redistribution of particles (Gradoń, 2009). Additionally the model can be implemented to calculate the effect of reductions (or increases) in $PM_{10}$ concentrations on human health, calculated as the reduction (or increase) in health costs associated with reduced (or increased) mortality (CE-Delft, 2017).

### 2.2. Physical Activity

Exposure to green space can affect people's behavior, including their inclination to engage in outdoor physical activity. Physical activity is beneficial to human health, promoting physical and mental health across lifespans (Staatsen et al., 2017; Klompmaker et al., 2018; WHO, 2016). Despite the potential risks associated with engaging in active transport (e.g., cycling, walk-

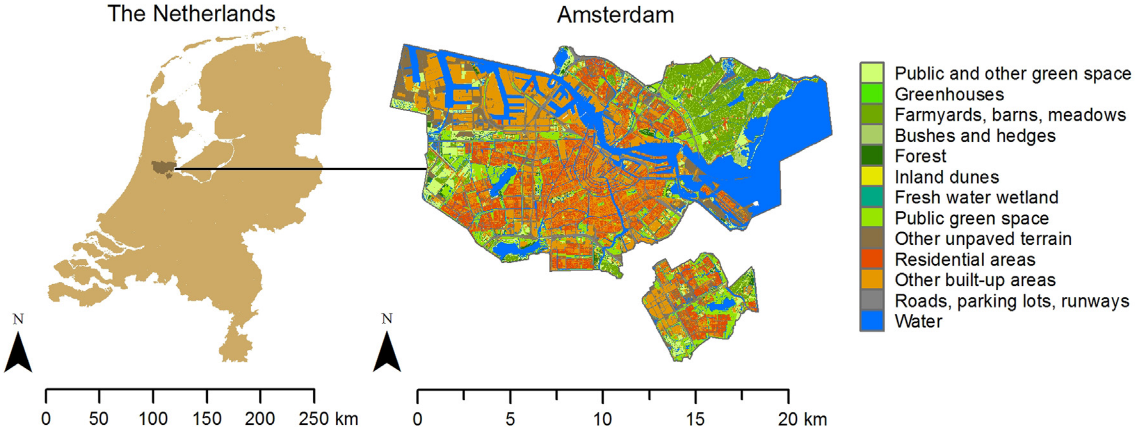

**Fig. 2.** Dominant land cover in the Municipality of Amsterdam. Based on the 2017 Ecosystem Unit Map (EUM) of the Netherlands developed by Statistics Netherlands (CBS; Eden and Van Leeuwen, 2016).

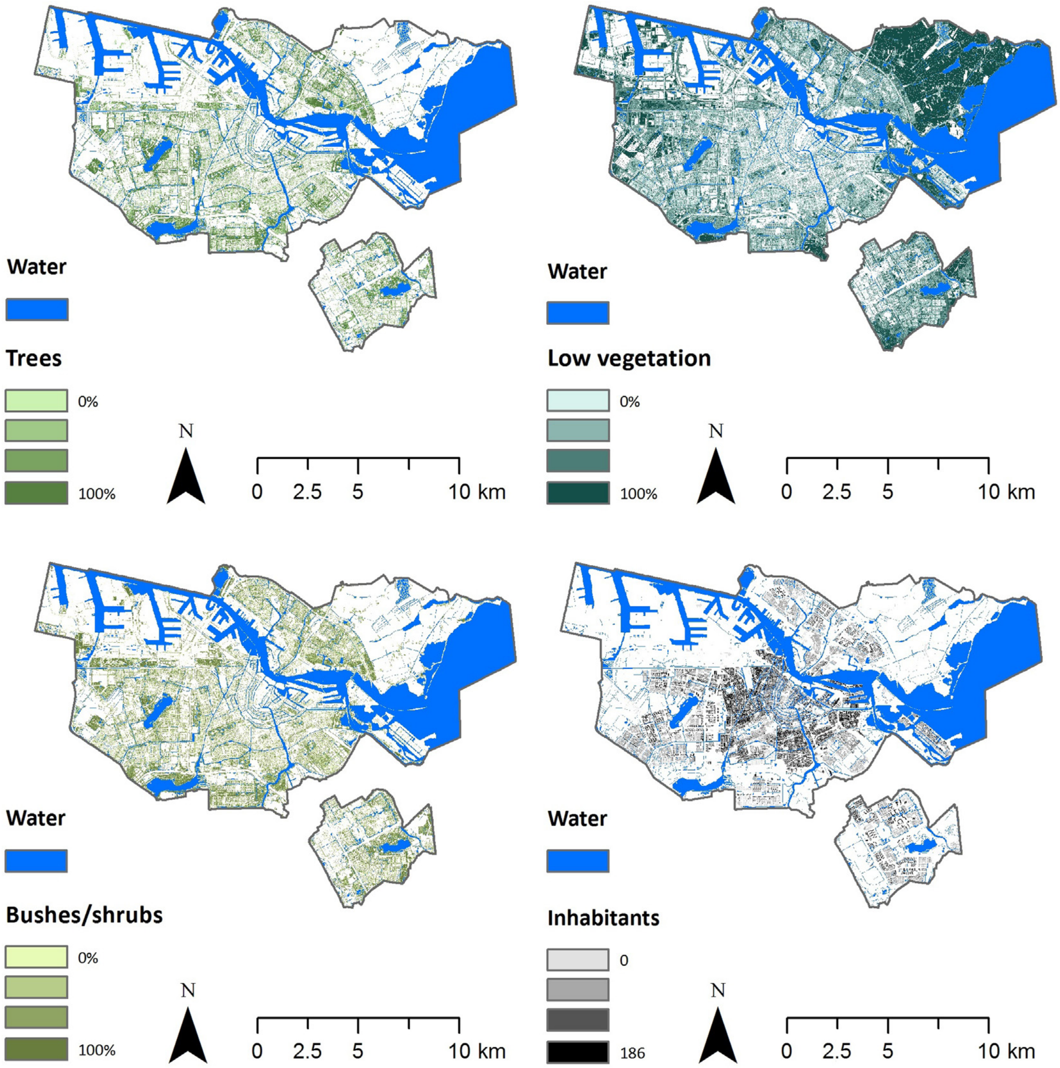

**Fig. 3.** Vegetation cover (percentage of trees, shrubs/bushes, low vegetation) and number of inhabitants, per cell (10 × 10 m) within the Municipality of Amsterdam. For each map, legends show quantile values. All quantile thresholds values are presented in the Supplementary Material (Table A5, Appendix 3).

ing), such as exposure to air pollution or traffic accidents, recent reviews have shown that the benefits of engaging in outdoor physical activity generally outweigh the costs (Staatsen et al., 2017; Kelly et al., 2014). The urban Physical Activity model captures the effect of urban green space on physical activity, as well as the resulting health benefits and economic gains. Based on the work of Maas (2008), the model calculates the time cycled by individuals to-from work that can be attributed to the availability of green space in their surroundings. The health benefits and resulting economic gains of cycling are calculated based on the methodology underlying the Health Economic Assessment Tool (HEAT), a tool developed by the World Health Organization that calculates the health and economic benefits of walking and cycling (Kahlmeier et al., 2017). The tool translates the time cycled by individuals to reduced mortalities, based on empirically-established quantitative relationships. It then calculates the associated economic gains from reduced mortalities, based on the value of a statistical life. Custom reference values used by the tool were tailored to values relevant in the Dutch context. A detailed description of the Physical Activity model, including reference values and their origin, is found within the Supplementary Material (Appendix 2).

### *2.3. Property value*

Natural and semi-natural elements in cities, such as trees, parks, gardens, and water, increase the amenity of residential areas, which is reflected in property values (Czembrowski and Kronenberg, 2016; Franco and Macdonald, 2018). Studies in the Netherlands have shown that a positive relationship exists between property prices, and vegetation and open water cover (Daams et al., 2016; Ruijgrok and de Groot, 2006; Luttik and Zijlstra, 1997). Based on these studies, the urban Property Value model captures the contribution to property prices by vegetation and open water. The model takes into consideration the availability of green and blue elements and their proximity from people's households.

### *2.4. Urban Cooling*

Cities recurrently experience higher temperatures than their surrounding rural areas, a phenomenon commonly referred to as the 'urban heat island (UHI) effect' (Rizwan et al., 2008). The UHI effect exacerbates heat extremes and is one of the leading causes of health hazards in cities (Lauwaet et al., 2018). The UHI effect is mainly a consequence of anthropogenic released heat (e.g., cars and industry) and of the heavy use of synthetic construction materials that store and re-radiate large amounts of heat (Rizwan et al., 2008). The roughness of infrastructure additionally reduces wind speed and hence its contribution to heat removal and transfer (Rizwan et al., 2008). Unsealed soil, vegetation, and surface water have a cooling effect during high temperatures. Vegetation increases the evaporation capacity of an area and provides shade, while soil releases heat more quickly than sealed areas (Akbari et al., 2001; Lauwaet et al., 2018). The cooling effect of vegetation has made planting vegetation the most widely adopted mitigation measure taken to tackle heat extremes in cities (Rizwan et al., 2008). Building on Lauwaet et al. (2018), the Urban Cooling model captures the reduction in the UHI effect by vegetation. The UHI effect is estimated as a function of vegetation cover, impervious cover, population density, and wind speed.

### *2.5. Urban health*

Vegetation influences human health in cities by mitigating pressures such as noise pollution, air pollution, and temperature extremes (Staatsen et al., 2017; Hartig et al., 2014; James et al., 2015). Evidence suggests that green space leads to improved health (e.g., improved cognitive function, improved psychological well-being, reduced prevalence of type 2 diabetes, reduced adverse pregnancy outcomes; Staatsen et al., 2017; Bratman, et al., 2019; Gascon et al., 2016) and reduced all-cause mortality (e.g., all-cause cardiovascular disease mortality; Staatsen et al., 2017; Kondo et al., 2018). The NC-Model captures the effect of urban green space on health and labor costs resulting from improved health conditions. Building on the TEEB-Stad Tool (https://www.teebstad.nl; KPMG, 2012; Maas, 2008) the contribution of green space to health is calculated as (i) the reduced costs associated with the incidence of seven disease categories (i.e., cardiovascular diseases, musculoskeletal diseases, mental diseases, respiratory diseases, neurological diseases, digestive diseases, and a miscellaneous category) and (ii) reduced number of visits paid to general practitioners. Inspired by the study 'The Economics of Ecosystems and Biodiversity (TEEB)' (Sukhdev and Kumar; 2008), the TEEB-Stad Tool enables the wider public to quantify the economic benefits of green and blue elements within cities in the Netherlands. The quantification of labor costs resulting from improved health conditions include reductions in costs associated with absenteeism, reduced labor productivity, and job losses (KPMG, 2012; Steenbeek et al., 2010).

### *2.6. Water Storage*

Water storage by vegetation and soils is a crucial function in cities, as urban flooding around the world becomes more prominent and damaging in response to climate change (Van Herk et al., 2011). Urban flooding is closely linked to the expansion in impervious cover and reduction in vegetation cover that is required to build infrastructure for growing urban populations (Wang et al., 2008). The replacement of vegetated cover by impervious surfaces decreases infiltration by compacting soils, decreases evaporation by reducing soil water volumes, and decreases interception through vegetation removal (Wang et al., 2008). The result is increased rainwater runoff that is charged with excess pollutants that are left unfiltered by vegetation and soils, and a higher risk of flooding. With 26% of its surface area under sea level, the Netherlands has developed cutting-edge technology and expertise that enabled it to become the best-protected delta in the world (Netherlands Environmental Assessment Agency, 2014). Despite this advantage, 59% of the country is still under threat of flooding (Netherlands Environmental Assessment Agency, 2014). Large infrastructure alone cannot meet the increasing challenges that climate change poses, calling for an integrated spatial planning approach that considers not only technological solutions but also nature-based solutions (Van Herk et al., 2011). The urban Water Storage model captures the avoided amount of rainwater in the drainage system due to water storage by vegetation, as well as the associated reduction in water treatment costs.

## 3. Results and discussion

Urban ecosystem service models were implemented to quantify and map indicators displayed in Fig. 1 and Table 1. Total ecosystem service supply and use values are presented in Table 3. Maps for ecosystem services, each represented by one supply or use indicator, are presented in Fig. 4.

In Table 3, total ecosystem service supply and use values are expressed in biophysical, social, and economic units and, in some cases, through the use of more than one indicator. A frequent concern associated with quantifying indicators in various units is that it leads to an "adding-apples-and-oranges-situation", obstructing their comparability and potential aggregation (Satz et al., 2013). Despite these disadvantages, considering multiple indicators and in multiple units is central for the holistic assessment of ecosystem services. First, it is not always possible to quantify the supply and use of an ecosystem service in identical units (Alam et al., 2016), yet these two components of ecosystem service delivery are closely interlinked. Ecosystem service supply is linked to the provision of ecosystem functions (Syrbe and Walz, 2012), which is best repre-

**Table 3**
Output supply and use values of six ecosystem services for the Municipality of Amsterdam.

| Ecosystem Service | Supply/Use | Indicator | Unit | Value |
|---|---|---|---|---|
| Air Quality Regulation | Supply | $PM_{10}$ retention | thousand kg/yr | 99 |
| | Use | Reduced health costs | million €/yr | 77 |
| Physical Activity | Use | Contribution to cycling (commuting) | million min/yr | 50 |
| | Use | Reduced mortality | lives/yr | 18 |
| | Use | Reduced costs from reduced mortality | million €/yr | 38 |
| Property Value | Use | Contribution to property value | billion € | 6.2 |
| Urban Cooling | Supply | Reduction in UHI effect | °C | 1.8 |
| Urban Health | Use | Reduced visits to GP | thousand visits/yr | 21 |
| | Use | Reduced health costs | million €/yr | 18 |
| | Use | Reduced labour costs | million €/yr | 88 |
| Water Storage | Use | Reduced rainwater in sewers | million $m^3$/yr | 18 |
| | Use | Reduced water treatment costs | million €/yr | 14 |

sented through the use of biophysical indicators. Ecosystem service use reflects the socioeconomic benefits that these ecosystem functions generate for people (Syrbe and Walz, 2012), hence best represented by social and economic indicators. For instance, vegetation and water lead to the yearly reduction of 99,000 kg of atmospheric $PM_{10}$ in Amsterdam, yet its value is only cultivated if this reduction leads to social or economic gains, in this case valued at €77 million/year. This brings us to the second point: different indicators speak to different audiences (Satz et al., 2013). A decision-maker that prioritizes the contribution of natural capital to the economy may be interested in the effect of green and blue infrastructure on property value (€6.2 billion) or on reduced labor costs (€88 million/year). A decision-maker focused on enhancing human well-being may be interested on the contribution of green space to human health (e.g., reduction of 21,000 yearly visits to general practitioners). A policy-maker dealing with climate change may prioritize natural capital's contribution to the reduction of the UHI effect (1.8 °C). The matter of prioritization brings us to the third point: expressing all ecosystem service use values in monetary units can be subjective and misleading (Satz et al., 2013). The aforementioned examples show how prioritizing monetary values when assessing the utility of green and blue infrastructure will undeniably shift the priority to property values, while other benefits are perhaps more critically needed in cities like Amsterdam, where only a few get to benefit from increased property values. When dealing with such a complex system, variety in choice of indicators may bring perspective, yet at the cost of simplicity.

Aggregation of ecosystem service indicators is a common practice within ecosystem service assessments, which requires commensurability among aggregated indicators. This can be done, for instance, by expressing ecosystem service values in monetary terms or transforming them into dimensionless values (Alam et al., 2016; Satz et al., 2013). Aggregation can be adopted to provide information on the extent and magnitude of ecosystem service bundles, and for quantifying composite indicators that enable the assessment of trade-offs and synergies among variables (Alam et al., 2016). Despite these advantages, we refrain from aggregating ecosystem service indicators, as it may lead to the overestimation or underestimation of relative ecosystem service values, thus hampering the objectivity of an assessment. Over- or underestimation of ecosystem service values can occur (i) if monetary values are disproportionately higher or lower than those of other ecosystem services, (ii) if several or no monetary values are available for an ecosystem service, or (iii) if double-counting takes place. Disproportionate variations in ecosystem service monetary values result from market imperfections (Bunse et al., 2015). For instance, property values are often subject to property bubbles, which highly affect property values and hence the attributed contribution by vegetation and water. Another example occurs with common-good (i.e., rivalrous, non-excludable) and public-good (i.e., non-rivalrous, non-excludable) ecosystem services, which are often free and non-marketed (Fisher et al., 2009; Bunse et al., 2015), so people often lack awareness of the role they perform in their everyday lives. For instance, $PM_{10}$ retention by vegetation is freely accessible to everyone (non-excludable), yet is limited by the availability of vegetation (rivalrous). Its non-marketed and, in this case, invisible nature make this ecosystem function and its benefits to humans difficult to perceive. Moreover, aggregation of monetary values may lead to overestimation if more indicators can be aggregated for one ecosystem service than for others, and to underestimation if no monetary indicator is available for an ecosystem service. One last problem with aggregation is that it may lead to double-counting. This may occur if indicators overlap, which is often the case due to the abstract nature of ecosystem functions and their benefits, and to the strong interlinkages among them (Gunton et al., 2017). For instance, overlaps may occur between the indicators for reduced mortalities from increased cycling (Physical Activity), reduced health costs due to the reduction of seven types of diseases (Urban Health), and reduced health costs from reduced atmospheric $PM_{10}$ concentrations (Air Quality Regulation). There may even be overlaps between different indicators for a single ecosystem service. Due to all abovementioned factors, aggregation is discouraged.

Supply maps in Fig. 4, including Air Quality Regulation, Urban Cooling, and Water Storage, show the complexity with which green and blue infrastructure perform ecosystem functions. Within the Air Quality map, the capture of $PM_{10}$ relies on two main factors: the type of vegetation and the total concentration of $PM_{10}$ in an area. Trees and water have the highest capacity for $PM_{10}$ retention, followed by shrubs and low vegetation (in descending order). Densely populated areas with a high degree of human activity often experience relatively high concentrations of particulate matter and thereby experience greater $PM_{10}$ uptake where vegetation or water is present. However, vegetation cover is less prominent in densely populated areas, where infrastructure is predominant. This explains the high degree of fragmentation in $PM_{10}$ uptake visible in the most densely populated parts of the city. The north-eastern part of Amsterdam seems to experience lower $PM_{10}$ uptake compared to densely populated areas. This occurs since population density in the northeast is substantially low, resulting in lower overall atmospheric $PM_{10}$ concentrations. Additionally, these areas are characterized by a predominant low vegetation cover, which retains less $PM_{10}$ than water, trees, and shrubs and bushes. Within the Urban Cooling map, the UHI effect is a function of three main variables: soil sealing (including built-up areas), population density, and wind speed. The UHI effect is most prominent in areas where population density is highest and where impervious cover is predominant. Areas where the reduction of the UHI is highest

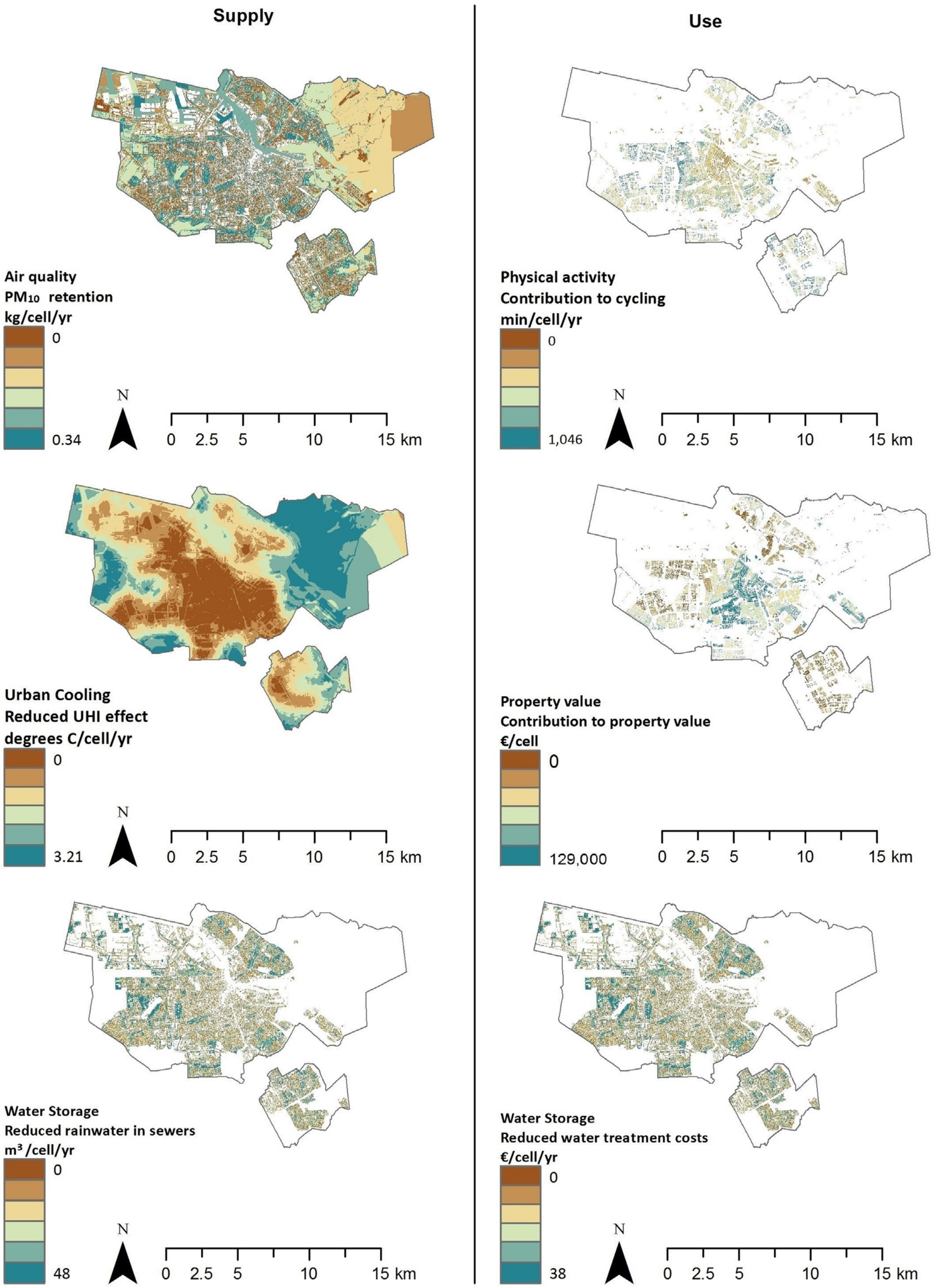

**Fig. 4.** Output maps obtained by applying urban ecosystem service models (cell = 10 × 10 m). One supply or use indicator is represented per ecosystem service, based on the indicators presented in Fig. 1 and Table 1. For each ecosystem service, legends are divided into six quantile values. All quantile thresholds values are presented in the Supplementary Material (Table A6, Appendix 3).

encompass larger extents of semi-natural and agricultural land, with where low population densities and impervious cover predominate. Within the Water Storage model, the reduced amount of rainwater in sewers relies on two main factors: vegetated cover, which determines the amount of rainwater stored, and population concentrations, which act as an indicator for the presence of extensive sewage systems. Hence, water storage is correlated with the percentage of vegetated cover in Amsterdam, and is visible in the populated fraction of the municipality.

Use maps in Fig. 4, including Physical Activity, Property Value, and Water Storage, show the close relationship that exists between ecosystem service use and the distribution of ecosystem service beneficiaries (population). The Physical Activity map shows the total amount of minutes cycled per cell that can be attributed to the availability of green space in an area. The Property Value map shows the contribution to property value that can be attributed to green and blue elements. The Water Storage map shows the monetary contribution of water storage by vegetated surfaces to reduced water treatment costs. At a first glance, the Physical Activity and Property Value maps show strong similarities. This is the case since both the number of individuals benefitting from increased cycling and the property value are linked to the distribution of housing units. However, taking a closer look will reveal that the distribution of ecosystem service values strongly differs between both maps, with the highest and lowest amounts of benefits taking place in different areas. The Physical Activity map relies mainly on the distribution of inhabitants and the amount of green space surrounding an area. This is why the most densely populated and vegetated areas experience the highest benefits. The Property Value map is closely linked to property values, hence ecosystem service use values are highest in neighborhoods with the highest property prices, even when green and blue elements are not predominant. The Water Storage use map shows a direct translation of the reduced rainwater in sewers form the Water Storage supply map into reduced water treatment costs. Hence, there is a full correlation between the Water Storage supply and use maps. Given that extensive sewage systems are linked to densely populated areas, the map also shows a close relationship to population distribution. However, ecosystem service values are more closely linked to the percentage of vegetated cover, which ensures water storage.

Output generated by use of the NC-Model provides useful insights on ecosystem functions, how their performance is affected by the distribution of natural elements, and how this in turn affects human well-being. However, models possess drawbacks that limit their objectivity and which should be considered when using model output to support decision-making. Society and ecological systems are extremely complex and are influenced by a perhaps infinite number of variables in a continuously changing fashion. As such, it becomes difficult to capture all relevant factors that determine the supply or use of an ecosystem service at the desired level of accuracy within models. For instance, the supply of Air Quality Regulation fails to capture the negative effect of trees within street canyons (Janhäll, 2015) and the Urban Cooling model does not consider the cooling effect of soils in cities, as a consequence of the lack of empirical findings necessary to integrate these factors. Another limitation hindering model accuracy comes from the spatial extrapolation of data, which requires making generalizations that do not always align with reality. Extrapolation inaccuracies are found both within input data obtained from various sources and within model output. For instance, the Physical Activity model provides information on the additional time people spend cycling due to the presence of green space in their surroundings. While this extrapolation is based on empirical findings linking green spaces and cycling behavior in the Netherlands (Maas, 2008), the distribution of additional minutes cycled presented in supply maps is based on a simplified reality, hence meant to be viewed as an indicator for the benefits provided by green infrastructure. Validation of ecosystem services could serve as a potential solution to assess model accuracy. However, this is not possible for most ecosystem services due to privacy concerns associated with the relevant indicator (e.g., the reduction of seven disease groups; the amount of time cycled by individuals) or due to their subjectivity (e.g., the contribution of natural elements to property value). In cases where validation is possible (e.g., $PM_{10}$ retention by vegetation and water; water storage), it is often time consuming and expensive.

Despite these drawbacks, the NC-Model takes a step towards nationally harmonized mapping and quantification of ecosystem services. First, detailed maps are needed for meeting national and international environmental policy targets (EZ, 2013; EC, 2011, 2013, 2019; CBD, 2010), and for supporting decision-making at the regional and local level (Hauck et al., 2013). The NC-Model makes use of the best available spatial data, accepted and endorsed by Dutch national and local governments, to map and quantify ecosystem services at a high resolution. The diversity of indicators to quantify ecosystem services offered speaks to different audiences and suits different contexts. This presents an opportunity for decision-makers to make choices in alignment with different priorities and circumstances. Second, the combination of quantification and high resolution mapping of ecosystem services is a powerful communication tool to inform local decision-makers and spatial planners concerned with the optimal allocation of natural elements to endorse the realization of socioeconomic gains. Supply maps communicate the complexity with which ecosystem functions take place, revealing how the design and choice of green and blue infrastructure can affect the overall supply of ecosystem services (Janhäll, 2015). Use maps are an effective way of displaying the distribution of ecosystem service benefits, which is central to addressing the issue of unequitable distribution of ecosystem services (Potschin and Haines-Young, 2011). The juxtaposition of supply and use maps tells the story behind the nature with which ecosystem functions take place (supply maps), and how these ultimately lead to socioeconomic gains (use maps). Third, publicly-available models can be customized to improve model inaccuracies, integrate novel insights and data, develop scenarios, or translate models to different geographical locations and extents (for an example of scenario development using the NC-Model to support spatial planning, see Paulin et al., 2019). Customization can be done by replacing custom with place-specific input datasets and reference values. This may prove difficult in situations where these inputs are not readily-available, yet can be corrected for by assimilating similar datasets and reference values (perhaps more) relevant at different spatial contexts. Input deficiency may also bring attention to the need for site-specific data and reference values necessary for developing parallel national and subnational ecosystem service assessment approaches.

## 4. Conclusions

International environmental policy-targets call for nationally harmonized approaches for quantifying and mapping ecosystem services (EC, 2011, 2013, 2019; EZ, 2013; CBD, 2010). This paper presented the NC-Model, a Dutch approach for quantifying and mapping ecosystem services within national boundaries. The model contributes to national harmonization efforts by synthesizing the knowledge of experts from national research institutes and integrating best-available datasets endorsed by national and local governments. Mapping national ecosystem services and integrating them into policy-making requires user-friendly, high-resolution maps that meet the needs of local decision-makers (Hauck et al., 2013; Martínez-López et al., 2019). High-resolution ecosystem supply and use maps in the NC-Model provide detailed spatial information useful for supporting spatial planners and decision-makers who wish to optimize the allocation of natural elements while supporting the needs of citizens. They paint a picture on the interlinkages that exist between natural elements, ecosystem functions, and socioeconomic well-being in a friendly manner, tailored to various audiences with differing priorities. The open-access nature of models enables their customization, supporting the sharing of knowledge and data to endorse ecosystem service modelling efforts by external parties within and outside the Netherlands.

A key limitation of the NC-Model concerns its inability to capture all relevant factors that contribute to the supply and use of ecosystem services, affecting model accuracy and hence the objectivity of assessments. This is problem is not unique to the NC-Model, as it is virtually impossible for any model to capture all factors in socio-ecological systems that affect the production and consumption of ecosystem services. To improve accuracy in output from spatially explicit ecosystem service models, we recommend conducting empirical research capturing the relationship between available spatial data, and proxy indicators for ecosystem functions and socioeconomic well-being. Such research should be conducted at different scales and locations, capturing spatial and thematic heterogeneity across geographical locations and extents. However, they should make use of similar techniques, ensuring the harmonized integration of reference values into models at different scales and locations. This will facilitate the comparability of results across space and the substitutability of reference values to suit different scales and locations. The integration of quantitative scale-specific empirical evidence on the relationships between ecological, social, and economic parameters within assessment tools will support a more accurate depiction of reality, endorsing higher objectivity in assessments. Capturing spatial and thematic detail at various scales and locations will additionally provide the choice of integrating variables into models based on their relevance in particular contexts, suiting the needs and expectations of decision-makers at different levels (Martínez-López et al., 2019; Hauck et al., 2013).

This paper demonstrates how the NC-Model can be implemented to quantify and map ecosystem services in the Dutch context for informing decision-makers and spatial planners. For a more thorough assessment of ecosystem services, this approach could be accompanied by a systematic assessment of trade-offs and synergies, hotspots and coldspots, or an analysis of correlations among ecosystem service input and output maps (Wang et al., 2017; Rabe et al., 2016; Li et al., 2016). The NC-Model may be adapted for use in other contexts by adaptation of its open access models to local data-availability and reference values. Models are under constant improvement by developing parties and open to recommendations from interested external parties. In the future, they may be expanded and integrated with similar models that are under development by national research institutes (Remme et al., 2018), such as the Netherlands Natural Capital Accounts, under development by WENR and CBS (Graveland et al., 2018).

## 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.

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.134973.

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