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Application of the Natural Capital Model to assess changes in ecosystem services from changes in green infrastructure in Amsterdam

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ABSTRACT

This paper demonstrates the utility of local models for assessing ecosystem services to support urban planning. It does so by application of the NC-Model, a spatially-explicit set of models for assessing ecosystem services in the Netherlands, to assess changes in ecosystem services in the Municipality of Amsterdam given the implementation of strategies from the Green Quality Impulse. The Green Quality Impulse is a spatial plan that envisions the development of Amsterdam's green infrastructure by 2025 to support the needs of Amsterdam's growing population. The NC-Model was implemented to spatially quantify six ecosystem services within a 'business-as-usual' scenario (only residential and population expansion considered) and three scenarios that capture changes in green infrastructure from the implementation of strategies from the Green Quality Impulse. Incorporation of local knowledge and data enabled quantification of ecosystem services at a high spatial resolution and identification of key factors that influence ecosystem service delivery. Such an approach can support urban planners who wish to better-understand the mechanism by which green infrastructure generates value for urban dwellers, to develop scientifically-sound spatial strategies that optimize ecosystem service supply and use, and to further communicate this information to decision-makers, investors, and local inhabitants in an accessible manner.

1. Introduction

The future of the world's population is urban (UN, 2019). Urban areas are commonly associated with economic growth, poverty reduction, and human development, behaving as centers for high-skilled labor, business, and knowledge exchange (UN, 2019). Despite these benefits, urbanization also leads to an increase in the occurrence of environmental hazards and health risks. For instance, the substantial replacement of vegetated cover by impervious cover to support infrastructure expansion has led to prominent flooding around the world (Van Herk et al., 2011; Wang et al., 2008). Air pollution released by traffic and industry increases the risk of respiratory and cardiovascular diseases, as well as mortality (Derkzen et al., 2015; Santibañez et al., 2013). Anthropogenic heat release (e.g. from cars, industry, houses) and the inability of heat absorption by synthetic construction materials contribute to the Urban Heat Island (UHI) effect, a leading cause of health hazards in cities (Rizwan et al., 2008; Lauwaet et al., 2018). Addressing the challenges posed by urbanization requires promoting a better understanding of the interconnected nature of green infrastructure and socioeconomic human wellbeing, supporting evidence-based urban planning (Haase et al., 2014; Keeler et al., 2019; Luederitz et al., 2015).

Green infrastructure (GI; i.e. soil, vegetation, and water; sometimes denoted as green and blue infrastructure) provides urban dwellers with valuable 'ecosystem services', or the (final) contributions by natural capital (i.e., Earth's ecosystems and underpinning geo-physical systems) to human wellbeing (Haines-Young and Potschin, 2018). More specifically, ecosystem services encompass functional ecological structures and processes (ESP) that generate socioeconomic benefits for humans. By mitigating pressures such as noise pollution, air pollution, and heatwaves, GI contributes to improved physical and mental health (Kruize et al., 2019; Staatsen et al., 2017), as well as reduced all-cause mortality (Staatsen et al., 2017; Kondo et al., 2018). GI mitigates the magnitude of peak runoff from precipitation events by redirecting or

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absorbing precipitation, or providing retention space for surplus water (Gunnell et al., 2019). Uncovered soil releases heat quicker than sealed areas, while vegetation increases an area's evaporation capacity and provides shade, together generating a cooling effect during heat extremes (Akbari et al., 2001; Lauwaet et al., 2018). Trees, parks, gardens, canals, and other GI increase the amenity of residential areas, which reflects in higher property values (Czembrowski and Kronenberg 2016; Franco and Macdonald, 2018). A variety of GI typologies (e.g., urban and peri-urban forests, tree-lined streets, peri-urban agriculture, brownfields) act as basis for nature-based recreational activities that support physical activity, social interactions, empowerment, and social cohesion (Cortinovis et al., 2018). The growing awareness of the many benefits that GI generates has led to an upsurge in the number of initiatives endorsing the integration of ecosystem services into urban planning (EC, 2013, 2019; https://www.c40.org/; https://www.iclei.org/; https://www.nature4cities.eu). Despite these initiatives, the translation of the ecosystem services concept from discourse to practice in the urban context remains limited (Hansen et al., 2015; Haase et al., 2014).

Integrating ecosystem services into urban planning requires readily-available ecosystem service assessment approaches that capture spatial and thematic detail relevant at various urban contexts (Paulin et al., 2020Keeler et al., 2019; Luederitz et al., 2015). GI distribution is grounded in sociocultural influences, such as histories of land development or evolving ideas about leisure and recreation (Wolch et al., 2014). In general, the pathway by which GI leads to ecosystem service delivery is highly contextual and hence not uniform across space (Luederitz et al., 2015). The same size, configuration, and composition of GI can lead to differential ecosystem service distribution, influenced by local ecological and socioeconomic characteristics (Keeler et al., 2019; Grafius et al., 2018). From an ecological perspective, the distribution of ESP is influenced by factors such as climate and landscape in heterogeneous spatial and temporal gradients (Paulin et al., 2020). From a socioeconomic perspective, the realization of benefits supported by ESP is determined by factors such as accessibility and safety in green spaces, as well as sociodemographic characteristics (e.g., income, education, age, gender, health status, cultural background, individual perceptions, institutional perceptions; Kruize et al., 2019; Murali et al., 2019; Luederitz et al., 2015). The degree of spatial and thematic heterogeneity that characterizes the urban landscape suggests that a universal toolkit for assessing the value of urban nature is unlikely to occur (Keeler et al., 2019). This calls for location-specific ecosystem service assessment approaches that capture ecological and socioeconomic detail relevant at the urban level (Luederitz et al., 2015; Keeler et al., 2019).

Such an approach is offered by the Natural Capital Model (NC-Model), a spatially explicit set of models for quantifying and mapping ecosystem services and accrued socioeconomic benefits within the Netherlands (Paulin et al., 2020; Remme et al., 2018). To account for heterogeneity that characterizes the urban environment, the NC-Model comprises a set of urban ecosystem service models. These models capture spatial detail by incorporating best-available local data, including population and remotely-sensed vegetation maps at a high resolution (10 × 10m; Paulin et al., 2020; Remme et al., 2018). Thematic detail is captured through assimilation of quantitative relationships between ecological and socioeconomic parameters respective to the Netherlands (Paulin et al., 2020). Urban ecosystem services research is often conducted from an ecological perspective, resulting in a lack of full engagement with all aspects of the ecosystem services cascade (Gómez-Baggethun and Barton, 2013; cascade model available in Potschin and Haines-Young, 2016). This limits the understanding necessary for ecosystem services management and integration into sustainable urban planning (Gómez-Baggethun and Barton, 2013). Urban ecosystem service assessment approaches should address ecological, economic, and also societal issues that determine the distribution and final use of ecosystem services (Gómez-Baggethun and Barton, 2013). The NC-Model captures ecological and socioeconomic factors contributing to ecosystem service delivery by spatially quantifying ESP underpinned by GI, and the social and economic benefits ESP support.

This paper presents an application of the NC-Model to assess the effect of changes in GI on ecosystem services and human wellbeing in the Municipality of Amsterdam. Amsterdam's population, alongside its number of residential units, is expected to increase substantially within upcoming years (Amsterdam Municipality, 2017a). To meet the socioeconomic needs of its inhabitants in the face of rapid urbanization, the Municipality has developed a number of policy initiatives, seeking to maintain and enhance the quality of public spaces (Amsterdam Municipality, 2010, 2015a, 2015b, 2017a, 2018, 2019a, 2019b). This assessment was performed to support the Green Quality Impulse (*KwaliteitsImpuls Groen*; Amsterdam Municipality, 2017b), a spatial plan for the expansion and improvement of Amsterdam's GI by the year 2025. The Green Quality Impulse envisions Amsterdam's expansion as a transition into a sustainable, climate-proof, and socially attractive city, in alignment with its demographic trends and economic ambitions (Amsterdam Municipality, 2017b). The aim of this study is to demonstrate the utility of the NC-Model for assessing urban ecosystem services to support urban planning. This paper builds on Paulin et al. (2020), which presents the first complete set of urban ecosystem service models available in the NC-model. Assessment results disclose information on how enhancements in GI may lead to changes in the distribution, relative performance, and overall performance of ESP and ecosystem services. This information is instrumental to support urban planning in the context of (i) communication and awareness raising; (ii) strategic planning and priority setting; and (ii) economic accounting and incentive design (Gómez-Baggethun and Barton, 2013; Haase et al., 2014).

2. Materials and methods

2.1. Study site

In the Netherlands, 92% of the population is concentrated in urban areas (UN, 2019). Amsterdam, its most populous municipality, is home to more than 850,000 inhabitants (https://www.ois.amsterdam.nl), confined to an area of 219 km^2 (Fig. 1). More than a third of the municipality's surface area consists of infrastructure and other built-up areas, a fourth comprises water bodies, and the rest consists of mainly semi-natural areas. Characterized by its complex canal structure, historically and culturally rich architecture, and thriving economy, Amsterdam is a hotspot for tourism and an attractive destination for local and international people aspiring for a place to live. By 2025, Amsterdam's population is expected to increase by roughly 70,000 (Paulin et al., 2019), which will be made possible by the creation of around 5,000 residential units per year (Amsterdam Municipality, 2017b). The expansion in grey infrastructure (i.e. built-up and paved areas) necessary to support the municipality's growing needs exerts ever increasing pressure on GI, the ESP it supports, and the essential benefits it provides to urban dwellers.

2.2. Assessment approach

To evaluate the effect of changes in ecosystem services resulting from the implementation of GI strategies, an assessment was conducted, consisting of four main stages. The first stage consisted of a workshop with decision-makers from the Municipality of Amsterdam, facilitated by the National Institute for Public Health and the Environment (RIVM) and De Urbanisten, an innovative consultancy firm for urban research and landscape design based in the Netherlands (http://www.urbanisten.nl/). To support the translation of objectives in the Green Quality Impulse into realistic spatial strategies, decision-makers were asked (i) to state their expectations regarding the introduction of new GI; and (ii) to share their knowledge on relevant trends and potential

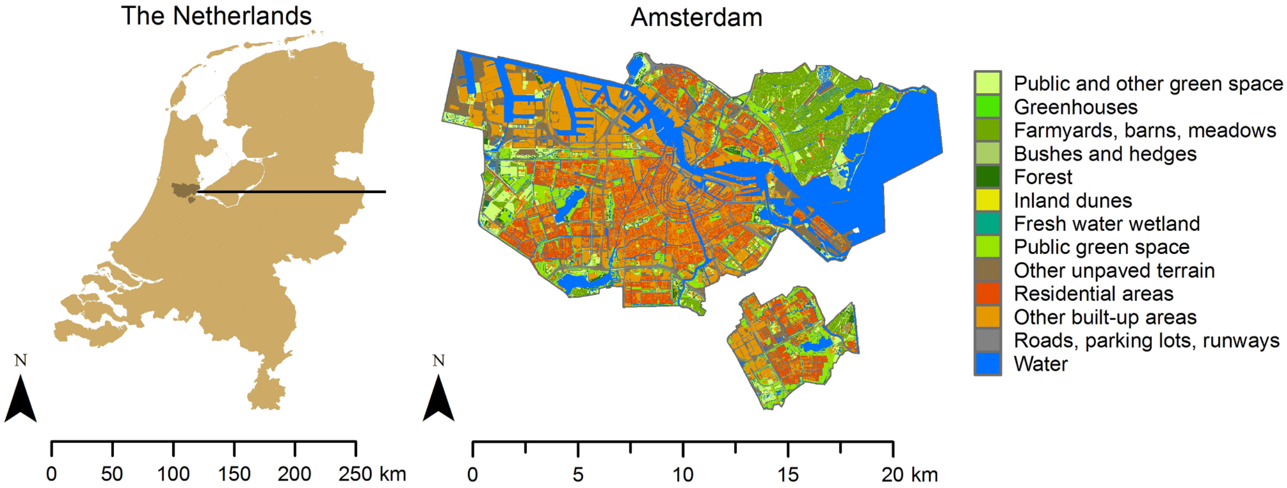


Fig. 1. Dominant types of land cover in the Municipality of Amsterdam (Paulin et al., 2020).

limitations for the formulation of spatial strategies. During the workshop, ecosystem service supply and use indicators were selected for their assessment. On the second stage of the assessment, urban design firm De Urbanisten developed GI spatial scenarios for the year 2025, capturing strategies from the GI plan and considering requirements established during the first workshop. In addition to changes in the municipality's GI, scenarios capture expected changes in residential infrastructure, as well as a projected population increase of roughly 70,000 inhabitants. On the third stage of the assessment, executed by RIVM, ecosystem service supply and use were quantified and mapped for three GI scenarios and for a reference scenario, where no alterations to GI take place. This enabled the comparison of values from GI scenarios with those of the reference scenario to estimate the effectiveness of different strategies. Changes considered encompass (i) expected changes in the performance and spatial distribution of ESP given the application of GI strategies, and (ii) the effects of such changes on the value and distribution of socioeconomic benefits across the city. The fourth stage of the assessment consisted of a workshop, facilitated by RIVM and De Urbanisten, where GI scenarios and expected associated changes in ecological and socioeconomic factors were presented to members of the Municipality of Amsterdam. In this final stage, workshop participants were provided the opportunity to express their views and opinions regarding results and the way were developed and communicated.

2.3. Modelling approach

Ecosystem services were assessed by use of the NC-Model. The model combines formulas and input data (i.e., spatial data and reference values) into algorithms to quantify and map ecosystem service supply and use for any given scenario (provided that input data requirements are met). Ecosystem service supply captures the distribution and total performance of final ESP that contribute to human wellbeing (Paulin et al., 2020). Ecosystem service use captures the distribution and total value of realized socioeconomic benefits underpinned by ESP (Paulin et al., 2020). As input, all models make use of a standard set of spatial data (details specified in Appendix A, Supplementary Material). Key intermediate input for all urban ecosystem service models includes detailed maps (10x10m resolution) showing the distribution of vegetation and population across urban areas (stepwise procedure for creating vegetation and population maps available in Paulin et al., 2020). In order to develop scenarios, input spatial data can be adapted to reflect changes that are expected to occur in each scenario (e.g., changes in the configuration or composition of vegetation). Ecosystem services were assessed for the year 2025, when Amsterdam's GI plan will reach its completion phase. Throughout the assessment process, only changes in GI that could be reflected as changes in model input, were included. Hence, some changes that could potentially affect ecosystem service delivery but are not included in the NC-Model, such as enhancements in the quality of GI, were not considered for this assessment.

Ecosystem services were quantified and mapped by use of six urban ecosystem service models comprised within the NC-Model (Paulin et al., 2020), namely the Air Quality Regulation, Physical Activity, Property Value, Urban Cooling, Urban Health, and Water Storage models. While the NC-Model captures ecosystem service and benefit indicators in a way that is compatible with the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018; https://cices.eu), the names ascribed to models comprise user-friendly terms that are instrumental when involving stakeholders and decision-makers perhaps less knowledgeable on ecosystem services terminology and concepts. Table 1 presents supply and use proxy indicators that were spatially quantified by use of each ecosystem service model. Classification of all proxy indicators according to CICES (version 5.1) is indicated in the Supplementary Material (Table A2, Appendix B). Fig. 2 illustrates the relationship between ecosystem service supply and use as considered in urban ecosystem service models, in alignment with the ecosystem services cascade (Potschin and Haines-Young, 2016). For some models, supply indicators are not available. This occurs since ecosystem service models often capture the way ecological structures (as opposed to processes) contribute to human wellbeing. Benefit-generating structures (e.g., vegetation and water) often comprise key model input, making their quantification redundant. The Urban Cooling model was only used to assess ecosystem service supply (i.e., reduction of the UHI effect), as there was no readily available approach for translating GI's contribution to urban cooling into socioeconomic benefits (e.g., enhanced health conditions, reduced health costs, enhanced labor productivity). All models are described in detail in Paulin et al. (2020), which also comprises an extensive 'Supplementary Materials' section providing stepwise procedures for the implementation of every model.

2.4. Scenarios

The Business As Usual scenario, or reference scenario, portrays a situation, where no changes other than expected population and planned residential expansion occur. Changes in the distribution of infrastructure were based on data from the 'Housing Plans Map' (*Woningbouwplannenkaart*) from the Municipality of Amsterdam (https://maps.amsterdam.nl/). The dataset shows areas where new residential plans have been made for the upcoming years, including the number of housing units that are expected to be built. Plans that fell

Table 1
Descriptions of ecosystem service supply and use proxy indicators for six ecosystem service models (Paulin et al., 2020).

Ecosystem service model	Supply/use	Indicator	Description
Air Quality Regulation	Supply	PM_{10} retention	Reduction in atmospheric PM_{10} concentrations by vegetation and water
	Use	Reduced health costs	Reduction in health costs from avoided PM_{10} related mortalities
Physical activity	Use	Contribution to cycling (commuting)	Contribution to time cycled by individuals for commuting purposes that can be attributed to the availability of green space in their surroundings
	Use	Reduced mortality	Avoided all-cause mortalities from enhanced health benefits due to the contribution to cycling (commuting)
	Use	Reduced costs from reduced mortality	Economic gains from reduced all-cause mortalities, based on the value of a statistical life
Property value	Use	Contribution to property value	Contribution by vegetation and open water to property prices
Urban cooling	Supply	Reduction in UHI effect	Contribution by vegetation and water to mitigation of the UHI effect
Urban health	Use	Reduced health costs	Reduction in health costs linked to the contribution by green space to mitigating the incidence of seven disease categories (i.e., cardiovascular diseases, musculoskeletal diseases, mental diseases, respiratory diseases, neurological diseases, digestive diseases, and a miscellaneous category)
	Use	Reduced visits to general practitioner	Avoided visits to general practitioners linked to the contribution of green space to improved health conditions
	Use	Reduced labor costs	Reduction in costs of absenteeism, reduced labor productivity, and job losses, linked to the contribution of green space to improved health conditions
Water storage	Supply	Reduced rainwater in sewers	Avoided rainwater in the drainage system due to water storage by vegetation
	Use	Reduced water treatment costs	Reduction in water treatment costs from avoided rainwater in the drainage system

within the phases ‘investment decision taken’ and ‘in construction with planned completion in the period 2018-2025’, were included. Neighborhood statistics from the input layer *Basisregistratie Addressen en Gebouwen* (BAG; Kadaster, 2019) were used to develop a spatially disaggregated map displaying the number of inhabitants that will reside in each new housing unit in the year 2025. Fig. 3 presents maps showing the distribution of inhabitants and three types of vegetation (i.e., trees, shrubs/bushes, low vegetation), which were developed for the BAU scenario.

Ecosystem services were assessed for three GI scenarios simulated for the year 2025, described hereunder (extensive scenario descriptions available in Paulin et al., 2019). Within each scenario, new vegetation types are introduced (Fig. 4). Table 2 presents the total change in spatial area for each vegetation type in each scenario. In some instances, a decrease in spatial area is seen, comprising transformations from current vegetation types to different typologies (e.g., low vegetation to shrubs/bushes or trees).

i) **Green Neighborhoods**: This scenario comprises a substantial increase in vegetation in areas that currently comprise little to no green. The main modifications to GI in this scenario include substantial conversions of parking spaces into green surfaces and grey roofs into green roofs.
ii) **Green Network**: This scenario envisions a strengthened ecological and recreational (e.g. cycling, sports, hiking trails) network within Amsterdam. The main modifications to GI include completing the main tree network connecting green areas, and the transformation of current vegetation to different typologies (e.g., converting different low vegetation typologies into shrub typologies).
iii) **Urban Parks**: This scenario integrates objectives from the Green Quality Impulse regarding the enhancement of urban parks for recreational use. The main changes captured within this scenario include the creation of new parks, expansion of existing parks, and increased net abundance of vegetation in existing parks.

3. Results and discussion

3.1. Changes in ecosystem services: total values

In Table 3, data and model outputs are presented, reflecting how changes in GI in each scenario affect total ecosystem service supply and use. First, an increase in value for nearly all ecosystem service indicators across all GI scenarios is expected. This is primarily the case since all scenarios comprise an increase in the extent of vegetated

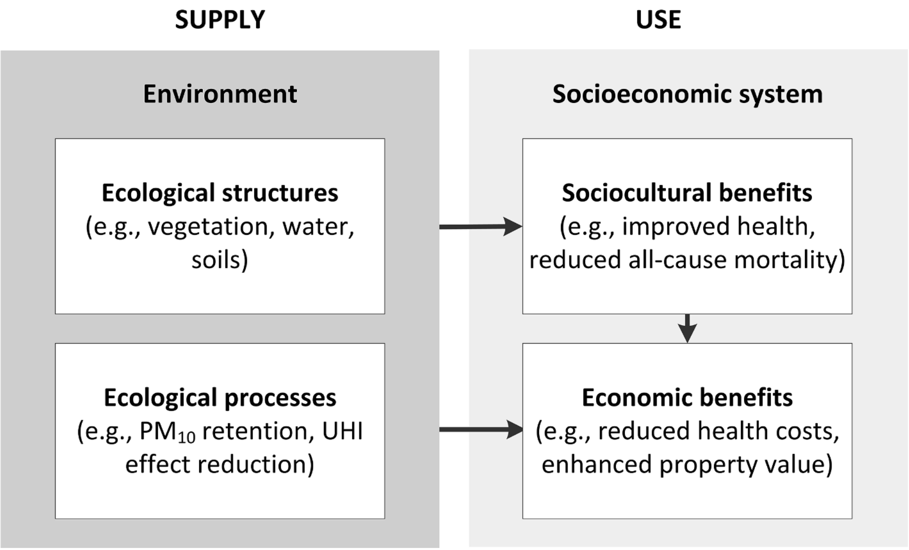


Fig. 2. Schematic diagram of relationship between ecosystem service supply and use within urban ecosystem service models. Supply captures ESP and use captures the realized contributions of ESP to society and the economy. Sociocultural benefits capture the direct contribution of ESP to human wellbeing. Economic benefits capture either (i) the direct contribution of ESP to the economy or (ii) the translation of accrued sociocultural benefits into monetary units.

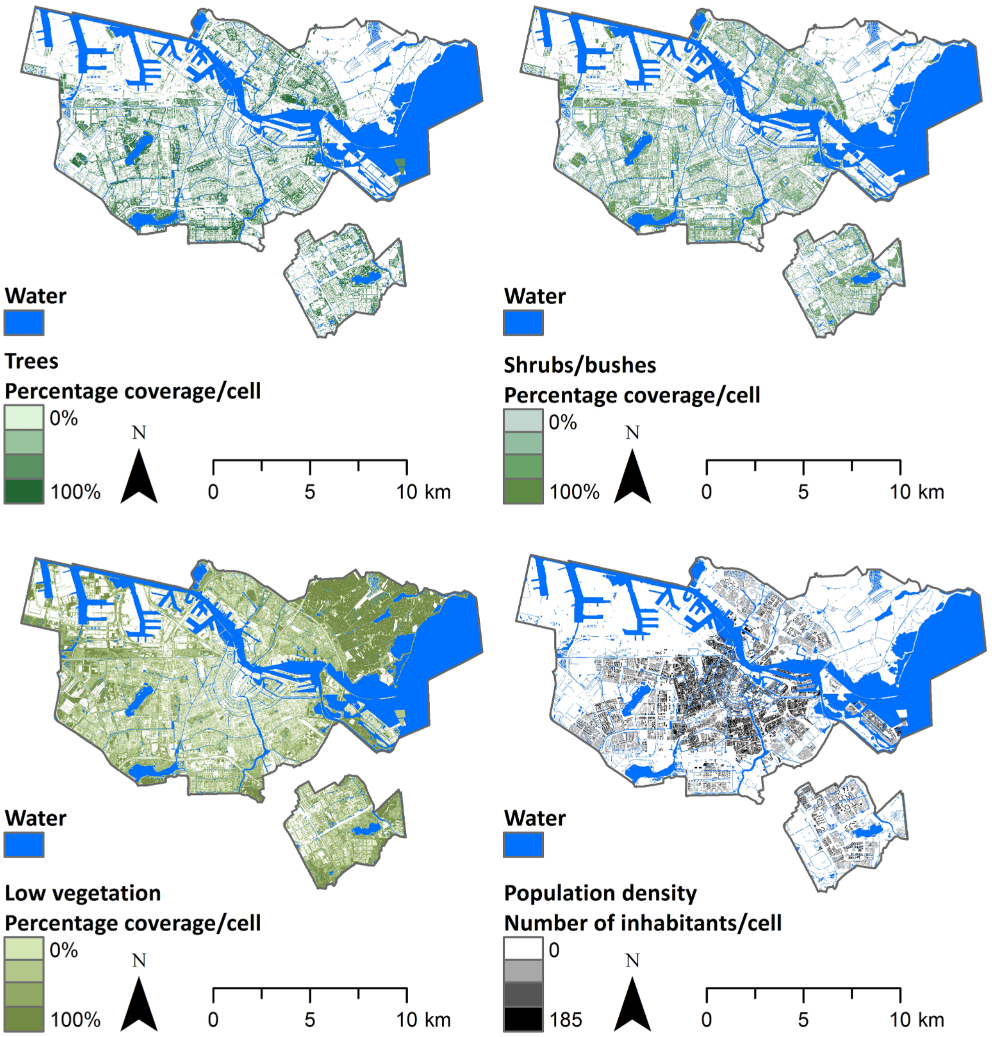


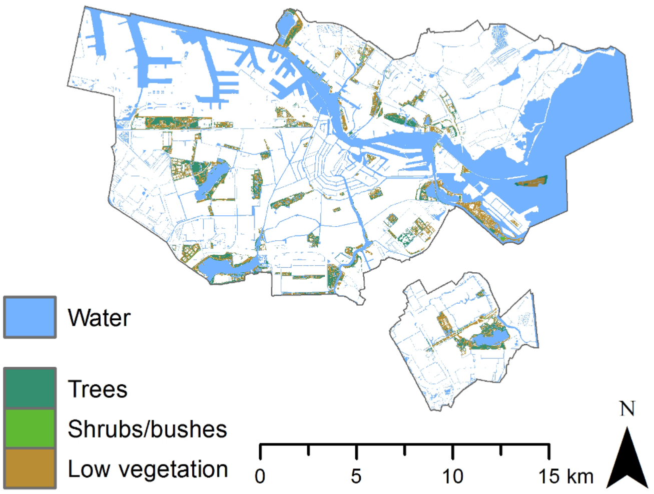
Fig. 3. Vegetation cover (percentage of trees, shrubs/bushes, low vegetation) and population density (number of inhabitants) per cell (10x10m) within the Business As Usual scenario (year = 2025). For each map, legends show quantile values. All quantile thresholds values are presented in the Supplementary Material (Table A3, Appendix C).

cover. Since ecosystem service models capture ESP and accrued socioeconomic benefits that are underpinned by GI, improvements in Amsterdam's GI generally lead to improvements in overall ecosystem service delivery. Second, the highest improvement in performance for most ecosystem service indicators assessed (7 out of 12) is expected in the Green Neighborhoods scenario. This is a somewhat unexpected outcome since the scenario (i) comprises the lowest net expansion in vegetated cover (249 ha), and (ii) comprises no transformation from herbaceous to woody vegetation, which leads to a higher contribution to ecosystem delivery within several models (e.g., Air Quality Regulation, Property Value, Urban Cooling). Substantial improvements in ecosystem service use in the Green Neighborhoods scenario occur since, in addition to the size and composition, the configuration of introduced GI (i.e., location and distribution) plays a key role in ecosystem service performance (Keeler et al., 2019; Grafius et al., 2018). Within the Green Neighborhoods scenario, GI is introduced in areas (i) where built-up infrastructure predominates (see Figs. 1 and 4) and (ii) which are densely populated. Introducing GI in areas where built-up infrastructure predominates leads to a higher marginal increase in ecosystem service performance than in areas where vegetation is already predominant. This is also the case when GI is introduced in densely populated areas, as they comprise a high concentration of potential ecosystem service beneficiaries (Vallecillo et al., 2018). Third, the Green Network scenario reveals the highest improvement in performance for Air Quality Regulation and Water Storage (supply and use) proxy indicators. Increases in PM_{10} retention and accrued health benefits can be attributed to the substantial expansion of tree cover (454 ha), as trees bear the highest capacity for PM_{10} retention out of all vegetation types covered by the Air Quality Regulation model. The Water Storage model captures the direct relationship between the areal extent of vegetated cover and its capacity for rainwater storage, as well as accrued economic benefits. Hence, substantial improvements in water storage and the economic benefits in the Green Network scenario can be attributed to the substantial net expansion in vegetated cover (410 ha) in the scenario. Finally, the Urban Parks scenario revealed the most substantial improvement in performance for Urban Cooling proxy indicators. This occurs since this scenario entails a substantial increase in tree cover (258 ha) confined to relatively small areas (e.g., parks). In the Urban Cooling model, two central factors contributing to the reduction of the UHI effect are the vegetation typology and vegetation density, where trees in high densities lead to a higher reduction than other vegetation typologies in lower densities.

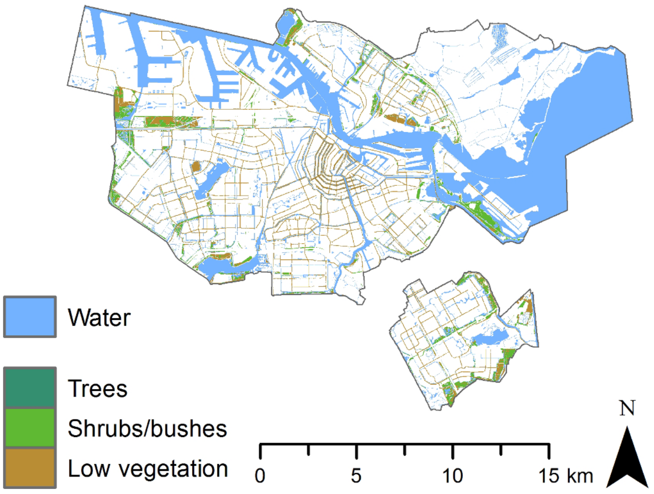
3.2. *Changes in ecosystem services: Spatial distribution*

To better understand how changes in GI affect ESP and accrued socioeconomic benefits, it is useful to juxtapose quantitative results with maps displaying the distribution of changes in ecosystem service

a) Urban Parks



b) Green Network



c) Green Neighborhoods

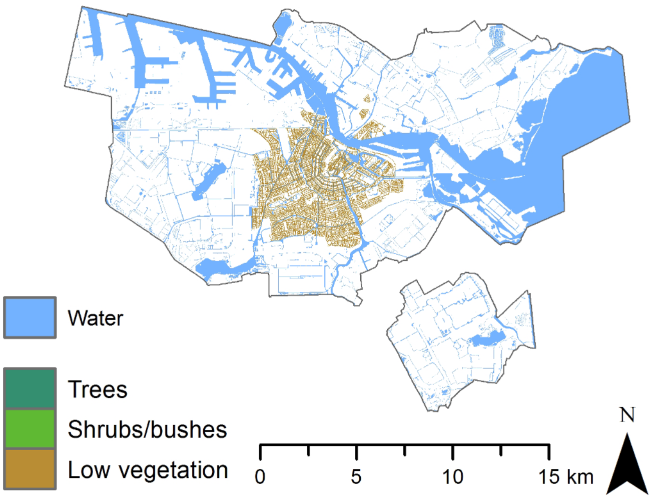


Fig. 4. Areas where new vegetation cover (i.e., trees, shrubs/bushes, low vegetation) is introduced for the Urban Parks, Green Network, and Green Neighborhood scenarios. Unshaded areas comprise areas where no value has been assigned.

Table 2
Total vegetation (i.e., trees, shrubs, bushes, low vegetation) coverage for one Business As Usual (BAU) scenario, and total change in coverage (increase/decrease) for three GI scenarios (= ha GI scenario – ha BAU scenario).

GI element	Unit	Total cover	Change in cover		
		Business As Usual	Green Neighborhoods	Green Network	Urban Parks
Trees	ha	1,173	-	454	258
Bushes/shrubs	ha	441	-	526	−79
Low vegetation	ha	6,010	249	−570	139
Total	**ha**	**7,623**	**249**	**410**	**318**

performance (Crossman et al., 2012). Fig. 5 presents maps displaying the distribution of changes in the performance of four ecosystem services, each represented by one supply or use proxy indicator. Notable improvements in ecosystem service performance are visible in areas where GI is introduced (see Fig. 4), an anticipated result as GI underpins the delivery of ecosystem service supply and use. A strong resemblance is visible between the distribution of changes in ecosystem service use estimated by use of the Physical Activity model (Fig. 5a) and the distribution of inhabitants (see Population density map, Fig. 3). This occurs since the distribution of inhabitants serves as a proxy for the distribution of potential ecosystem service beneficiaries. This does not necessarily imply that the spatial distribution of ecosystem service use is always correlated with population distribution, as the mechanisms leading to the realization of ecosystem service benefits vary in nature. For instance, within the Water Storage model, water retention is directly related to the spatial extent of vegetated cover in an area. Ecosystem service use captures reductions in water treatment costs associated with water stored by vegetated areas in areas with extensive sewage systems. Hence, a strong resemblance is visible between the distribution of changes in ecosystem service use estimated by use of the Water Storage model (Fig. 5b), and the distribution of introduced vegetation (see Fig. 4a). Changes in the distribution of ecosystem service supply (Fig. 5c and d) occur primarily in areas where GI is introduced (Fig. 4a and b), yet the distribution pattern of such changes varies substantially. This accentuates the complexity with which ESP take place. While no resemblance is visible between population distribution and changes in ecosystem service supply, human populations may play an indirect role in the distribution of ESP (e.g., by manipulating the distribution of GI and exerting ecological pressures that require mitigation).

3.3. Changes in ecosystem services: Relative values

Assessing ecosystem service delivery by use of various indicators expressed in various units is useful since (i) ecosystem service supply and use are intricately interconnected yet cannot always be expressed in identical units (Alam et al., 2016), and as (ii) it enables the communication of ecosystem service values to audiences with different backgrounds and preferences (Satz et al., 2013). Despite these advantages, incommensurability of ecosystem service indicators also restricts their comparability and potential aggregation. Comparability enables the assessment of tradeoffs and synergies among ecosystem services, contributing to (i) instrumental decision-making based on information on ecosystem service gains and losses, and (ii) conceptual discussions that shape the way decision-makers and stakeholders think about ecosystem service policies (Wright et al., 2017). Aggregation is instrumental for estimating the total value of ecosystem service bundles and comparing them across time and space (Yang et al., 2019). However, it can also lead to double-counting and over- or underestimation of individual ecosystem service values, hampering the objectivity of results (Paulin et al., 2020). Because of this, we refrain from aggregating ecosystem services in this study. Instead, commensurability is

Table 3
Total ecosystem service values for a Business As Usual scenario (year = 2025) and differences in values for three GI scenarios in reference to the Business As Usual scenario. Outlined in dark boxes are encased the highest increases in ecosystem service values per GI scenario per proxy indicator considered (i.e. supply or use).

Ecosystem service model	Supply/ Use	Indicator	Unit	Total value	Difference in value (BAU as reference)		
				Business As Usual	Green Neighb.	Green Network	Urban Parks
Air Quality Regulation	Supply	PM_{10} retention	thousand kg/yr	98.6	2.9	8.1	3.3
	Use	Reduced health costs	million €/yr	4.8	0.1	0.4	0.2
Physical Activity	Use	Contribution to cycling (commuting)	thousand hours/yr	54	8	5	2
	Use	Reduced mortality	lives/yr	19	3	2	1
	Use	Reduced costs from reduced mortality	million €/yr	42	6	4	2
Property Value	Use	Contribution to property value	billion €	6.36	0.10	0.08	0.02
Urban Cooling	Supply	Reduction in UHI effect	°C	1.78	0.00	0.01	0.04
Urban Health	Use	Reduced visits to general practitioner	thousand visits/yr	23	3	2	1
	Use	Reduced health costs	million €/yr	20	3	2	1
	Use	Reduced labor costs	million €/yr	96	13	9	4
Water Storage	Supply	Reduced rainwater in sewers	million m^3/yr	17.6	1.2	1.4	0.8
	Use	Reduced water treatment costs	million €/yr	13.8	0.9	1.1	0.6

achieved by calculating the percentage change in value of each ecosystem service proxy indicator for each GI scenario in reference to the Business As Usual scenario. For comparability, results are visualized in a radar plot (Fig. 6), a common approach for illustrating relative values of ecosystem service indicators within bundles and across scenarios (Demestihas et al., 2019).

Evaluating relative changes in ecosystem service performance across scenarios enables the assessment of total changes in individual performance indicator values and total changes in ecosystem service bundles across scenarios. It also enables the assessment of heterogeneity within scenarios by providing information on overall changes (i.e., mean) against individual changes (i.e., SD) of performance indicator values. In a nutshell, five main conclusions can be drawn based on the assessment of relative values in this case example:

i) **Highest relative increase.** The highest relative increase in ecosystem service performance indicator values is seen for indicators modelled by use of the Physical Activity and Urban Health models, given the application of strategies in the Green Neighborhoods scenario.
ii) **Lowest relative increase.** Ecosystem service performance indicators modelled by use of the Property Value model reveal the lowest relative increase given the implementation of GI strategies (0–2%).
iii) **Green Neighborhoods.** Implementation of strategies in this scenario lead to the highest relative increase in individual indicator performance, with a 14–16% increase in six performance indicators. All performance indicators considered, this scenario reveals the highest general increase in proxy indicator performance and highest heterogeneity in changes (mean = 9%, SD = 6%).
iv) **Urban Parks.** Implementation of strategies in this scenario lead to a relatively low increase in individual indicator performance (0–5%). All performance indicators considered, this scenario reveals the lowest general increase in proxy indicator performance and lowest heterogeneity in changes (mean = 3.3%, SD = 1%).
v) **Green Network.** Implementation of strategies in this scenario lead to a moderate increase in individual indicator performance, with all but two performance indicators revealing an 8–10% increase. All performance indicators considered, this scenario reveals a moderate in proxy indicator performance and moderate heterogeneity in changes (mean = 8%, SD = 3%).

3.4. Urban planning

This study's application of the NC-Model provides information on how the implementation of GI strategies can lead to changes in the distribution, relative performance, and overall performance of ecosystem service supply and use. Assessment results are instrumental to support urban planning in the context of (i) communication and awareness raising; (ii) strategic planning and priority setting; and (iii) economic accounting and incentive design (Gómez-Baggethun and Barton, 2013; Haase et al., 2014). We expand on these points below.

i) **Communication and awareness raising.** This assessment provided quantitative and illustrative information on how changes in GI can affect ecosystem service delivery and hence the socioeconomic wellbeing of urban dwellers. The juxtaposition of high-resolution maps and quantitative values revealed that changes in the size, configuration, and typology of GI are key determinants to changes in ecosystem service delivery. Displaying relative changes in ecosystem service values across scenarios by use of radar plots enabled comparison of highly complex information in a clear and user-friendly manner. This kind of information is instrumental for urban planners who wish to better understand the mechanism by which GI contributes to the urban quality of life and to further disseminate this information to the public. Urban planners that participated in this study's final workshop (i.e., presentation of results) exhibited a higher interest in the mechanism by which GI supports ESP and socioeconomic wellbeing, than in the economic value that GI generates, providing a glimpse of their preferences and priorities in the context of urban planning. For some participants, the many ecosystem services that GI generates and the

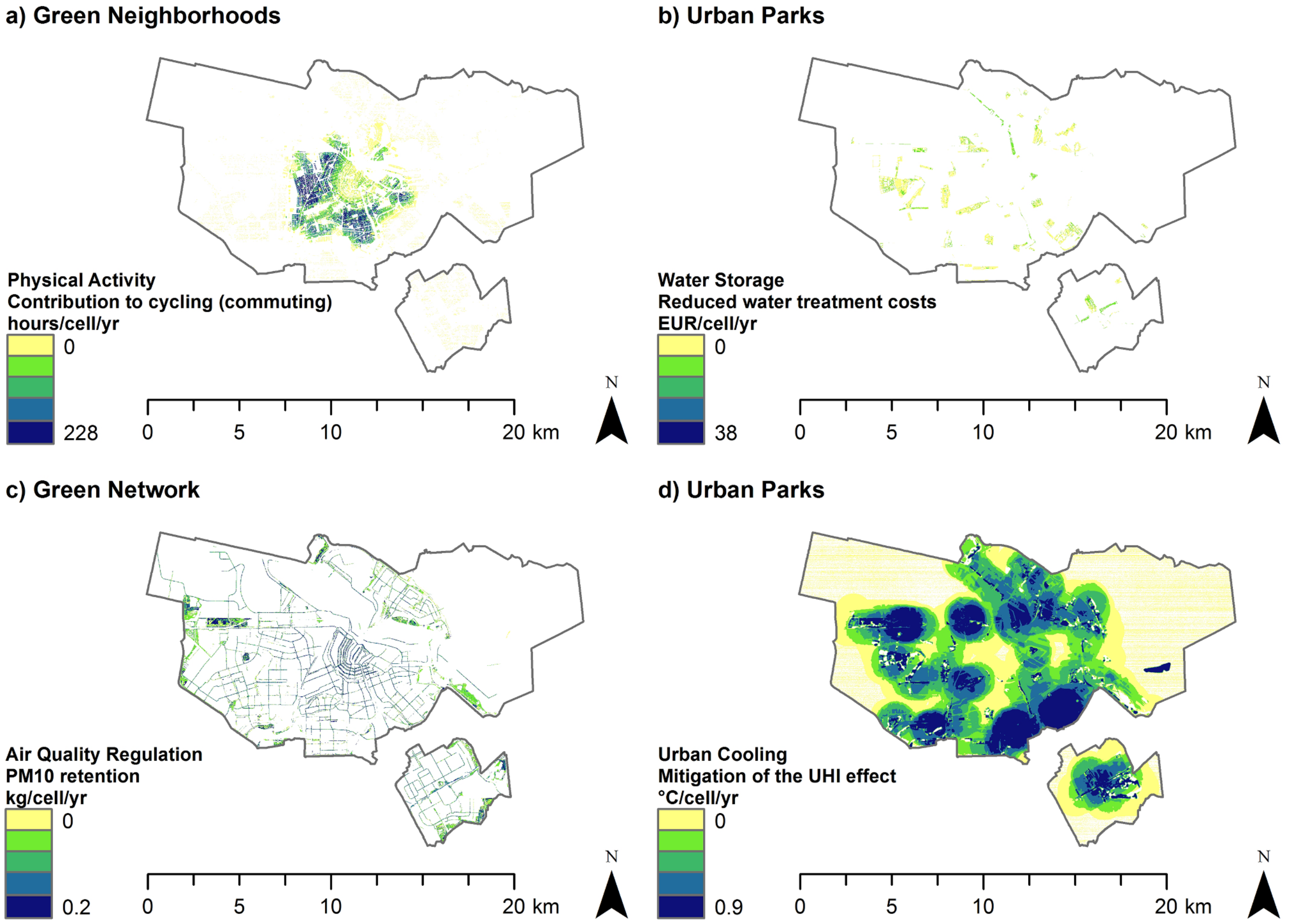


Fig. 5. Changes in the performance of four ecosystem service supply and use for different scenarios in reference to the Business As Usual scenario (cell size = 10x10m). For each map, legends show quantile values. All quantile thresholds values are presented in the Supplementary Material (Table A4, Appendix C). Unshaded areas comprise areas where no value has been assigned. Additional maps displaying changes in the distribution of ecosystem service supply and use across scenarios, see Supplementary Material (Appendix D).

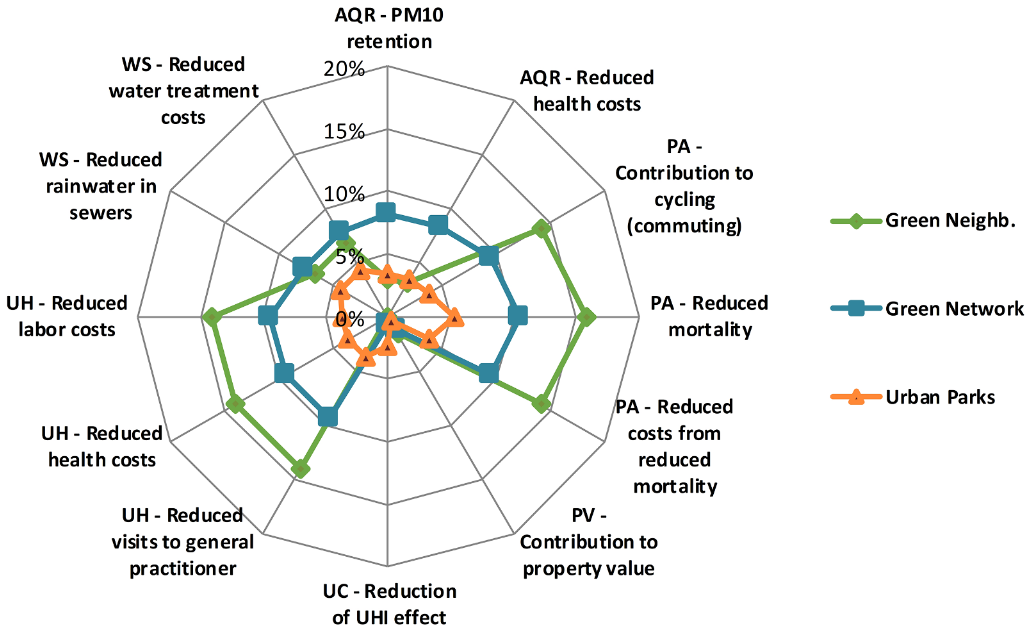


Fig. 6. Total relative change (percentage increase) in ecosystem service values per GI scenario in reference to the Business As Usual scenario. AQR = Air Quality Regulation; PA = Physical Activity; PV = Property Value; UC = Urban Cooling; UH = Urban Health; WS = Water Storage. Detailed statistics on percentage changes per indicator and heterogeneity across scenarios, are presented in the Supplementary Material (Table A5, Appendix C).

process leading to their delivery were virtually unknown prior to the workshop, emphasizing the value of the approach for awareness-raising. By obtaining results in various formats (tables, maps, radar plots, indicators expressed in various units), urban planners were equipped with tools to further disseminate results for communication and decision-making purposes, in a way that speaks to various target groups (e.g., decision-makers, investors, local inhabitants).

ii) **Strategic planning and priority setting.** Assessment results can be adopted by urban planners to develop, rethink, and prioritize GI strategies in alignment with local objectives, based on scientifically-sound information. In Amsterdam, a number of policy initiatives (Amsterdam Municipality, 2010, 2015a, 2015b, 2017a, 2018, 2019a, 2019b) epitomize the desire to improve the quality of public spaces to enhance the quality of life of Amsterdam's rapidly growing population. To make this desire a reality, the Green Quality Impulse (Amsterdam Municipality, 2017b) will lay out the implementation plan for expanding and redesigning Amsterdam's GI to support its transition into a sustainable, climate-proof, and socially attractive city. This study's results revealed that expected changes in the distribution and performance of ecosystem services, resulting from changes in GI, are not homogeneous across space. This can be explained by the complex and diverse mechanisms that underpin the delivery of each ecosystem service. In better understanding the factors that influence ecosystem service delivery (e.g., distribution and composition of GI, population distribution), as well as the tradeoffs that exist among ecosystem services, urban planners in the Municipality of Amsterdam can rethink and prioritize GI strategies to target objectives from the Green Quality Impulse (e.g., emphasizing the reduction of the UHI effect and enhancement of water storage for climate resilience), as well as areas where societal challenges (e.g., heat stress, flood risk, low income) overlap.

iii) **Economic accounting and incentive design.** The lack of awareness of the many benefits that GI can generate in urban areas often results in conversion of urban nature into built infrastructure, resulting in ecosystem service loss (Gómez-Baggethun and Barton, 2013). Building a case for investments in GI requires transparency regarding capital and operational costs, as well as socioeconomic benefits, that investments in GI entail (Schäffler and Swilling, 2013; Maes et al., 2015). In doing so, GI can be viewed from a more positive light, not solely as a source of cost but also as an investment opportunity (Ernst, 2020). In this study, the costs associated with investments in GI were not considered, as the Green Quality Impulse is in its development phase so this information is not readily-available. A complete assessment of the expected efficacy of each strategy for meeting local objectives would require juxtaposition of the (capital and operational) costs of implementation, with associated improvements in the performance of ecosystem services. For instance, implementation of the Green Neighborhoods strategy reveals the highest increase in value for most indicators. This was a somewhat surprising finding for urban planners, given the lower expansion in vegetated cover relative to other strategies, and as the strategy envisions no transformation from herbaceous to woody vegetation. The expected improvement in ecosystem service delivery occurs since GI is introduced in densely populated areas with predominant built-up cover, which often host a high abundance of beneficiaries and ecological pressures that require mitigation. Despite these benefits, introducing GI in densely populated areas is often costly due to previous removal or degradation of green space in ways that are difficult to reverse (Kruize et al., 2019; Vallecillo et al., 2018). In Amsterdam, densely populated areas include post-war residential neighborhoods, comprising relatively small housing units with no front yard and small backyards. Introducing GI in sealed areas would entail high costs due to the presence of infrastructure (e.g., sewers, gas, water, electricity, internet cables). This accentuates (i) the need to consider the costs of particular GI strategies when evaluating the benefits they accrue (Kruize et al., 2019), and (ii) the significance of considering GI as a fundamental aspect of urban development and not just as an end-of-the-pipe solution.

4. Limitations

The assessment approach presented in this paper can be useful to inform urban planners on the complex nature by which GI generates value for urban dwellers. However, it is important that all limitations associated with such an assessment approach are elucidated to receptors of results for their unbiased interpretation and appropriate consideration within urban planning. First, models adopted for quantifying and mapping ecosystem services provide a simplification of real systems, as it is not objective (nor possible) to consider all aspects that characterize inherently complex coupled socioecological systems (Paulin et al., 2020). Hence, only the most relevant factors affecting ecosystem service performance, for which instrumental knowledge and data is available, are considered. For instance, trees in street canyons can lead to an increase atmospheric PM_{10} concentrations (Janhäll, 2015). This factor is currently not considered in the Air Quality Regulation model due to limitations in knowledge and data. In turn, this may lead to an overestimation of the contribution by trees to PM_{10} retention in the Green Network scenario, where trees are added along streets. Second, a diverse yet limited selection of ecosystem service performance indicators is assessed. This results from limitations in data and empirical research required to assess a more comprehensive, locally-relevant suite of ecosystem services. This may lead to an overestimation of assessed ecosystem services and an underestimation of omitted ecosystem services (Paulin et al., 2020). Improving model objectivity would require the development of periodically-repeated empirical research capturing relationships between ecological and socioeconomic parameters relevant at the urban scale in the Netherlands. The continuous assessment of empirical relationships relevant in the Netherlands could provide valuable input for continuously developing and calibrating the current suite of models in the NC-Model.

5. Conclusions

Through its incorporation of best-available local knowledge and data (e.g., Dutch spatial datasets and empirically-established relationships linking ecological and socioeconomic parameters), the NC-Model enables the spatial quantification of Dutch urban ecosystem services at high spatial and thematic detail. In this study, the model was successfully implemented to spatially quantify ecosystem services in the Municipality of Amsterdam at a high resolution, considering locally-relevant environmental and socioeconomic characteristics (e.g., PM_{10} concentrations that require mitigation, GI typologies whose local value reflects in property values). Implementation of the NC-Model across scenarios that capture GI strategies from Amsterdam's Green Quality Impulse, provided detailed insights on how the implementation of each strategy may influence ecosystem service delivery. Changes in GI from the application of each strategy are expected to heterogeneously affect the total performance and distribution of different ecosystem services, accentuating the complexity of the mechanism that underpins ESP and accrued socioeconomic benefits. In general, the distribution and composition of GI, as well as population distribution, were identified as key factors affecting ecosystem service delivery. Changes in ecosystem service supply were primarily affected by changes in the distribution and composition of GI, while changes in ecosystem service use were significant where population densification is prominent. In capturing ecosystem services and (ecological and socioeconomic) factors that influence their performance in fine detail, such an approach can foster a better understanding among urban planners on the mechanism by which GI generates value for urban dwellers. This is instrumental for urban planners who wish to develop strategies that optimize ecosystem service delivery in alignment with local objectives, and to further communicate this information to decision-makers, investors, and local inhabitants in simple but scientifically-sound manner.

The availability of input data and knowledge required to model urban ecosystem services in fine detail, capturing relevant local characteristics, varies significantly across different geographical locations. Where local spatial data is absent or poor in quality, the use of existing datasets produced at the regional and global scales is endorsed. In the absence of local empirically-established relationships between ecological parameters, empirically-established relationships obtained in regions with similar environmental characteristics is endorsed for modelling ESP. In the absence of local empirically-established relationships between ecological and socioeconomic parameters, empirically-established relationships obtained in regions with similar socioeconomic characteristics is endorsed for modelling ecosystem service use. Even though data and benefit transfer may reduce the level of accuracy and hence the objectivity of results, it can provide an opportunity for endowing urban planners with valuable information on the value of GI and its contribution to human wellbeing. Given the adequate communication of uncertainties, local approaches for assessing urban ecosystem services can endorse the optimal allocation of GI to mitigate the pressures of urbanization and to promote the fair distribution of ecosystem services.

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 data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2020.101114.

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