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Assessing urban ecosystem services in support of spatial planning in the Hague, the Netherlands

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HIGHLIGHTS

- Spatial model to support planning of multifunctional Green Infrastructure (GI).
- Environmental and GI characteristics explain ecosystem service (ES) variations.
- Applying ES-specific weights affect "hotspots" for GI development priority.
- The model can be deployed for other cities and for other ES.

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ABSTRACT

Green infrastructure (GI) is increasingly addressed in urban planning and research to enhance urban sustainability and resilience through the provisioning of ecosystem services (ES). Yet, few applications exist of planning models for multifunctional GI in high spatial and thematic detail that simultaneously align with stakeholder interests. We address these gaps by developing and presenting a spatially explicit model to inform urban planners on priority areas for multifunctional GI development. This model was made possible by spatial analyses on multiple scales, enabling us to assess ES in sufficient detail, while simultaneously matching the preferences for scale and ES-indicators of decision makers and urban planners. The model involves a novel weighting scheme based upon the local capacity of GI to mitigate problems. We applied our model to the city of The Hague using a set of three policy-relevant problems: air pollution, the urban heat island effect and storm water flooding. Our results show that the capacity of GI to mitigate these problems varies spatially, both within and between ES, and depends on local characteristics of GI and the environmental context. We illustrate the relevance of using a multi-scale approach in spatial ES analysis, and underline that GI planning measures should be assessed in high spatial detail due to their often locally distinct ES capacity. Our approach makes important strides towards the deployment of nature-based solutions for urban challenges in the light of demands for increasing resilience and sustainability.

1. Introduction

By 2050, 70% of the world's human population is projected to live in cities (United Nations, 2018). Urban challenges, such as climate change, biodiversity loss and environmental pollution are therefore of high priority (Seto, Parnell, & Elmqvist, 2013). To ensure cities' sustainability and to increase their resilience, ecosystem services (ES) are increasingly addressed in urban planning and research as a concept to relate urban ecosystems and biodiversity to human wellbeing (Ahern, 2011; Haase et al., 2014; McPhearson et al., 2015). In this light, nature based solutions (NBS) have emerged in policy and science as "Actions to protect, (..) manage, and restore natural or modified ecosystems, addressing societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits'' (Cohen-Shacham et al., 2016, p.2). Among others, NBS hence involve enhancing ES through the management or creation of green infrastructure (GI)

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(Albert et al., 2019). While the concept of GI has various definitions, we here follow the definition of the European Commission (2019, p.8): “Green infrastructure is a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services." Examples of ES supplied by GI include the mitigation of climate change effects, e.g. providing cooling during heat waves (Schwarz, Bauer, & Haase, 2011); alleviation of social problems, e.g. through the delivery of physical and mental health benefits (Gomez-Baggethun et al., 2013); and of economic problems, e.g. the retention of stormwater by soils and vegetation instead of costly drainage systems (McPhearson et al., 2015).

Successful design and implementation of NBS in urban planning requires insights in the relationship between green infrastructure (GI) and ES (Veerkamp et al., 2020). While specific benefits derived by GI are increasingly assessed in scientific literature, for instance through field measurements (e.g. Klemm et al., 2015) or expert surveys (e.g. Elliott et al., 2020), fewer studies have assessed urban ES at a high spatial and thematic resolution. The latter is important because cities are ecologically heterogeneous, and the distinction between GI types and their structural characteristics are critical for ES supplied by GI (Haase et al., 2014). Examples include studies by Derkzen, van Teeffelen, & Verburg (2015) and Madureira & Andresen (2014), who both used detailed land cover data to assess urban ES patterns. In addition, Graça et al. (2018) assessed structural variables, especially of trees, including tree (leaf) density, size and condition. Escobedo & Nowak (2009) calculated air pollutant removal capacities by vegetation based upon leaf area density.

Recent insights suggest that, in addition to the characteristics of GI itself, ES supply is also affected by social practices, the cultural context, as well as the environmental context (e.g. air pollution concentrations, built infrastructure) (Andersson et al., 2015; Kremer et al., 2016). While assessing social and cultural conditions requires additional social scientific methods that go beyond the scope of most spatial ES assessments (Daniel et al., 2012), the environmental context can generally be well integrated, provided that high resolution spatial data is available.

In addition to assessing ES at sufficiently high resolution, matching the scale of ES quantification and modelling to the spatial scale at which urban planning is done remains another challenge (Kremer et al., 2016). Examples include the district, street or individual house level. Presenting findings on a scale and resolution relevant to urban planners and decision makers increases the odds that ES models and results are understood and implemented. For instance, Baró, Gómez-Baggethun & Haase (2017) quantified ES on the municipality scale because related policies in the study area are implemented at that level. Larondelle & Lauf (2016) adapted a neighborhood scale because planning, prediction and modelling in the study region was done at this level. Other studies use census tracts, villages (e.g. Meerow, 2019) or socio-economic strata (e.g., Graça et al. 2018) for similar reasons. This suggests the need to adapt multiple scales to assess urban ES in sufficient detail, while also ensuring the relevance of the model to decision makers and planners.

To further improve the policy relevance of spatial ES models, the ES and associated indicators should be selected in collaboration with stakeholders, who are often faced with multiple relevant urban problems. It is widely understood that GI can provide multiple ES concurrently, which is well suited to the multi-faceted demands of urban stakeholders (Hansen & Pauleit, 2014). Nevertheless, the literature and application of GI in urban planning has focused largely on optimizing or providing a single benefit (Hansen et al., 2019; Finewood, Matsler, & Zivkovich, 2019; Meerow, 2020), and is rarely expressed in ways relevant to stakeholders. Hence, there is a need for application-oriented, i.e. problem-focused, frameworks for assessing the potential synergies and trade-offs inherent to the multifunctionality of GI (Cortinovis & Geneletti, 2018; Hansen et al., 2019).

The challenges discussed above indicate that ES should be assessed at a high spatial resolution, while also accounting for the relevance of the scale and the ES indicators for policy and planning. To account for the multifunctionality of GI (including trade-offs), incorporating location-specific demands of stakeholders can enable the assessments of multiple ES simultaneously in decision making. This allows the user to determine spatial hotspots for GI development. Accounting for stakeholder priorities is already increasingly common in spatial assessments (e.g. Kremer, Hamstead, & McPhearson, 2016; Madureira & Andresen, 2014; Meerow & Newell, 2017). A logical next step would be to introduce a weighting scheme based upon the capacity of GI to mitigate relevant location-specific problems, considering the projected problem-solving performance and prioritization by stakeholders. This allows both supply and demand of ES to be accounted for. In combination, this allows for communicating differences in effectivity of GI, to incorporate perceived usefulness in analyses, and to combine multiple ES in GI planning at the resolution and scale relevant to stakeholders. A tool to inform spatial planning of multifunctional GI that incorporates a weighting scheme based on ES capacity has, to our knowledge, not been introduced yet in scientific literature.

Therefore, this study aimed to develop and apply a spatially explicit ES model to inform decision makers and urban planners on priority areas for GI development, based on the weighted capacity of GI to provide ES. Similar to Larondelle & Lauf (2016), we used a multi-scale approach by examining ES on a high resolution, while also aggregating the results to a level that was relevant for management of the urban area. The model was developed for and applied to the city of The Hague, The Netherlands. The Hague is an example of a rapidly developing urban area, and was one of the members of the now defunct global ‘100 Resilient Cities initiative’ (AECOM, 2018), which aimed to collectively build urban resilience in a holistic way. The municipal council aspires to foster the city’s resilience, by addressing the problems of air pollution, heat stress and stormwater runoff through the explicit protection, conservation and enhancement of GI (AECOM, 2018; Municipality The Hague, 2012). Strategies to support urban planning of multifunctional GI have not yet been developed for The Hague. This study contributes to achieving this, thereby taking the interests of decision makers into account through active collaboration.

2. Methods

We followed a stepwise approach in developing a spatially explicit GIS-based model to quantify three urban ES in relation to GI. The three ES were air quality regulation, urban heat island reduction and stormwater retention. The selection of these ES was based on discussions with senior policy advisors of the municipality, and relevant policy documents on urban problems and GI (AECOM, 2018; Municipality The Hague, 2012; 2015; 2019). In the following paragraphs we describe the case study, the GI inventory, and the analysis of the relevant urban problems as well that of the corresponding ES, respectively. We used ArcGIS version 10.6.2, Python (GeoPandas and Pandas, open source Python packages), and Microsoft Excel 2016 for data processing and analysis. A schematic visualization of the methodological steps can be found in Appendix A.

2.1. Case study area

The municipality of The Hague is located in the west of the Netherlands (Fig. 1). With over 540.000 inhabitants it is the third largest municipality of the Netherlands (CBS, 2020). The Hague has a surface area of 85.620 ha, including 944 ha of large green areas and 725 ha of small-scale neighborhood green areas (AECOM, 2018). The coastal area is characterized by a dune landscape, whereas the old city center typically has a high density of buildings, but little vegetation. The share of GI increases closer towards the municipality’s outer borders.

Concentrations of air pollutants in The Hague were found to frequently exceed the European standard (RIVM, n.d.). The urban heat island effect is particularly severe in The Hague, due to lack of vegetation and surface water, high building density, a large share of impervious areas, and little reflection of sunlight (van der Hoeven & Wandl,

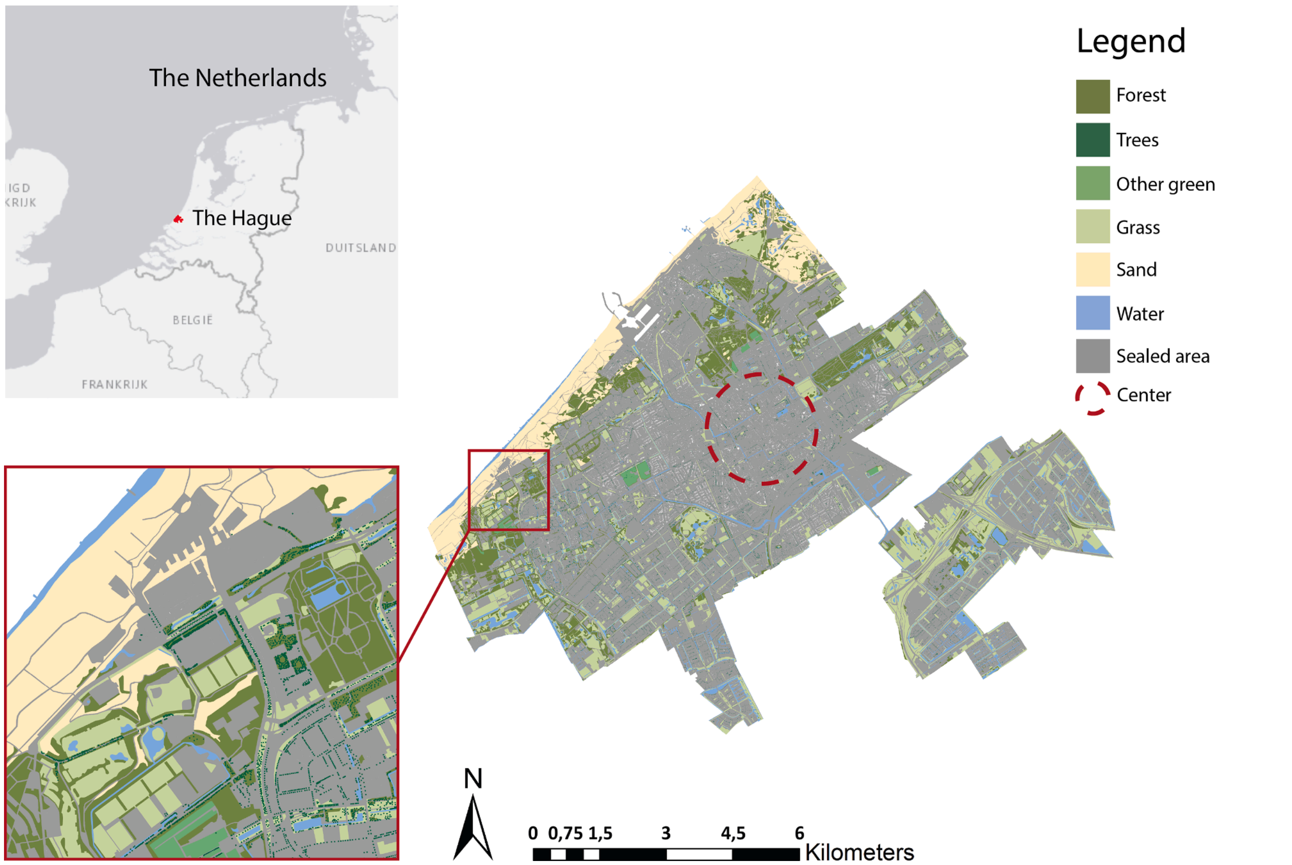

Fig. 1. Map of The Hague, the Netherlands with distinguished land cover types. The inset zooms into these high resolution land cover data used as input for analyzing GI (Kadaster, 2017; Den Haag Dataplatform, 2018).

2018). Finally, the Hague has insufficient stormwater retention capacity, leading to frequent flooding of streets, gardens, and houses (Municipality The Hague, 2012). Projections for the Netherlands show that in the coming decades extreme rain events will increase by 25% to 108% (Lenderink et al., 2011). Resilience to bounce back from the aforementioned issues can be fostered through strategic planning of green infrastructure.

In light of the aforementioned problems in The Hague, regular contact was held between the authors and the municipality. Between October 2018 and May 2019, monthly meetings with the chief resilience officer of the municipality and relevant staff members were organized to update them on the research, to sharpen research questions and methods, as well as to continuously verify the application of our research.

2.2. Green infrastructure inventory

The focus of this paper was on green spaces (land), thereby excluding blue spaces (water) from the ES analysis. We assessed GI types using land cover data of TOP10NL, a digital topographic map issued by the Dutch land registry and mapping agency, as the primary database and enriched the database with data of individual trees (Kadaster, 2017; Den Haag Dataplatform, 2018). We classified the data, which were available as polygon or data points, as forest, individual trees, grasslands, other GI, sand, water and sealed area (see Appendix B for details on data handling). All trees, both individual and in forests, were assumed to be broadleaved, as the data showed that the share of broadleaved trees was over 95%. Grasslands included herbaceous plants and shrubs. Other GI included graveyards, fruit farms, sport fields and moorland. Sealed surfaces included amongst others buildings, roads, and railways (Fig. 1).

2.3. Spatial assessment of air pollution, the urban heat island effect and stormwater runoff

We mapped the air pollutant concentrations, the temperature and the stormwater runoff per land cover type cell. The results were then aggregated to a neighborhood resolution, as stakeholders expressed a strong preference for this resolution to present the results.

For air pollution, we focused on particulate matter with a diameter smaller than 10 μm (PM_{10}). Annual mean PM_{10} concentrations (in μg/m^3) were obtained at a 25 m resolution (RIVM, 2017). The map gives data for the year 2017, which was the most recent dataset at the time of conducting the analysis.

We assessed the urban heat island (UHI) effect based upon land surface temperatures (c.f. Meerow & Newell, 2017; van der Hoeven & Wandl, 2018). Temperatures were derived from remote sensing data of Landsat 8 (USGS, 2019) on a 30 m resolution at daytime on a summer day (July 28th 2018) with low cloud cover (<10%). Although land surface temperature (LST) is not directly representative for air temperature, it presents highly detailed, empirical evidence of spatial temperature differences. The extent of the urban heat island effect was obtained by subtracting the temperature of rural surroundings from the temperature of each of the land cover type units.

Stormwater runoff was modelled for an extreme rain event of 100 mm in 2 hours, which is representative of a relatively rare rain event, occurring less than once in 10 years (KNMI, n.d.). We used the SCS runoff curve method developed in the USDA TR-55 (USDA, 1986) to estimate the stormwater runoff for a specified rain event while taking into account the soil type and soil cover and the fact that the storage capacity changes over the course of a rain event. Relevant soil characteristics (hydrologic soil group) were retrieved from NASA (2017). The following equations (1 and 2) were applied:

$$R = P - \frac{(P - 0.2*S)^2}{(P + 0.8*S)} \tag{1}$$

$$S = \frac{1000}{CN} - 10 \tag{2}$$

in which R stands for the maximum retention in inches, which for the purpose of our study was converted into mm. The curve number (CN) presents the maximum storage capacity based upon the hydrologic soil group (HSG) and the land cover type. S is the maximum retention after rainfall begins and P is the rainfall in inches. Details on the assumptions made for the CN can be found in Appendix C.

2.4. Mitigation of PM_{10} concentrations, the urban heat island effect, and stormwater runoff by green infrastructure

We assessed how each urban problem was mitigated by GI through the provision of ES. To this end, we quantified the capacity of the different GI types to provide these services and spatially assessed the relationship between GI and the PM_{10} concentration, temperature and stormwater runoff.

For each ES, we based our spatial modelling indicators on three criteria: (1) validity and quantifiability, (2) relevance for decision makers and (3) spatial explicitness, the latter also in light of the practical feasibility to assess and monitor these indicators. These criteria were based on reviews by van Oudenhoven et al. (2018) and Heink et al. (2016), which focused on ensuring that information of ES assessments optimally informs decision makers.

2.4.1. PM_{10} removal

We assessed PM_{10} removal capacity of GI with the pollution flux method (Nowak, 1994). The dry vertical deposition velocity V_d of the pollutant, which is specific to vegetation types, was multiplied by the concentration of air pollutants C to obtain the quantity of removed particulate matter ($F = V_d * C$). V_d was set to a mean value of 0.0064 m/s, based upon a leaf area index (LAI) of 6 (Nowak, Crane, & Stevens, 2006) and then adjusted to the actual LAI (Bottalico et al., 2016). The LAI was derived on a 10-meter resolution from Sentinel-2 remote sensing data, on an in-leaf season day (July 5th 2018) with low cloud cover (<10%), and adjusted to LAI using the Sen2Cor processor in the SNAP software (ESA, 2019). We assumed a resuspension rate of 0.5 (Tallis et al., 2011; Zinke, 1967). The value was multiplied by the number of days of the in-leaf season and the number of seconds per day (3600). This led to the following equation (3):

$$F\left(\frac{\frac{g}{m^2}}{year}\right) = V_d*C*LAI*0.5*\frac{365}{2}*3600 \tag{3}$$

This equation does, however, not indicate to what extent GI actually reduces atmospheric air pollutant concentrations. To do so, we assessed the relationship between the LAI (as independent variable) and the PM_{10} concentration (as dependent variable) using Ordinary Least Squares (OLS) regression. We adopted both the pollution flux method and OLS analysis, in order to gain a better understanding of the relationship between air pollutant deposition due to LAI and air pollution concentration reduction by GI.

2.4.2. Reduction of the urban heat island

To determine the relative cooling capacity of different GI types, the mean land surface temperature was calculated for each land cover type. These temperatures were then compared to those of rural surroundings to examine the extent of the UHI in The Hague for different land cover types.

Because of the locally specific cooling capacity of GI (Klemm et al., 2015), the capacity of GI to reduce the UHI effect was calculated on the basis of differences between the local mean GI temperature, the local mean temperature of sealed surfaces and the temperature measured in rural surroundings as follows (4, 5 and 6):

$$\text{For } T_{sealed} > T_{GI}: \ \% \text{ reduction of } UHI = \left(1 - \frac{(T_{GI} - T_{rural\ surroundings})}{(T_{sealed\ area} - T_{rural\ surroundings})}\right)*100 \tag{4}$$

$$\text{For } T_{sealed} \leq T_{GI}: \ \% \text{ reduction of } UHI = 0 \tag{5}$$

$$\text{For } T_{GI} \leq T_{rural\ surroundings}: \ \% \text{ reduction of } UHI = 100 \tag{6}$$

where T_{sealed} is the temperature of built area (e.g. roads and buildings), T_{GI} is the temperature of green infrastructure, and $T_{rural\ surroundings}$ is the temperature of GI in rural surroundings of The Hague.

2.4.3. Stormwater retention

The maximum stormwater retention by GI was calculated by combining the interception of a given land cover type and the infiltration in the soil, which was specific for the hydrologic soil group. The SCS runoff curve method was again applied to estimate the capacity of GI to retain stormwater during an extreme rain event. The maximum water retention by GI was calculated by subtracting the runoff from the precipitation. We determined the extent to which GI can avoid stormwater runoff by calculating the mean stormwater storage values per land cover type and soil type for a rain event of 100 mm in 2 hours.

2.5. Hotspots for multifunctional GI

In order to maximize the multifunctionality of GI in reducing the three urban problems, we determined whether their spatial distribution was synergetic, or if trade-offs would have to be accounted for when implementing green infrastructure interventions. Similar to the approach used by Meerow & Newell (2017), we assessed these contrasts for each neighborhood (N = 114) by analyzing the relationship between the air pollutant concentrations, temperature and stormwater runoff, using Pearson's bivariate correlation analysis.

We then identified hotspots for GI development, using a novel ES capacity-based weighting scheme applied per neighborhood. For this purpose, we considered each problem (air pollution, urban heat island, and stormwater runoff) as a separate criterion and normalized each problem from 0 to 1. We then assigned weights to each problem based upon the capacity of GI to mitigate one problem as compared to the other problems considered, per neighborhood, using the following equation (7):

$$W_{criterion\ i} = \frac{R_{criterion\ i}}{(R_{criterion\ 1} + R_{criterion\ 2} + R_{criterion\ 3})} \tag{7}$$

in which W is the weight of the criterion, ranging between 0 and 1. R is the reduction (%) of the problem by GI in the neighborhood, calculated as the ratio between the ES capacity, as specified in Section 2.4, and the extent of the problem. To consistently assess all three ES capacities, the UHI reduction capacity was corrected for the surface area of GI (see Appendix D for details). The weight for each problem was then multiplied with the corresponding criterion and the total of all the weighted problems was summed to obtain the final priority index (8):

$$\text{Priority index} = W_{criterion\ 1}*\text{Criterion } 1 + W_{criterion\ 2}*\text{Criterion } 2 + W_{criterion\ 3}*\text{Criterion } 3 \tag{8}$$

Finally, we compared the hotspot map, in which the weighting scheme above was applied, to a hotspot map in which equal weights were applied, thereby assuming that GI can reduce each of the three problems equally. For the equal weighting scheme, we applied the following formula (9):

$$\text{Priority index} = \frac{1}{3}*\text{Criterion } 1 + \frac{1}{3}*\text{Criterion } 2 + \frac{1}{3}*\text{Criterion } 3 \tag{9}$$

2.6. Scale considerations for urban planning

We investigated if the model could be used on a relevant smaller scale (i.e. neighborhood), as most policy interests and urban greening initiatives target this scale. This case study served to illustrate the model's application for analyzing urban planning decisions, and involved modifying the extent of GI in a high priority neighborhood in The Hague. The different GI scenarios were based on the program of the Dutch nature and environmental federations (in collaboration with the organization 'Duurzaam Den Haag' ('Sustainable The Hague')), who provided funding for expanding the number of trees in the Netherlands with 3% in the coming years (De Natuur en Milieu Federaties, 2019). Assuming the trees will be distributed evenly over the Dutch municipalities and neighborhoods, this would result in an expansion of around 200 trees per neighborhood. For our calculation we used 100 and 500 trees per neighborhood to illustrate a relatively modest and high scenario, respectively. Additionally, we compared the situation for a 100% tree covered surface with a sealed surface, representing the most extreme scenarios. The scenarios were applied to Schilderswijk-Noord, a neighborhood that was identified in our analysis as a hotspot for GI development (>0.9 for both weighting schemes, see Section 3.3). We assessed how increased tree cover would affect the air quality, temperature and stormwater retention capacity in the neighborhood.

Firstly, we determined the current percentage of trees in the neighborhood. We then calculated the new percentage of tree covered surface assuming a surface area of 28 square meter canopy per tree (Pretzsch et al., 2015). Furthermore, an LAI of 3 was assumed, based upon prior assessment of the LAI of tree-covered surfaces in The Hague. By combining these values with the ES capacities, we calculated the prospective mean PM_{10} concentration, LST and stormwater retention capacity in the neighborhood for two scenarios.

3. Results

3.1. Spatial assessment of air pollution, the urban heat island effect and storm water runoff

The PM_{10} concentration, land surface temperature and stormwater runoff are relatively high in neighborhoods located in or around the city center (Fig. 2). Although exceptions apply, we find that with increasing distance from the center the problems generally decrease. The PM_{10} concentrations vary between 21.2 μg/m^3 in the center (Schildersbuurt West) and 17.5 μg/m^3 near the municipality border (Ockenburgh). These values approach or even exceed the air quality guideline for PM_{10} of the WHO (2018), which is 20 μg/m^3. The highest LST is not in the urban center, but in Kerketuinen & Zichtenburg (Fig. 2), consisting mainly of an entirely built-up business park, with a mean of 32.7 °C. The lowest mean temperature is 27.2 °C in a neighborhood adjacent to the municipality border (Marlot, Fig. 2). All neighborhoods show a substantial amount of runoff in response to a 100 mm rain event, ranging from 42 mm (Tedingerbuurt) and 88 mm in the urban center (Laakhaven Oost, Fig. 2).

The extents of air pollution, urban heat island effect, and stormwater runoff are largely synergetic (Pearson's correlation of 0.71, 0.78 and

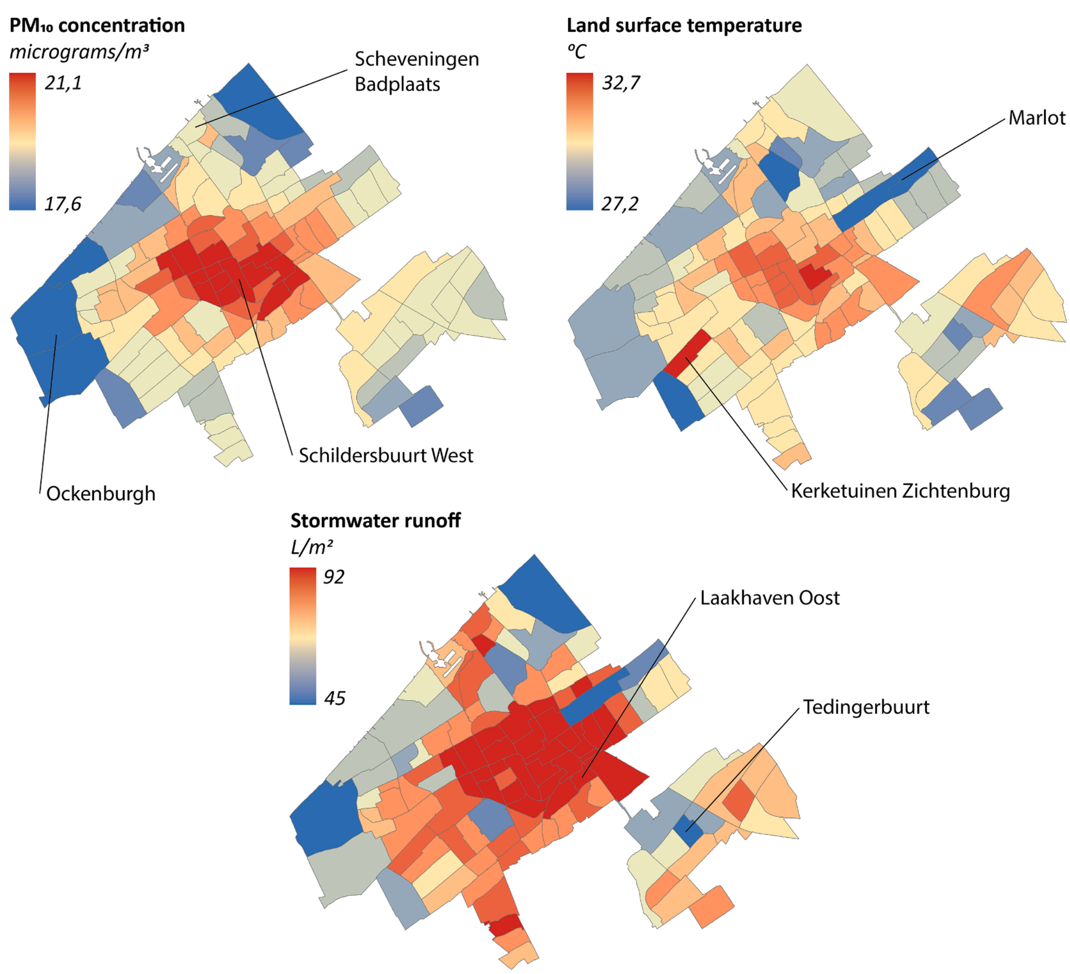

Fig. 2. Maps of the assessed urban problems, averaged per neighborhood: PM_{10} concentration (upper left), land surface temperature (upper right) and stormwater runoff (bottom).

0.63 respectively, and $p < 0.0001$). However, we also identified a number of conflict areas, with respect to the prioritization of targeting individual problems over others. For instance, the neighborhood Scheveningen Badplaats shows a low priority for PM_{10} removal (0.45) but a high priority for stormwater retention (0.87). The neighborhood Kerketuinen & Zichtenburg shows a high priority for cooling (1.00) but a low priority for PM_{10} removal (0.42). These trade-offs may partly be explained by differences in GI availability and GI characteristics, but also by other factors, such as emissions from traffic, the proximity to the coast, and soil characteristics.

3.2. Mitigation of urban problems by green infrastructure

The capacity of ES to mitigate urban problems varied by GI type (for local cooling and stormwater retention capacity) and by LAI in a given GI type (related to the PM_{10} removal capacity).

3.2.1. PM_{10} removal

The amount of PM_{10} captured is linearly and positively related to the LAI. For an LAI of 2, which represents the mean value for tree-covered surfaces in the area, and a PM_{10} concentration of 18 μg/m^3, approximately 0.08 g/m^2 per year is removed. However, according to our OLS regression analysis, the actual reduction in PM_{10} concentration becomes less pronounced with an increasing LAI, described in the equation (10) below.

$$\%\ reduction\ PM_{10}\ concentration = \frac{1.146*LAI}{20.57} \tag{10}$$

For GI with an LAI of 2, the air pollutant concentration is approximately 11% lower compared to a non-vegetated surface (Fig. 3). The LAI and PM_{10} concentration show a moderate negative correlation ($R^2 = 0.3199$ and $p < 0.0001$).

3.2.2. Reduction of the urban heat island

Although the land surface temperatures corresponding to different land cover types are not statistically different from each other, general trends suggest lower temperatures of all GI types as compared to sealed areas (Fig. 4). We compared the results with the temperature of the coolest rural area in the vicinity of The Hague, which was 23.0 °C on July 28th 2018. This value is exceeded by the mean temperatures for all the land cover types in The Hague. Tree covered surfaces show the lowest mean temperature (27.9 °C) compared to other land cover types, followed by 'other GI' (28.3 °C), grassland (29.2 °C), sand (29.3 °C), and sealed surfaces (30.6 °C). The results suggest that, on average, trees reduce the urban heat island effect by approximately 35% compared to sealed areas, while 'other GI' does so by 29% and grasslands by 16%.

3.2.3. Stormwater retention

The capacity of GI in The Hague to retain stormwater varies between 61 and 87 mm for a rain event of 100 mm, depending on the type of GI and the hydrologic soil group (Fig. 5). Sealed surfaces can hardly retain any stormwater (6 mm), while sand (or bare soil) still shows a substantial storage capacity (39–55 mm).

3.3. Hotspots for multifunctional GI

The priority scores for the two weighting schemes, i.e. equal weights and weights based upon ES capacity, based on the three normalized problem criteria are presented in Fig. 6a and Fig. 6b, respectively. Differences between the identified priority areas for GI development are indicated in Fig. 6c. The mapped differences illustrate how priority scores can change substantially when applying a non-equal weighting scheme. Because the neighborhoods in the center have a high priority score for each problem, their overall priority scores show only few changes. In contrast, neighborhoods adjacent to the outer municipal border show the largest differences, the largest being 0.24 out of 1 for the neighborhood De Bras (Fig. 6). For this neighborhood, normalized problem values for PM_{10} removal, UHI reduction and stormwater retention were 0.14, 0.10 and 0.73 out of 1, respectively. The weights based upon the ES capacity for the three criteria were 0.17, 0.10 and 0.73 respectively, resulting in a higher priority score compared to equal weights.

Similarly, the priority score for the neighborhood Oostduinen decreased with 0.14 when applying the non-equal weighting scheme. This neighborhood has a relatively high problem score for UHI reduction (0.42) compared to PM_{10} removal and stormwater retention (0.08 and 0.03 respectively). However, the ES-based weight for UHI reduction was only 0.01, compared to 0.11 and 0.88 for PM_{10} removal and stormwater retention, respectively.

3.4. Case study: Scale considerations for urban planning

According to our analysis, neither the low (100 trees) nor the high scenario (500 trees) resulted in notable differences in air quality, temperature and amount of stormwater runoff in the neighborhood Schilderswijk-Noord, as compared to the current situation (Table 1). The addition of 500 trees decreased the mean PM_{10} concentration of the neighborhood with 0.4%, the land surface temperature with 0.3% and

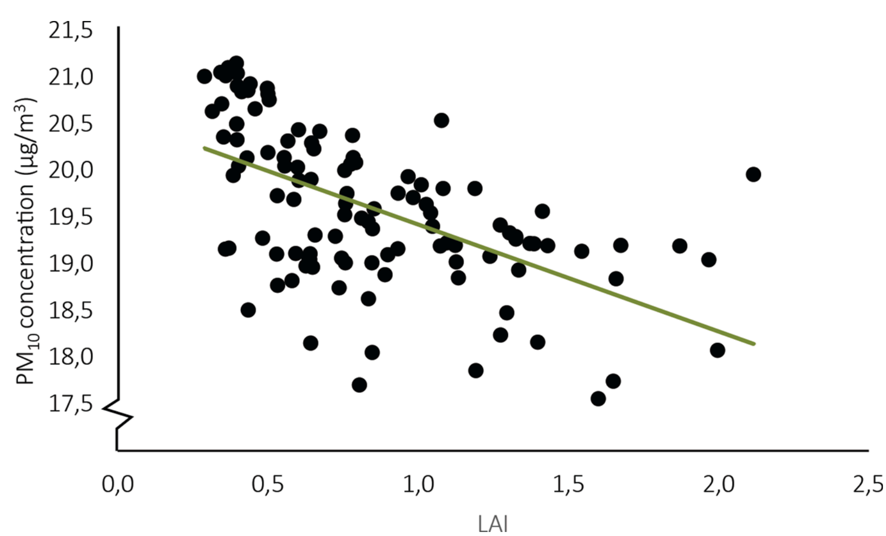

Fig. 3. Relationship between the PM_{10} concentration and Leaf Area Index (LAI).

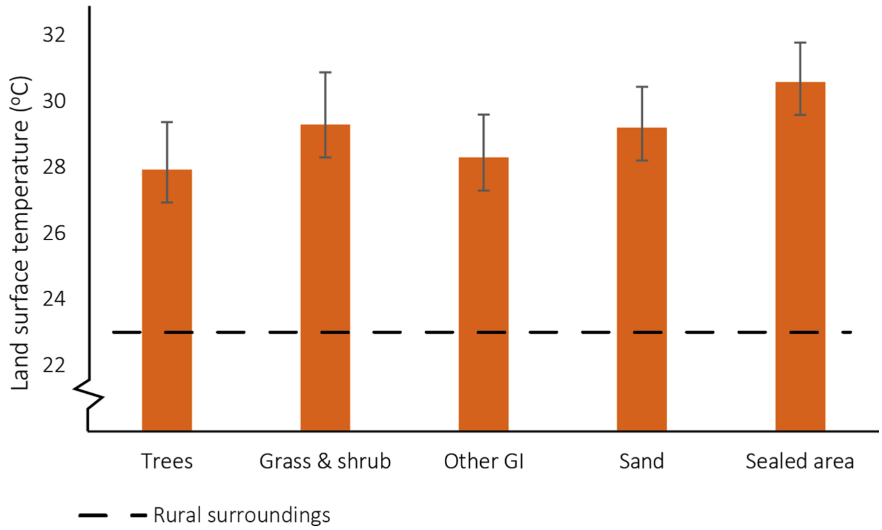

Fig. 4. Average land surface temperature (LST) for different land cover types in The Hague compared to the temperature of rural surrounding area.

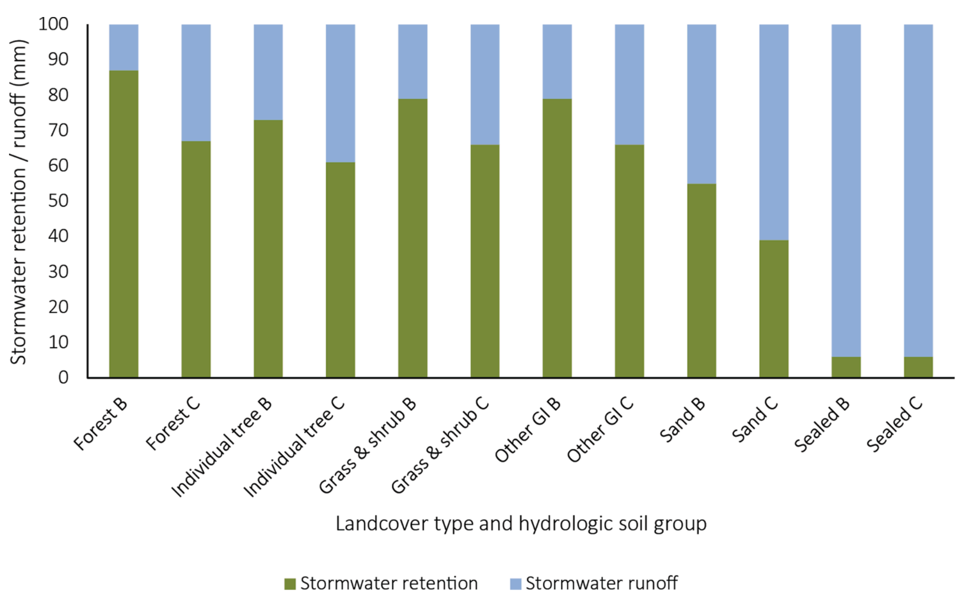

Fig. 5. Stormwater retention and stormwater runoff for different landcover types and soil types for a rain event of 100 mm.

the stormwater runoff with 2.2% (assuming HSG B). However, when we compare a 100% tree-covered surface with a 100% sealed surface, a substantial reduction in the PM_{10} concentration of 17%, a reduction in the land surface temperature of 9% and an increase in the stormwater retention capacity to 86% is attained.

4. Discussion

In this study, we developed and applied a spatially explicit ES model to inform decision makers and urban planners on priority areas for GI development, based on the weighted capacity of GI to provide urban ES in high spatial and thematic detail. Because this tool relates to and weighs the capacity to mitigate relevant societal challenges in cities, it can be seen as informing on an important aspect of urban Nature-Based Solutions.

We assessed the ES based upon GI characteristics as well as PM_{10} concentration, land surface temperature, soil type and rain intensity. The modelled ES capacities of GI are subject to uncertainties, mostly relating to data availability and spatial resolution. Spatial data of the PM_{10} concentrations, LAI and land surface temperature was available or computed to a higher resolution than available before, yet it did not allow for a detailed city-wide analysis of different GI types. Because the GI data were available at a higher resolution than other data, there was a discrepancy between the ES capacity and GI characteristics, among others. In the case study, this resulted in uncertainty in the LAI value associated to single trees, while the calculations assumed a homogeneous canopy. Despite these uncertainties, the case-study results were sufficiently accurate to draw conclusions on the models' suitability for evaluating GI planning decisions, which will be discussed later.

In addition to challenges related to data availability and resolution, it remained challenging for the ES model to account for other important local factors affecting urban ES capacity, such as the configuration and elevation of buildings. This is particularly relevant for the cooling capacity and PM_{10} removal capacity of GI, and explains the high variation in these results. However, spatial ES models with a higher level of detail were either unavailable or did not meet our indicator criteria related to spatial explicitness and stakeholder relevance. The modelled ES capacities for the distinguished GI types generally compare to those available in scientific literature (c.f. Derkzen et al., 2015; Farrugia et al., 2013; Kremer, Hamstead, & McPhearson, 2016; Mitz et al., 2021).

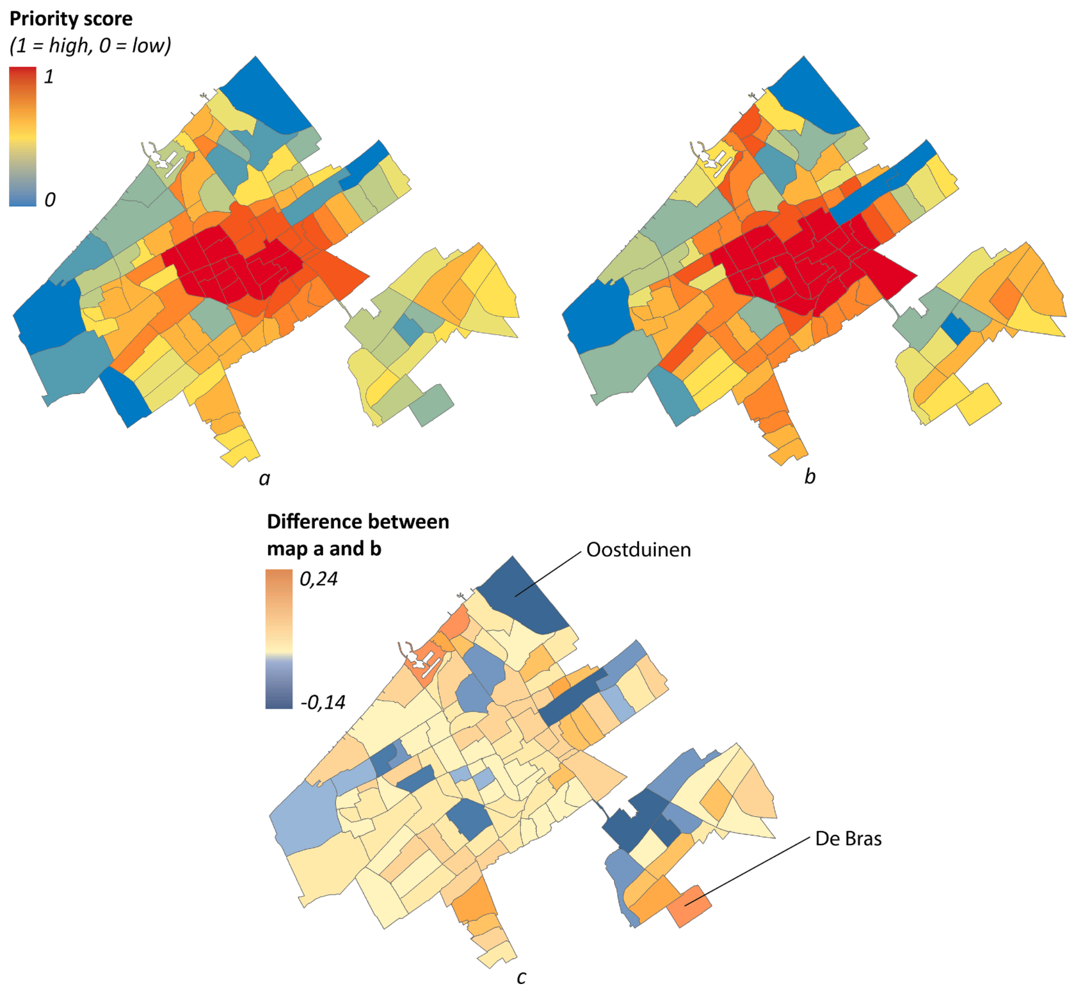

Fig. 6. Priorities for GI development based upon equal weights (a) and weights based upon the problem reduction capacity of GI (b). Fig. 6c shows the differences between map a and b.

Table 1
Projections of siting 100 to 500 trees in a neighborhood that was identified as a hotspot for GI development, and comparisons with a 100% tree covered surface and a 100% sealed surface for multiple criteria associated with urban problems. Dark grey indicates a minor effect (<1% improvement), lighter grey a small effect (1–10% improvement) and the lightest grey a substantial effect (>10% improvement).

	Current situation	Low scenario (+100 trees)	High scenario (+500 trees)	100% tree cover	100% sealed surface
Tree (%)	5.8	6.3	8.4	100	0
LAI	0.4	0.4	0.5	3.0	0
PM_{10} (μg/m^3)	20.1	20.1	20.0	17.1	20.6
LST (°C)	32.2	32.2	32.1	27.9	30.6
Stormwater runoff (mm)	91	91	89	13	94

Future iterations of the model could be expanded to further specify ES supply rates, for instance by including elevation, drainage systems and more soil types to calculate stormwater runoff. In addition, more detailed spatial data on GI characteristics, air temperature and air-pollutant concentrations could be obtained, for instance through local measurements. However, in the current iteration of the model, the relation between GI and ES provision was key, as illustrated by words of one decision maker d.d. 21 February 2019: "We want to know for sure what happens when we plant × number of trees in that street, and if we change the landscaping of that park. How much water will we then capture, how much cleaner will the air get, per tree?". Reality is of course much more complicated, and the following discussion will therefore mostly focus on challenges of assessing the relationship between GI and ES, while remaining relevant to decision makers.

The model was primarily developed to identify hotspots for GI planning, rather than to evaluate the effect of specific GI planning measures. Our analysis identified both synergies and tradeoffs for ES, highlighting the importance of considering multiple ES simultaneously in GI planning (Cortinovis & Geneletti, 2018; Hansen et al., 2019). This is illustrated by our finding that 18 neighborhoods showed>30% difference between PM_{10} reduction capacity and stormwater retention capacity of GI. Similar, albeit smaller, differences were also found between cooling capacity and stormwater retention capacity, and between cooling capacity and PM_{10} removal capacity.

Besides differences in GI availability per neighborhood, trade-offs could also be explained by differences in GI characteristics, such as the type of GI (e.g. comparing grassland parks to tree rows and gardens), soil type or the leaf area density. Problem-related factors, such as differences in traffic emissions (PM_{10} concentration) or proximity to the coast or rural areas (temperature) further explain trade-offs. This underlines the importance of specifying the type of GI in analysis, planning and communication, as well as considering multiple indicators from the ES and problem side for a better grasp of location-specific problems and solutions. Most of all, however, the occurrence of ES hotspots and trade-offs indicates the importance of applying weights to ES criteria, in order to support optimal GI planning (Kremer, Hamstead, & McPhearson, 2016; Meerow, 2019).

We introduced a new weighting scheme for the identification of GI hotspots, based upon the local capacity of GI to mitigate urban sustainability and resilience problems, i.e. the provision of ES. Because ES provision is specific to GI characteristics and location, the weighting scheme introduces important information prior to further spatial modeling. Employing the weighting scheme and multiple indicators contributes to eliminating the a priori assumption that all GI contributes equally to the provision of all urban ES.

We note the following to consider when implementing the weighting scheme in urban planning. First, consistent inclusion of the GI surface area per neighborhood is crucial in the ES calculation (Gupta et al., 2012). Potential equity issues caused by unfair prioritization of certain ES, are thereby avoided (Jennings, Larson & Yun, 2016). Second, because cities are highly diverse in their physical structure, determining locally specific weights is key (Haase et al., 2014). We accomplished this by identifying weights on a neighborhood level. While this presented a higher level of detail than previous studies, the spatial resolution may still be optimized to make a more precise estimate of the ES capacity of future GI.

The weighting method can be combined or further enhanced with stakeholder-derived weights, in which the perceived importance by stakeholders of multiple ES is considered (Mao et al., 2020). Assuming an equally weighted importance of the considered ES by stakeholders, we found that the application of weights based upon the local problem mitigation capacity changed the priority map for GI development (with a maximum increase in priority found of 0.24 out of 1). We argue that it is important to consider the weighing because, although GI can provide multiple benefits, the local supply of one ES can be preferred over another when GI at that location has a higher ES capacity. For example, the capacity of GI to lower air pollutant concentrations is often found to be limited at local scales (c.f. Parsa et al., 2019) indicating that other measures (e.g. reduced traffic rates) might be more effective in reducing air pollution. The contribution of GI might be substantially larger for other ES, e.g. tree canopy can significantly contribute to local cooling (Klemm et al., 2015). Similarly, our results showed that the capacity of GI to lower air pollution levels was typically low compared to the capacity of GI to retain stormwater. By linking supply of ES to its local demands (by weighting), our approach enables planners and decision makers to make choices in local GI investments to increase resilience to urban problems.

Our modelling results show the relevance of assessing urban ES per land cover unit at high spatial resolution. This helps to account for the complexity of urban structures and the diversity of urban GI types and characteristics. We also show the need to aggregate the results to a spatial scale that is relevant to stakeholders. The advantage of such a multi-scale perspective is that the high-resolution data can be used to assess complex urban GI structures and to evaluate its benefits, while the aggregation of the results to administrative borders can be used to match the management and decision-making scale of urban landscapes (Larondelle & Lauf, 2016). The growing availability of open source data, e.g. via governmental institutions and remote sensing platforms, increasingly enables such high-resolution analysis, although there still is a need for a wide range of empirical, high resolution data sources (e.g. air pollutant concentrations and air temperature). We note, however, that the spatial data considered for this study differed considerably from that of the municipality. Especially the municipality's information on the types and amount of GI in The Hague was quite incomplete compared to our data, and environmental data was of lower resolution and specificity too. This is partly explained by the fact that not all GI is situated within the jurisdiction of the municipality (Personal communication, March 18, 2019). With this study we increased the availability and diversity of detailed spatial data and assessment methods for urban ES, which was also made available to the municipality of The Hague.

To further explore the multi-scale approach with our model, we conducted a smaller scale urban planning case study, mirroring the decision-making scope of the municipal council and tree-planting initiatives. We evaluated the addition of 100 and 500 trees in a high priority neighborhood. The results of our hotspot analysis show that the neighborhood resolution enables the identification of priority areas for GI development. However, the case study also underlines the need to assess specific, local-scale GI benefits in more detail (c.f. by Cortinovis & Geneletti (2018) and Hansen et al. (2019)). This would require the data to be of similarly fine spatial resolution, and a more detailed assessment of the neighborhoods. The latter also relates to opportunities for GI development, which might be more challenging in closely built up areas, requiring the adoption of innovative solutions, e.g. vertical greening systems, green roofs and small GI patches.

This tool was designed to be used by urban decision makers and planners, who increasingly recognize the need to adapt to urban challenges, such as climate change and air pollution. NBS are widely recognized as a valuable concept and tool towards achieving sustainable development (Veerkamp et al., 2020). Our study on multifunctional GI signifies progress towards applying NBS to tackle urban challenges in The Hague. Land cover data, administrative borders and (empirical or modelled) spatial data on GI and ES were retrieved from public data registers and remote sensing platforms, which increases the transferability of our method for other cities. However, while we focused on environmental indicators for resilience and sustainability, GI can provide additional socio-economic benefits that are often associated with NBS. Especially cultural ES are often highly valued in the urban context (Gomez-Baggethun et al., 2013). We found that such cultural benefits, especially recreation, were dealt with in a different department of the municipality, which indicates that 'nature and biodiversity' were not directly coupled to such intangible benefits. Awareness is increasing, however, as we found that local decision makers were generally concerned about the repercussions of uneven GI distribution, as less affluent neighborhoods might be more vulnerable to problems such as the UHI. Our model is suitable for such analyses as it allows assessing the distribution of GI among the city on different spatial scales. Moreover, the flexibility of scale levels allows for the inclusion of indicators that may only be available on certain spatial scales, in particular social indicators such as those related to social vulnerability. Finally, following the NBS principles, biodiversity benefits should be considered as well (Cohen-Shacham et al., 2016). This aspect is often underrepresented in urban ES and NBS studies, and GI should be based on sound biodiversity analyses (Seddon et al., 2019). Combining aspects of biodiversity, social inequality and location-specific environmental challenges would enable a comprehensive evaluation of nature-based solutions that can be employed for local spatial planning.

5. Conclusion

GI is increasingly addressed in urban planning and research as an effective tool to enhance urban sustainability through the provisioning of multiple ES. Yet, few applications exist of planning models for multifunctional GI in high spatial and thematic detail that simultaneously align with stakeholder interest. In this study, we developed a spatially explicit model to support urban planning of multifunctional GI. We introduced a new weighting scheme for the identification of priority areas for GI development, based on the local capacity of GI to mitigate urban environmental problems, namely air pollution, urban heat island and stormwater runoff. We show that the weighting scheme can substantially change the priority score for GI development, especially for neighborhoods outside the urban center. Our model distinguishes between different GI structures and allows for aggregation into administrative borders, and can therefore be used by decision makers and urban planners at different scales. The coarser scale is particularly useful for identifying problem areas where the employment of NBS will be most effective, whereas the smaller scales allow assessing the local effect of specific GI planning measures. Our model can be extended to a wider range of ES, depending on the relevance for the study area, and can also be expanded to a broader study area or to other urban areas, as the model makes use of data that is largely open access or available by local governments. Also, the weighting scheme can incorporate stakeholder-derived weights, based on the perceived importance of various ES.

Our analysis identified both synergies and tradeoffs for ES, highlighting the importance of considering multiple ES simultaneously in GI models. The study presents a high-resolution spatially explicit model that is particularly useful for assessing urban ES, because of the heterogeneity of urban structures, environmental context and green infrastructure in particular, that results in an uneven distribution of ES supply and demand. Although biodiversity and socio-economic aspects should be considered in urban NBS design, our ES model signifies an important step towards evaluating GI measures in urban environments.

CRediT authorship contribution statement

Janneke van Oorschot: Conceptualization, Methodology, Software, Investigation, Writing - original draft. **Benjamin Sprecher:** Supervision, Conceptualization, Writing - review & editing. **Maarten van 't Zelfde:** Software, Resources, Visualization. **Peter M. van Bodegom:** Validation, Conceptualization, Writing - review & editing. **Alexander P.E. van Oudenhoven:** Supervision, Conceptualization, Methodology, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104195.

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