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Strategic green roof placement in Toronto to maximize benefits while incorporating citizen preferences

Matthew Jung [a], Sharlene L. Gomes [b], Roy P. Remme [a,c,*]

[a] Institute of Environmental Sciences CML, Leiden University, Leiden, the Netherlands
[b] IHE Delft Institute for Water Education, Delft, the Netherlands
[c] Natural Capital Project, Stanford University, Stanford, USA

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ABSTRACT

Green roofs provide a broad range of ecosystem services, including air quality regulation, temperature regulation, flood regulation, and habitat provision. Through strategic placement they can address multiple urban challenges. However, city governments often do not engage in strategic spatial and fail to consider citizen preferences. To address this, we developed an approach for strategic placement of green roofs, based on the four mentioned ecosystem services for Toronto, Canada. We designed an approach based on biophysical information, which we further enriched with data on citizen preferences for different ecosystem services. We used literature-derived criteria and spatial analysis to identify optimal green roof placement locations for each ecosystem service separately, and the four services combined. A citizen survey was conducted (n = 402) to rank ecosystem services based on preferences. Mean rankings were used for a citizen-weighted model for strategic green roof placements. Our approach identified key priority areas for Toronto, while also highlighting that a significant portion of the city's rooftops are sub-optimal for maximizing the benefits of all four ecosystem. However, by focusing on turning roofs in hotspot areas (0.2–1.2 % of total roof space) into green roofs, the four ecosystem services could be enhanced simultaneously. Results showed large spatial variations in priority areas between individual ecosystem services. However, comparing results across the biophysical and citizen weighted approach for all ecosystem services combined indicated similar priority areas, suggesting citizen support for prioritisation related to biophysical needs. Moreover, citizen involvement in governance practices can foster transparency, inclusivity, and satisfaction in strategic planning of green roofs. The methods employed in this study can be adapted to other cities worldwide, enabling more strategic, participatory approaches to implementing green roofs to enhance multiple ecosystem services where they are valued most.

1. Introduction

Green roofs (i.e., rooftop entirely or partially covered with vegetation and growth medium (Yu et al., 2017)) are valuable nature-based solutions that do not occupy additional space in an urban landscape, provide a broad range of ecosystem services (ES), and can support urban biodiversity (Francis and Jensen, 2017; Nguyen et al., 2022; Wang et al., 2022). Green roofs can provide provisioning ES (i.e., tangible goods and services from ecosystems), often in the form of food production (Whittinghill and Rowe, 2012), and cultural services (i.e., benefits people gain from interacting with nature), such as aesthetics (Kotzen, 2018), alongside regulating ES (i.e., ecosystem processes that provide benefits to people), biodiversity support through the creation of new habitat, and support ecological processes needed for these small-scale ecosystems to function.

We focus our research on regulating ES and biodiversity support, as these are key functions of green roofs (Besir and Cuce, 2018). Key regulating ES that green roofs provide are flood regulation, temperature regulation, and air quality regulation, alongside habitat provision for biodiversity. Green roofs are an effective measure for retaining stormwater, and can therefore play a role in mitigating flood risk (Mentens et al., 2006; Chen et al., 2015; Abualfaraj et al., 2018). Nature in cities, including green roofs, can help decrease temperatures, which can be excessive particularly in summer due to the urban heat island effect (Deilami et al., 2018; Koomen and Diogo, 2017; Ouldboukhitine et al., 2014). Vegetation on green roofs has the potential to regulate air quality

* Corresponding author at: Institute of Environmental Sciences CML, Leiden University, Leiden, the Netherlands.
E-mail address: r.p.remme@cml.leidenuniv.nl (R.P. Remme).

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by retaining pollutants, such as particulate matter (Nowak et al., 2006; Speak et al., 2012). Urban nature is critical for supporting a wide array of species (Beninde et al., 2015), and green roofs can serve as stepping stones that connect urban green spaces and remaining natural habitats (Francis and Lorimer, 2011; Vergnes et al., 2013; Haaland and van den Bosch, 2015).

Cities around the world have implemented policies and incentives to enhance the use of green roofs on buildings (Liberalesso et al., 2020; Savarani, 2019), for example through mandates (e.g., Basel (Switzerland), Portland (USA), Toronto (Canada)) or zoning incentives (e.g., Austin (USA), Philadelphia (USA)). However, none of the identified approaches include approaches that strategically identify priority areas for green roof placement. Motivations for the policies often relate to biodiversity support or climate adaptation (Savarani, 2019). However, the identified policies do not target particular areas of the cities, where the benefits may be highest. In other words, cities do not include strategic spatial planning into the development of their green roof policies and plans. As per Albrechts (2004), strategic spatial planning for green roofs implies that they are selectively spatially implemented, geared towards pressing issues, and considering some placements more important than others. To maximize the potential of green roofs to provide multiple ES, it matters where they are placed (Aleksejeva et al., 2022).

To date, limited research on urban green roof planning and strategic placement has been carried out, reducing green roof potential for effectively providing ES at scale or supporting biodiversity (Parker et al., 2020). For example, green roofs are known to be valuable components of biodiversity corridors, but can fail if they are installed on tall buildings that create vertical barriers for some species (MacIvor, 2016). Recently, literature related to strategic green roof placement has been growing, exploring the concept from various angles (Aleksejeva et al., 2022; Hoeben and Posch, 2021; Langemeyer et al., 2020; Slootweg et al., 2023; Venter et al., 2021). Considering the potential to enhance biodiversity, human wellbeing, air quality, and temperature regulation, Aleksejeva et al. (2022) identified problem areas in Tokyo and categorized buildings based on their potential to benefit these ES. In Detroit, Sanchez and Reames (2019) examined spatial and social parameters to address climate justice issues and equitable urban heat island mitigation. They concluded that green roofs were most present in affluent urban areas that did not experience the most extreme heat island effects. Langemeyer et al. (2020) took a holistic approach in Barcelona, considering expert stakeholder priorities to determine strategic green roof placements, highlighting the potential for considering various perspectives while planning nature-based solutions. Venter et al. (2021) used stakeholder interests and problem mapping to identify gaps in green roof implementation strategies in Oslo, exposing underutilized areas. Hoeben and Posch (2021) investigated green roof efficiency in different building development types in Graz, while Slootweg et al. (2023) explored potential locations for combined green roof and solar panel installations in Amsterdam, uncovering green roof synergies, minimizing trade-offs.

Existing strategic planning studies highlight possibilities for green roof placement from limited perspectives. Some studies focus on (bio) physical aspects, i.e., quantifying ES or human conditions and parameters such as temperature, runoff, or health metrics (DeNardo et al., 2005; Liu et al., 2021; Williams et al., 2019). Despite the variety of approaches to strategic green roof planning, there is a gap in the research, specifically a lack of consideration for citizen preferences. Very few studies include social aspects, such as people's preferences or demands (Langemeyer et al., 2020). The combination of, or comparison between, biophysical and stakeholder preference approaches is rarely made for green roofs. Studying both the biophysical optimal placement of green roofs for different ES and biodiversity, as well as understanding social preferences can help identify hotspots and priority areas of focus for investing in green roofs. This can help ensure that green roof planning projects in cities are designed to maximize their regulatory ES while also garnering public support. Research on green roofs highlights the importance of stakeholder engagement in the planning of green roofs (Venter et al., 2021).

The city of Toronto, Canada has recognized the potential benefits of green roofs. Toronto is anticipated to face numerous climate change-induced challenges, including increased rainfall intensity resulting in flooding (Rincón et al., 2022), increased frequency and duration of heat waves (Jandaghian and Akbari, 2021), poorer air quality (Whaley et al., 2015), and increased amount of invasive species from the South driving native species elsewhere (City of Toronto, 2019a). Therefore, the city has set ambitious climate goals, and implemented the 'Green Roof Bylaw' in 2009 to introduce green roofs to the city that can help address environmental challenges (City of Toronto, 2019b; Toronto Municipal Code Chapter 492, Green Roofs, 2017). The bylaw is the first of its kind in North America and requires green roofs for new developments over 2000 m^2 in gross floor area. The bylaw's goal is to help the city reach climate resilience goals, such as carbon neutrality by 2040, improved stormwater management, increased building energy efficiency, improved air quality, greater biodiversity, and urban heat island mitigation. However, an assessment for strategic placement is missing. Also, public awareness regarding the bylaw is limited, and no citizen consultation related to ES prioritization was performed (Lee, 2017). There is no connection between citizens perspectives and green roof decision-making in Toronto. Understanding how citizens value different regulating ES can help drive Toronto towards a future desired by its inhabitants. A consensus among cohorts, such as age groups, income ranges, or level of education can guide policymakers and urban planners in developing targeted strategies for green roof implementation that align with the preferences and needs of the diverse population.

Our core objective is to develop an approach that combines biophysical and citizen-based weighting that can be used for strategic planning of green roofs, using Toronto as a case study. We aim to analyze spatial prioritization of Toronto's roof space for green roof placement to maximize potential benefits from ES. We assess where additional biophysical supply of the three regulating ES and biodiversity support has highest potential to address multiple challenges, and how citizen preferences for regulating ES and biodiversity support affect spatial priorities for green roof placement. To achieve these objectives, we model the previously listed regulating ES: flood regulation, temperature regulation, and air quality regulation, as they provide key benefits to urban citizens (Gómez-Baggethun and Barton, 2013; Keeler et al., 2019). For biodiversity support, we model habitat provision, which can be classified as an ES (Haines-Young and Potschin, 2018). We conducted a survey among Toronto citizens to understand their preferences for the different ES, and weighted the model output based on these preferences. This study advances green roof research by providing an analysis of strategic placement for multiple ES, and provides a framework for identifying optimal locations for green roofs based on their potential to maximize benefits. A spatial analysis of this nature, let alone one that incorporates citizen demand has yet to be executed in an urban context, to the best of our knowledge.

2. Methods

2.1. Study area

Toronto is the largest city in Canada, with a population of over 2.8-million in 2021 (Statistics Canada, 2022). The downtown core consists of high-rise buildings greater than 100 m in height, with more mid-rise buildings found outwards of the downtown core, followed by residential neighbourhoods with single detached houses along its perimeter (Wang et al., 2015). The city is divided into 25 wards, each with a representative, which comprise the Toronto city council (Fig. 1). The city council is responsible for local governance in Toronto, and makes decisions regarding land use planning, licensing, and development applications.

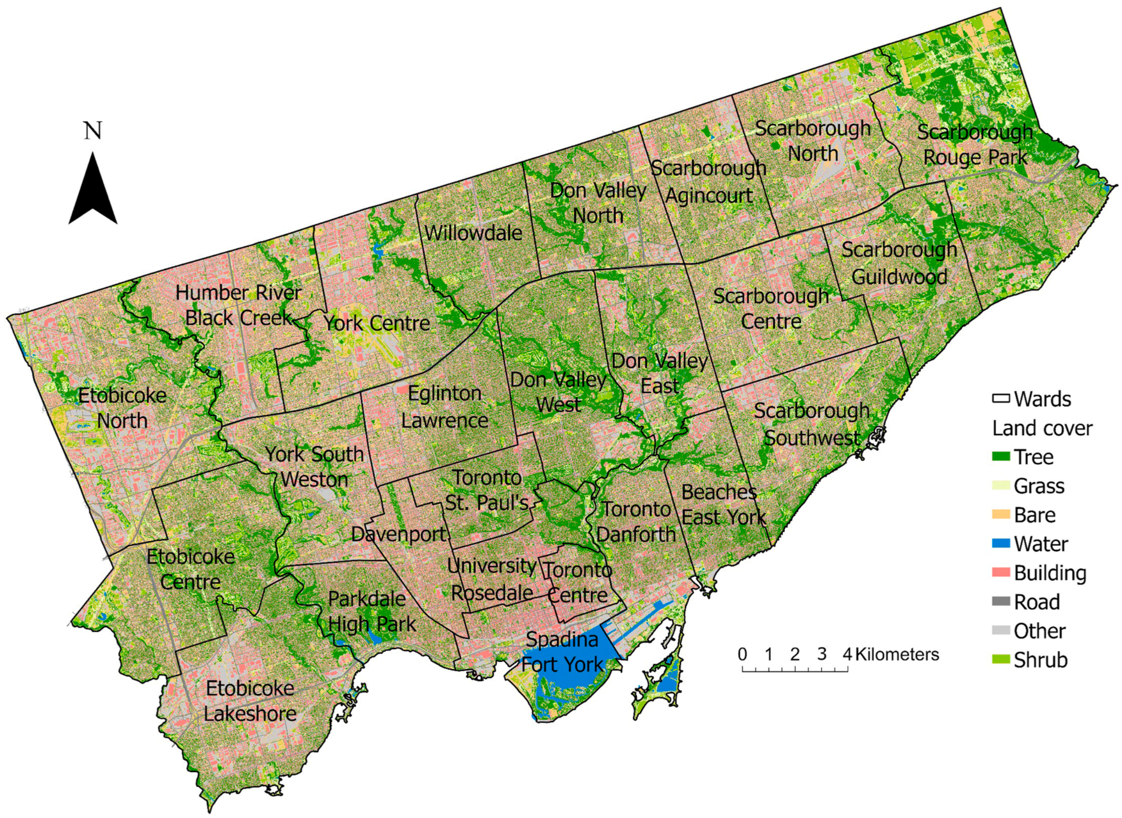

Fig. 1. The study area, Toronto (Canada), with the ward boundaries and general land cover pattern (City of Toronto, 2022, 2024b).

2.2. General approach

This study consists of three main components. First, spatial modelling for four ES provided by green roofs, namely flood regulation, temperature regulation, air quality regulation, and habitat provision (Section 2.3). Second, a city-wide survey to assess citizen's prioritization of these four ES (Section 2.4). Third, spatial analysis and comparison of strategic placement of green roofs based on the ES, through biophysical analysis and a weighted analysis based on citizen preferences, to assess overlaps and mismatches (Section 2.5). ArcGIS PRO (Version 2.9.5) (ESRI, 2022) and InVEST software (Integrated Valuation of Ecosystem Services and Tradeoffs, version 3.14.0) (Natural Capital Project, 2024) were used to develop, model, and analyze spatial output. Spatial data layers were acquired from the City of Toronto's official geodatabase and global datasets recommended for InVEST models (Table 1).

2.3. Biophysical priority mapping of ecosystem services

2.3.1. Flood regulation

To determine green roof priority areas for flood regulation, we applied an approach that identifies flood retention in urban areas, namely the Urban Flood Risk Mitigation model from the InVEST software (Natural Capital Project, 2024). The model is designed to map the role of natural infrastructure in mitigating stormwater flooding, and uses a combination of land use types (Fig. 1), soil hydrological groups, and the curve number approach. The soil hydrological groups describe the amount of expected runoff from saturated soils (Natural Capital Project, 2024). The curve number approach provides an empirical hydrological parameter to predict direct runoff or infiltration from excess rainfall (USDA, 1986). To assess flooding, we modelled an extreme precipitation event (100 mm) that can occur in Toronto (City of Toronto, 2024a). Values for curve numbers were based on van Oorschot et al. (2024). Appendix A provides a detailed overview of the model input variables and parameters. We used the runoff retention output from the model (10 × 10 m resolution), which calculates the proportion of runoff retained in a particular pixel (0–1, where 1 equals full retention). To identify priority areas for green roof placement for flood mitigation, the inverse of the runoff retention map was used (higher scores mean higher priority for green roof placement). The priority scores were averaged to a 100 × 100 m aggregated resolution, to account for the large local variability in land use types around the green roofs that directly affect local runoff retention.

Table 1
Spatial layer sources used to model optimal green roof placements in Toronto.

Data	Description	Source
Toronto ward boundary	Vector layer, boundaries for 25 city wards	(City of Toronto, 2024b)
Toronto landcover	Raster layer with 8 landcover types at 10 m resolution	(City of Toronto, 2022)
Industrial zones	Vector layer with urban zoning, including industry	(City of Toronto, 2024e)
Highways	Line layer with road centerlines, including highways	(City of Toronto, 2024d)
Urban green spaces	Vector layer with public urban green spaces	(City of Toronto, 2024c)
Building height	Vector layer with data on buildings, including average building height	(City of Toronto, 2023)
Soil Hydrological Groups	Global raster layer with four soil hydrological groups at 250 m resolution.	(Ross et al., 2018)
Reference evapotranspiration	Global raster layer with reference evapotranspiration at 30-arc seconds resolution	(CGIAR-CSI, 2019)

2.3.2. Temperature regulation

We used the InVEST Urban Cooling model to map the current heat mitigation potential of natural infrastructure in Toronto (Natural Capital Project, 2024). The model calculates a heat mitigation index based on shade, evapotranspiration, and albedo, as well as land cover type and distance from cooling areas (i.e., vegetated areas larger than 2 ha). The model takes air blending (set at 500 m distance per Natural Capital Project, 2024) and a maximum cooling distance of vegetation (set at 450 m distance per Natural Capital Project, 2024) into account. We applied average high temperatures of July (27 °C) and a maximum urban heat island effect of 2 °C (Chakraborty and Lee, 2019). The heat mitigation index provides an estimate of temperature reduction of an area (0–1, with higher values indicating higher heat mitigation). Parameterisation of the look-up table required from the model was based on van Oorschot et al. (2024). For details on model parameters and variables, see Appendix A. To assess priority areas for green roofs to mitigate heat we inverted the heat mitigation index (0–1, higher values indicate higher priority to add green roofs to mitigate heat).

2.3.3. Air quality regulation

To model priority areas for air quality regulation, we assessed areas in close proximity to key sources of pollution. To optimally regulate air quality at the source, we identified roofs within a 200 m buffer from major roads (e.g. highways) and from industrial zones where green roofs could be placed (Baik et al., 2012; Evans et al., 2019; Patton et al., 2017; Puett et al., 2014). Beyond approximately 200 m, pollutants become much more dispersed and retaining them becomes less critical. To identify source areas of pollution, layers showing industrial zones (City of Toronto, 2024e) and highways (City of Toronto, 2024d) were used. A 200 m buffer around these two features was generated within which a priority score of 1 was given (high priority). Based on Euclidean distance, the priority score was linearly reduced between 200 and 1000 m around industrial zones and highways. Beyond 1000 m a priority score of 0 was given (lowest priority).

2.3.4. Habitat provisioning

We modelled priority areas for habitat provisioning of green roofs based on criteria from relevant literature. Green roofs can potentially serve as stepping stones for biodiversity. For distance we based our criteria on studies by Aleksejeva et al. (2022), Wang et al. (2017) and Wang et al. (2022), widely covering a broad set of taxa, ranging from plants to insects and birds. These studies suggest that green roof placement within 50–100 m of existing urban green spaces can support species dispersal. Rooftops less than 50 m above ground level were considered, to limit vertical barriers for many species. Moreover, placement of green roofs in locations that have relatively little green space in situ should be prioritized.

To model habitat provision, three steps were taken. First, Euclidean distance from larger green spaces (e.g., parks and forests) was determined (City of Toronto, 2024c). For this model layer, roofs within 50 m of green spaces were given highest priority (score 1), roof between 50 and 100 m distance were given a score of 0.8, between 100 and 200 m, a distance score of 0.6, between 200 and 500 m, a distance score of 0.4, and beyond 500 m distance, a score of 0.2. Second, based on vegetation in the land cover map (City of Toronto, 2022) the fraction of smaller scale vegetation (grass, shrubs, trees) was mapped at 100 × 100 m resolution. The greenness map was inverted to create a priority map for added vegetation (0–1, high values indicate high priority for additional vegetation). The distance-based scores and inverted greenness scores were averaged per cell to create a priority score. Finally, within the priority map, scores of buildings with an average height of over 50 m (City of Toronto, 2023) were set to 0.

2.4. Survey

To assess citizen preferences for ES provided by green roofs, a city-wide survey was conducted. The survey was designed using Qualtrics software (Version 05.2023) (Qualtrics, 2005). The digital survey was open between 15/03/2023 and 14/05/2023 and was distributed through various mechanisms. A survey link was shared via social media (LinkedIn, Twitter, Instagram, Facebook), both through the first author's network and through public groups. In addition, respondents were recruited in public spaces of Toronto (sidewalks, parks, bus stops, shopping areas), by handing out and posting flyers with a QR code.

The main goal of the survey was to understand how inhabitants of Toronto valued different ES that green roofs offer, specifically flood regulation, temperature regulation, air quality regulation, and habitat provision, by asking participants to rank these ES in order of importance. Each ES was described in the survey to eliminate misunderstanding. The ranking data was used for further analysis in this study. Additional questions relating to socio-demographic data were collected to test differences between ES ranking of respondents, using Ordinal Linear Regression analysis. As no statistical differences were found, this data was not included in this article. Finally, the survey was also used to collect data on citizen awareness of Toronto's green roof bylaw (binary), their stance on increasing green roofs in the city (score from 0 (negative) to 10 (very positive)), and their views on the benefits of green roofs, for Toronto's climate goals and unscored co-benefits (cultural services and mental health) (five point Likert scale). This data is used to illustrate citizen interest and knowledge on the topic, but was not used in statistical analysis or weighting.

In total, 501 responses were collected for the survey, of which data from 402 respondents was analyzed as they resided within the study area. The 99 responses from people living outside the study area were omitted. Responses were aligned with Toronto census data regarding gender, with slightly higher representation of women than men (48.5 % and 46.7 % respectively) (Government of Canada, 2022). Regarding age, there was an overrepresentation of ages 18–44 (80.3 % of respondents, while representing 38.5 % of Toronto's population), and an underrepresentation of inhabitants under age 18 (1.2 % of respondents, 18.6 % of the population) and age 55 and older (6.7 % of respondents, 30.0 % of the population) (Government of Canada, 2022). Regarding ethnicity, most respondents were white (67.9 %, vs. 43.5 % of the population), followed by Asian (15.6 %, vs. 38.8 % of the population) (Government of Canada, 2022). Most respondents indicated that they had an income that was higher than average for the Toronto population. See Appendix B for further details on the survey questions, summary statistics of respondents, analysis of socio-demographic effects on responses, and analysis of other survey questions not central to this study.

2.5. Spatial analysis

Priority maps were created for each individual ES, based on priority scores in the 90th percentile per service (i.e., all grid cells were selected with values that fall in the 90th percentile for that particular ES). Histograms and boxplots for the maps at grid cell level are provided in Appendix C. The individual maps were analyzed at ward level based on mean priority scores.

To create the biophysical green roof prioritisation map (the biophysically weighted map) for the four ES combined, the four original maps of each individual ES were summed. Each individual ES map had priority scores ranging from 0 to 1. The summed map of the individual ES was subsequently divided by four to obtain a biophysically weighted map with values between 0 and 1. The 90th percentile of the combined ES map was used to identify priority areas.

To create a priority map based on citizen preferences the mean ES value rank by Toronto citizens from the survey was used. In the survey the four ES were ranked, providing a value range between 1 and 4, with 1 being highest priority and 4 lowest priority. The mean valuation ranking of flood regulation, air quality regulation, habitat provision, and temperature regulation from the survey results were used to calculate the weights. Weights were calculated from the original rank values and then standardized as follows:

$$\text{Weight}_x = (\text{Max rank} - \text{mean rank}) / (\text{Max rank} - \text{Min rank})$$

$$\text{Standardized weight} = \text{Weight}_x / (\text{Weight}_{air} + \text{Weight}_{temperature} + \text{Weight}_{stormwater} + \text{Weight}_{habitat})$$

Where x is the ES for which the weight is calculated, $Weight_x$ is the unstandardized weight of an individual ES, *Max rank, mean rank, and min rank* are the maximum rank (4), mean rank, and minimum rank (1) that were obtained in the survey. The individual biophysical ES maps (each ranging from 0 to 1) were multiplied with their standardized weights, combined and divided by four to create the citizen weighted green roof prioritisation map with values between 0 and 1. A priority map was created based on the 90th percentile scores.

To analyze hotspots or ES priority the 90th percentile maps for individual ES were overlayed, creating maps with scores between 0 and 4, where higher values indicate higher overlap between priority areas for multiple ES (i.e., in cells with higher scores more priority areas for the individual ES overlapped). This was done for both the biophysical and citizen weighted maps. Results for both the biophysical and citizen weighted approaches were also analyzed and compared at the ward level, by analysing mean prioritisation scores per ward.

3. Results

3.1. Biophysically assessed priority areas for different ES

Biophysically assessed priority areas (i.e., the biophysically weighted assessment) for green roof placement vary substantially per mapped ES (90th percentiles, Fig. 2). Priority areas for temperature regulation and air quality regulation show clustered patterns directly around industrial zones and highways, while priority areas for flood regulation and habitat provision are more scattered across the city. Priority areas for temperature regulation are clustered primarily in western wards. For air quality regulation, the 90th percentile contained about three times as much roof space (3.3 km^2, cut-off value 1.0) as for the other three ES (approximately 1.1 km^2 each).

Mean priority scores at the city level are highest for flood regulation (0.70), followed by temperature regulation (0.63) while scores for habitat provision were substantially lower (0.34) (Fig. 3). Mean priority scores for air quality regulation showed substantially higher variation than for the other ES (mean = 0.55). Outliers for habitat provision indicate central districts (Spadina-Fort York and Toronto Centre) with dense built-up infrastructure and relatively low quantities of urban green spaces.

3.2. Citizen preferences for ecosystem service

Regarding citizen preferences (i.e., the citizen weighted assessment), air quality regulation was the most frequently top-ranked ES (43 %), followed by habitat provision (26 %), then temperature regulation (17 %), and finally flood regulation (15 %) (See Appendix B). The mean rankings follow the same order and were used to set weights for the citizen weighted approach for green roof prioritisation after normalisation (Table 2). Air quality regulation was found to be most important, while flood regulation was found to be least important by citizens.

The survey showed that respondents are usually not aware of Toronto's green roof bylaw (80 % of respondents). However, they do have a very positive attitude towards green roof, with over 90 % of the respondents agreeing that the City of Toronto should promote the construction of more green roofs (68 % strongly agreed, 24 % somewhat agreed). The importance of green roofs for achieving the climate goals in Toronto was scored highly by survey respondents, with an average score of 7.5 and 54 % giving a score of 8 out of 10 or higher. 75 % of respondents thought that roofs provide cultural value to Toronto in the form of benefits to health, learning, social connections, sensory experiences, cultural and symbolic importance, and identity (50 % strongly agreed, 28 % somewhat agreed). Green roofs were also largely seen as good for mental health (60 % of respondents strongly agreed, 27 % somewhat agreed).

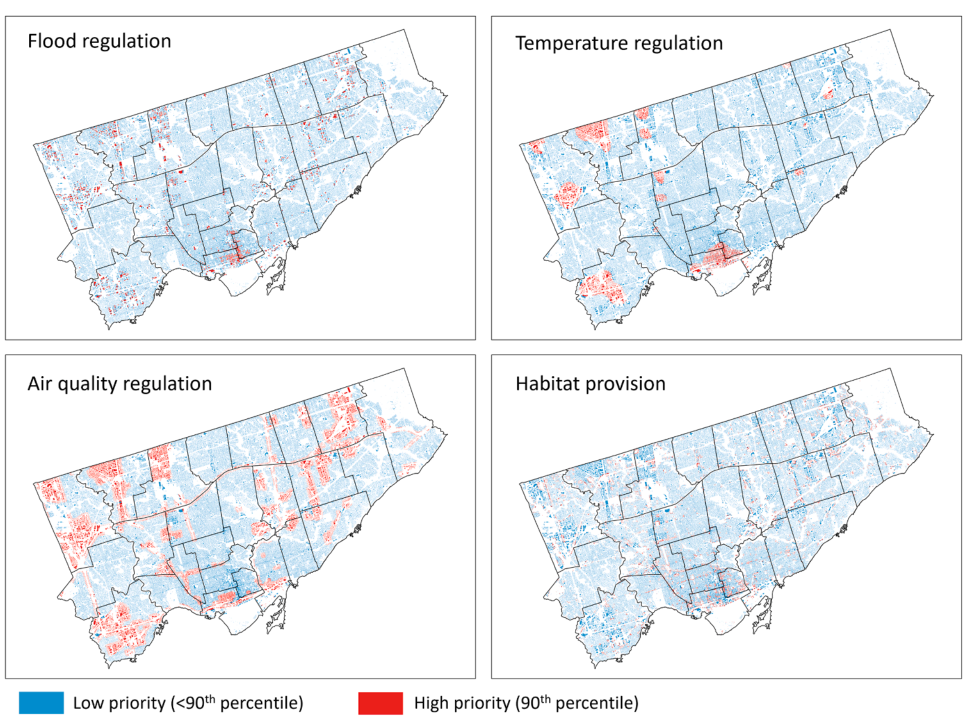

Fig. 2. High and low priority areas for green roof placement for the three mapped ecosystem services and habitat provision.

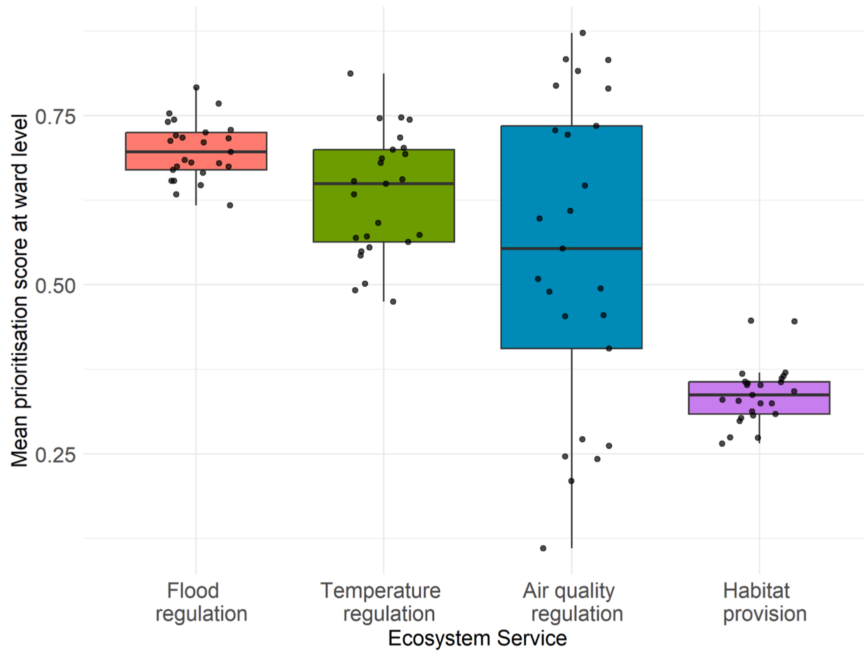

Fig. 3. Boxplots for mean normalized prioritisation values per ward for the four ecosystem services. Black dots represent mean normalized prioritisation values for individual wards.

Table 2
Mean ecosystem service ranking among Toronto citizens (n = 402). Normalized weight represents inverted weights of each ecosystem service in respect to their relative ranking.

Ecosystem service	Mean ranking (1−4)	Normalized weight (0−1)
Air quality regulation	1.85	0.35
Habitat provision	2.46	0.26
Temperature regulation	2.76	0.21
Flood regulation	2.93	0.18

3.3. Comparing biophysical and citizen-based prioritisation of green roof placement

Green roof prioritisation areas for combined ES occur throughout Toronto (Fig. 4). Biophysical prioritisation and citizen-weighted prioritisation show very similar spatial patterns, with clusters of priority areas in some of the more densely built-up and industrialized areas of the city. Variations in priority areas occur locally, as can be seen in the insets for Spadina-Fort York, where more roofs are prioritized based on biophysical assessment than when using the citizen weighted approach.

Only a very small percentage of roof area falls within the highest category of hotspot overlap (0.2 % for biophysical prioritisation, 1.2 % for citizen weighted prioritisation), while nearly 60 % of Toronto does not have hotspots for any ES (Fig. 5). In the case of biophysical prioritisation, the largest hotspot category is for hotspots of a single ES (24 %). For the citizen weighted prioritisation, the largest hotspot category is for scores between 1 and 2 (nearly 23 %), meaning that at least two different ES have hotspots in an area. Within hotspot areas, categorisation differs substantially between the biophysical and citizen weighted approaches, with the citizen weighted approach generally providing higher hotspot scores, as can be seen in the inset for Spadina-Fort York.

At the ward level, there are differences between the mean prioritisation scores of the two used approaches, although the variation in scores between the biophysical and citizen-weighted approaches stays within 10 % of the mean ward values (Fig. 6). For 14 wards the biophysical approach had higher mean prioritization scores, while in only 6 wards the citizen-weighted approach had higher mean scores. In 5 wards the scores of both approaches were approximately equal. The differences between the approaches are largest in wards that have either relatively high mean prioritisation scores, or relatively low prioritisation scores. For both approaches, Spadina-Fort York had the highest mean prioritisation score (0.73 for the biophysical approach, and 0.76 for the citizen weighted approach), while Willowdale had the lowest score (0.40 and 0.37 respectively). The most extreme differences occur in Don Valley East, where the citizen weighted approach scores 0.044 higher, and Willowdale where the biophysical approach scores 0.027 higher. An overview of prioritization scores per ward can be found in Appendix D.

4. Discussion

4.1. Strategic green roof placement insights for Toronto

Toronto currently does not apply strategic approaches for green roof placement, possibly resulting in suboptimal placement of new green roofs. In this study, we designed an approach to introduce strategic planning of green roofs, based on a biophysical assessment as well as a citizen-weighted assessment. We identified priority areas to enhance four ES that relate to targets the city government has set (Toronto Municipal Code Chapter 492, Green Roofs, 2017). Key focal areas for green roof prioritization include wards with densely built-up areas, such as central wards (e.g., Spadina-Fort York) and areas with large industrial zones (e.g., Etobicoke North and Scarborough North), where environmental pressures such as air pollution sources, high levels of imperviousness, and lack of urban green spaces are prominent. Our results show that both at the level of individual roofs (Fig. 4) and at the level of wards (Fig. 6) the two approaches identify similar priority areas based on the four included ES, suggesting that citizens would generally support green roof placement in areas relevant for a broad range of ES. Contrary to findings by Lee (2017), our results also suggest that citizens are aware of benefits from green roofs. A sense of inclusion and ownership could be fostered by involving citizens in planning and governance of green roofs, and representing their preferences (Mattijssen et al., 2015; Ripoll González and Gale, 2020), while also improving provision of ES that are lower on the preference list of most citizens.

Our results show large spatial variations in priority areas across

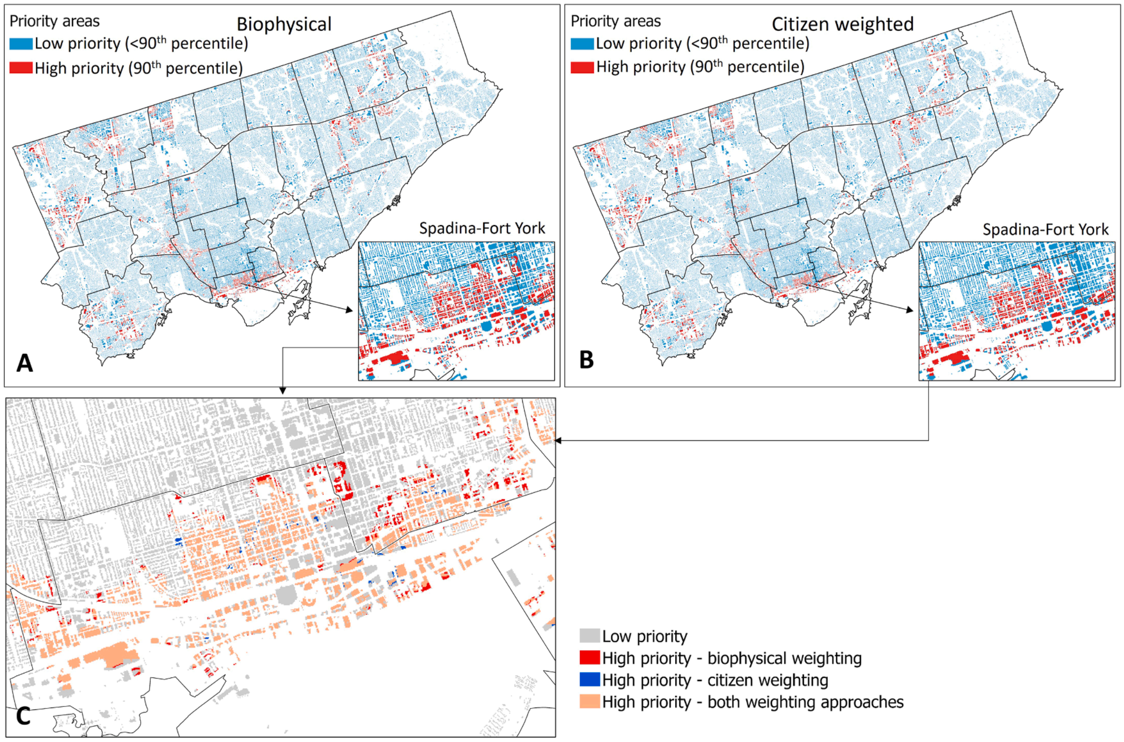

Fig. 4. Priority areas for green roofs based on the four ecosystem services combined, with (a) biophysical weighting and (b) weighting based on citizen preferences. Map (c) shows the overlap and differences in priority areas between the weighting approaches for Spadina-Fort York and Toronto Centre.

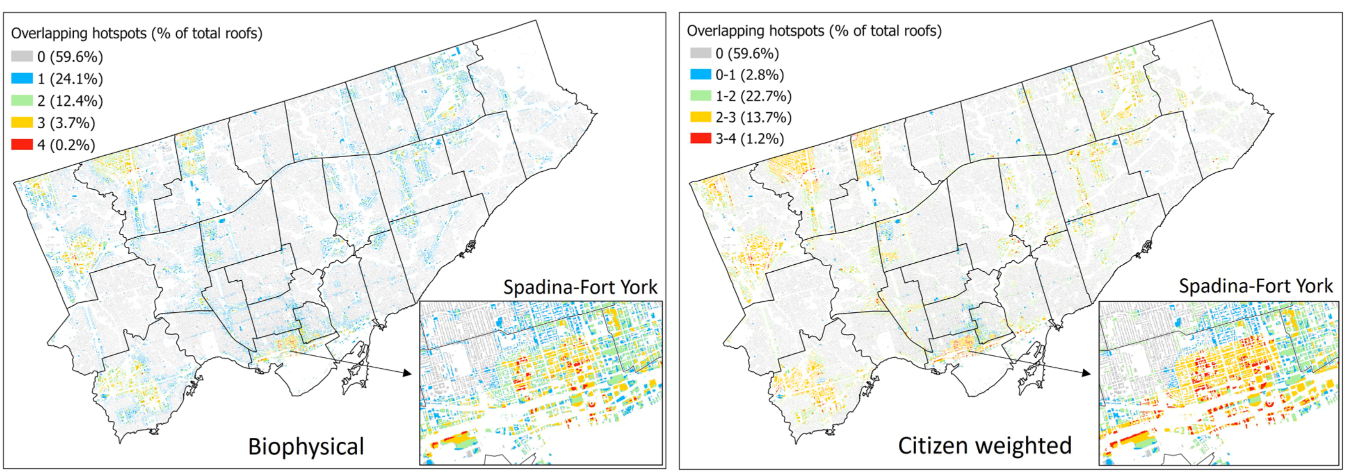

Fig. 5. Overlap in hotspots (90th percentile) of the four ecosystem services, using equal weights (biophysical) and weighted based on citizen preferences. Inset map shows Spadina-Fort York.

different ES, ranging from very dispersed (habitat provision) to highly clustered (air quality regulation and temperature regulation). Air quality regulation priority areas covered the largest amount of roof space (3.3 km^2), as all roofs in close vicinity to industrial areas and highways received the highest priority score. Air quality regulation was also deemed to be the most important ES by survey respondents, which aligns with findings of previous research (Fernandez-Cañero et al., 2013). The highest mean priority score from a biophysical perspective was for flood regulation (Fig. 3), while this received the lowest priority from citizen, showing that people's awareness and preferences may not always coincide with the biophysical need for particular ES (Castro et al., 2014). It is worth noting that green roofs provide ES, regardless of their location, but this study focused on optimizing placements to maximize benefits.

Both the biophysical and citizen weighted approaches confirmed that a large portion of Toronto rooftops are suboptimal for strategic green roof placement. Our results show that Toronto has few rooftops that maximize potential benefits of all four ES considered: 0.2 % of all rooftops if only considering biophysical aspects, and 1.2 % when including citizen preferences. These areas should be the first areas of focus for the City of Toronto when developing new green roofs, in particular, the roofs that are identified as key hotspots in both approaches. Areas that are a hotspot for at least one, but preferably multiple ES should be prioritised to enhance synergies. Installing green roofs according to the priority maps will improve the likelihood of meeting the climate and environmental goals set by the city (City of Toronto, 2019b). Additionally, strategic placement based on the priority maps would not only benefit the neighbourhoods the green roofs are installed

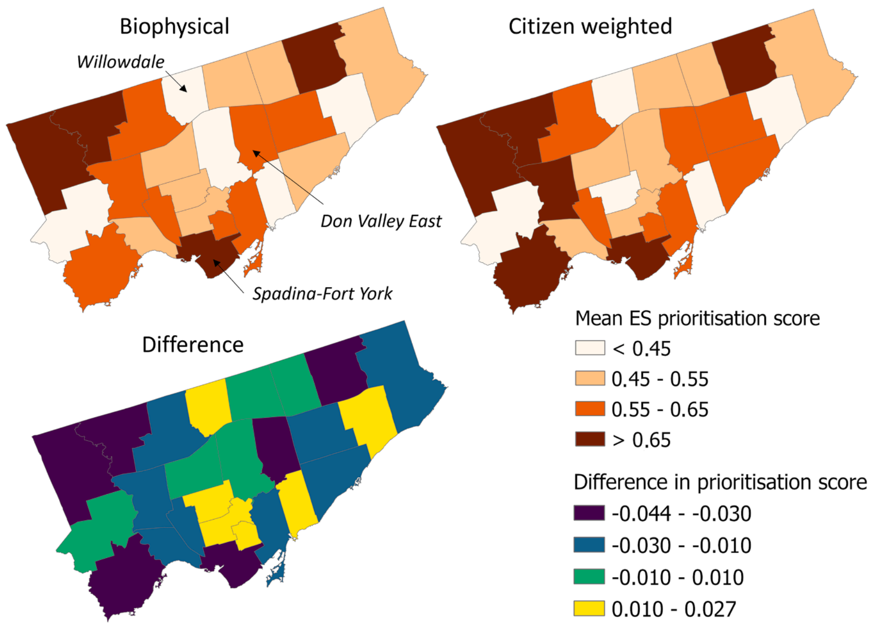

Fig. 6. Mean green roof prioritisation scores at ward level for unweighted (biophysical) and weighted based on citizen preferences, and the difference between the two approaches. Positive values (blue classes) indicate the biophysical score was higher compared to the citizen weighted score, negative values (yellow class) indicate that the biophysical score was lower compared to the citizen weighted score. The green class indicates that the biophysical score and citizen weighted score were approximately equal.

in, but instead will likely contribute to the whole city, as many ES affect their larger surroundings (Serna-Chavez et al., 2014). For example, preventing air pollutant dispersal by partially capturing it at the source will positively affect pollutant concentrations in other parts of the city (Nowak et al., 2006), and larger green spaces help mitigate urban heat up to several hundred meters away (Gao et al., 2022).

Based on our analysis, we recommend the city revisits the conditions set in its green roof bylaw. Strategic placement could help improve the identification of buildings that require green roofs, to improve optimal placement. By identifying priority areas, the city can incentivize existing developments and/or mandate new developments to install them, thus increasing the likelihood to achieve their climate and environmental objectives in a targeted way. Progress towards goals set by policy plans such as the biodiversity strategy (City of Toronto, 2019a), climate adaptation strategy (City of Toronto, 2021), resilience strategy (City of Toronto, 2019b), or Wet Weather Flow Management Plan to reduce urban flooding (City of Toronto, 2006) can be advanced through strategic green roof placement. Strategic efforts could improve synergy across urban strategies and policies, to more effectively contribute to multiple goals.

4.2. Insights for strategic green roof placement approaches

Our approach to integrate and compare a biophysically weighted assessment with citizen-weighting is a key advancement for strategic green roof placement. This study provides a first insight into the broader potential and need for such integrated approaches with a focus on green roofs. Similar approaches have been developed for broader scale green infrastructure development, such as the Green Infrastructure Spatial Planning (GISP) model developed for Detroit, USA (Meerow and Newell, 2017). Like our approach, the GISP approach also combined spatial ES maps with stakeholder preferences. Meerow and Newell (2017) showed that, in addition to providing information on focal areas for strategic green infrastructure planning, these types of approaches can also provide insights into synergies and trade-offs if applied during ongoing planning processes. Our tailored approach enhances these possibilities by zooming in on a specific nature-based solution type (i.e., green roofs) and directly informing specific urban policies, at a higher spatial resolution than for example GISP.

A core advantage of an approach that combines biophysical data and citizen preferences is that it can legitimize the use of biophysical assessment approaches among citizens when the different approaches largely align, as observed in Toronto. In cases where biophysical prioritization and citizen preferences may not align, the approach could provide a relevant baseline for stakeholder debates between planners and citizens, with the opportunity to enhance participatory decision making (Meerow and Newell, 2017). At the very least participatory approaches to strategic planning can raise awareness about the importance and diversity of benefits related to green roofs and other urban green infrastructure (Campagna et al., 2020).

Previous green roof research focused solely on overall ES benefits, ignoring citizen priorities (Langemeyer et al., 2020; Venter et al., 2021; Hoeben and Posch, 2021; Aleksejeva et al., 2022; Slootweg et al., 2023). Such studies identified various heterogeneous green roof placements (Aleksejeva et al., 2022; Slootweg et al., 2023), while others found more homogenous, or patch-like patterns (Langemeyer et al., 2020; Venter et al., 2021), where we find mixed results. Langemeyer et al. (2020) included scientist valuation of ES but excluded citizen perspectives. Considering citizen interests can increase social justice and citizen satisfaction (Ripoll González and Gale, 2020), by giving their opinions weight, but also to identify if differences exist between citizen groups. Our study did not show differences between sociodemographic groups of Toronto citizens on importance of green roofs and the most valued ES (Appendix B). However, such an analysis was not central to our survey. To draw conclusions on equity and justice, a more topically focused survey with a larger and more demographically representative sample size would be advised.

In addition to the ES we address in this study, synergies have been identified in previous literature that go beyond the individual overlays we observed. For example, increased urban temperatures and poor air quality are linked, as each can contribute towards the other (Hereher et al., 2022). Slootweg et al. (2023) found synergies between solar power generation and green roof performance. Understanding how strategic placement of green roofs can contribute towards multiple sustainability challenges expose ideal planning scenarios for urban planners, citizen groups, or local government. Findings of this study can act as a starting point for this process.

4.3. Limitations and future research

An important note regarding our analysis is that priority maps for individual ES showed distinctly different distributions in the data (Appendix C). Air quality regulation priority areas had a strong bimodal distribution, with many grid cells with value 1 (within 200 m of pollution sources) and many grid cells with value 0 (all cells beyond 1000 m from a pollution source). Temperature regulation and flood regulation were more normally distributed, while habitat provision had a peak for grid cells with value 0. These different distributions affected the aggregated ES maps, with the maps with higher average priority scores (air quality regulation, temperature regulation, flood regulation) weighing more heavily than habitat provision. This was the case in the biophysical approach, but was further enhanced in the citizen-weighted approach, as air quality regulation obtained the highest weight, and habitat provision the lowest weight (Table 2). Further standardization of scores may have adjusted for the implicit biophysical weighting. However, the priority scores are also a reflection of the need to focus on particular areas more strongly than others. We therefore opted to preserve the implicit biophysical weighting in our approach. Future research could explore weighting of ES, both through further standardization of biophysical approaches, but also through further exploration of weighting by different stakeholder groups.

In this study we assessed four ES, based on Toronto's green roof bylaw. However, green roofs provide more benefits than those we investigated (Cook and Larsen, 2021). We did not address provisioning or cultural services in this study, such as food provisioning, aesthetics, or positive impacts on physical and mental health. We therefore did not holistically provide insights on ES provision, but rather targeted core environmental challenges (climate, pollution, and biodiversity loss) that were also identified as focal points by the Toronto city government (Toronto Municipal Code Chapter 492, Green Roofs, 2017). Moreover, we did not assess issues such as economic effects or energy saving. Future research could include such benefits, which go beyond the policy and incentive structures of city governments. Previous research has already provided insights into some of the additional benefits, that can be included in future research on strategic green roof planning approaches. For example, installing green roofs for water retention in New York city is 18 times more cost-effective than installing grey infrastructure (Abualfaraj et al., 2018), resulting in reduced taxes. They also contribute economically by increasing property value (Manso et al., 2021), sometimes by as much as 16 % (Ichihara and Cohen, 2011). Akkose et al. (2021) found that retrofitting older buildings, with possibly poor insulation, reduces energy consumption by up to 50 %. Green roofs in an urban setting can be beneficial to mental health by decreasing stress and anxiety just from observing them in an urban setting (Wang et al., 2016), while improving cognitive function (Lee et al., 2015), as well as overall wellbeing (Yuen and Jenkins, 2020; Rezaei et al., 2021). Aleksejeva et al. (2022) considered well-being in strategic green roof placement studies.

Another consideration for strategic planning of green roofs that we were not able to include in this study due to our study scope as well as data limitations, is the structural feasibility for installation, including the load-bearing capacity, slope, heritage status, and age of roofs and buildings. For example, older buildings may not be able to carry the load of a green roof, making installation infeasible (Shafique et al., 2018). Slootweg et al. (2023) designed a spatial model to assess such aspects for Amsterdam, and replicating a similar approach would be relevant for other cities, including Toronto. The combination of understanding benefits, but also identifying barriers would further enhance strategic planning approaches and help more accurately determine which roofs have high priority but also high opportunity for conversion into green roofs, particularly for retrofitting. For Toronto, identifying technical opportunities and barriers as such would help to determine which roofs within the highest priority class would be technically suitable for green roof installation.

The models and survey approach used in this study can be further refined to establish more accurate spatial prioritisation and better identify differences between citizen groups. There is potential within spatial modelling to tailor methodologies to local context. Here we used more generalizable approaches in combination with local spatial data. For example, for flood regulation and temperature regulation we adapted outputs from InVEST models to assess where green roofs could contribute most. While these models have been applied and calibrated internationally for assessing ES supply (Bosch et al., 2021; Hamel et al., 2021; Lourdes et al., 2022; Veerkamp et al., 2023), they have not been specifically designed to address spatial prioritisation questions. Other approaches, such as heuristic optimisation tools could be considered, which have been applied to prioritize for both biodiversity and ES in various contexts (Cimon-Morin and Poulin, 2018; Schröter and Remme, 2016), but these still rely on underlying spatial output generated through for example InVEST. Relating to the applied models, the approaches for habitat provision and air quality regulation build on broad criteria from international literature. This lacks insight on dispersal patterns of local wildlife or meteorological details on wind patterns and pollutant concentrations needed to identify particular prioritisation requirements. Moreover, our citizen-based approach relied on a city-wide sample that was not fully representative of the city's population. For example, some age groups (elderly and children/young adults), ethnicities, and lower income groups were underrepresented in the sample. Additionally, we had too few respondents to sufficiently assess differences within the group, based for example on demographics or geographical location. Refinements to the models and the survey approach would decrease spatial uncertainty in results and provide an opportunity to delve into deeper dimensions of citizen preferences, targeting interests of particular populations to improve environmental justice. Citizen participation could also be incorporated into monitoring and evaluation of green roof programs, to shed light on whether such programs are providing the expected benefits to different citizen groups.

In this study, we applied a generalizable approach that enhances its applicability in cities in other contexts, as many of the required data sources are commonly available, and the spatial approaches rely on widely applied software and peer-reviewed international literature. To improve strategic green roof planning in other contexts, it is key to further validate the biophysical relationships identified in Toronto. Additionally, understanding how citizen preferences for green roofs vary within and between cities will help determine whether these strategies can be generalized and widely advised to city governments on a broader scale.

5. Conclusion

We tested an approach to improve strategic green roof planning based on four key ES they provide: air quality regulation, temperature regulation, flood regulation, and habitat provision. We applied the approach to Toronto, but designed it as a generalizable approach that could also be replicated in other urban contexts.

While green roofs can be an affordable and effective measure to address multiple sustainability challenges at once, potentially providing multiple ES simultaneously, we found no evidence that they are currently being strategically planned in Toronto. Our results show that strategic green roof planning could enhance such multifunctionality in areas where it is most needed. We show that key priority areas for individual ES vary substantially, ranging from clustered areas to very dispersed roofs. However, when the ES are combined, the biophysical approach shows core priority areas clustered throughout the city in which multiple ES can be addressed simultaneously. When weighting the model with citizen preferences the core priorities remain robust, and the two approaches show very similar patterns spatially. By focusing on turning 0.2–1.2 % of the current roof space into green roofs in the key hotspot areas, four ES can be enhanced simultaneously in the areas where they are needed most.

Participatory governance approaches could be further implemented as a tactic to develop strategic green roof placement to also empower citizens and foster informed decision making. Such an approach would maximize ES potential in Toronto, while considering the values of its citizens. Doing so will also contribute towards to goals and visions that the city has set to accomplish, in a transparent and citizen-representative manner.

CRediT authorship contribution statement

Roy P. Remme: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Sharlene L. Gomes:** Writing – review & editing, Supervision, Conceptualization. **Matthew Jung:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.128798.

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