# Creating urban green infrastructure where it is needed – A spatial ecosystem service-based decision analysis of green roofs in Barcelona

Johannes Langemeyer [a,b,*], Diego Wedgwood [a], Timon McPhearson [c], Francesc Baró [a,b], Anders L. Madsen [d,e], David N. Barton [f]

[a] Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), Edifici Z (ICTA-ICP), Carrer de les Columnes s/n, Campus de la UAB, 08193 Cerdanyola del Vallès, Spain
[b] Hospital del Mar Medical Research Institute (IMIM), Carrer Doctor Aiguader 88, 08003 Barcelona, Spain
[c] Urban Systems Lab, The New School, USA
[d] HUGIN EXPERT A/S, DK-9000 Aalborg, Denmark
[e] Aalborg University, DK-9220 Aalborg, Denmark
[f] The Norwegian Institute for Nature Research, Norway

HIGHLIGHTS

- The article addresses the question of where to build green roofs most effectively with regard to citizen needs.
- A spatial multi-criteria screening tool for the creation of green roofs is developed.
- Ecosystem service deficits are spatially defined by combined social-ecological evaluation criteria.
- Finally, the optimal green roof design for an effective ecosystem service provision is determined.

GRAPHICAL ABSTRACT
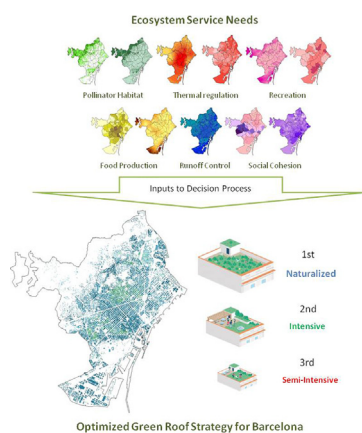
ABSTRACT

As cities face increasing pressure from densification trends, green roofs represent a valuable source of ecosystem services for residents of compact metropolises where available green space is scarce. However, to date little research has been conducted regarding the holistic benefits of green roofs at a citywide scale, with local policymakers lacking practical guidance to inform expansion of green roofs coverage. The study addresses this issue by developing a spatial multi-criteria screening tool applied in Barcelona, Spain to determine: 1) where green roofs should be prioritized in Barcelona based on expert elicited demand for a wide range of ecosystem services and 2) what type of design of potential green roofs would optimize the ecosystem service provision. As inputs to the model, fifteen spatial indicators were selected as proxies for ecosystem service deficits and demands (thermal regulation, runoff control, habitat and pollination, food production, recreation, and social cohesion) along with five decision alternatives for green roof design (extensive, semi-intensive, intensive, naturalized,

* Corresponding author at: Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), Edifici Z (ICTA-ICP), Carrer de les Columnes s/n, Campus de la UAB, 08193 Cerdanyola del Vallès, Spain.
E-mail address: johannes.langemeyer@uab.cat (J. Langemeyer).

and allotment). These indicators and alternatives were analyzed probabilistically and spatially, then weighted according to feedback from local experts. Results of the assessment indicate that there is high demand across Barcelona for the ecosystem services that green roofs potentially might provide, particularly in dense residential neighborhoods and the industrial south. Experts identified habitat, pollination and thermal regulation as the most needed ES with runoff control and food production as the least demanded. Naturalized roofs generated the highest potential ecosystem service provision levels for 87.5% of rooftop area, apart from smaller areas of central Barcelona where intensive rooftops were identified as the preferable green roof design. Overall, the spatial model developed in this study offers a flexible screening based on spatial multi-criteria decision analysis that can be easily adjusted to guide municipal policy in other cities considering the effectiveness of green infrastructure as source of ecosystem services.

## 1. Introduction

As cities across the globe rapidly grow and densify, urban greenery plays an increasingly vital role as nature-based solutions (NBS) to the sustainability challenges associated with urbanization (EC, 2015; Kabisch et al., 2017). For metropolitan populations who otherwise lack access to nature, green infrastructure (GI) represent primary local sources of ecosystem services (ES). GI can be defined as strategically planned network of green and blue spaces such as parks, gardens and ponds; whereas ES include air purification, recreation, and food supply and are defined as the contribution of ecosystems to human well-being (Gómez-Baggethun et al., 2013; Keeler et al., 2019). However, the expansion of GI is frequently constrained by new and existing urban development, often at high density, forcing municipalities to seek its integration with other urban infrastructures such as buildings. In this context, green roofs (GRs) – the vegetated coverage of building rooftops – are gaining momentum as a solution for densely populated metropolises to ensure adequate supply of regulating ES like stormwater management, thermal regulation, ecological habitat (Oberndorfer et al., 2007), to enhance the local provision of food (Buehler and Junge, 2016), but also to provide less tangible non-material and cultural ES like relaxation and social integration (Mesimäki et al., 2017).

Worldwide, GRs are sprouting up as architects and planners embrace rooftop gardens as aesthetically intriguing yet functional spaces. Municipalities are actively promoting GR installation through policy instruments like construction regulations and economic incentives (Carter and Fowler, 2008; Berardi et al., 2014), while academic study of the subject has grown exponentially (Shafique et al., 2018; Sutton and Lambrinos, 2015). Despite this rising popularity, to date GRs have not been significantly studied from the perspective of urban planning and land use policy in the face of an enhanced provision of ES. GR research has often been limited in scope to technical models or comparisons of individual test rooftops (MacIvor and Lundholm, 2010; Abualfaraj et al., 2018), offering little insight to planners seeking guidance for informed GR expansion at a citywide scale. Moreover, existing assessments tend—with some exceptions (Nurmi et al., 2016)—to focus on quantifiable material ES (Lundholm and Williams, 2015) without broader consideration of the cultural benefits of GRs (Czemiel Berndtsson, 2010). In particular, the lack of investigation into the cultural ES of GRs discounts a number of non-material benefits that are often seen the most important ES to be provided in cities (Camps-Calvet et al., 2016).

Further, while the ES of GRs are inherently dependent on specific design choices like plant species, substrate depth, and accessibility (Dvorak and Volder, 2010), many studies neglect to account for the variability of these factors. Indeed, the common GR nomenclature is fairly reductive, often only differentiating between two typologies: 'extensive', low-maintenance groundcover like grass and sedum with shallow substrates, and 'intensive', full rooftop gardens with deep substrates and active usage comparable to ground-level parks (Rowe, 2011). Such binary classification is limited in accounting for the true complexity of design wherein two nominally 'extensive' roofs can have drastically dissimilar construction, species heterogeneity, and/or intended use (Mahdiyar et al., 2018),

thereby differentiating the ES they can provide. By neglecting to account for the wider breadth of GR designs and associated barriers (economic, structural, and institutional) as well as potentials in ES provision, much GR research lacks applicability and can stymy development of effective policy (Williams et al., 2010). In the few recent studies that attempt to investigate the large-scale implementation of GRs, the limitations are progressively reduced. However, there is still some way to go to increase a wider applicability and comparability of these studies.

By way of example, Karteris et al. (2016) calculated the potential contribution of GRs to energy performance, carbon sequestration, and rainwater retention in Thessaloniki, Greece, but did not account for the synergies and trade-offs between these benefits that could be assessed using the well-established framework of ES mapping that distinguishes the supply, demand, and flow of ES (Crossman et al., 2013). Meanwhile, although Grunwald et al. (2017) follows this approach to explore how rooftop greening in Braunschweig, Germany could provide four ES—thermal climate, air quality regulation, water retention, and habitat for biodiversity—the policy-making implications of their findings are relatively limited. This could be added by means of a decision support tool like Multicriteria Decision Analysis (MCDA) allowing for the comparison of multiple alternatives through the performance and weighting of disparate variables (e.g. Langemeyer et al., 2016). Finally, while Velázquez et al. (2018) incorporated some expert feedback in basic MCDA to prioritize potential GR locations in Madrid, Spain based on air pollution, traffic, existing greenery, and population density, their study—like the others listed—does not account for non-material ES, nor adequately differentiates between different GR designs.

Here, we seek to unify and improve upon the disparate approaches of these studies by offering a spatial policy screening tool that integrates the techniques of MCDA-supported ES mapping with the flexibility of the mixed data non-parametric approach of Bayesian Belief Networks (BBNs). BBNs are graphical models (Nielsen and Jensen, 2009) that are particularly useful to support decision analysis. As MCDA, they can incorporate a wide range of both qualitative and quantitative data (Chen and Pollino, 2012).

The spatial screening tool developed for the study was applied to the case study city of Barcelona, Spain with the specific objectives of: (Abualfaraj et al., 2018) to identify city-wide ES deficit areas where GRs have the greatest potential to fill an existing lack of supply of material and non-material ES; and (Agència d'Ecologia Urbana de Barcelona (BCNecologia), 2010) to identify the most suitable GR design for optimized ES provision potential in those areas. Further, the tool is designed to be adaptable to support the effective implementation of other NBS in cities, offering a methodology that can be tailored to variations in available data and the needs of planners.

## 2. Material & methods

### 2.1. Description of the study area

The chosen study area for this assessment is the municipality of Barcelona, the capital of Catalonia, Spain. Administratively divided into ten

districts and 73 neighborhoods (see Appendix A), Barcelona is home to 1.62 million inhabitants within its 102 km² area, making it one of the densest and most compact municipalities in Europe. There is highly limited green space per capita, amounting to 7 m²/inhabitant in the city center (17,62 m²/inhabitant when including the peri-urban park Collserola), which is very low in European comparison (Baró et al., 2015). Located on the northeastern coast of the Iberian Peninsula, the region is characterized by a Mediterranean climate averaging approximately 600 mm of annual rainfall and typical yearly temperatures ranging between 9 °C and 24 °C. The city's iconic rooftop terraces—long utilized as elevated social spaces (Contreras and Castillo, 2015)—offer accessible and mostly structurally sound sites for rooftop greening (Fig. 1). According to the Municipal Urban Ecology Agency, Barcelona had installed 115 GRs by 2014 (BCNecologia, 2014) and current plan are to expand this cover by 5431 m² in 2019 and up to 22,000 m² in 2030 as part of its citywide stimulus program to expand NBS (BCN, 2017b). However, this represents a tiny fraction of the GR expansion possibilities in the city, as approximately 65 ha of suitable rooftops have been identified on publicly owned buildings alone (BCNecologia, 2010). In order to promote widespread adoption of GRs in Barcelona, this study's spatial MCDA framework may assist future GR decision-making and prioritization processes.

## 2.2. Green roof design alternatives

Five GR design alternatives were selected based on Barcelona's guidelines (Contreras and Castillo, 2015), including three standard industry typologies—extensive, semi-intensive, and intensive—that are differentiated by substrate depth, associated vegetative capacity, and maintenance requirements (FLL, 2002; NTJ, 2012). Additionally, two specialized use categories—naturalized and allotment—were used to evaluate the effect of intended usage on ES provision. Naturalized roofs are typically planted with endemic species emulating natural habitats like meadows, while allotment roofs are explicitly designed for rooftop agriculture. These five alternatives represent a wide range of economic, structural, and maintenance requirements, as indicated in Table 1.

A workshop was conducted on June 5th, 2018 exploring GRs as NBS for Barcelona (See Appendix B for workshop materials). The participants of the workshop ($n = 31$) included academics, municipal officials, NGO representatives, and private sector GR experts (see Appendix C for a listing of the experts). Prior to the workshop, attendees viewed several presentations on public and private GR initiatives in Barcelona. The participants represent broadly the local expertise on NBS in Barcelona. Following an explanation of the study objectives and model criteria, workshop participants were split into three moderated groups. To allow for differentiated debates, split-out groups were formed heterogeneously, making sure each group included experts from academia, city planning (from different scales), NGOs and private sector representatives. The experts were then asked to evaluate: (1) which ES should be prioritized with regard to the given deficits in Barcelona, (2) the capacity of different GR types to provide ES, and (3) the feasibility to implement different design alternatives.

(1) In order to determine which ES should be prioritized in Barcelona, a collective weighting approach was applied, consisting in the distribution of 30 'pebbles' between six categories of ES (see Section 2.3 for their selection). The results of this exercise are shown in Fig. 2 and Table 2.

(2) To define the extent each of the five design alternatives are capable to provide ES, a group exercise requested the unanimous grading of ES under each design alternative from 1 to 3 ('little to no', 'intermediate', and 'strong' provision). Average score are shown in Table 3.

(3) The general feasibility of installing the five design alternatives considered economic, structural, and institutional barriers, which were ranked individually by workshop participants on a Likert scale of 1 to 5 ('very low' to 'very high'). Results from the ranking exercise are presented in Table 4.

## 2.3. Ecosystem services

Six ES attributed to GRs were chosen as most relevant in the study area: thermal regulation (micro and regional climate regulation), stormwater runoff control, habitats for pollinators, food production, recreational opportunities, and the facilitation of social cohesion (Berardi



**Fig. 1.** Barcelona rooftops seen from Parc del Turó del Putget.
Picture by Börkur Sigurbjörnsson derived from Flickr.com under CC BY 2.0.

**Table 1**
GR design alternatives (Contreras and Castillo, 2015).

| Alternative | Substrate Depth (cm) | Weight (kg/m$^2$) | Cost (€/m$^2$) | Maintenance | Vegetation |
|---|---|---|---|---|---|
| Extensive | 10–15+ | 120–225 | 70–90 | Low | Succulents, perennial herbs, grasses, ornamentals, underground perennials |
| Semi-intensive | 15–30+ | 150–450 | 90–130 | Med | Grasses, herbs, aromatics, bulbs, creepers, small shrubs |
| Intensive | 30–100+ | 650+ | 150+ | High | Above, with medium to large shrubs, small to large conifers, palms, or other trees |
| Naturalized | 15–30+ | 200–450 | 70–130 | Low | Predominantly indigenous species, wildflowers, and shrubs |
| Allotment | 30–40+ | 450+ | 120+ | High | Garden vegetables, aromatic and medicinal plants, fruit trees |

et al., 2014; Lundholm and Williams, 2015; Mesimäki et al., 2017). While not an exhaustive list of GR-related ES—other ES provided by GRs include aesthetics, mediation of noise, and protection of the building structure—these services make GR relevant NBS for a variety of urban problems (urban heat island, flash flooding, social inequities, etc.), allowing for a holistic assessment of GRs' benefits. Moreover, demand for these ES can be estimated using spatial proxies available at the citywide scale, unlike other services associated with GRs. For instance, building-specific GR benefits like noise insulation, roof longevity, and thermal insulation (Rowe, 2011) were not included due to a lack of data on individualized structural envelopes and energy usage.

This section presents theoretical justifications for the studied ES and their associated demand indicators (spatially determining the deficit of each of these ES across the study area), along with the calculations and classifications made in GIS and HUGIN used to create and weight the initial input rasters. An overview of the ES indicators is given in Appendix D. The relative weights of the indicators were established by the analysts, based on the respective literature and personal knowledge about their relevance in the case study city. We acknowledge that the selection and weighting of indicators is somewhat arbitrary, a more sophisticated approach for example based on a Delphi consultation of experts was beyond the scope of this study. However, the resulting models and sub-models can be easily adapted in order to incorporate different weights, indicators or even additional ES.

### 2.3.1. Thermal regulation

One ES frequently associated with GRs is the regulation of urban temperatures, both via passive building insulation and active mitigation of the Urban Heat Island effect, or the anthropogenic warming of urban settlements above their rural surroundings (Li et al., 2014). GRs have been proposed as an effective method for addressing urban heat by increasing albedo (solar reflectance), insulating rooftop membranes, and cooling the rooftop surface directly via vegetative evapotranspiration. Indeed, experimental and modeling research indicates GRs can reduce surrounding temperatures by as much as 3 °C (Santamouris, 2014). Such mitigation is particularly important in warm climates like Barcelona where the heat island can elevate urban temperatures by up to 8

°C (Moreno-Garcia, 1994), posing a significant health threat to vulnerable populations during heat waves, including elderly, children and poorer parts of the population who often lack access to air conditioning (Harlan et al., 2006). Therefore, to evaluate the demand for thermal regulation, two components of heat risk were selected as equally-weighted indicators for this model: UHI intensity and heat stress vulnerability.

_2.3.1.1. Urban Heat Island intensity._ Although UHI can be estimated by models and/or remote sensing of surface temperature, direct measurement of air temperature was selected as a more representative input for this model. Martin-Vide et al. (2015) evaluated UHI across Barcelona from October 2014 to March 2015 by measuring air temperature from vehicles moving along three transects of Barcelona. Based on their analysis, using mapped temperature isolines from three dates with low, intermediate, and high UHI, a single raster was created in ArcGIS (version 10.6.2) depicting average difference in air temperature across the region. Unsurprisingly, UHI was highest in the densely built central districts of Eixample and Gràcia and lowest around the outskirts of the city near the mountains and coastline. For uniform distribution, the raster was divided into ten classes by 1/2 standard of deviation (STD) which were given a positive, linear correlation with cooling demand.

_2.3.1.2. Heat vulnerability._ Demographic heat risk has previously been evaluated in multiple ways, using income, age, and race as mediators (Aubrecht and Ozceylan, 2013). In this study, a pre-existing heat vulnerability map was obtained from the City of Barcelona that evaluated risk via the following indicators, selected based on input from Barcelona Public Health Agency: elderly (75+ years) population density, building energy performance, vegetation, and low educational attainment (BCN, 2018a). The resulting map classified Barcelona into five vulnerability categories (very low to very high), which were scaled positively and linearly to ES demand in HUGIN. The most vulnerable areas were identified in the North along the Besòs River extending into Nou Barris and Horta, and south in Sants-Montjuïc (Fig. 3).

### 2.3.2. Runoff control

Attenuating and delaying the release of stormwater runoff is another major ES provided by GRs (Lundholm and Williams, 2015). During intense rainstorms, many urban areas are vulnerable to flash flooding due to the prevalence of impermeable surfaces and insufficient retention capacity of conventional drainage systems. Flooding of this kind in Barcelona can cause millions of Euros in property damage within flood-prone neighborhoods (Velasco et al., 2013). In 2018—the year
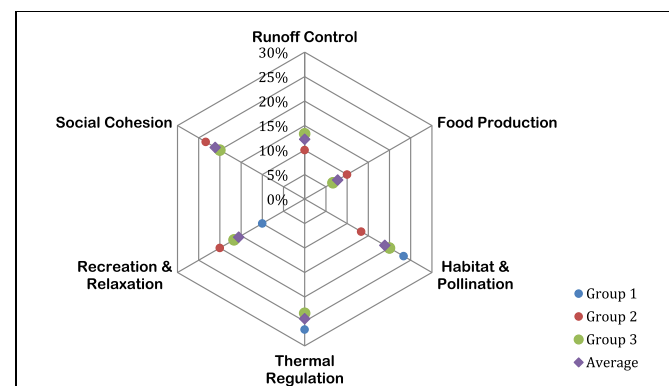


**Fig. 2.** Ecosystem service prioritization weights. Based on a group evaluation (Pebble-distribution method) embedded within an expert workshop ($n = 31$), conducted in Barcelona (Spain), 5th June 2018.

**Table 2**
Expert prioritization of ecosystem service needs. Based on a group evaluation (Pebble-distribution method) embedded within an expert workshop (n = 31), conducted in Barcelona (Spain), 5th June 2018.

| Ecosystem service | Group 1 n = 8 | Group 2 n = 7 | Group 3 n = 9 | Average n = 31 |
|---|---|---|---|---|
| Thermal regulation | 26.67% | 23.33% | 23.33% | 24.44% |
| Runoff control | 13.33% | 10.00% | 13.33% | 12.22% |
| Habitat & pollination | 23.33% | 13.33% | 20.00% | 18.89% |
| Food production | 6.67% | 10.00% | 6.67% | 7.78% |
| Recreation & relaxation | 10.00% | 20.00% | 16.67% | 15.56% |
| Social cohesion | 20.00% | 23.33% | 20.00% | 21.11% |

**Table 3**
Estimated ecosystem service provision by different green roof design alternatives. Based on a group evaluation (Likert-scale) embedded within an expert workshop (n = 31), conducted in Barcelona (Spain), 5th June 2018.

| Ecosystem service | Green roof design alternative | | | | |
|---|---|---|---|---|---|
| | Extensive | Semi-intensive | Intensive | Naturalized | Allotment |
| | Average Score (Group 1\|2\|3) | | | | |
| Thermal regulation | 0.50 | 0.83 | 1.00 | 0.83 | 0.33 |
| | (0\|1\|0.5) | (0.5\|1\|1) | (1\|1\|1) | (1\|0.5\|1) | (0.5\|0\|0.5) |
| Runoff control | 0.33 | 0.75 | 0.75 | 0.67 | 0.67 |
| | (0\|0.5\|0.5) | (1\|0.5\|0.75) | (1\|0.5\|0.75) | (0.5\|0.5\|1) | (0.5\|0.5\|1) |
| Habitat & pollination | 0.42 | 0.50 | 0.67 | 1.00 | 0.58 |
| | (0\|0.75\|0.5) | (0\|0.5\|1) | (0.5\|0.5\|1) | (1\|1\|1) | (0.5\|0.25\|1) |
| Food production | 0.00 | 0.17 | 0.67 | 0.33 | 1.00 |
| | (0\|0\|0) | (0\|0.5\|0) | (0.5\|1\|0.5) | (0.5\|0.5\|0) | (1\|1\|1) |
| Recreation & relaxation | 0.33 | 0.83 | 1.00 | 0.67 | 1.00 |
| | (0\|0.5\|0.5) | (0.5\|1\|1) | (1\|1\|1) | (0.5\|1\|0.5) | (1\|1\|1) |
| Social cohesion | 0.17 | 0.83 | 1.00 | 0.50 | 1.00 |
| | (0\|0.5\|0) | (0.5\|1\|1) | (1\|1\|1) | (0.5\|0.5\|0.5) | (1\|1\|1) |
| Total contribution (Max 6) | 1.75 | 3.92 | 5.08 | 4.00 | 4.58 |

this study was conducted—there were seven extreme precipitation events with over 25 mm rainfall within less than 24 h, and local peaks of over 70 l/m$^2$ in less than an hour. GRs can reduce the risk of flooding by retaining up to 85% of excess stormwater and delay the runoff release (Czemiel Berndtsson, 2010).

In order to evaluate the potential demand for this attenuation, the current potential for runoff across Barcelona was estimated. Stormwater runoff is most often expressed in terms of runoff coefficients, which represent the percent runoff resulting from a rainstorm. These coefficients are highly affected by land cover and soil permeability, but also by slope and rainfall intensity (Sriwongsitanon and Taesombat, 2011). As such, a land use-based estimation of runoff coefficients was selected.

*2.3.2.1. Runoff coefficient.* In lieu of calculating local runoff coefficients, general values were derived from land use classes akin to the methodology of Puccinelli et al. (2012). Runoff coefficients were assigned in line with European Corine Land Cover (Corine) classes according to four soil permeability levels. To improve upon the coarse resolution of Corine data, a detailed Land Cover Map of Catalonia (LCMC, 2009) was obtained, and the base land cover matched to equivalent Corine classes based on the European Environment Agency (EEA), 2017. Updated land use covers were then assigned corresponding runoff coefficients averaged from the four Corine permeability levels. The resultant map shows Barcelona to have generally high coefficients due to the density of the built environment, with the greener Collserola and Montjuïc areas absorbing more runoff. Coefficients were scaled in the range of 0 to 1, with deciles scaled linearly and positively with demand (Fig. 4).

*2.3.3. Pollinator habitat*

GRs play an important role in promoting urban biodiversity as habitats for local fauna, particularly insects and some birds, that pollinate urban flora and regulate invasive pests (MacIvor and Lundholm,

2010). Indeed, GRs can contribute to 'green corridors' that allow these beneficial species to circumvent urban barriers to movement (Orsini et al., 2014). To identify the deficit in such connectivity, this study simplified the ESTIMAP pollination model (Zulian et al., 2013) that uses land cover to estimate two indicators of pollinator habitat potential: floral availability and nesting suitability. These indices were both given negative linear correlation to demand, weighted 3:1 towards floral availability as nesting sites are less prevalent within urban settings (Stange et al., 2017).

*2.3.3.1. Floral availability & nesting suitability.* The original ESTIMAP framework modeled the relative pollination potential of wild insects across Europe by assigning two habitat suitability scores between 0 and 1 to Corine classes, adjusted for agricultural crop type and proximity to roads, water bodies, and forest edges (Zulian et al., 2013). As with runoff control, Corine scores were translated to the urban scale by correlating to the LCMC (2009), averaging both base cover and composite land use classes to account for industrial and port areas. Due to the compact scope and lack of typical agriculture and forest edges, adjustment of this base score was deemed unnecessary. Both maps show Barcelona to be widely unsuitable for pollinators, apart from predominantly green areas like Collserola and some larger parks (Fig. 5).

*2.3.4. Food production*

As GRs increasingly emerges as an auxiliary source of healthy food production and food security (Whittinghill and Rowe, 2011), they offer significant potential for urban agriculture, particularly in cities like Barcelona where agricultural land is inexistent and existing urban gardens for the production of food are scarce (Camps-Calvet et al., 2016). At maximum capacity, rooftop farming is estimated to be able to supply large parts of cities' fruits and vegetables demands (Orsini et al., 2014). To evaluate demand for such production, three indicators

**Table 4**
Feasibility of different green roof design alternatives considering economic, structural, and institutional barriers. Based on individual evaluations (Likert-scale ranking) embedded within an expert workshop (n = 31), conducted in Barcelona (Spain), 5th June.

| Feasibility score | Green roof design alternative | | | | |
|---|---|---|---|---|---|
| | Extensive | Semi-intensive | Intensive | Naturalized | Allotment |
| | No. of votes (*percent*) | | | | |
| Very Low = 1 | 2 (8.33%) | 0 (0.00%) | 4 (16.67%) | 2 (8.33%) | 0 (0.00%) |
| Low = 2 | 1 (4.17%) | 7 (29.17%) | 6 (25.00%) | 2 (8.33%) | 2 (8.33%) |
| Medium = 3 | 5(20.83%) | 8 (33.33%) | 6 (25.00%) | 10 (41.67%) | 11 (45.83%) |
| High = 4 | 12 (50.00%) | 7 (29.17%) | 5 (20.83%) | 10 (41.67%) | 9 (37.50%) |
| Very High = 5 | 4 (16.67%) | 2 (8.33%) | 3 (12.50%) | 0 (0.00%) | 2 (8.33%) |
| Aggregate (Max 5) | 3.63 | 3.17 | 2.88 | 3.17 | 3.46 |
| Normalized (Min-Max) | 1.00 | 0.39 | 0.00 | 0.39 | 0.78 |

(a)

(b)



**UHI Intensity (°C)**
[1/2 STD]
- 0.00 - 1.04
- 1.04 - 1.42
- 1.42 - 1.81
- 1.81 - 2.19
- 2.19 - 2.57
- 2.57 - 2.95
- 2.95 - 3.33
- 3.33 - 3.72
- 3.72 - 4.10
- 4.10 - 5.17

**Heat Vulnerability**
[Class]
- 1 = Very Low
- 2 = Low
- 3 = Average
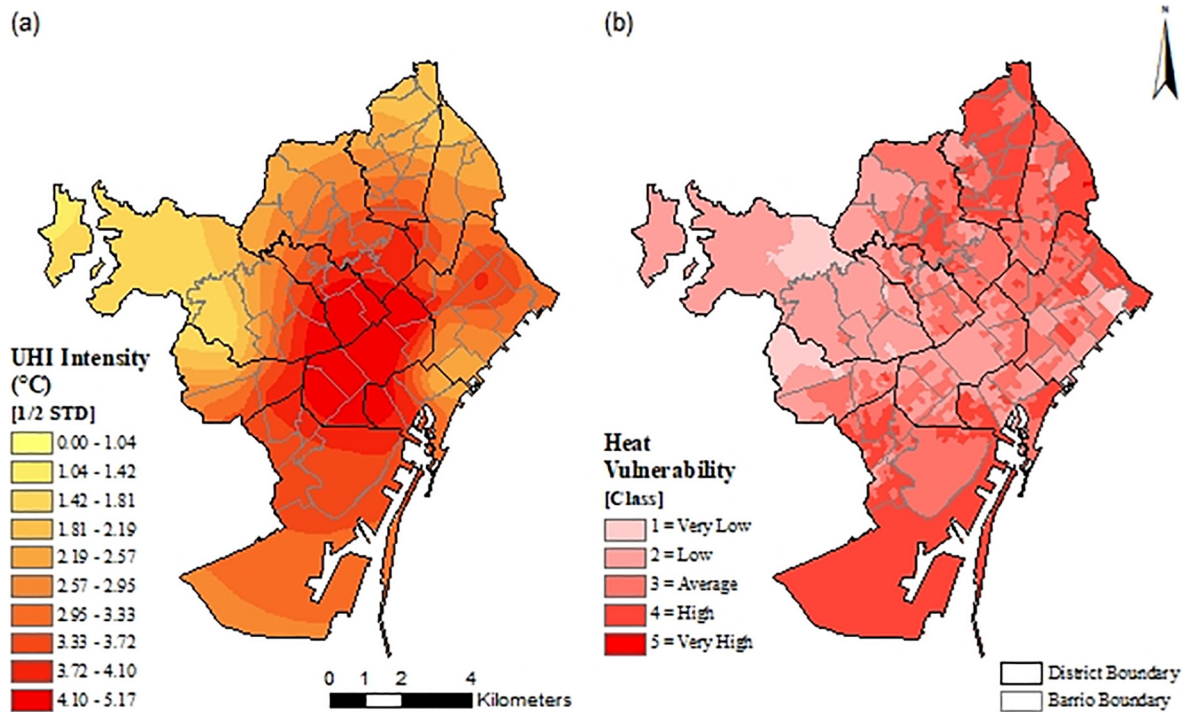- 4 = High
- 5 = Very High

District Boundary
Barrio Boundary

0  1  2    4
Kilometers

**Fig. 3.** Demand for thermal regulation. (a) Urban heat island (UHI) effect (Martin-Vide et al., 2015), (b) demographic vulnerability to heat (BCN, 2018a); STD - Standard deviation.

were selected, including walking distance to existing urban gardens (weighted 60%), population density (weighted of 30%), and grocery store count per neighborhood (weighted 10%).
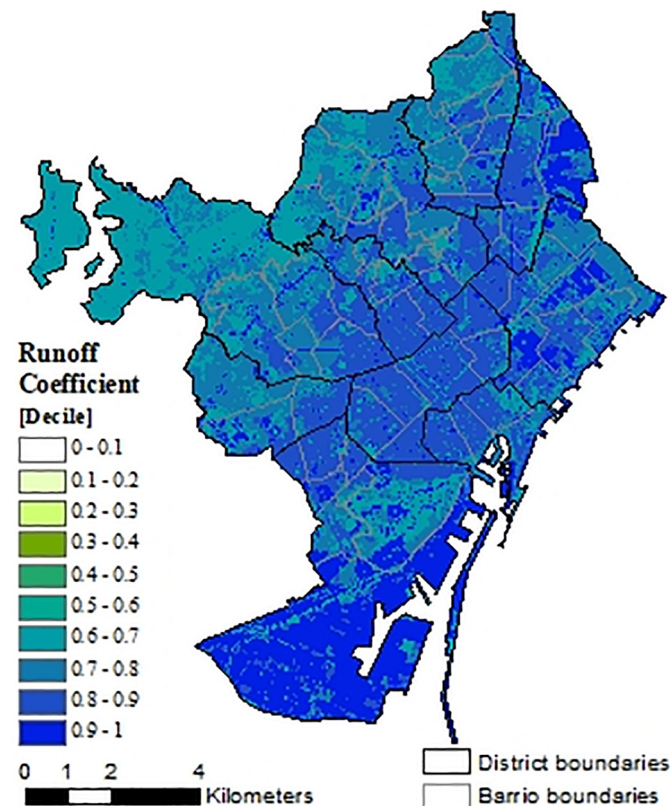


**Runoff Coefficient**
[Decile]
- 0 - 0.1
- 0.1 - 0.2
- 0.2 - 0.3
- 0.3 - 0.4
- 0.4 - 0.5
- 0.5 - 0.6
- 0.6 - 0.7
- 0.7 - 0.8
- 0.8 - 0.9
- 0.9 - 1

0  1  2    4
Kilometers

District boundaries
Barrio boundaries

**Fig. 4.** Demand for runoff control. Land-use based runoff coefficients (LCMC, 2009; Puccinelli et al., 2012).

*2.3.4.1. Garden network distance to community gardens.* While participation in urban gardens is highly variable, evidence suggests that most community gardens are predominantly utilized by residents of its immediate neighborhood (Meenar and Hoover, 2012). Thus, walking distance to existing urban gardens plays an important role in assessing the demand for new rooftop gardens. Excluding private and school gardens, 44 extant urban garden sites were obtained from Camps-Calvet et al. (2016) and the crowd-sourced Barcelona-Sostenible Map (BCN, 2018b). Utilizing a similar methodology to Meenar and Hoover (2012), the network walking distance around each garden site was calculated in ArcGIS as 300 m buffer service areas using a map of walkable Barcelona streets, created from the open-source OpenStreetMap (OSM) base layer (OSM, 2018). The resulting map shows Barcelona to be generally relatively well serviced by urban gardens, other than city outskirts and areas within the neighborhood of Sarrià-Sant Gervasi, although urban gardens are generally undersized and can only serve a relatively small number of beneficiaries, which is why the surrounding population density is critical to be considered.

To evaluate relative demand in HUGIN, a simple distance decay function was adapted from the formula for facility accessibility found in Giles-Corti and Donovan (2002), which was given an inverse relationship to demand and normalized to a 0 to 1 scale:

$$q(d) = 1 - \left(\frac{d_0}{d}\right)^{\beta} \qquad (1)$$

where $q$ is the relative demand for a new facility, $d$ is the distance to an existing facility, and $\beta$ is the facility-specific distance decay factor, assumed to be 1 for urban gardens.

*2.3.4.2. Population density.* While ES are inherently defined by their benefit to humans, certain services are felt more directly than others; for instance, a garden's vegetable harvest is more tangibly beneficial to a local user than its runoff absorption. Population density was therefore considered a mediator of demand for food production (as well as for recreation), which provide explicit and localized benefits to individual
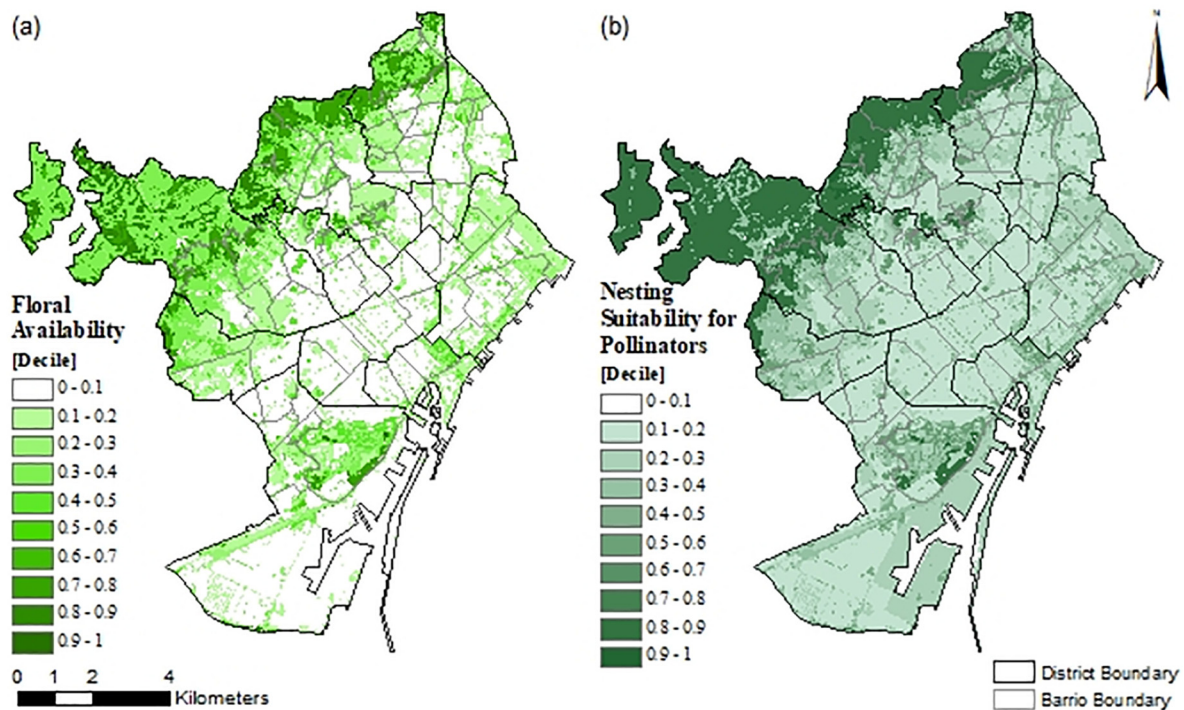
**Fig. 5.** Demand for pollinator habitat. (a) Floral availability and (b) nesting suitability for pollinators (ESTIMAP, LCMC, 2009; Zulian et al., 2013).

residents. Heat vulnerability and ethnic heterogeneity indicators already account for population distribution.

To calculate population density, a map of Catalonia was obtained from IDESCAT with the 2016 population distribution visualized in a multiresolution grid of 62.5, 125, and 250 m (IDESCAT, 2016), sized according to the quadtree method of Lagonigro et al. (2017) to ensure that each pixel contained a threshold of 17 residents. This grid was clipped to Barcelona city limits and converted to a 2 × 2 m resolution raster displaying people/ha (a lower resolution could have been chosen but we aimed at matching the resolution of the indicators with that of the rooftop layer, further described under Section 2.4.1). Population in Barcelona is centrally concentrated with the densest areas located in historical settlements like Ciutat Vella and Sant Andreu. This population density raster was classified into nine groups with a ½ standard deviation (STD) range and a null class with zero inhabitants.

*2.3.4.3. Neighborhood grocery store count.* Urban residents generally obtain their vegetables from markets and groceries, so the presence or absence of these facilities affects the need for alternate produce sources like GRs (Walker et al., 2010). Food accessibility has been studied extensively, often via GIS assessment of store density (Caspi et al., 2012). For this study, 2028 properties were selected from a geocoded list of all businesses in Barcelona (BCN, 2016b), labelled as 'Fruit and Vegetables' or manually identified using known supermarket chain names (e.g. 'Condis' or 'Dia'). When intersected with local neighborhoods in ArcGIS, grocery stores are found to be located predominantly within high-traffic areas such as Gràcia and Raval. The count of grocery stores was then classified into ten groups using the Jenks natural breaks method and scaled negatively and linearly to demand (Fig. 6).

*2.3.5. Recreational opportunities*

GI generally assumed to offer many opportunities for recreational activity (Bancroft et al., 2015) which, in turn, are associated with numerous health benefits (Sugiyama et al., 2014). The association between GRs and recreation, while lacking empirical quantification, is frequently cited in both academic and grey literature that mention potential for physical recreation through gardening activities, walking, and other

forms of physical activity, e.g. outdoor gym and yoga (Spala et al., 2008). We assume GR to partly compensate the lack of opportunities for "ground-based" recreation, given by walkability of streets, fitness facilities, and the availability of parks (Holliday et al., 2017). Therefore, neighborhood walkability was selected as primary indicator with 35% model weight, distance to existing sport facilities and neighborhood greenness were weighted 25% each, and population density (see Section 2.3.4) was attributed 15% weight.

*2.3.5.1. Neighborhood walkability.* Neighborhood walkability is a well-established indicator of physical activity within the built environment (McCormack and Shiell, 2011). Often estimated using proxy-based models with variables such as land use and network form (Lefebvre-Ropars et al., 2017), walkability can be accurately assessed via tabulating 'proximity journeys' of under 10 min that are typically local and non-motorized. Using a data set of 24,000 telephone interviews conducted in Barcelona as part of the 2006 regional Everyday Mobility Inquiry, Marquet and Miralles-Guasch (2015) analyzed the weekday travel of residents over 16 years of age and mapped the relative frequency of proximity trips at a neighborhood level. While most of the city was relatively uniform (22–27% of all travel), older, denser areas like the Old Town, Poble Sec, and San Andreu showed more (27–30%) proximity trips while lower walkability (19–22%) was observed in the districts of Sarrià-Sant Gervasi and Sant Martí. For the study model, these three classes were scaled linearly and negatively with demand.

*2.3.5.2. Sports facility distance.* The usage of sports facilities like gyms and sports fields for physical activity is greatly affected by distance to users' homes (Giles-Corti and Donovan, 2002). Network walking distance was calculated in ArcGIS using 100 m and 500 m service area buffers around sport facility locations, compiled from 466 addresses labelled as 'Sports' on the city commercial properties list (BCN, 2016b), along with 364 sports fields labelled as 'sport zones' on the Barcelona sub-parcel map (BCN, 2012) or with the composite land use 'sport areas' on the LCMC (2009). The resultant map shows sports facilities distributed generally evenly, with a slight lack of coverage in el Barri Gòtic and other non-settled outskirt areas. Demand
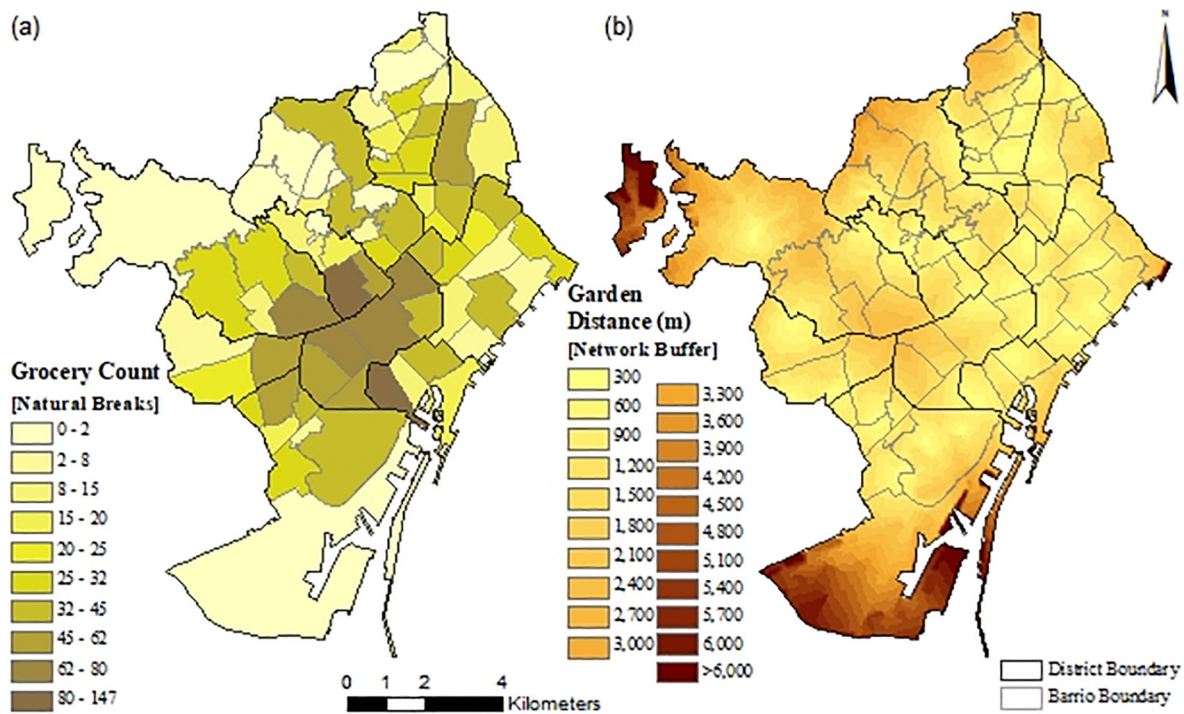
Fig. 6. Demand for food production. (a) Neighborhood grocery count, (b) walking distance to urban gardens.

was calculated using the distance decay formula (Eq. (1)), with $\beta = 1.16$ per Giles-Corti and Donovan (2002).

*2.3.5.3. Neighborhood greenness.* The location and ES supply of existing GI is assumed to lower the demand for new green spaces like GRs. While such provision is implicitly assessed in the model using land use-based indicators for some ES, we deemed an additional measure of greenness was necessary for recreation (as well as for social cohesion), as multiple studies suggest that GI mediates physical and psychological health through these mechanisms (Maas et al., 2009). Surrounding greenness was used as the chosen indicator over objective proximity to GI, per the findings of Dadvand et al. (2016). To quantify surrounding greenness, the normalized difference vegetation index (NDVI) of the city was obtained from the city, classified such that all NDVI values above 0.18 were considered as 'green' (Barcelona Regional, 2015). Subsequently, percent greenness was calculated for each census tract by dividing the 'green' area by total tract area. To account for proximity, this percentage was then added to the average percent greenness of all neighboring tracts, and the result normalized to a maximum of 1 (Fig. 7).

*2.3.6. Social cohesion*

Broadly characterized as interpersonal relationships that facilitate cooperation and trust (Chan et al., 2006), social cohesion is an intangible ES that is difficult to quantify yet forms a key component of urban life. GRs offer great potential to provide this as communal spaces that promote social interaction and a unique sense of place (Mesimäki et al., 2017), in line with numerous studies that suggest that GI potentially facilitates social cohesion (e.g. Maas et al., 2009; Markevych et al., 2017) and strengthens social ties (Kaźmierczak, 2013).

Further, allotment gardens can foster shared values and community identity (Langemeyer et al., 2018), suggesting a similar potential for rooftop gardens in particular. This study used two established indirect proxies to evaluate demand for social cohesion: income inequality and ethnic heterogeneity (Easterly et al., 2006). These indicators were each weighted 40% in HUGIN, with an additional 20% assigned to

neighborhood greenness (see Section 2.3.5) to account for the potential mediating effect of on the ground GI.

*2.3.6.1. Income differential.* Income inequality may be correlated with decreased social trust, particularly in poorer neighborhoods (Kawachi et al., 1997). To represent income inequality in Barcelona, this study used the city's Available Family Income (RFD) statistic, which combines Gross Family Income with education level, employment, car ownership, and real estate prices (BCN, 2016a). This indicator is calculated at the neighborhood level and compared against the average income of all Barcelona residents. As of 2016, the wealthiest areas were in eastern Barcelona around the Sarrià-Sant Gervasi and Les Corts districts, with the poorest located in the north around Nou Barris and south in Sants-Montjuïc. Data was then classified using 1/2 STD with demand increasing linearly and positively away from the mean.

*2.3.6.2. Ethnic heterogeneity.* Although subject to some debate among experts, ethnic heterogeneity has generally been shown to negatively affect social cohesion (Laurence, 2009). To calculate this heterogeneity in Barcelona, nationality statistics were used in lieu of ethnicity data, which is not collected in Spain (BCN, 2017a). The 178 nationalities present in Barcelona were grouped into ten cultural clusters per the GLOBE study (House et al., 2004; Mensah and Chen, 2013). Diversity between these groups was then calculated for each census tract using Theil's entropy score (Iceland, 2004):

$$E_i = \sum_{r=1}^{r} \Pi_{ri} \times \ln\left(\frac{1}{\Pi_{ri}}\right) \qquad (2)$$

where $E$ is the entropy of a tract, $i$, and $\Pi$ signifies the population of a particular ethnic group, $r$. Results of this calculation determined that Ciutat Vella and parts of Sant Martí are the most diverse areas of Barcelona, with less heterogeneity being observed further away from the coast. Entropy scores were classified by 1/2 STD and scaled linearly and positively with demand (Fig. 8).
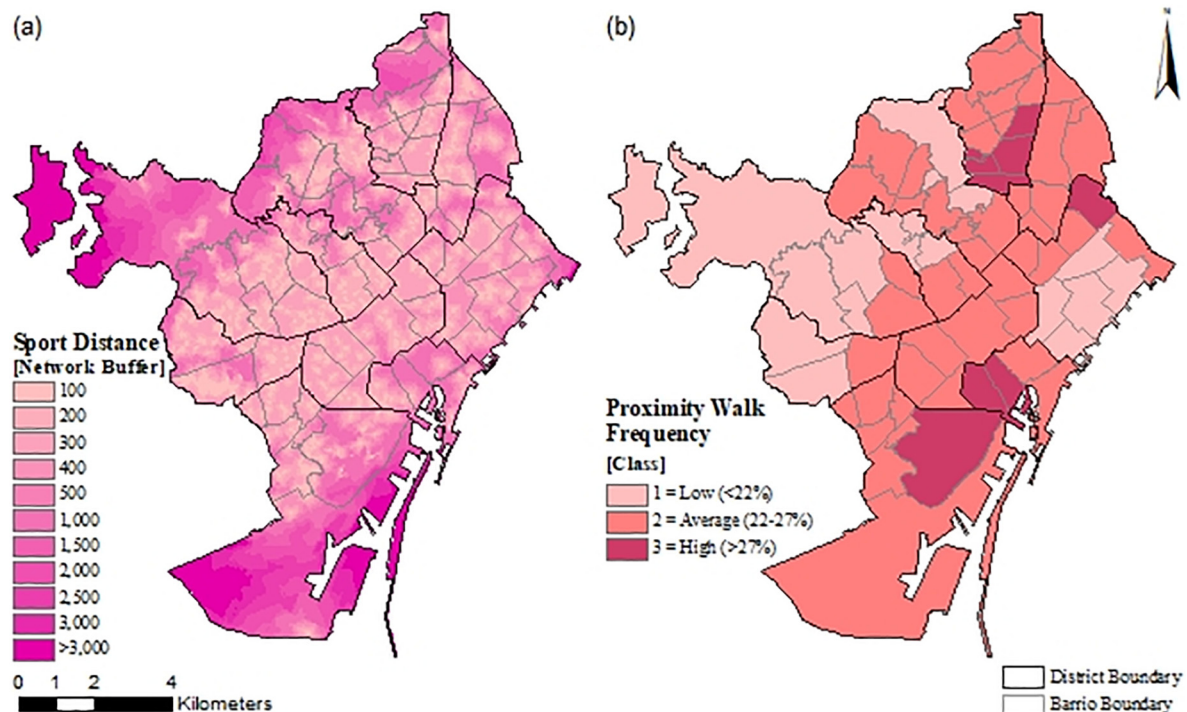
**Fig. 7.** Demand for recreational opportunities. (a) Walking distance to sport facilities, (b) relative frequency of proximity walks (Marquet and Miralles-Guasch, 2015).

## 2.4. Model construction

The spatial MCDA framework of this study encompasses two complementary BBN models. Firstly, an *ES demand model* assessed the deficit (or need) for six ES across Barcelona in order to identify where the implementation of GRs would have the most benefit. A second *ES supply model* evaluated the potential ES provision of each rooftop in the city under five GR design alternatives that best match the ES demand in a specific location.

### 2.4.1. Model structures

The study models were constructed using HUGIN Researcher v8.6, the original commercial BBN modeling software (Andersen et al., 1989). BBN modeling is grounded in fundamental probability theory dating from the 18th century, BBNs have been used since the 1980s for a vast array of applications, ranging from epidemiology to development of artificial intelligence (Barton et al., 2012). BBNs are a particularly useful tool for decision-support analysis as they can incorporate a wide range of both qualitative and quantitative data (i.e. expert opinion and experimental outputs), are easily updated as new information becomes available, and allow for both inductive and deductive reasoning (Chen and Pollino, 2012). For more in-depth information on how to build and evaluate BBN models see for example Kjærulff and Madsen (2013), Marcot et al. (2006), or Jensen (2001).

In a BBN, variables are graphically represented by nodes linked together within a non-looping causal network. Each node can exist in a number of possible states (i.e. nesting suitability on an index between '0' and '1'). The latest version of HUGIN can also spatially integrate with Geographic Information Systems (GIS) using a plug-in for the open-source mapping software QGIS. This tool links GIS raster layers to HUGIN nodes in a BBN, which are then calculated for each individual pixel creating a new output map.

Thus, the general modeling approach for both BBNs was to first obtain or create spatial indicators of ES demand using ArcGIS Desktop 10.6 and QGIS v 2.18.15 (for further details see Appendix E). All input rasters were standardized by resolution ($2 \times 2$ m), extent (Barcelona municipal limits), and projection (ETRS 1989 UTM Zone 31N). Layers were then assigned *input nodes* in HUGIN using numeric interval states (i.e. '0–0.5' and '0.5–1') corresponding to raster classifications appropriate to the data type. ES with different units were scaled in HUGIN to a standard index for direct comparison, as required by multi-attribute value functions in MCDA (Kremer et al., 2016). Additionally, results from the expert workshop were added as *weighting nodes* with numeric or labelled states (i.e. 'extensive' or 'intensive'). Finally, BBNs culminated in output *utility nodes* that used model-specific formulae to evaluate the demand of each ES. This utility was first calculated solely in HUGIN for baseline results, and then mapped in QGIS in order to visualize ES demand.

*2.4.1.1. Demand model.* For the demand model (Appendix F) input nodes, representative spatial indicators were selected for each ES (Appendix D). Indicator raster classifications were scaled to a standard index of potential demand between 0 and 1 using individual *scaling nodes* with decile intervals. Overall scaling was either positive or negative (i.e. demand rises with temperature but decreases with greenery) and followed a linear trend or distance decay curve.

Scaling nodes were then combined into a single *aggregate node* for each ES, weighted according to the relative weight of each indicator. This raw ES demand was further adjusted according to expert feedback on Barcelona's ES deficits and needs (Table 2) to evaluate expected utility.

The expected utility for each potential GR location is computed conditional on the ecosystem services provided at each location (L). The identification of a location $\delta(L)$ in the supply model determines the ecosystem services at that location before GR implementation. The expected utility associated with utility of ecosystem service (j) ($Uj$) is computed by summing the parent configuration over the product of the utility function and the joint probability distribution of the parent variables determining the ecosystem service (conditional on the choice of location):

$$EU(Uj|\delta(L)) = \sum_{W,Sj} u_{Uj}(W,Sj) * p(W,Sj|\delta(L)) \qquad (3)$$

where
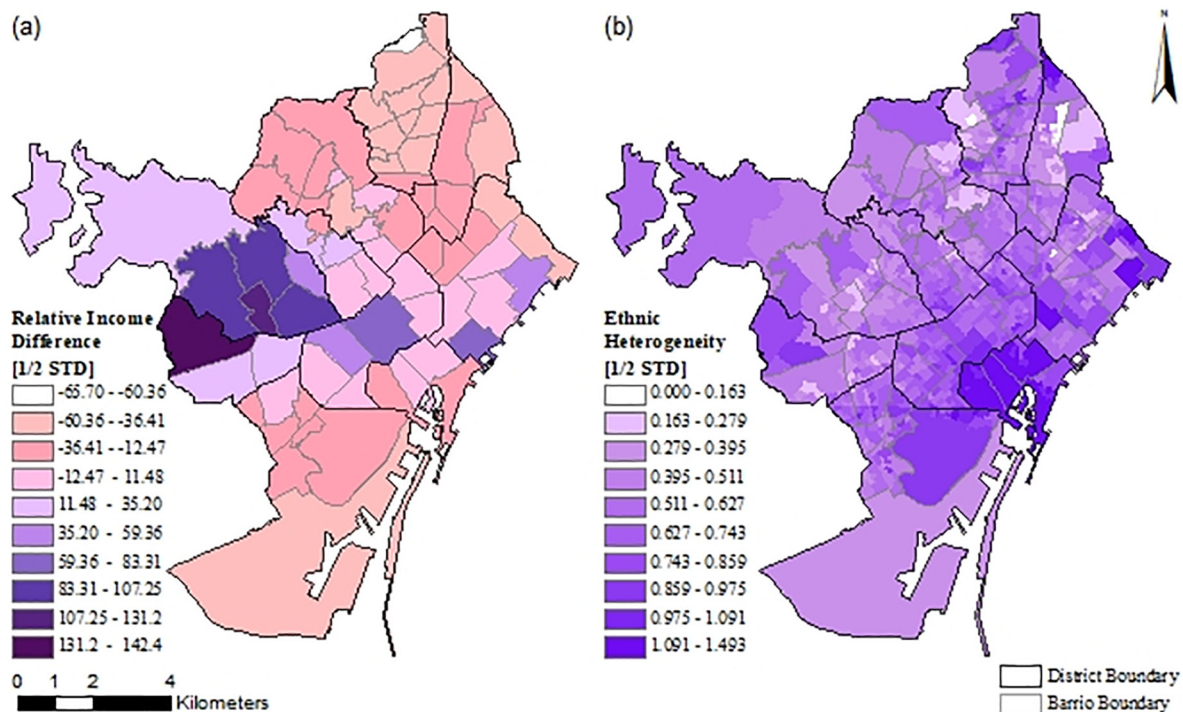
p( ) = marginal probability

**Fig. 8.** Demand for social cohesion. (a) Relative income difference assessed by Available Family Income (RFD), (b) ethnic heterogeneity assessed by entropy of nationalities. STD - Standard deviation.

W = stakeholder criteria weights

Sj = scaled ecosystem service j (each ecosystem service is scaled/normalized in order to be comparable)

The total expected utility at each location is the sum of the expected utilities (EU) of each service.

HUGIN software QGIS plug-in can be used to compute the Maximum Expected Utility (MEU) in all rasters which was mapped in QGIS to form an aggregate ES demand raster, along with the individual utilities of each ES.

*2.4.1.2. Supply model.* To create the spatial inputs of the supply model (Appendix G), the individual ES output rasters from the demand model were then clipped in ArcGIS using a masking layer depicting all rooftops in Barcelona, created from maps of Barcelona sub-parcels (BCN, 2012) and potential green roofs (BCNecologia, 2014). The resulting layers represent the modeled ES deficit at the location of the city's rooftops before GR are implemented. In HUGIN, these layers were given input nodes with twenty 0.01 interval states between 0 and 0.2.

Additionally, a *decision node* (D) was created with the five design alternatives as labelled states. This node was linked to six weighting nodes representing percent ES contribution, each with three 0.33 intervals between 0 and 1, matching the expert groups' evaluation of ES provision by different GR design alternatives (Table 3). Similarly, the decision node was linked to a feasibility weighting node (F), weighting the GR design alternatives with the individual Likert scale feasibility responses of the experts (Table 4), translated to 0.2 numeric interval states between 0 and 1. Expected utility nodes for each ecosystem service (j) produced by the GR design, were defined by the following expression:

$$EU(Uj|\delta(D)) = \sum_{F,Sj} u_{Uj}(F, Sj) * p(F, Sj|\delta(D))$$
$$= \sum_{F,Sj} u_{Uj}(F, Sj) * P(Sj|\delta(D)) * P(F) \qquad (4)$$

where

p() = marginal probability.

F = feasibility weighting of each green roof design

Sj = scaled unmet ecosystem service demand j potentially met by GR design

Only $(P(Sj|\delta(D))$ depends on the choice of GR design $\delta(D)$. This distribution is computed by inference in the BBN model. The total expected utility is the sum of the expected utilities of each GR design alternative.

Utility nodes for each ES were defined by the following expression:

$$P_s(a) = F(a) \times E_s(a) \times Q(s) \qquad (5)$$

where *P* signifies the expected utility of ES provided by GR, *s*, that each GR alternative, *a*, provides; *F* and *E* represent the expert-evaluated feasibility and extent of ES provision for each alternative, respectively; and Q indicates the full provision of each ES.

Five output maps were then created in QGIS representing the MEU for each of the design alternative decisions. These maps were analyzed and synthesized in ArcGIS to produce a single map depicting which GR design provides the highest potential contribution to ES provision.

The spatial outputs of the BBN demand and supply models depict aggregate potential ES deficit and provision across Barcelona, using standardized indices for each ES ranging between 0 and 1. These rasters were analyzed in ArcGIS (version 10.6.2) using Zonal Statistics to identify the rasters' maximum, minimum, mean, and standard of deviation at the city, district, and neighborhood scales. Supplementary results of the two models are presented in Appendix H.

## 3. Results

### 3.1. Demand model results

The output of the demand model, representing the weighted, aggregated ES demand across Barcelona, highlights clear areas where GR development should be encouraged. ES demand in Barcelona was lowest in the Collserola Natural Park in northwest, increasing dramatically as

the built environment densifies. Notably, both the minimum (0.306) and maximum (0.722) demand values were found in the Horta-Guinardó district, highlighting the extreme differences between Collserola and the urbanized neighborhoods adjacent to them. Indeed, potential demand was concentrated in the densely populated residential neighborhoods, generally located centrally (Raval, Barri Gòtic, and Eixample) but with several isolated areas of high demand present in the East (Besòs i Maresme) and North (Verdun, Teixonera, and Carmel). The largest mean district demand was observed in Sants-Montjuïc, which was responsible for almost a quarter of Barcelona's total demand and exceeded what would be 'expected' based on its area relative to the rest of the city by 2.2% (Fig. 9).

Disaggregated into individual ES, habitat for pollinators was identified as the most needed ES. Demand for thermal regulation was also high for all districts apart from Sarrià-Sant Gervasi and Les Corts, where it was surpassed by recreation and social cohesion. Demand for these cultural ES was important across the city, averaging 16.1% and 17.1% respectively of the Barcelona mean. Social cohesion was predicted to be the second most demanded ES, reflecting the high importance given to this ES by experts.

### 3.2. Screening tool results

The output of the screening tool estimated the potential ES provision potential of the five design alternatives for every rooftop in Barcelona and identified the highest contributing design for that location. The estimated potential ES provision of GRs in Barcelona was found to be relatively small, ranging from 0.12 to 0.28 on the index. By nature of the model design, the potential ES provision was relative to the aggregate demand, so Sants-Montjuïc was correspondingly identified as the district with the largest portion (20%) of Barcelona's aggregate ES provision. As an industrial zone, this district has several factories with large rooftops that collectively offer a mean potential ES provision of 0.23. This district mean is surpassed only by that of Ciutat Vella, which had the greatest mean provision due to its dense concentration of rooftops in an area of high need, similar to Eixample which had the third highest mean (Appendix H.4). At the neighborhood level, roofs with the highest ES provision generally correlated with the 'hotspots' of demand, although differences in rooftop density identified additional areas (Ciutat Meridiana, Roquetes, and Font de la Guatlla) that could be suitable for GRs (Fig. 10).
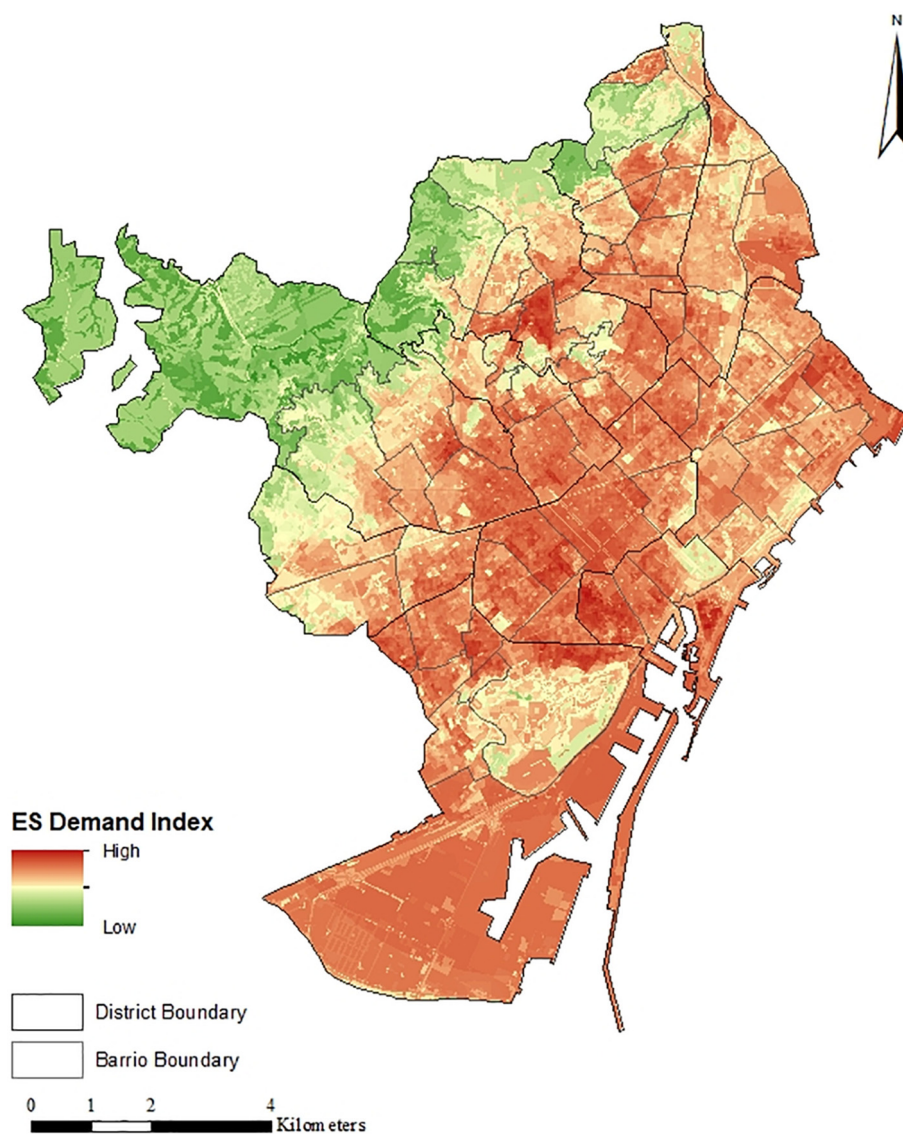


**Fig. 9.** Demand model output. The aggregated demand across Barcelona's ten districts for six ecosystem services (ES) calculated using fourteen spatial indicators in HUGIN Researcher and QGIS. ES demand is indexed between 0 and 1, and each district's portion of total city demand is displayed along with the percent difference of this value from what would be expected based on district area.
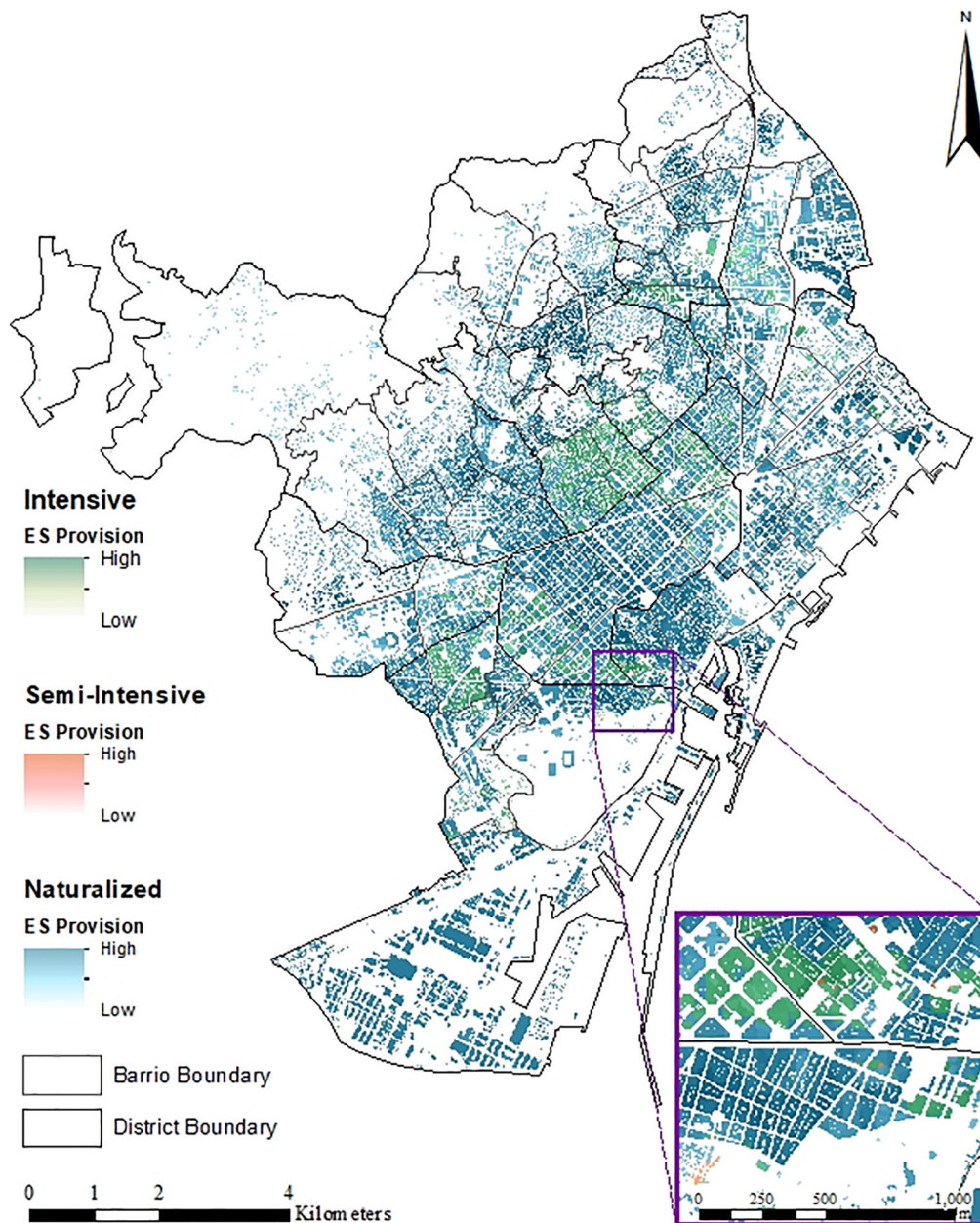
**Fig. 10.** Screening tool output. The maximum estimated ES provision of all rooftops in Barcelona if GRs were implemented, based on ES demand and expert weighting of five design alternatives. In each raster cell, the design alternative with the maximum ES provision was selected for mapping.

For the decision component, naturalized roofs were selected as the optimal GR design for the majority of Barcelona, accounting for 87.5% of rooftop area (Appendix H.2). Intensive roofs were picked for the bulk of the remainder and were deemed most effective in the neighborhood of Gràcia, where they were the chosen design for nearly half of the rooftops. Semi-intensive roofs accounted for only 0.05% of the rooftop area, despite a comparable city-wide mean provision to intensive roofs. Neither extensive nor allotment roofs were selected.

## 4. Discussion

### 4.1. Green roof prioritization

Results from the city-wide models operationalized in this study offer a number of findings that support future land use policy in Barcelona yet are also applicable to GI development elsewhere. From a prioritization perspective, the model identified numerous neighborhoods across

Barcelona where GRs could offer important NBS to the city's environmental challenges. As expected, the areas that are identified as priorities for GR tended to be densely populated urbanized neighborhoods, often with diverse residential populations. GR development in these areas could be directly beneficial to local communities, provided that design and implementation are undertaken with input from residents to preserve the character of the neighborhood (Anguelovski et al., 2017).

While the greatest potential GR benefits were concentrated in the continuous urban fabric of Barcelona's center, numerous areas of high demand of ES were also identified in communities located on the outskirts of the city, often adjacent to expansive areas of greenery like the Collserola mountain range. This suggests that proximity to green areas may have less of an impact on aggregate ES demand than more immediate factors like urban form or parcel land cover, as well as specific vulnerabilities and needs of the population. As there is considerable debate concerning the mechanisms by which green space services the local community (Triguero-Mas et al., 2015; Markevych et al., 2017),

planners should not preclude GR installation near existing GI nor assume the extent of ES provision based purely on level of 'greenness.'

In addition to the aforementioned residential areas, particularly high potential for GR implementation was found in the industrial park to the South of the city. Although only 20% of the land within this zone is covered by structures, the large area of individual factory rooftops offer significant potential for GR development, particularly if using low maintenance designs that provide regulating ES like thermal regulation and runoff control that are especially useful when considering impermeable surfaces common to industrial parks (Snodgrass and Snodgrass, 2006). Moreover, industrial roofs have been suggested as ideal sites for rooftop farming, although structural limitations like sloped or thin metal roofs must be factored into the planning process (Sanyé-Mengual et al., 2015). Nevertheless, this study's findings reinforce the notion that policymakers should consider all possible building types and future usages for GR initiatives.

We see potential in our modeling to inform spatially tailored GI policies. In Barcelona, it might help steering financial incentives provided by the City Council for the implementation of GRs, in terms of location and GR type. Applied to Paris, where the creation of green roofs is mandatory (in new buildings), it might help refining the requirements for GR designs; this might also be the case in New York City were a similar legislation is underway. Yet, the model was run with relative large amounts of input data, which might not necessarily be available in other smaller or global South cities. Nevertheless, the selection of indicators embeds some flexibility, allowing for adaptation to local data availabilities and complemented by expert judgment, as shown here with the capacity of different GR types to provide ES (Table 3). While such expert judgment involves its own limitations—as further discussed in the following—it can be invaluable where formal data is missing. It is also worth mentioning that the ES demand model is not limited to informing GR policies but might be applied to any other GI planning.

### 4.2. Green roof design considerations

The results of the supply model clearly indicate the primacy of naturalized roofs over other design alternatives in Barcelona. A possible explanation is that the high importance placed on habitat and pollination by the demand model translated to the naturalized roof alternative dominating its competition in the supply model. These results suggest that biodiversity and green connectivity should be prioritized by policymakers. Yet, another conclusion might be a need for recalibration of the model and the selection of additional indicators beyond the ESTIMAP model. However, some experts did indicate they consider naturalized roofs were essentially more effective extensive roofs, due to their similar design characteristics (see Table 1).

Such expert bias may also explain why allotment roofs rated so well for feasibility and estimated ES provision, despite a disproportionately low assessed need (by the experts) for Barcelona. Workshop participants toured a functioning allotment garden immediately before the workshop and were lectured about their dietary and social benefits, which certainly could have influenced their subsequent discussion. As these instances suggest, over-emphasis on qualitative expert inputs is an understandable critique of this study, as qualitative data in general can be perceived as suffering from subjectivity and generalization (Landuyt et al., 2013). However, this drawback can easily be addressed via additional workshops and future model calibration, i.e. explicitly incorporating probabilities and uncertainty measures related to qualitative data. The latter correction represents a strength of BBN-based analysis.

A more severe limitation in our study is given by the lacking availability of data on housing structure and the actual capacity of roofs to carry diverse types of GRs, including naturalized and intensive GR, which rendered the highest potentials with regard to ES deficits in the city of Barcelona, but which might also require important structural

investments to be implemented and which cannot be created on all types of buildings. Similarly, the relatively equal weighting of intensive and semi-intensive roofs could be attributed to underestimating the true economic and structural differences between the two alternatives. These considerations underscore that the provision of ES cannot be the only relevant criteria for the implementation of GRs. Economic, structural, and institutional barriers have only been treated superficially in this study, other relevant aspects, such as labor, water, energy, fertilizer needs have not been considered in this study but would most likely influence the final selection of GR alternatives considerably.

### 4.3. Model improvement

The spatial BDA framework proposed in this study represents a proof of concept, with significant opportunities for future refinement and expansion. For instance, the current BBN models would benefit from continued iterative development allowing for improved scaling via expert calibration or expanded scope based on stakeholder feedback (Marcot et al., 2006). Indeed, the expert workshop identified several priority ES for Barcelona –namely, air filtration, noise reduction, and environmental education– that may prove capable of improving the BBN's applicability to local policy goals. Additionally, the spatial indicators of the modeled ES could be expanded by more precise information (e.g. the size of urban gardens for food production would provide additional information on the deficit in food supply), updated with more recent data or augmented using emerging technological advances that allow for the remote identification of rooftop materials (Nadal et al., 2017). With such technology, a third BBN module could well be added to the framework for the purpose of predicting suitable GR by synthesizing a variety of structural, economic, and institutional factors.

Clearly there is significant room for development, particularly if the framework fully embraces the extensive functionality provided by HUGIN, such as the upcoming ability to visualize uncertainty over a geographic area following Landuyt et al. (2015). The model is highly sensitive to expert assumptions, the software's core probabilistic calculations offer a way of capturing uncertainty in expert judgment and identifying uncertainty of unobserved variables (e.g. roof and building loading capacity, subsoil characteristics). By way of example, one possible scenario could be to implement quantitative ES modeling of GRs, integrating model uncertainty (e.g. following Marcot, 2012). As this was not the focus of this investigation, the potential ES provision of GRs was estimated in a fairly simplistic manner using exclusively qualitative inputs derived from expert preferences. While this method has been used to estimate non-material ES like GR aesthetics (Lee, 2014; Loder, 2014), it could be improved with the introduction of experimental values from multiple sources. To account for spatial and experimental variability, uncertainty between this data could first be evaluated in HUGIN and then the merged with the expert preferences in an integrated and novel approach to assessing a GR's ES provision.

### 5. Conclusions

The novelty of this study lies in its multi-faceted approach to policy screening that is within the first of the field of GR research to incorporate cultural ES as well as a plurality of alternate design scenarios. This approach allows for holistic analysis of the myriad factors that affect the ES provision of GRs, resulting in an assessment of both potential ES demand across Barcelona (or any city) and the potential ES provision of five unique design alternatives. The study shows important insights to inform Barcelona's GR Strategy. The overarching model structure developed in this study is applicable to other locations and research questions. Indeed, parallel applications are ongoing for Oslo and New York City, which will allow for comparison between GR policy and provision across different cities. However, the application is constrained by large data availability and the possibility to collaborate with a diverse group of qualified experts, which might hamper its application elsewhere.

Although focused specifically on GRs, this study establishes a spatial multi-criteria screening approach that can address several pressing issues facing urban planners when seeking to prioritize any type of GI development or investment, for example estimating where investments in NBS are most effective and understanding what type of design goals should be emphasized to maximize ES benefit to local residents. The multi-criteria screening framework encompasses both material and non-material ES inputs and is powered by a modular BBN architecture that allows for easy modification and updating. Further, by integrating both quantitative and qualitative inputs, the framework offers results that are transparent, scientifically robust, and immediately relevant to stakeholder concerns.

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