

Interactive spatial planning of urban green infrastructure – Retrofitting green roofs where ecosystem services are most needed in Oslo

Zander S. Venter^a, David N. Barton^a, Laura Martinez-Izquierdo^b, Johannes Langemeyer^{c,d}, Francesc Baró^{c,h,i}, Timon McPhearson^{e,f,g}

^a Norwegian Institute for Nature Research - NINA, Sognsveien 68, 0855 Oslo, Norway

^b Nabolagshager, 0191 Oslo, Norway

^c Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona, Spain (UAB), Edifici Z (ICTA-ICP), Carrer de les Columnes s/n, Campus de la, Spain UAB, 08193 Cerdanyola del Vallès, Spain

^d Department of Geography, Humboldt Universität zu Berlin, Germany

^e Urban Systems Lab, The New School, New York, NY, USA

^f Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

^g Cary Institute of Ecosystem Studies, Millbrook, NY, USA

^h Vrije Universiteit Brussel (VUB), Geography Department, Pleinlaan 2, B-1050, Brussels, Belgium

ⁱ Vrije Universiteit Brussel (VUB), Sociology Department, Pleinlaan 2, B-1050, Brussels, Belgium

ARTICLE INFO

Keywords:

Green roofs
Ecosystem services
Participatory mapping
Urban planning
Green space

ABSTRACT

Spatial multi-criteria decision analysis (MCDA) is increasingly being used to inform urban green infrastructure planning. We explore the use of modern cloud computing technologies (Google Earth Engine) to facilitate public access to spatial MCDA of ecosystem services from green infrastructure. Using the spatial prioritization of green roof retrofitting in Oslo, Norway, as a case study, we present a web application that is a generalizable tool for engaging stakeholders in spatial planning of ecosystem restoration and nature-based solutions. In our application, green roof designers, owners and operators identified the relative importance of a suite of potential ecosystem services (ES) gained from retrofitting of green roofs, conditional on preference profiles expected by users of different building functional types. The ES assessed included temperature regulation, stormwater runoff mitigation, habitat for biodiversity, aesthetic value, and noise reduction. In Oslo we found high spatial correlation in ES deficits, implying that even large differences in stakeholder preferences for individual ES will lead MCDA to identify common interests in the spatial targeting of green roofs. Nevertheless, we found the interactive spatial MCDA web application to have potential for improving planning process efficiency in engaging stakeholders. In more heterogeneous urban landscapes, with lower spatial correlation of individual ES, spatial MCDA also has scope to improve the output efficiency of spatial targeting of nature-based solutions such as green roofs. Link to web application: <https://nina.earthengine.app/view/green-roof-mcda>.

1. Introduction

Green infrastructure is expanding rapidly in cities around the world as a nature-based solution for meeting multiple sustainability and resilience goals (Andersson et al., 2019; Frantzeskaki et al., 2019; Keeler et al. 2019). Green infrastructure has been described as a form of urban ecological infrastructure Childers et al., 2019 that can provide multiple ecosystem services (ES), or benefits to human health and well-being (Gomez-Baggethun and Barton, 2013). Given that cities face many challenges to achieve normative goals for more sustainable and resilient futures (Elmqvist et al. 2019), including climate driven extreme events (McPhillips et al., 2018; Depietri et al., 2018) and historical legacies of inequality (Grove et al., 2018; Locke et al., 2020), investing in solutions

that can deliver multiple benefits is critical, especially in the context of limited financial and other resources. Green infrastructure, precisely because of the multiple benefits it can provide from cooling, to stormwater absorption to sites for urban agriculture and recreation, has begun to go mainstream in policies, plans, and management strategies to improve urban livability (Andersson et al. 2019). Green infrastructure can have many components, including parks, rain gardens, community and allotment gardens, and green roofs.

Green roofs, like other forms of green infrastructure, are often hybrid green-grey infrastructure that integrate urban ecosystem components into the built form of the city (Depietri and McPhearson 2017). Benefits of green roofs can be many, but are also subject to the social, ecological, and technological contexts they are embedded in. A social-ecological-

<https://doi.org/10.1016/j.ecoser.2021.101314>

Received 2 October 2020; Received in revised form 20 May 2021; Accepted 6 June 2021

Available online 15 June 2021

2212-0416/© 2021 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

technological systems (SETS) framework has been used in urban ecology (McPhearson et al., 2016; Keeler et al., 2019) to understand that solutions such as green roofs depend on many aspects of the urban environment including: the structural integrity of building roofs, the maintenance and stewardship aspects, the local and regional climate, the type of green roof ecosystem designed and installed, the legal frameworks to enable green roof installation, and many other SETS contexts that interact to impact the benefits that green roofs can provide, including different perceptions of and preferences for benefits.

Green roofs provide both public and privately appropriated ES in urban areas, including improved storm-water management, better regulation of building temperatures and reduction of CO₂ emissions, reduced urban heat-island effects, increased urban wildlife habitat, reduced noise pollution due to the absorption of sound waves through soil and plants, enhanced community safety and quality of life, provide areas for recreation and opportunities to enjoy outdoor living spaces, contribution to local food production and boost the local economy creating jobs in many sectors (Susca et al., 2011; Turner et al., 2011; Whittinghill and Rowe, 2012; Berardi et al., 2014; Van der Horst et al., 2013). The retrofitting of green roofs on buildings that are often unused can also contribute to solving challenges related to climate change and rapid urbanization (Benedict & McMahon, 2002; Bugliarello, 2006).

Multi-criteria decision analysis (MCDA) has been advocated as a tool to integrate ES into green infrastructure planning (Saarikoski et al., 2016). MCDA theory is rooted in operational research (e.g. Mendoza and Martins, 2006) and provides a framework that supports decision-making in complex social-ecological systems (Garmendia & Gamboa, 2012; Munda, 2008; Saarikoski et al., 2019; Zia et al., 2011; EF). A common approach for developing an ES-based MCDA framework consists of several consecutive steps, which have been summarized by Langemeyer et al. (2016) as: (a) problem definition, (b) definition of *alternatives* (consisting, for example, of alternative land-use options), (c) selection of ES as *evaluation criteria* (and corresponding indicators to assess them), (d) scoring of criteria with regard to each alternative, (e) *weighting* of criteria (although the weighting is not necessarily made explicit), and (f) prioritization of alternatives through the application of an aggregation model. The latter follows different approaches to aggregate or compare the alternative, with regard to the evaluation criteria, such as un-weighted and weighted summation (e.g. Grêt-Regamey et al., 2013), Analytic Hierarchy Process (AHP) (Saaty, 1980), ideal point approaches, where a specific optimal target values for the criteria are defined (e.g. Opricovic & Tzeng, 2007; Sanon et al., 2012), and pair-wise-comparison approaches (Oikonomou et al., 2011) among others.

Integrated assessments of ES based on MCDA provide multiple entry points (a-f) for the engagement with stakeholders (Langemeyer et al., 2016, 2018). The inclusion of stakeholders in MCDA is most relevant (and most commonly applied) for the elicitation of criteria weights (Mascarenhas et al., 2016; Allain et al., 2017). Different stakeholder perceptions of the relative benefits from each ES are expected to be important in understanding trade-offs and conflicts of interest regarding planning priorities for green roofs. Drawing on Funtowicz & Ravetz (1994) and Fish et al. (2016), participatory approaches to establish weights are recommended in practical application of MCDA in land-use planning. However, the elicitation of criteria weights is often limited to a small number of stakeholders, through individual surveys or deliberative group exercises (e.g., Karjalainen et al., 2013; Srdjevic et al., 2013; Zhang and Lu, 2010; Zia et al., 2011), with potential implications of injustice (Langemeyer & Connolly, 2020; Venter et al., 2020c). The consideration of a wider range of stakeholder interests - especially in the MCDA weighting step - promotes a more differentiated green infrastructure decision-aid, and thus enhances the inclusiveness and relevance of integrated green infrastructure assessments.

While ES assessments are often applied at landscape scale with recommendations on spatial targeting of GI at the level of administrative units (e.g. García et al., 2020; Ramyar et al., 2020), applications to green roof spatial planning requires targeting with street, property and

structure level resolution (Daniels et al., 2018; Kuller et al., 2019; Langemeyer and Connolly, 2020). The evaluation of green roof implementations has recently been objective of spatial MCDA approaches based on the assessment of ES (cf. Langemeyer et al., 2020). These spatially explicit MCDA approaches indicate promising pathways for the selection of optimized green roof types and optimal geographical location for their implementation. Langemeyer et al. (2020) follow the innovative approach to target ES needs for effective green roof implementations, considering both accessibility of benefit providing green infrastructure as well as spatial distributions of social vulnerabilities. Yet, the two most advanced approaches (Langemeyer et al., 2020, focusing on Madrid and Barcelona, Spain, respectively), which we build on in this study are limited in the level of benefits and the amount of stakeholder objectives that have been considered, and thus provide a limited understanding of the tradeoffs and synergies between GI benefits/ES and applicability for urban green roof planners.

This study demonstrates the implementation of spatial MCDA to prioritize green roof locations at city scale with building resolution. In the Methods section, we describe the Oslo case study context, priority ES and the policy need for an application that identifies building sites where transforming existing roof space to green roofs would make the greatest potential contribution to priority ES in the city. Next we describe a survey of green roof owners, designers and operators used to identify potential variation in ES demand associated with different building functional types. We describe how this data provides the basis for importance weights attributed to ES in the MCDA. In the following section we describe the ES mapping data input to the MCDA. Next we describe the implementation of the MCDA in the Google Earth Engine (GEE) online web application, aimed at providing public user-customized access to the mapped ES input layers, valuation, and results. In the results sections we present the spatial analysis of ES deficits, and evaluate the trade-offs between different ES and the spatial prioritizations produced by different stakeholders in the MCDA model. We present interactive features of the GEE application aimed at promoting interaction with the data and results of the MCDA. Finally, we compare the GEE implementation of MCDA for green roofs with recent state-of-the-art applications. We discuss pros and cons in relation to the research application's support for municipal planning and implementation of green roofs.

2. Methods and materials

2.1. Study area and context

Oslo has been one of the fastest growing cities in Europe since 2000 (Oslo Kommune, 2013a, 2013b), attributed to high birth rates, intra-national migration, and international migration. Extensive residential development is limited by the Marka peri-urban forest greenbelt. The Municipal Plan to 2030–2050 proposes residential densification around transport nodes, and transformation of brownfields. Oslo's street level greenview index is 28,8% (Treepedia, <http://senseable.mit.edu/treepedia/cities/oslo>). Oslo's built zone has 47% green space cover, with 60 m² of regulated green space per inhabitant (Oslo Kommune 2018). Within the built zone additional surface area for green infrastructure at ground level is severely limited. However, Oslo's first Green Roofs Strategy proposal identified 14 million m² of existing flat roof space potentially suited for transformation to green roofs (Oslo Kommune 2018). The first Green Roof Strategy identified the following ecosystem service (ES) objectives in the city's planning of green roofs to 2030: better stormwater management, conservation of the city's biodiversity; spaces for recreation, socialisation, learning and experience; local food production; aesthetics; temperature regulation in and between buildings; improved air quality and noise mitigation; and CO₂ sequestration. The most recent Green Roof Strategy proposal simplifies the objectives of green roofs to include "nature, water, energy and health" (Oslo Kommune 2020).

The strategy is accompanied by a new norm introduced in 2019 for blue green factor (BGF) scoring of building permits (Oslo Kommune 2019). The BGF norm scores different types of green surfaces and qualities at property level, including green roofs, in terms of their relative contribution to: stormwater regulation and greenviews for recreation, further indicating the city's priority ES in implementing green infrastructure. The BGF implements a simple spatial targeting at city landscape level (Supplementary Material S1). Developers are required to achieve a minimum BGF score which is lower in the city core due to space limitations, and higher in mostly residential areas between the dense core and the peri-urban greenbelt. From its inception in 2014, Oslos BGF has undergone simplifications in response to property developers' claim that criteria and scoring are too complicated to implement.

Based on the above analysis of municipal strategies, plans and norms, we identified a need for an assessment tool for green roofs that is sufficiently detailed to differentiate properties' ES potential, while accessible enough to understand the input data, and model function. Between (i) the city wide zoning of residences around transport nodes, (ii) the broad two-zone differentiation in minimum BGF requirements and (iii) the detailed design of blue- green infrastructure at property level, there is potential for 'meso-level' spatial targeting of BGI that can differentiate priorities at neighbourhood and even street level. The Green roof MCDA App is designed to fill this 'planning space', while raising public awareness and demand for BGI through the visualisation of ES supply across the cityscape.

2.2. Stakeholder ecosystem service preferences

The App allows users to specify their personal ES preference weights, and to explore the implications of different weightings on spatial targeting of green roofs in Oslo. In order to provide users with a starting point for this exploration, we elicited ES weights from 12 green roof owners, managers and designers. ES weights were obtained in an in-depth interview lasting 1–1.5 hours in May–July 2019. Interviewees were selected based on their experience with different building functional types. Building functional types have different occupants with different preferences, and we selected interviewees to reflect these differences. The building functional types represented included urban farming, shopping mall, private residence, housing association, offices, community centre, protected/historic, theatre, hospital and hotel.

The interview was divided into three parts addressing (1) the type of

building and green roof the interviewee had experience with, (2) barriers and opportunities to transformation of existing roofs in Oslo, (3) relative importance of private and public benefits from ES for building functional types, and ecosystem profiles of basic green roof designs. The ES benefit weights from part 3 were used to generate the default preference profiles in the App for the private and public benefits from ecosystem services. Here, "private" refers to benefits enjoyed on property, and "public" refers to benefits enjoyed off-property/in the neighborhood around the property with the green roof. The full interview guide can be found in Supplementary Material S1 and the resulting MCDA weight profiles in Supplementary Material S2. The resulting default preference profiles for ecosystem services from the different building functional types in the App are shown in Table 1.

2.3. Ecosystem service criteria, scaling and deficit mapping in MCDA

The spatial prioritization of green roofs was based on a multi-criteria decision approach where criteria are defined by a number of GIS mapping layers (Table 2) that identify urban ecosystem conditions at building level resolution across the city. Layers identify ecosystem condition in service areas around each roof as proxy indicators of the regulating, provisioning, cultural and supporting service deficit and potential of green roofs (Fig. 1). Low ecosystem condition areas are defined as ES deficit areas (Langemeyer et al. 2020). These are normalized by census district population density to identify areas with the highest population weighted exposure to ES deficit. Population density has been used a proxy for potential demand (Vallecillo et al., 2018). The MCDA assumes a utility function in municipal green roof planning where buildings in areas with highest population weighted ES deficit are priorities for transformation to green roofs. We used the Google Earth Engine (GEE) JavaScript API (Gorelick et al., 2017) to generate the mapping layers and implement the MCDA. GEE is a cloud-based platform for geospatial analysis that leverages Google's computational infrastructure to make GIS and remote sensing analyses more efficient and scalable.

We used a map layer of about 53,000 roofs (>10 m² surface area and < 30 degree slope) identified in the Oslo Green Roof Strategy as feasible roof area for green roof installation (Oslo Kommune 2018). Following the logic of a spatial MCDA (Langemeyer et al. 2020), each roof is an alternative subject to a targeting decision.

Land surface temperature data was used to map the distribution of heat over the city which defines areas in need of green infrastructure to

Table 1
Ecosystem service importance weights by stakeholders building functional types.

	Ecosystem service:	Private benefits on property from:		Public benefits in neighbourhood from:				
		On property greenview	On roof street noise mitigation*	Temperature regulation	Stormwater regulation	Habitat for pollinators	Street greenview	Green space amenities
Building functional types:	Urban farming	0.1	0.1	0.1	0.4	0.1	0.0	0.1
	Shopping mall	0.0	0.0	0.2	0.2	0.2	0.2	0.2
	Private residence	0.1	0.1	0.0	0.3	0.2	0.2	0.2
	Housing association	0.2	0.2	0.0	0.2	0.2	0.1	0.2
	Offices	0.2	0.2	0.0	0.3	0.2	0.0	0.2
	Community centre	0.0	0.0	0.0	0.4	0.4	0.1	0.1
	Protected/historic	0.1	0.1	0.1	0.3	0.1	0.1	0.1
	Theater	0.1	0.1	0.0	0.5	0.2	0.0	0.2
	Hospital	0.3	0.3	0.1	0.2	0.2	0.1	0.0
	Hotel	0.0	0.0	0.2	0.4	0.1	0.1	0.1
	Average	0.11	0.11	0.07	0.31	0.18	0.09	0.13
CICES 5.1 code:		3.1.2.4	2.1.2.2	2.2.6.2	5.2.1.2	2.2.2.1	3.1.2.4	3.1.1.1
Green Roof Strategy criteria								

*Note: on private property ecosystem services have the same default importance weights (see Supplementary Material S1). (CICES v5.1 codes for each ecosystem service <https://cices.eu/resources/>).

Table 2

GIS mapping layers of ecosystem condition used in the MCDA of green roof targeting in Oslo. Related ecosystem service (ES) deficit categories are highlighted in color including regulating (R), provisioning (P), cultural (C), supporting (S) services. All layers are scaled by population density to represent relative population exposure to ES deficits.

Layer name	R	P	C	S	Description
On property greenview					Percentage green space based on property-level vegetation cover as a proxy for proximal green space deficit
On roof street noise mitigation					Modelled street level noise levels as a proxy for noise reduction deficit
Temperature regulation					Land surface temperature during July 2018 heat wave as a proxy for temperature regulation deficit
Stormwater regulation					Modelled stormwater runoff based on property-level land cover as a proxy for stormwater regulation deficit
Habitat for pollinators					Pollinator habitat suitability within 250m of each roof as a proxy for biodiversity deficit
Street greenview					Spatially-interpolated green view index at street level as a proxy for proximal green space aesthetics
Green space amenities					Percentage public green space within 250m of each roof as a proxy for distal green space deficit
Population density					Residential population density 250m grid as a proxy for population exposure to ES deficits (potential demand)

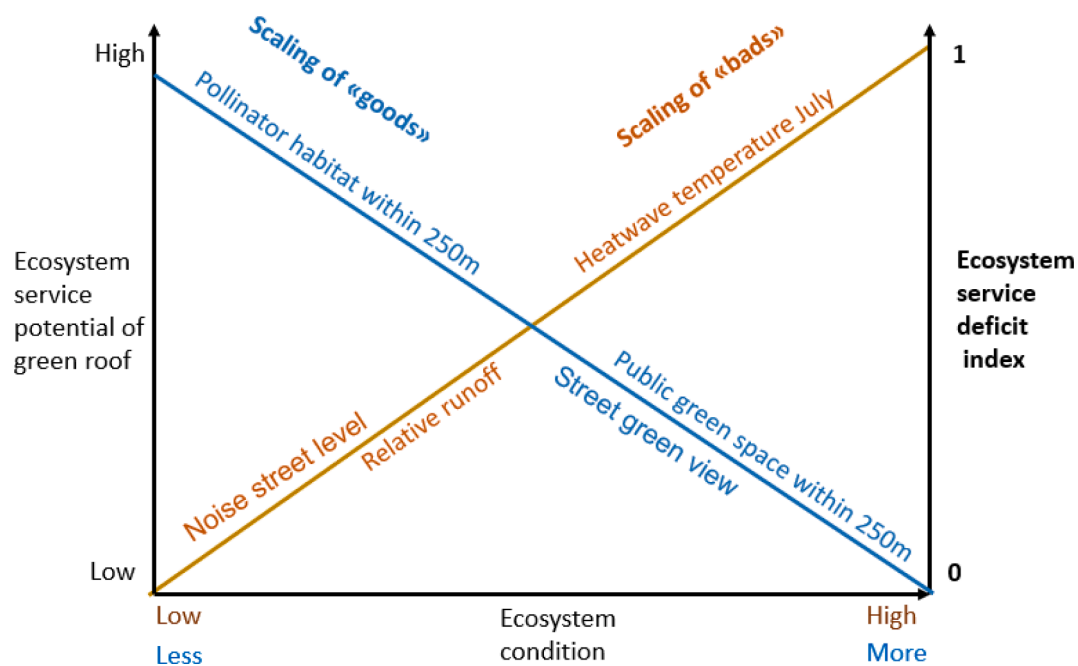


Fig. 1. Scaling of ecosystem condition to represent ecosystem service deficit and potential supply by green roofs.

deliver heat regulation services. We calculated satellite-derived land surface temperatures from Landsat 8 OLI/TIRS sensors using the single-channel algorithm developed by Jiménez-Muñoz et al. (2008) and elaborated on in Venter et al., (2020b). Data were collected over July 2018 during which Norway experienced a severe heatwave.

To define areas in need of stormwater runoff regulation, and are therefore priorities for green roofs, we employed a mechanistic hydrological model based on the rational formula to map annual runoff at the property level. The primary model inputs include terrain slope, property dimensions, and surface land cover with associated runoff coefficients. We used the Norwegian Digital Terrain Model data to measure property slope and a Sentinel-2 land cover product (<http://urban.nina.no/>) to define grass, tree and impervious surface area. These were ingested into the model to estimate runoff assuming a mean annual rainfall of 800 mm and a one in 20-year storm event. For details about the runoff model please refer to Sælthun et al. (2021).

Green roofs offer habitat for urban biodiversity as provisioning and supporting ES. We used pollinator habitat suitability as a proxy for biodiversity distribution within the city. Roofs that are located in areas with low pollinator habitat suitability are therefore priorities for planting green roofs. We used a pollinator suitability map produced by expert weighting of an urban land cover map (Stange et al., 2017; Zulian et al., 2013)) to calculate pollinator habitat within 250 m of each roof in the city. We used 250 m because this is the typical foraging distance of wild bees which are keystone species in urban biodiversity assemblages.

To identify properties with very little existing green space, and therefore priorities for green roofs, we mapped green space at three levels: on-property, on-street and neighborhood. On-property green space was calculated as the percentage vegetation (tree, shrub and grass) cover within each city property. The vegetation cover was derived from the same Sentinel-2 land cover product as used in the stormwater runoff model. We calculated on-street greenness using the green view index data for Oslo provided by the Treepedia project (Seiferling et al., 2017). The green view index quantifies the amount of green space perceived by a person walking along a street using Google Street View imagery. To characterize distal or neighborhood green space, we calculated the percentage of public green space within 250 m of each city roof. Here public green space was defined as parks and green corridors digitized by the Oslo Bymiljøtaten.

Green roofs may act as outdoor refuges from street level noise pollution. We used a high resolution city noise map for Oslo (Oslo Kommune, 2013a, 2013b) to identify roofs located in noisy areas that would most benefit from green roofs.

Finally, to estimate the spatial distribution of potential exposure to ES deficits and potential demand for ES from green roofs, we used a map of population density at 250 meter resolution supplied by the Statistics Norway (<https://kart.ssb.no/>). Population density is multiplied by the weighted sum of ES deficit, and can be switched on/off to assess differences in priorities with and without a proxy indicator of demand. With a 250 m grid resolution population density is a proxy for residential and neighborhood ES exposure, but not exposure associated with commuting, workplace, shopping and recreation away from home.

2.4. MCDA implementation and online web application

To maintain computational efficiency we used a simple weighted average of GIS criteria layers to produce the final MCDA prioritization layer. All GIS input layers were first normalized between zero and one using the 5th and 95th percentile values to define the data range. This was done to prevent outlier values from skewing the normalization process. Stakeholder weightings were used to assign relative weights to each GIS input layer and then a weighted average was calculated. This approach assumes that planners would also use a linear additive utility function to prioritize green roof locations. The resulting map defined the prioritization of areas for green roofs ranging from zero (low priority) to one (high priority).

Apart from its utility to perform computation and analysis of large datasets, GEE allows for the programming of an interactive user interface known as a GEE web app. These online web applications allow one to deliver spatial data and results in an interactive map to end users who have no GEE credentials or scientific background. The web apps are developed in the GEE JavaScript API and are designed to facilitate science communication and act as “sandbox” environments to develop prototype web applications that can later be developed into more complex applications using the Google App Engine and Python API or similar. We programmed a web app to deliver the green roof MCDA as a tool to support municipal zoning in the implementation of the Green Roof Strategy of Oslo and for increasing public interest and engagement with spatial planning of green infrastructure. We coded for a user interface with widgets that allow users to toggle different GIS input layers, assign various criteria weightings and then render and compare the resulting prioritization in real-time. The background MCDA computation (weighted average of input criteria) takes place in raster format at 1 m spatial resolution. The raster format is a matrix/gridded geospatial data format that can be used for efficient computation at any spatial scale. All inputs and outputs are clipped to the building roof geometries in Oslo.

A beta-version of the App was presented to researchers and stakeholders during a workshop (October 2019) to evaluate and suggest improvements to app functionality. Three of the participants had been interviewed to obtain default preference profiles (urban farming, private residence, office) for the MCDA.

3. Results

3.1. Ecosystem service deficits

There were 53,000 roofs within the Oslo built-up zone that were used in the spatial prioritization exercise. The ES deficit scores vary substantially over the city with large ES deficits for roofs in the city center and low ES deficits for roofs in the city outskirts (Fig. 2). ES deficits appear largest in areas with the highest population density which is due to the associated building density and lack of surrounding green space. High density population areas are used as a proxy indicator for demand for ES. By this measure ES supply is not adequately matched to demand over space.

3.2. Ecosystem service trade-offs

We found that there were no clear spatial trade-offs between ES in Oslo (i.e. one ES increases while another decreases). Instead, many ES were correlated over space. A cluster of ES that are positively correlated include habitat for pollinators, greenspace amenities, and street greenview (Fig. 3). Another cluster includes on property greenview, stormwater regulation, and temperature regulation. None of the ES were negatively correlated over space and therefore we did not expect to see significant trade-offs between stakeholder preferences. Therefore differences in MCDA criteria weightings were not expected to produce strong contrasts in spatial targeting of green roofs in that most stakeholder profiles will result in high priority scores for roofs in the city center with relatively little vegetation ground cover.

3.3. MCDA spatial prioritization outputs

As stated, many ES criteria layers are already strongly correlated over the city with no strong trade-offs (Fig. 3). After calculating the weighted-average ES deficit scores (i.e. green roof priority scores) based on the stakeholder-specific weightings in our MCDA, as expected prioritizations were strongly correlated to one another also across stakeholder preference profiles (Fig. 4).

The one outlier was the community stakeholder profile which was negatively correlated to the hospital, hotel and office profiles (Fig. 4).

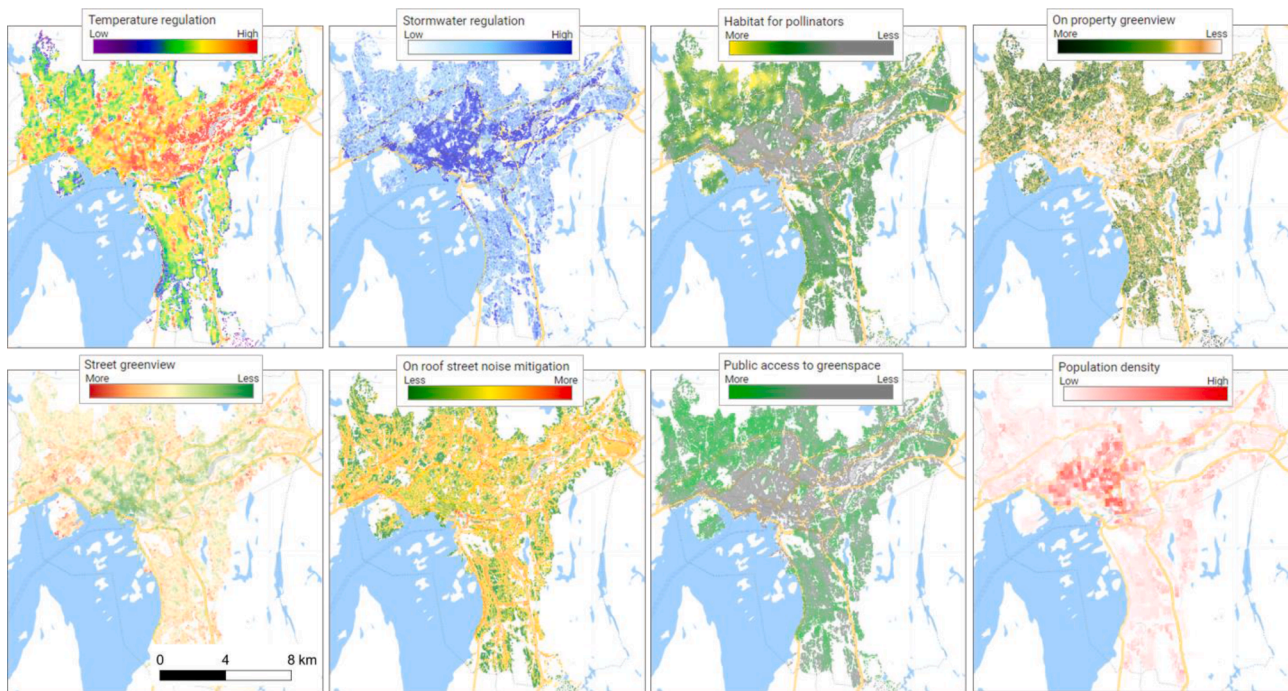


Fig. 2. Maps showing spatial distribution of GIS map layers of ES deficit used in the MCDA of green roof targeting in Oslo. ES deficit layers are based on rescaled ecosystem condition so that they represent a proxy for ecosystem service deficit ranging from low to high deficit (left to right of color bars; see Fig. 1 for explanation). Please refer to Table 1 for layer descriptions.

The community stakeholder profile attributed higher priority to stormwater runoff mitigation and biodiversity ES criteria relative to hospital, hotel and office stakeholders (Table 1). Stormwater runoff and biodiversity ES layers are more diffuse over the city and therefore this results in a more diffuse prioritization of roofs for green roof establishment. This relative comparison is illustrated in Fig. 5. Community centre stakeholders weighted biodiversity and stormwater regulation as higher priorities compared to hotel stakeholders, reflected in the higher priority placed on roofs with a deficit of green infrastructure surrounding them (blue coloured buildings in Fig. 5).

3.4. Web application functionality enabling stakeholder engagement

The primary output of the green roof MCDA web application is a map of the weighted sum ES deficits indicating green roof priority for different stakeholder profiles. Users are able to toggle between profiles and explore the distribution of green roof priorities by zooming in and out and panning across the city. Users can also input their own hypothetical ES criteria weightings and render the MCDA result on-the-fly. We also catered for the ability to compare priority maps from contrasting stakeholder profiles using a screen slider widget (see center panel in Fig. 5). Users can slide over the zoomable map and explore roofs that are under- or over-prioritized relative to a contrasting stakeholder profile. This could help with stakeholder dialogue about the trade-offs of prioritizing a specific building for green roof development.

A further functionality of the web application is the ability to click on individual building roofs to extract ES criteria weightings specific to that roof (Fig. 6). In this way, users can begin to investigate why some roofs are prioritized over other roofs and how this varies across space at both the neighborhood and city scale.

Population density is applied as a scaling factor to ES deficit (Fig. 7) providing a proxy indicator for areas of highest demand defined as highest aggregate population deficit exposure. When applying the population density scaling the MCDA identifies a band of optimal green roof locations in central residential neighbourhoods, but not in the commercial city centre.

4. Discussion

The study presents an MCDA web application to engage with stakeholders in GI design in a way that is intuitive for people. The approach opens new pathways for capturing 'plural values' (Arias-Arévalo et al., 2018; Cooper et al., 2016; Kenter, 2016), considering diverse societal needs and preferences at city scale, which potentially allows to overcome core shortcomings of deliberative group valuation in attendance, such as limited stakeholder representation, dominant value framings and power dynamics (Kenter et al., 2016; Lo & Spash, 2013; Wilson & Howarth, 2002), while information about trade-offs both between ES and between different stakeholder perspectives is interactively available within the valuation phase.

4.1. An informed valuation approach

A deliberative valuation process is especially useful when the decisions at stake demand compromise solutions among a limited number of stakeholders (Langemeyer et al., 2018). By contrast our spatial MCDA might be called an *informed valuation* approach, which has its strength in emphasizing societal differences in ES preferences and inequalities in the access of benefits across larger numbers of stakeholders and larger scales. An informed valuation approach enhances stakeholder knowledge and enables them to make better informed choices on criteria weights. Although similar web-based MCDA tools have been developed before (e.g. Padró et al., 2019), these are so far lacking a broader differentiation in objectives in order to become useful tools for supporting ES trade-off analysis from a stakeholder perspective. In this vein, it is important to highlight that even those MCDA approaches that put emphasis on the analysis of trade-offs between ES (e.g. Grêt-Regamey et al., 2013) or between different stakeholder groups (e.g. Munda 2008), are generally targeted to inform decision makers and show limitations in establishing informed criteria weights. However, the informed valuation approach applied here does not only inform stakeholders, but also widens the evaluative space for planners and policy-makers allowing for a deeper understanding of contextual and perceptual factors that

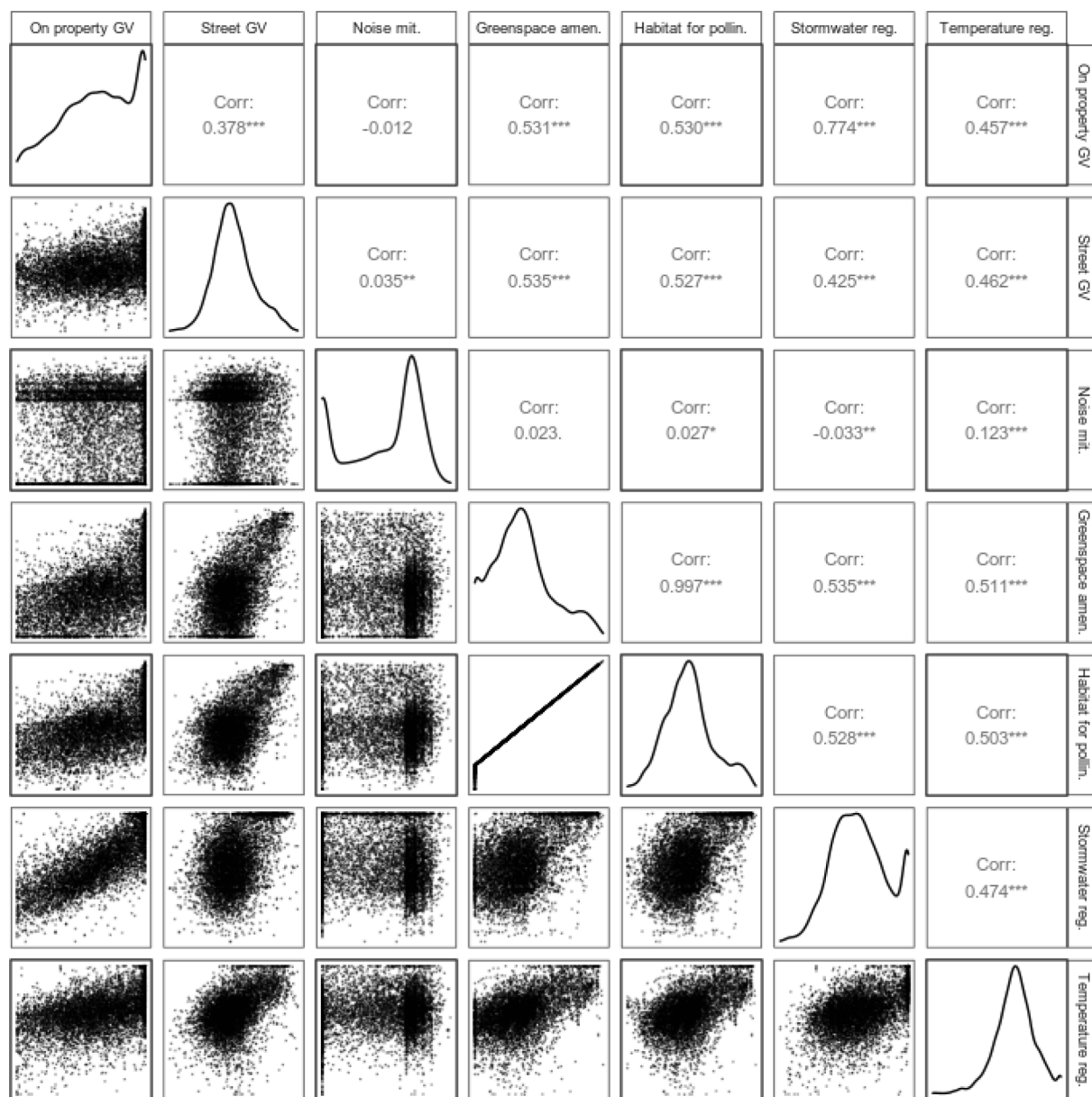


Fig. 3. Correlation matrix between ecosystem service scores for roofs ($n = 53,000$) in Oslo. All ecosystem service scores are scaled between 0 and 1 and therefore no X- and Y-axis text is shown. The lower part of the matrix shows the scatter plots for ecosystem services combinations where each point represents an individual roof in the city. The upper half of the matrix shows the Pearson correlation coefficient and the level of statistical significance. The variable distribution is shown on the diagonal. Abbreviations: GV (greenview; mit. (mitigation); amen. (amenities); pollin. (pollinators); reg. (regulation).

enhance ES benefits.

4.2. Stakeholder feedback and uptake potential

A workshop to evaluate the beta-version of the app revealed a differentiated picture of pros and cons of an interactive tool to raise awareness about ecosystem services (ES). Workshop participants appreciated the overview of ES gradients at city level. The clearly delineated ES deficit of the city centre was commented on as relevant input to municipal planning. Workshop participants quickly, and without further technical instruction, engaged the different ES map layers. They started to use the tool to zoom in to familiar neighbourhoods and buildings. This interactive functionality with map scale and resolution revealed a counter-intuitive drawback of the tool. One participant remarked that he had expected using the zoom function to be like “parachuting” - the closer you get to the ground the more detail you

expect to see. While the satellite image of landcover has high resolution, the ES maps have lower resolution, and because of smoothing functions employed across service areas, display little variation when zoomed to street or building level. Some participants expressed disappointment that individual buildings did not present discrete ES values differentiating them from adjacent buildings. An explanation offered by the model developers was that the tool does not represent the effects of potential green roof designs on the building. Users were disappointed that building functional types were not identified for each building. Consequently, the app does not provide guidance on what green roof design is recommended for a building that is identified as being in a high deficit area. A further weakness in the GEE functionality that was observed concerned the inability to save, store and aggregate preference weightings across many users. The results can be saved only by doing a screen copy. The purpose of the GEE app was explained as providing a “sandbox” to discuss decision-support tool features desired by

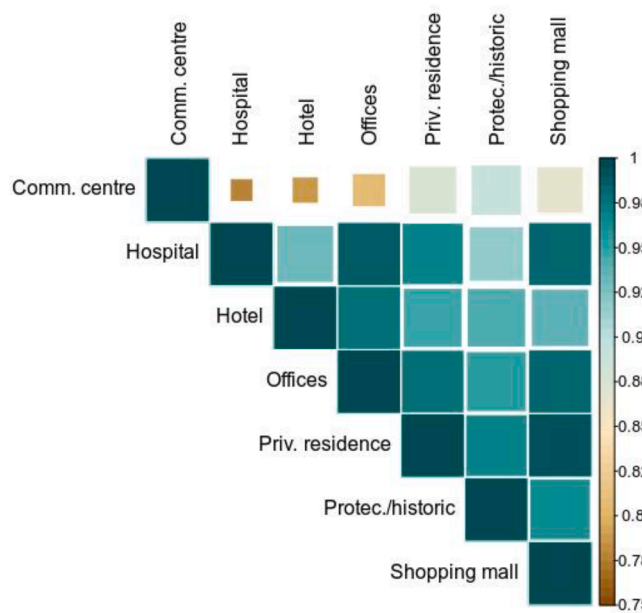


Fig. 4. Correlation matrix for weighted-average ES deficit scores (i.e. spatial prioritization scores) under different stakeholder profiles. Correlations are based on prioritization scores for all roofs in Oslo ($n = 53,000$). Pearson correlation coefficients form the basis for the size and the color of each square.

stakeholders. More advanced user interface and database features would need to be programmed in more flexible environments.

4.3. Ecosystem service valuation assumptions

From a technical MCDA modeling perspective we acknowledge that the linear utility function assumed by the weighted summation of normalized ES scores is a simplification. It also assumes that all the value functions scaling ES are linear and deterministic. It was implemented here due to its simplicity in obtaining preference profiles and its computational efficiency in providing summary maps of different preference profiles in real-time. More flexible non-linear valuation functions with uncertainty ranges (Beinat 1997) have been implemented in a spatially explicit Bayesian network model (Langemeyer et al. 2020). The Bayesian network model was not possible to implement in the GEE modeling environment.

4.4. Decision-support constraints and opportunities

A possible drawback of the modeling process we adopted was an apparent research-driven definition of the decision objective and criteria. We identified the spatial targeting purpose of the model based on a desktop study of municipal plans, strategy and norms, supplemented by individual interviews. ES included in the app were compatible with documented municipal policy priorities, but the desktop-based approach did not open up for possible innovations in e.g. new criteria for priority-setting that could have emerged from a group-based co-creation approach (Langemeyer et al. 2020). A defence of the modeling approach was that a consultative co-design process was followed in development

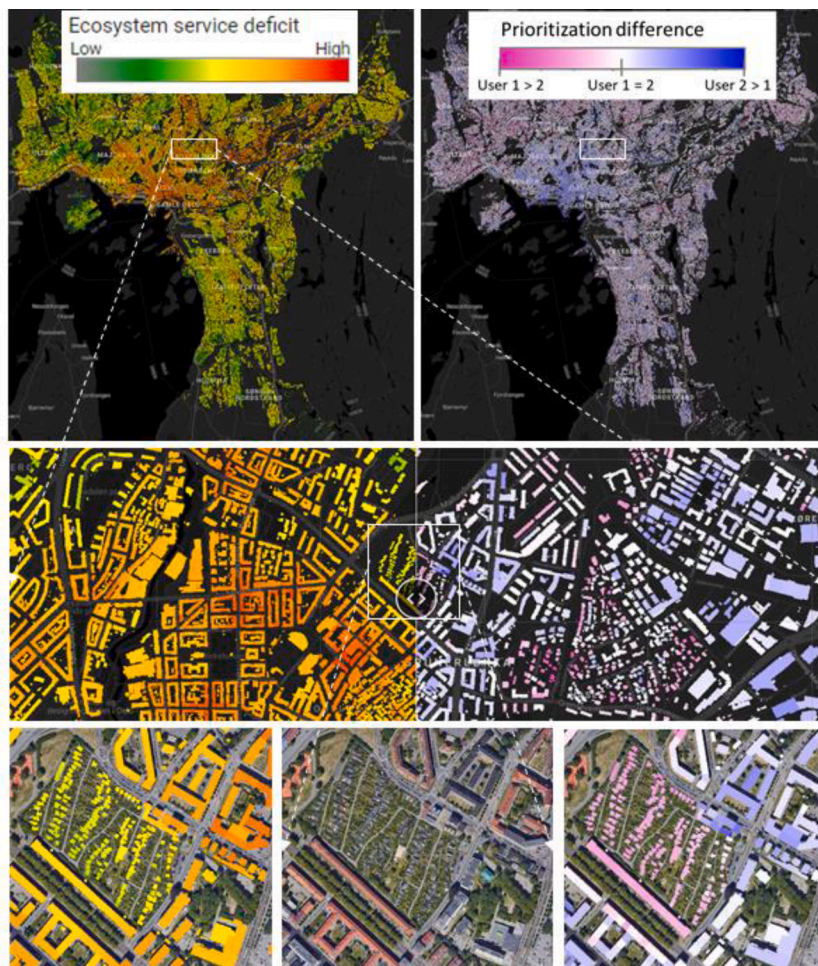


Fig. 5. Maps showing outputs of the MCDA producing a map of the weighted sum of ecosystem service deficits, and consequent green roof priority (left-hand maps). The difference in prioritization for two contrasting stakeholder profiles (community, user 1 vs hotel, user 2) is mapped in right-hand maps to illustrate potential trade-offs and synergies. Blue roofs are those that have a higher priority under the community centre relative to the hotel profile. White bounding boxes identify zoomed extents for borough (center row) and neighborhood (bottom row) scales.



Fig. 6. Screenshot of the MCDA web application highlighting the ability to select individual roofs (blue border) and extract statistics of ecosystem service deficit scores.

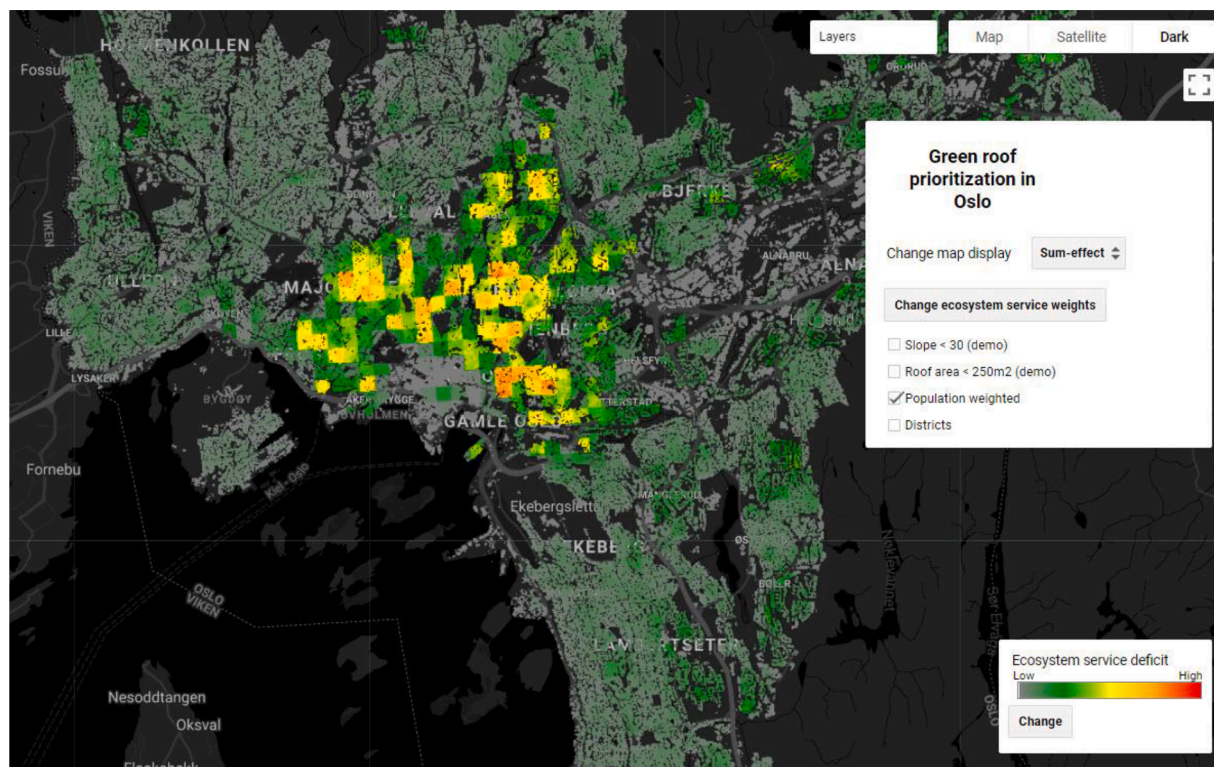


Fig. 7. Screenshot highlighting ecosystem service deficit areas scaled by population density as a proxy for areas of highest demand.

of Oslo's Green Roof Strategy. The criteria we included in the app followed the main priorities identified in a prior co-design process.

4.5. Spatial and temporal correlation of ES deficits and spatial prioritization

An advantage of the app in relation to a co-creation objective to promote learning, is the ease with which users can test different

preference profiles. In our Oslo case, ES deficits combined with similarity in stakeholder preference profiles did not reveal large differences in the spatial targeting of green roofs across different stakeholders. The spatial gradient of vegetation from city core to periphery strongly correlates with ES. The high correlation of ES deficits with population density is a pattern observed in other cities (Langemeyer et al. 2020). The general implication for spatial MCDA is that basic spatial analysis of ecosystem service correlation may reveal coincidences of stakeholders'

interests despite even strong differences in preferences for individual ES. In our Oslo case, differences between stakeholder preference happened to be moderate. A more differentiated spatial targeting map is obtained when engaging the population density criteria scaling ES deficit. The resulting map revealed priority areas in a residential belt in the urban core of the city, but excluding the downtown commercial area with low population density. Workshop participants observed that this would be a significant modification to the zoning identified in the bluegreen factor norm (Supplementary Material S1) which identifies the urban core as a homogenous area. A weakness of population density as a proxy indicator for exposure is that it does not represent ES exposure for inhabitants during daily activities outside of their residential neighbourhood. This modifies current planning incentives for blue-green infrastructure promoted by Oslo Municipality, which include the whole city centre (Oslo Kommune 2019). Ideally, future iterations would include spatial data on population mobility in order to incorporate the temporal nature of population density through the day and year.

4.6. Transferability of the approach to other cities

Despite the Oslo-specific pros and cons of the MCDA web application, there remains scope for testing similar MCDA approaches in other cities. Land use/cover data is the primary input into the ES surplus/deficit layers used in the Oslo MCDA. While we acknowledge that not all cities will have access to detailed spatial data (e.g. LiDAR digital terrain model, population density etc.), high resolution land cover data can be generated from open-access satellite data such as Copernicus Sentinel data (e.g. Baamonde et al., 2019; Qiu et al., 2019; Venter et al., 2020a) for any location globally. Further, the GEE platform used to deploy the web application is available free of charge for research purposes. Therefore the approach presented here is broadly transferable and policy-relevant in other cities, especially those with dense and compact neighborhoods where green infrastructure is scarce. In Barcelona, for instance, it could support the priority-setting process of current municipal funding incentives for the implementation of green roofs. Similarly, in New York City, which recently passed legislation requiring all new buildings to have solar or green roofs, the approach here could be used to help prioritize where to focus limited funds to support new green roof installations.

5. Conclusion

In this study we evaluate prioritization green roof locations at city scale with building-level resolution, using an interactive multi-criteria decision analysis implemented in a GEE platform. Based on a desktop study of municipal plans, strategies and norms we identified a gap in mapping tools at area planning level. The app was developed as a 'meso-level' spatial tool for targeting green roofs at neighbourhood and street level. The main objective of the app is to provide a model "sandbox" where stakeholders and researchers can identify further planning priorities and functionalities desired in an operative decision-support tool. For the Oslo application our analysis revealed high spatial correlation in ES deficits. Under these conditions even large differences in stakeholder preferences for individual ES in MCDA will lead to common interests in spatial targeting of green roofs. The non-technical and interactive functionality of the online spatial MCDA was perceived as a useful tool for the process efficiency of engagement with stakeholders, but MCDA itself was not crucial for the spatial targeting results. In our particular Oslo case, simple spatial analysis of residential population exposure to ES deficits was sufficient to improve on current zoning and permitting tools. Current green roof projects are largely focused on new office and commercial buildings in the city centre. We identified a residential belt within the inner city as the area with highest potential for green roof retrofitting to satisfy public ES demands in Oslo. In other cities with more heterogeneous distribution of green infrastructure, lower spatial correlation of ES and greater differences in stakeholder ES preferences,

the use of online spatial MCDA tools can be expected to improve on both process and outcome efficiency in spatial planning of nature-based solutions and urban nature restoration.

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.

Acknowledgements

This research was funded through the 2015–2016 BiodiverSA COFUND call for research proposals, with the national funders the Swedish Research Council for Environment, Agricultural Sciences, and Spatial Planning; Swedish Environmental Protection Agency; German Aerospace Center (DLR); National Science Centre (Poland); the Research Council of Norway; and the Spanish Ministry of Science, Innovation and Universities. DNB acknowledges support from the Research Council of Norway to the ENABLE project through the BiodiverSA COFUND 2015–2016 call for research proposals. JL acknowledges support from the ERC Consolidator Grant 818002-URBAG awarded to Gara Villalba. FB acknowledges support from the EU's Horizon 2020 framework program for research and innovation (project NATURVATION, grant agreement ID: 730243). TM was supported by US National Science Foundation grants (#1444755, #1927167, and #1934933). Thanks to Zofie Cimburova, Diego Wedgewood and Nabolagshager for help with data collection and analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoser.2021.101314>.

References

- Allain, S., Plumecocq, G., Leenhardt, D., 2017. How do multi-criteria assessments address landscape-level problems? A review of studies and practices. *Ecol. Econ.* 136, 282–295.
- Andersson, E., Langemeyer, J., Borgström, S., McPhearson, T., Haase, D., Kronenberg, J., Barton, D.N., Davis, McKenna, Naumann, S., Röschel, L., Baró, F., 2019. Enabling urban green and blue infrastructure to improve contributions to human well-being and equity in urban systems. *Bioscience*. <https://doi.org/10.1093/biosci/biz058>.
- Arias-Arévalo, P., Gómez-Baggethun, E., Martín-López, B., Pérez-Rincón, M., 2018. Widening the evaluative space for ecosystem services: a taxonomy of plural values and valuation methods. *Environ. Values* 27 (1), 29–53.
- Baamonde, S., Cabana, M., Sillero, N., Penedo, M.G., Naveira, H., Novo, J., 2019. Fully automatic multi-temporal land cover classification using Sentinel-2 image data. *Procedia Comput. Sci.* 159, 650–657.
- Beinat, E., 1997. *Value Functions for Environmental Management*. Kluwer Academic Publishers.
- Benedict, M.A., McMahon, E.T., 2002. Green infrastructure: smart conservation for the 21st century. *Renewable Resour. J.* 20 (3), 12–17.
- Berardi, U., Ghaffarianhoseini, A., Ghaffarianhoseini, A., 2014. State-of-the-art analysis of the environmental benefits of green roofs. *Appl. Energy* 115, 411–428.
- Bugliarello, G., 2006. Urban sustainability: dilemmas, challenges and paradigms. *Technol. Soc.* 28 (1), 19–26.
- Childers, Daniel, Bois, Paul, Hartnett, Hilary, McPhearson, Timon, Metson, Genevieve, Sanchez, Christopher A., 2019. Urban Ecological Infrastructure: An inclusive concept for the non-built urban environment. *Elem. Sci. Anth.* 7 (1), 46. <https://doi.org/10.1525/elementa.385>.
- Cooper, N., Brady, E., Steen, H., Bryce, R., 2016. Aesthetic and spiritual values of ecosystems: recognising the ontological and axiological plurality of cultural ecosystem 'services'. *Ecosyst. Serv.* 21, 218–229.
- Daniels, B., Zaunbrecher, B.S., Paas, B., Ottermanns, R., Ziefle, M., Roß-Nickoll, M., 2018. Assessment of urban green space structures and their quality from a multidimensional perspective. *Sci. Total Environ.* 615, 1364–1378.
- Depietri, Yaella and Timon McPhearson. 2017. Integrating the grey, green, and blue in cities: Nature-based solutions for climate change adaptation and risk reduction, (pp91–109) in: Kabisch, N., Korn, H., Stadler, J., Bonn, A. (Eds), *Nature-based Solutions to Climate Change in Urban Areas: Linkages Between Science, Policy, and Practice*, Springer.
- Depietri, Yaella, Dahal, Khila, McPhearson, Timon, 2018. Multi-hazard risk in a coastal megacity. *Nat. Hazards Earth Syst. Sci.* 18, 3363–3381. <https://doi.org/10.5194/nhess-18-3363-2018>.

- Elmqvist, Thomas, Andersson, Erik, Frantzeskaki, Niki, McPhearson, Timon, Folke, Carle, Olsson, Per, Takeuchi, Kazuhiko, 2019. Sustainability and resilience for urban transformations. *Nat. Sustainability* 2, 267–273. <https://doi.org/10.1038/s41893-019-0250-1>.
- Fish, R., Saratsi, E., Reed, M., Keune, H., 2016. Stakeholder participation in ecosystem service decision making. in: Potschin (Ed.), *Routledge Handbook of Ecosystem Services*. Routledge, pp. 256–270.
- Frantzeskaki, Niki, McPhearson, Timon, Collier, Marcus J., Kendal, Dave, Bulkeley, Harriet, Dumitru, Adina, Walsh, Claire, Noble, Kate, van Wyk, Ernita, Ordóñez, Camilo, Oke, Cathy, Pinter, Laszlo, 2019. Nature-based solutions for urban climate change adaptation: linking the science, policy, and practice community for evidence-based decision-making. *Bioscience*. <https://doi.org/10.1093/biosci/biz042>.
- Funtowicz, S.O., Ravetz, J.R., 1994. The worth of a songbird: ecological economics as a post-normal science. *Ecol. Econ.* 10 (3), 197–207.
- García, A.M., Santé, I., Loureiro, X., Miranda, D., 2020. Green infrastructure spatial planning considering ecosystem services assessment and trade-off analysis. Application at landscape scale in Galicia region (NW Spain). *Ecosyst. Serv.* 43, 101115.
- Garmendia, E., Gamboa, G., 2012. Weighting social preferences in participatory multi-criteria evaluations: a case study on sustainable natural resource management. *Ecol. Econ.* 84, 110–120.
- Gomez-Baggethun, E., Barton, D.N., 2013. Classifying and valuing ecosystem services for urban planning. *Ecol. Econ.* 86, 235–245. <https://doi.org/10.1016/j.ecolecon.2012.08.019>.
- Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google Earth Engine: planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* 202, 18–27.
- Grêt-Regamey, A., Celio, E., Klein, T.M., Wissen Hayek, U., 2013. Understanding ESs trade-offs with interactive procedural modeling for sustainable urban planning. *Landscape Urban Plann.* 109 (1), 107–116. <https://doi.org/10.1016/j.landurbplan.2012.10.011>.
- Grove, M.J., Ogden, L., Pickett, S., et al., 2018. The Legacy Effect: Understanding How Segregation and Environmental Injustice Unfold over Time in Baltimore. *Annals of the Association of American Geographers*, 108: 524–37.
- Jiménez-Muñoz, J.C., Cristóbal, J., Sobrino, J.A., Soria, G., Ninyerola, M., Pons, X., 2008. Revision of the single-channel algorithm for land surface temperature retrieval from Landsat thermal-infrared data. *IEEE Trans. Geosci. Remote Sens.* 47 (1), 339–349.
- Karjalainen, T.P., Marttunen, M., Sarkki, S., Rytönen, A.-M., 2013. Integrating ESs into environmental impact assessment: an analytic-deliberative approach. *Environ. Impact Assess. Rev.* 40, 54–64.
- Keeler, Bonnie L., Hamel, Perrine, McPhearson, Timon, Hamann, Maike, Donahue, Marie, Prado, Kelly Meza, Arkema, Katie, Bratman, Gregory, Brauman, Kate, Finlay, Jacques, Guerry, Anne, Hobbie, Sarah, Johnson, Justin, MacDonald, Graham, McDonald, Robert, Neverisky, Nick, Wood, Spencer, 2019. Social-ecological and technological factors moderate the value of urban nature. *Nat. Sustainability* 2, 29–38.
- Kenter, J.O., 2016. Shared, plural and cultural values. *Ecosyst. Serv.* 21 (B), 175–183.
- Kenter, J.O., Jobstovgt, N., Watson, V., Irvine, K.N., Christie, M., Bryce, R., 2016. The impact of information, value-deliberation and group-based decision-making on values for ecosystem services: integrating deliberative monetary valuation and storytelling. *Ecosyst. Serv.* 21, 270–290.
- Kuller, M., Bach, P.M., Roberts, S., Browne, D., Deletic, A., 2019. A planning-support tool for spatial suitability assessment of green urban stormwater infrastructure. *Sci. Total Environ.* 686, 856–868.
- Langemeyer, J., Connolly, J.J.T., 2020. Weaving notion of justice into urban ecosystem service research and practice. *Environ. Sci. Policy* 109 (2020), 1–14. <https://doi.org/10.1016/j.envsci.2020.03.021>.
- Langemeyer, J., Baraibar, S., Palomo, I., Gómez-Baggethun, E., 2018. Participatory Multi-Criteria Decision Aid: A way to operationalize ecosystem services. *Ecosystem Services*, 30, Part A, 49–60. DOI:10.1016/j.ecoser.2018.01.012.
- Langemeyer, J., Gómez-Baggethun, E., Haase, D., Scheuer, S., Elmqvist, T., 2016. Bridging the gap between ecosystem service assessments and land-use planning through multi-criteria decision analysis (MCDA). *Environ. Sci. Policy* 62, 45–56.
- Langemeyer, J., Wedgwood, D., Barton, D., Baró, F., McPhearson, T., 2020. Creating nature-based solutions where they are needed – a spatial ecosystem service-based decision analysis of green roofs in Barcelona. *Sci. Total Environ.* 707 (10), 135487. <https://doi.org/10.1016/j.scitotenv.2019.135487>.
- Lo, A.Y., Spash, C.L., 2013. Deliberative monetary valuation: in search of a democratic and value plural approach to environmental policy. *J. Econ. Surveys* 27 (4), 768–789.
- Locke, D.H., Hall, B., Grove, J.M., Pickett, S.T.A., Ogden, L.A., Aoki, C., Boone, C.G., O'Neil-Dunne, J.P.M., [in review]. Residential housing segregation and urban tree canopy in 37 US Cities. Submitted to Urban Sustainability. Preprint available here: <https://osf.io/preprints/socarxiv/97zcs>.
- Mascarenhas, A., Ramos, T.B., Haase, D., Santos, R., 2016. Participatory selection of ecosystem services for spatial planning: Insights from the Lisbon Metropolitan Area, Portugal. *Ecosyst. Serv.* 18, 87–99.
- McPhearson, T., Pickett, S.T.A., Grimm, N., Niemelä, J., Alberti, M., Elmqvist, T., Weber, C., Haase, D., Breuste, J., Qureshi, S., 2016. Advancing urban ecology toward a science of cities. *Bioscience* 66 (3), 198–212. <https://doi.org/10.1093/biosci/biw002>.
- McPhillips, L., Chang, H., Chester, M.V., Depietri, Y., Friedman, E., Grimm, N.B., Kominoski, J.S., McPhearson, T., Méndez-Lázaro, P., Rosi, E.J., Shiva, J.S., 2018. Defining extreme events: a cross-disciplinary review. *Earth's Future*. <https://doi.org/10.1002/2017EF000686>.
- Mendoza, G.A., Martins, H., 2006. Multi-criteria decision analysis in natural resource management: a critical review of methods and new modeling paradigms. *For. Ecol. Manage.* 230, 1–22.
- Oikonomou, V., Dimitrakopoulos, P.G., Troumbis, A.Y., 2011. Incorporating ecosystem function concept in environmental planning and decision-making by means of multi-criteria evaluation: the case-study of Kalloni Lesbos, Greece. *Environ. Manage.* 47 (1), 77–92.
- Oprić, S., Tzeng, G.H., 2007. Extended VIKOR method in comparison with outranking methods. *Eur. J. Oper. Res.* 178 (2), 514–529.
- Oslo Kommune, 2013. Oslo Og Green! Application to become European Green Capital 2016. Submitted 31.10.2013.
- Oslo Kommune, 2013. STØYKARTLEGGING 2012 Oslo, Asker, Bærum, Skedsmo, Lørenskog, Rælingen og Oppegård Støysituasjon for året 2011. Bymiljøetaten.
- Oslo Kommune, 2018. GRØNNE FRAMTIDSUTSIKTER Strategi for grønne tak og fasader i Oslo Byggningsintegrerte grønne strukturer 2019–2030. Bymiljøetaten.
- Oslo Kommune, 2019. Blågrønn faktor for boliger i Oslo—Norm. 11.12.2019.
- Oslo Kommune 2020. Høring på Forslag til strategi for grønne tak og fasader (Sak: 201502863 – 22). Plan og Bygningsetaten.
- Padró, R., La Rota-Aguilera, M., J., Giocoli, A., Cirera, J., Coll, F., Pons, M., Pino, J., Pili, S., Serrano, T., Villalba, G., Marull, J., 2019. Assessing the sustainability of contrasting land use scenarios through the Socioecological Integrated Analysis (SIA) of the metropolitan green infrastructure of Barcelona, Metropolitan Laboratory of Ecology and Territory of Barcelona.
- Qiu, C., Mou, L., Schmitt, M., Zhu, X.X., 2019. Local climate zone-based urban land cover classification from multi-seasonal Sentinel-2 images with a recurrent residual network. *ISPRS J. Photogrammetry Remote Sensing* 154, 151–162.
- Ramyar, R., Saedi, S., Bryant, M., Davatgar, A., Hedjri, G.M., 2020. Ecosystem services mapping for green infrastructure planning—the case of Tehran. *Sci. Total Environ.* 703, 135466.
- Saarikoski, H., Mustajoki, J., Barton, D., Geneletti, D., Langemeyer, J., Gómez-Baggethun, E., Marttunen, M., Antunes, P., Keune, H., Santos, R., 2016. Multicriteria decision analysis and cost-benefit analysis: comparing alternative frameworks for integrated valuation of ecosystem services. *Ecosyst. Serv.* 22, 238–249.
- Saarikoski, H., Mustajoki, J., Hjerpe, T., Aapala, K., 2019. Participatory multi-criteria decision analysis in valuing peatland ecosystem services—trade-offs related to peat extraction vs. pristine peatlands in Southern Finland. *Ecol. Econ.* 162, 17–28.
- Saaty, T.L., 1980. A scaling method for priorities in hierarchy structures. *J. Math. Psychol.* 15, 234–281.
- Sæthun, N.R., Barton, D.N., Venter, Z.S., 2021. REO: estimering av overflateavrenning fra urbane felt. Beregningsgrunnlag for et arealdifferensiert overvannsgebyr (revidert utgave). Oslo: Norsk institutt for naturforskning (NINA) 2021 (ISBN 978-82-426-4723-8) 33 s. NINA rapport 1851b.
- Sanon, S., Hein, T., Douven, W., Winkler, P., 2012. Quantifying ES trade-offs: the case of an urban floodplain in Vienna, Austria. *J. Environ. Manage.* 111, 159–172. <https://doi.org/10.1016/j.jenvman.2012.06.008>.
- Seiferling, I., Naik, N., Ratti, C., Proulx, R., 2017. Green streets—quantifying and mapping urban trees with street-level imagery and computer vision. *Landscape Urban Plann.* 165, 93–101.
- Srdjevic, Z., Lakicevic, M., Srdjevic, B., 2013. Approach of decision making based on the analytic hierarchy process for urban landscape management. *Environ. Manage.* 51 (3), 777–785.
- Stange, E., Zulian, G., Rusch, G., Barton, D., Nowell, M., 2017. Ecosystem services mapping for municipal policy: ESTIMAP and zoning for urban beekeeping. *One Ecosyst.* 2.
- Susca, T., Gaffin, S.R., Dell'Osso, G.R., 2011. Positive effects of vegetation: Urban heat island and green roofs. *Environ. Pollut.* 159 (8–9), 2119–2126. <https://doi.org/10.1016/j.envpol.2011.03.007>.
- Turner, B., Henryks, J., Pearson, D., 2011. Community gardens: sustainability, health and inclusion in the city. *Local Environ.* 16 (6), 489–492.
- Vallecillo, S., La Notte, A., Polce, C., Zulian, G., Alexandris, N., Ferrini, S. and Maes, J., 2018. Ecosystem services accounting: part I—Outdoor recreation and crop pollination. Publications Office of the European Union, Luxembourg.
- Van der Horst, L., Townsend, L., Jacobs, A., 2013. Merging man with nature: Restoring the environmental functions and processes of Sørhellinga and the regional biotope diversity by creating a green roof. Term paper. INA Department. Norwegian University of Life Sciences.
- Venter, Z.S., Brousse, O., Esau, I., Meier, F., 2020a. Hyperlocal mapping of urban air temperature using remote sensing and crowdsourced weather data. *Remote Sens. Environ.* 242, 111791.
- Venter, Z.S., Krog, N.H., Barton, D.N., 2020b. Linking green infrastructure to urban heat and human health risk mitigation in Oslo, Norway. *Sci. Total Environ.* 709, 136193.
- Venter, Z.S., Shackleton, C.M., Van Staden, F., Selomane, O., Masterson, V.A., 2020c. Green Apartheid: Urban green infrastructure remains unequally distributed across income and race geographies in South Africa. *Landscape Urban Plann.* 203, 103889.
- Whittinghill, L.J., Rowe, D.B., 2012. The role of green roof technology in urban agriculture. *Renewable Agric. Food Syst.* 27 (04), 314–322.
- Wilson, M.A., Howarth, R.B., 2002. Discourse-based valuation of ecosystem services: establishing fair outcomes through group deliberation. *Ecol. Econ.* 41 (3), 431–443.
- Zhang, X., Lu, X., 2010. Multiple criteria evaluation of ecosystem services for the Ruogai Plateau Marshes in southwest China. *Ecol. Econ.* 69 (7), 1463–1470.
- Zia, A., Hirsch, P., Songorwa, A., Mutekanga, D.R., O'Connor, S., McShane, T., Brosius, P., Norton, B., 2011. Cross-scale value trade-offs in managing social-ecological systems: the politics of scale in Ruaha National Park, Tanzania. *Ecol. Society* 16 (4).
- Zulian, G., Maes, J., Paracchini, M., 2013. Linking land cover data and crop yields for mapping and assessment of pollination services in Europe. *Land* 2, 472–492.